Chapter 6
Riparian Forests: Longitudinal Biodiversity Islands in Agricultural Landscapes

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Abstract Riparian buffers safeguard the only remaining forest fragments in many agricultural landscapes of the Colombian Andean region. These linear landscape elements contribute to the conservation of terrestrial biodiversity in agricultural landscapes by providing shelter, reproduction sites, food, and connectivity for arthropods, amphibians, mammals and birds. Thus, riparian buffers play a critical role as biodiversity islands. In addition, forested riparian buffers protect aquatic environments and water quality by reducing the input of pollutants from catchment areas, improving physical habitat with shade, and adding allochthonous materials that provide the main source of energy for stream ecosystems. This chapter summarizes the results of research conducted during the past two decades by the Center for Research in Sustainable Agricultural Systems (CIPAV) in the Central Andes coffee-growing region of Colombia. These studies highlight the critical role of forested riparian buffers for conservation and ecosystem services. We provide a synthesis of lessons learned on the effects of both cattle grazing and riparian forest cover on stream ecosystems. This body of research also demonstrates that streams protected by riparian forests support complex and biodiverse macroinvertebrate assemblages and may respond positively to the ecological restoration of riparian strips. The chapter concludes with recommendations for restoring and protecting riparian buffers from agricultural practices, partially through incentives to landowners. These insights have emerged from decades of research and institutional experience on riparian restoration initiatives.

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F. Montagnini (ed.), *Biodiversity Islands: Strategies for Conservation in Human-Dominated Environments*, Topics in Biodiversity and Conservation 20,
https://doi.org/10.1007/978-3-030-92234-4_6

Keywords Andean streams · Colombian Andes · Ecological restoration · Riparian biodiversity · Riparian buffers · La Vieja River

6.1 Introduction

Forested riparian buffers (also known as riparian forests) are strips of vegetation that grow along rivers and streams, and around springs and wetlands. These longitudinal elements, distributed along the water network, act as biodiversity islands, connecting forest fragments, conserving water sources, and providing environmental benefits to adjacent agroecosystems (Ericsson and Stevens 1996; Naiman et al. 2000; Schroth et al. 2004; Lees and Peres 2007; Palmer et al. 2014; Luke et al. 2019).

In Colombia, forested riparian buffers, which have an average width of 24 m, are often the only patches of woody vegetation that remain in many agricultural landscapes. Although forested riparian buffers often occupy small land areas, they make a disproportionate contribution to the landscape-scale conservation of birds, arthropods, and other organisms that provide essential services such as biological pest control, seed dispersal, pollination and carbon sequestration (Schroth et al. 2004; Marczak et al. 2010).

However, despite their importance, these forest strips are being destroyed and replaced with pastures or cropland, which has had negative effects on aquatic environments, water quality, and terrestrial biodiversity (Braccia and Voshell 2007; Chará et al. 2007; Riseng et al. 2011; Skłodowski et al. 2014). This is the case of the Central Andes coffee-growing region of Colombia, where many forests, including riparian corridors, were replaced with coffee or banana plantations and pastures during the second half of the twentieth century (Sadeghian et al. 1999). In some areas of this region, land cover transformation has been successfully reversed through restoration projects carried out by local farmers and the Center for Research in Sustainable Agricultural Systems (CIPAV, an autonomous Colombian organization with 35 years of experience in research, training and outreach on sustainable agricultural production systems; Calle 2020). Several of the restoration projects developed by CIPAV in this coffee-growing region have focused on the implementation of environmentally friendly agroforestry and silvopastoral systems and the release of riparian areas for forest restoration (Calle 2020).

This chapter synthesizes the findings of research conducted for two decades along with restoration projects in this coffee-growing region. These studies evaluated the role of riparian forests in the protection of terrestrial biodiversity and aquatic environments by monitoring the results of several restoration initiatives focused on these key landscape elements. The chapter ends with a synthesis of the lessons learned from these studies, together with recommendations that can be applied to riparian restoration.

6.1.1 Study Area

The region of central-western Colombia known as the “Eje Cafetero” (coffee-growing region) includes a variety of ecosystems of the Central Andes (Cordillera Central), from lowland rainforests to snow-capped mountains. Its high biodiversity and unique ecosystems are threatened by landscape transformation to establish pastures or crops. For this reason, it has been recognized internationally as a conservation priority (CARDER-FONADE 2002; Uribe-Gómez 2008). In the 1990s, many coffee growers in the region eliminated their plantations as a result of the economic instability triggered by the fall of international coffee prices, making pastures for bovine livestock become the dominant land use at elevations between 1200 and 1800 m (Sadeghian et al. 1999). The adoption and management of livestock grazing systems have changed the species composition and vegetation structure of riparian buffers in this region (Chará-Serna et al. 2015; Fig. 6.1).

CIPAV studies were done at La Vieja river basin in the Central Andes coffee-growing region (Fig. 6.2). These watersheds are located on rolling hills and valleys, at altitudes between 900 and 2400 m, with average annual rainfall of 1900–2600 mm and mean temperature between 12 and 24 °C, varying with elevation. Rainfall exhibits a bimodal seasonality, with two annual periods of high precipitation (April–May and October–November). The studies focused on the effects of agricultural systems (mainly cattle ranching) on headwater micro-basins (<100 ha), the role of forested riparian buffers in mitigating these effects on aquatic environments, and the conservation of terrestrial biodiversity.

Fig. 6.1 Riparian forest in a cattle ranching landscape, coffee-growing region of Colombia. (Photo: Julián Chará)

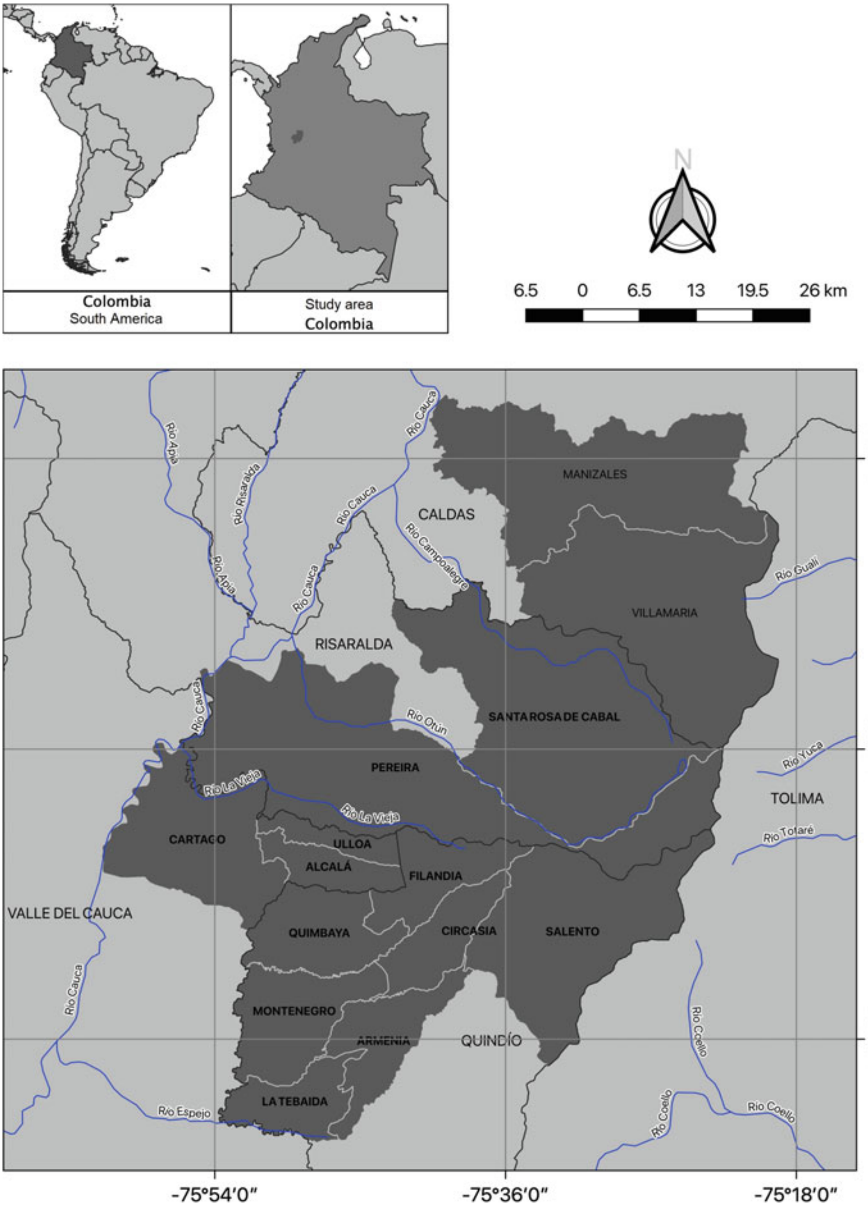

Fig. 6.2 Study area in the Central Andes coffee-growing region, Colombia. (Map: Julián Mendivil)

Close to 20% of the land in La Vieja river basin is covered by secondary, mature and riparian forests. The most species-rich botanical families in this area are Lauraceae, Rubiaceae, Moraceae, Euphorbiaceae and Fabaceae. Abundant species in riparian forests include *Ocotea* sp., *Calliandra pittieri*, *Miconia* sp., *Cordia* *alliodora*, *Guadua angustifolia*, *Cupania americana*, *Sorocea trophoides*, *Oreopanax cecropifolius*, *Piper crassinervium*, *Anacardium excelsum*, *Cecropia angustifolia*, *Croton magdalenensis*, *Heliconia platystachys*, *Brosimum alicastrum*, *Aiphanes horrida*, *Cinnamomum triplinerve*, *Guarea guidonia* and *Urera caracasana* (Méndez and Calle 2010). A large portion of this species richness is confined to riparian forests, in contrast with the agricultural matrix, where the diversity of woody plants is very low (Méndez and Calle 2010).

6.2 Riparian Forests and Biodiversity

Riparian forests link terrestrial and aquatic ecosystems through processes that occur at different spatial scales. At the watershed scale, these forests contribute to ecological functions that depend on species movement or landscape connectivity. On a local scale, riparian forests provide organic matter and shade to streams, maintain slope stability, and protect stream beds, thereby determining habitat quality and aquatic biodiversity.

6.2.1 Terrestrial Biodiversity (Regional or Watershed Scale)

Riparian forests protect some of the most biodiverse and dynamic ecosystems on the planet (Naiman et al. 2005). Their vegetation may include unique species assemblages and sustain animal populations that depend on these ecosystems for shelter, reproduction, food and passage (Moore and Richardson 2003; Sabo et al. 2005). Studies on mammals, birds and dung beetles have shown that forested riparian buffers support more terrestrial biodiversity than the surrounding agricultural matrix (Fajardo et al. 2009; Gray et al. 2014; Zimbres et al. 2017; Luke et al. 2019). These ecosystems are biodiversity islands because they are often the last forest remnants in agricultural landscapes. In this context, their conservation and restoration help mitigate biodiversity loss and habitat fragmentation (Lees and Peres 2007). Due to their linear configuration, riparian forests act as biological corridors, connecting forest patches in fragmented landscapes, and facilitating migration and dispersal of birds, mammals, reptiles, amphibians, insects and other organisms that provide key ecosystem services (Naiman et al. 2005; Medina et al. 2007; Gray et al. 2017).

Studies conducted in agricultural landscapes of the Colombian coffee-growing region have found that compared to all other types of ecosystems, forested riparian buffers and forest fragments have the most structurally complex and species-rich vegetation (Table 6.1). Out of 390 woody plant species known to exist in the agricultural basin of La Vieja river, 278 species (71%) were found in riparian forests (Calle and Méndez 2009), where the dominant species include *Guadua angustifolia* (bamboo), *Cupania americana*, *Sorocea trophoides*, *Oreopanax cecropifolius*, *Piper crassinervium*, *Anacardium excelsum* and *Cecropia angustifolia*.

Table 6.1 Bird, woody plant and dung beetle species richness in riparian forests and other land uses in cattle farms of the Central Andes coffee-growing region (CSCRP: Colombian Sustainable Cattle Ranching Project) (http://ganaderiacolombianasostenible.co)

Land use	Woody plant species richness (Calle and Méndez 2009)	Bird species richness (Fajardo et al. 2009)	Woody plant species richness (CSCRP)
Riparian forest	278	103	183
Secondary and mature forest	264	92	199
Secondary growth areas	–	88	–
Bamboo forest (*Guadua angustifolia*)	89	–	–
Agriculture	86	–	–
Scattered trees in paddocks	–	–	15
Live fences	–	–	25
Intensive silvopastoral systems	–	–	18
Enhanced treeless pasture	–	45	1
Natural treeless pasture	102	38	–

More recent studies done in this coffee-growing region by the Colombian Sustainable Cattle Ranching Project (http://ganaderiacolombianasostenible.co), found a high diversity of plants in riparian forests (unpublished data; Table 6.1). Some threatened and scarce tree species were found in riparian forests, including *Cedrela odorata*, *Swietenia macrophylla*, *Podocarpus oleifolius*, *Anacardium excelsum* and *Astronium graveolens*.

Additionally, compared to other landscape elements and land uses in the region, riparian forests in this basin showed the highest bird species richness (103 of the 229 species in the landscape, ≈45%), and contained most of the 41 bird species of global conservation concern recorded in the region (Fajardo et al. 2009) (Table 6.1). Endemic and nearly endemic bird species observed in this study include the 'grayish piculet' (*Picumnus granadensis*), 'flamerumped tanager' (*Ramphocelus flammigerus*), 'apical flycatcher' (*Myiarchus apicalis*), 'crested ant-tanager' (*Habia cristata*), 'bar-crested antshrike' (*Thamnophilus multistriatus*), 'scrub tanager' (*Tangara vitriolina*) and 'grasshopper sparrow' (*Ammodramus savannarum*).

6.2.2 *Aquatic Biodiversity (Local Scale)*

Forested riparian buffers mitigate the impact of agricultural activities on aquatic ecosystems through different mechanisms. Riparian vegetation filters and retains sediments, organic matter, nutrients, chemical substances and pathogens released from the catchment area, preventing them from entering aquatic ecosystems. Furthermore, tree shade reduces fluctuations in water temperature, and the roots of dense

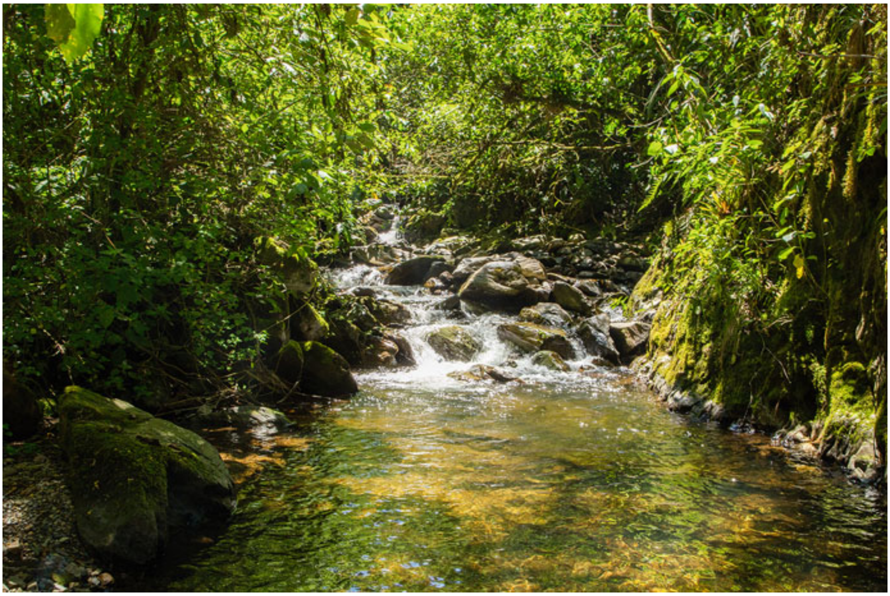

Fig. 6.3 Stream protected by a riparian forest on a cattle farm in the coffee-growing region, Colombia. (Photo: Carlos Pineda)

vegetation stabilize riverbanks, protecting them from erosion (Osborne and Kovacic 1993; Mingoti and Vettorazzi 2011; Schilling and Jacobson 2014; Tanaka et al. 2016) (Fig. 6.3). Together, these mechanisms enhance hydrological regulation, improve water quality and contribute to the conservation of aquatic biodiversity.

Studies done in agricultural landscapes of the Central Andes coffee-growing region have shown that headwater streams protected with riparian forests often contain a considerable diversity of aquatic macroinvertebrates (Chará et al. 2007; Giraldo et al. 2014; Villada et al. 2017; Ramírez et al. 2018). This biodiversity is also related to water quality and characteristics of the streambed such as the abundance of stones (Table 6.2). Macroinvertebrate orders like Ephemeroptera, Plecoptera and Trichoptera (also known as EPT taxa) play an important role in processing leaf litter contributed by the riparian vegetation to the aquatic environment and are particularly sensitive to habitat alteration. Therefore, they are considered bioindicators of conserved ecosystems. Up to 77% of the families and 42% of the genera of Trichoptera reported for Colombia were found to be associated with forested riparian buffers (Ascúntar et al. 2014).

Recent studies of small streams protected by riparian forests within agricultural landscapes have expanded the known distributions of several species of the orders Trichoptera, Plecoptera and Coleoptera in Colombia (Zúñiga et al. 2014, 2015; González-Córdoba et al. 2015, 2016). Additionally, research in these small ecosystems has resulted in the discovery and description of new aquatic insect species for the country (Molineri et al. 2016). These findings support the value of small streams as unexpected reservoirs of biodiversity in agricultural landscapes.

Table 6.2 Mean values of physical and biological variables in watersheds of the Central Andes coffee-growing region of Colombia. The impact estimate is the arithmetic difference between watersheds with forested and pasture-dominated riparian buffers. Based on Chará et al. (2007), Giraldo et al. (2014), Villada et al. (2017), Ramírez et al. (2018) and summarized in Giraldo (2019)

Variable	Watersheds with forested riparian buffers n = 24	Watersheds with pasture-dominated riparian buffers n = 30	Impact estimate (%)
Width of streambed (bank to bank) (m)	2.3	4.2	82.6 (+)
Depth (cm)	17.5	13.1	25.1 (−)
% of rocks	67	13	80.5 (−)
% of mud	18	61	238.8 (+)
Macroinvertebrates			
Mean abundance	751.8	2811.2	274 (+)
Richness	83	72	13.2 (−)
% EPT[a]	36.1	4.2	88.3 (−)
% Diptera	25.5	42.5	66.6 (+)
% Mollusca	9.7	42.2	335 (+)
Water quality			
Temperature (°C)	18.4	21.8	18.4 (+)
Total solids (mg L^{-1})	85.5	146.8	71.6 (+)
Total suspended solids (mg L^{-1})	9.7	139	1332.9 (+)
BOD $_{5\text{-}20^\circ\ C}$ (mg. $L^{-1}O_2$)	2.3	6.2	169.5 (+)
Ammonia nitrogen (mg.L^{-1} N-NH_3)	0.47	0.67	42.5 (+)
Dissolved oxygen (mg.L^{-1})	6.1	4.3	29.5 (−)
Fecal coliforms (MPN. 100 mL^{-1})	1596.3	36200.6	2167.7 (+)

[a]Ephemeroptera, Plecoptera, Trichoptera
BOD biochemical oxygen demand, *MPN* most probable number

Similar studies have shown that the elimination of riparian forests often triggers severe changes in the composition of the aquatic fauna, such as a loss of diversity of sensitive EPT taxa, and an increase in the abundance of groups that are tolerant to organic pollution, such as Diptera and Mollusca (Chará et al. 2007; Giraldo et al. 2014; Ramírez et al. 2018) (Table 6.2). Agricultural practices have also been shown to affect aquatic macroinvertebrates indirectly, by increasing nitrogen concentrations and reducing the width of forested riparian strips. These alterations reduce habitat quality for aquatic fauna by limiting the availability of coarse substrates within stream channels (Chará-Serna et al. 2015).

Riparian forests provide large quantities of coarse particulate organic material (leaves, flowers, fruits, branches) to the aquatic environment. These organic inputs are the primary source of energy for food webs in forested headwater streams, where the closed canopy limits light availability and primary productivity (Hynes 1975; Vannote et al. 1980; Wallace et al. 1997). The processing of allochthonous inputs of organic matter initiates the transfer of energy that then flows through the aquatic food web in these ecosystems (Jones 1997; Wallace et al. 1997; Lamberti and Gregory 2006; Aldridge et al. 2009; Yoshimura 2012). Coarse plant material also maintains aquatic biodiversity by providing habitats and physical structures that are used by fauna (Suurkuukka et al. 2014). In a comparative study of protected and unprotected streams, Giraldo (2019) found a greater abundance (584 vs. 40 individuals), richness (10 vs. 5 genera) and biomass (3.6 vs. 0.35 g) of leaf-processing macroinvertebrates per grasp in streams with riparian forests.

In addition, riparian vegetation offers shelter for emerging adult stages of aquatic insects, which may not be able to fly far and constitute an important food source for birds, bats, amphibians and other insectivorous species. Riparian forests provide habitat for other species of arthropods, mollusks, crustaceans, and small fish that are consumed by terrestrial organisms, contributing to the transfer of energy between terrestrial and aquatic ecosystems (Paetzold et al. 2005).

6.3 Impacts of the Loss of Riparian Forests on Streams

Even though riparian forests perform essential functions related to the protection of water quality and biodiversity, they have been highly impacted around the world (Kuglerová et al. 2014). Farmers often remove riparian forests to establish pastures and crops because the riparian forest soils are richer in nutrients than the surrounding areas (Naiman et al. 2005). Replacing native forests with pastures or crops leads to several negative effects, including increased inputs of sediments and pollutants to water sources, reduced water regulation capacity, and biodiversity loss (Duehr and Siepker 2006; Chará et al. 2007; Lorion and Kennedy 2009; Turunen et al. 2019). Table 6.2 summarizes several differences in physical, biological and water quality variables between water sources with and without the protection of the riparian vegetation. Unprotected sites tend to have shallower water, lower proportions of coarse substrates, lower species richness, higher abundance of organisms and higher values in parameters such as water temperature, solids, biochemical oxygen demand (BOD), nitrogen, and fecal coliforms.

The following list presents some lessons learned about the effects of livestock and riparian forests on headwaters of the Central Andes coffee-growing region (described in detail in Giraldo (2019), based on studies of water quality, habitat quality, aquatic macroinvertebrates and the flow of coarse particulate organic matter (Chará et al. 2007, 2011; Camargo et al. 2011; Giraldo et al. 2014; Chará-Serna et al. 2015; Galindo et al. 2017; Ramírez et al. 2018; Giraldo 2019).

- Cattle grazing in catchment areas causes undesirable effects such as soil compaction, reduced infiltration capacity, varying degrees of erosion, and the loss of forests that protect streams. Comparative studies of soils under two types of riparian vegetation carried out in the area have found that soils had lower apparent density (0.7 vs. 0.9 g/cm^3), higher total porosity (70% vs. 60%) and lower susceptibility to compaction (85% vs. 88.3%) in bamboo (*Guadua angustifolia*) riparian forests than in pastures (Camargo et al. 2011).
- The degradation or removal of riparian forests reduces canopy cover and shade. Vegetation structure and composition become simplified as plant covers dominated by grasses and pioneer shrubs (mostly Piperaceae and Melastomataceae) replace more diverse woody vegetation.
- Although woody plants from nearby areas continue to disperse their seeds to degraded riparian strips, the vigorous growth of grasses may temporarily inhibit the establishment of trees and shrubs. In sites without restoration treatments, pastures can cover up to 52% of the area (Galindo et al. 2017).
- The loss of riparian forests and their buffering services amplifies the negative effects of grazing on watersheds. Without shade, water temperature, organic matter, nutrients and pathogens increase while dissolved oxygen decreases (Chará et al. 2007; Giraldo et al. 2014). Each of these changes implies a loss of water quality with negative consequences for nearby human populations in addition to local species.
- The removal of riparian woody vegetation facilitates the direct access of cattle to streambeds. Without the strong roots that stabilize stream margins, cattle trampling rapidly deteriorates banks and slopes.
- Damage to the banks accelerates erosion and sedimentation of the streambed and changes channel morphology. The average width of the bed in unprotected streams is 5.4 m, compared to 2.2 m in sites protected by riparian forests (Chará et al. 2007).
- Streams where riparian forests have been eliminated and cattle have direct access to the channel tend to be shallower than protected streams, with a significant fraction of coarse substrates being replaced by fine sediments such as silt and sand. In cattle areas, up to 100% of the riverbed of unprotected streams can become covered by very fine substrates (Giraldo et al. 2014).
- The loss of riparian forest reduces the inputs of wood, litter, and other coarse materials in streams. Fallen organic matter forms important microhabitats such as pools and small turbulences, provides colonization substrates for organisms, and is an essential source of energy for macroinvertebrates. Pools occupy a smaller proportion of the area in streams impacted by livestock activities than in those protected by riparian forests (13% vs. 46%, respectively; Chará et al. 2007).
- Lower water quality and modified physical conditions of streams cause changes in macroinvertebrate communities. In these circumstances, groups that tolerate habitat degradation, such as mollusks (Physidae) and dipterans (mainly of the Chironomidae and Simuliidae families) tend to increase in abundance and dominance, but the overall richness of species, families, and orders tends to decrease.

- On average, streams protected by riparian forests receive 7.3 times more leaf litter per year than unprotected streams (9150 kg vs. 1255 kg per hectare of woody vegetation, respectively; Giraldo 2019).
- Leaves form the largest proportion of litter that enters forested streams. However, in buffer strips covered by grasses, a qualitative change occurs in the composition of accumulated material when the inputs of wood, flowers and fruits are lost. Due to the lack of logs that form pools and structures that retain materials on the stream bed, the rate of storage can be four times lower in streams with grasses (Giraldo 2019).
- Although the studied watersheds are immersed in agricultural landscapes and occupy relatively small areas (<100 ha), their aquatic ecosystems harbor impressive biodiversity, represented mainly by macroinvertebrates. The conservation of these watersheds is essential to protect this biota. Small watersheds are also the main sources of water for rural communities, so their conservation is also critical from a public health perspective.

6.4 Restoration of Riparian Forests in Agricultural Landscapes

Riparian restoration should start by guaranteeing the protection of existing forest remnants and improving connectivity between the upper and lower sections of watersheds. When restoring riparian forests, it is useful to define a set of clear objectives or reference conditions in terms of ideal forest structure and composition. The selection of restoration techniques will depend on the specific conditions of each site, including the characteristics of the remnant vegetation, soil conditions, and the proximity to seed sources (e.g., other forest fragments).

The restoration of riparian areas in agricultural landscapes should be prioritized, facilitating the gradual reestablishment of woody vegetation and its associated ecological functions in terrestrial and aquatic ecosystems (Meli et al. 2019). Certain characteristics of restored riparian forests, such as their width, length, and vegetation structure, determine the magnitude of the environmental benefits of restoration, such as reductions in nutrient cycling rates, the protection of aquatic environments, and landscape-scale biodiversity conservation.

Fencing riparian strips is one of the most popular methods to initiate the restoration of riparian forests in agricultural landscapes. Fencing has been shown to enhance the natural regeneration of riparian vegetation by preventing the access of cattle to riparian areas. For example, riparian strips that had been protected from grazing during the last 10 to 14 years in La Vieja river basin had recovered a similar assemblage of dominant species as reference forest ecosystems in the area, including common species of trees such as *Cupania americana*, *Inga edulis*, *Cecropia angustifolia* and *Croton magdalenensis*, and some locally threatened species such as *Anacardium excelsum*, *Oreopanax cecropifolius*, *Trichilia pallida*, *Aiphanes horrida*, *Nectandra turbacensis*, *Ocotea macropoda* and *Machaerium capote*

Table 6.3 Vegetation structure in reference sites and riparian buffers undergoing restoration at La Vieja river basin (Calle and Holl 2019)

	Reference	Restored
Average tree species density	8.5 species ha^{-1}	19 species ha^{-1}
Density of tree stems	300 stems ha^{-1}	750 stems ha^{-1}
Basal area	8 m^2 ha^{-1}	14.6 m^2 ha^{-1}
Average canopy cover	Not available	89%
Grass cover	Not available	< 5%

(Calle and Holl 2019). Additionally, restored areas had more species, a higher density of tree stems, higher canopy cover and lower grass cover than reference forests (Table 6.3).

Different factors may slow down or prevent the spontaneous regeneration of woody species in fenced riparian buffers. A frequent issue in deforested cattle ranching watersheds is the uncontrolled growth of grasses on the riparian strips. Dense grass growth may inhibit the regeneration of shrubs and trees, even after the removal of grazing, temporarily halting secondary succession. Techniques of assisted natural regeneration, such as the periodic control of competing plants and the enrichment planting of pioneer trees, can be used to accelerate forest recovery. Fast-growing shrubs can be planted to shade out grasses, slow their growth and facilitate the regeneration of woody plants, offsetting the inhibitory effects of grass growth. For example, Galindo et al. (2017) studied the effect of *Tithonia diversifolia* and *Piper auritum* planted at high-density to shade the grasses and facilitate the establishment of native trees. After 15 months, *T. diversifolia* was able to reduce grass cover by 81% and enhanced the survivorship of native trees planted underneath.

Riparian restoration efforts can also have beneficial effects on aquatic environments. A recent study of several cattle ranching watersheds in the Andean region of Colombia showed that the early growth of native vegetation in riparian strips enhances the chemical and biological properties of aquatic ecosystems (Giraldo et al. 2020). The biochemical oxygen demand (BOD), which measures organic water pollution, was significantly lower in the studied streams 36 months after the beginning of riparian restoration activities. Similarly, restored streams showed an increase in dissolved oxygen, as well as a decrease in turbidity and fecal coliforms. Regarding the composition of biological communities, the relative abundance of tolerant aquatic insects of the family Chironomidae (Diptera) significantly decreased through the 3 years of sampling, whereas the abundance of the family Hydropsychidae (Trichoptera) showed moderate increases. Together these bio-indicators suggest that the stream ecosystem is being restored.

6.5 Conclusions and Recommendations

Given the strategic value of riparian forests, all initiatives to protect and restore these landscape elements and their ecosystems should be designed with the complete basin in mind. The following recommendations are based on lessons learned through various studies carried out by CIPAV in Colombian cattle ranching landscapes (Murgueitio and Ibrahim 2009; Chará and Giraldo 2011; Calle et al. 2012; Chará et al. 2018; Giraldo 2019).

6.5.1 Watershed Scale

- Conservation initiatives for riparian areas and aquatic environments should prioritize landscape elements that can gradually reestablish some ecological functions of forests. Tree coverage should be increased not only in stream banks, but in the entire catchment areas.
- The adoption of silvopastoral systems, agroforestry systems, strategically placed live fences, windbreaks, and other tree-based elements promote the recovery of soil, biodiversity, hydrologic regulation, microclimate, natural biological pest control, and carbon sequestration.
- Agrochemicals should be reduced gradually and finally eliminated in pastures and cropland. Veterinary medicines should be used more sparingly to reduce water pollution.
- Solid wastes and urine from livestock facilities should be treated with agroecological practices that enhance nutrient recycling in farming systems, such as water decontamination with biodigesters and the production of compost.

6.5.2 Stream Segment Scale

- A necessary first step when restoring forest cover in heavily eroded or degraded riparian strips is the restriction of livestock access to the streams.
- Drinking stations must be provided at each paddock to prevent cattle from entering into streams.
- One key action when conserving riparian forests within agricultural landscapes is fencing of existing forest fragments and guaranteeing their effective protection.
- After fencing the riparian strip, the process of assisted natural regeneration involves controlling competing plants and enrichment planting with native species. Together, these actions promote the recovery of aquatic environments.
- Riparian forest restoration accelerates the recovery of aquatic biodiversity and key ecological functions, such as the processing and transfer of leaf litter within the ecosystem.

- An important principle that should guide the restoration of riparian forests is the provision of heterogeneous leaf litter to the aquatic ecosystem. Planted and regenerating species should provide thick and thin, small and large leaves, and both fast and slow decaying litter. Since the organisms that contribute to the fragmentation of leaf litter require some palatable, nutrient dense food resources, tree species that provide such attractive resources for aquatic organisms should be included in the restoration treatments.
- Trees that contribute significant amounts of litter to the soil of the riparian areas will be attractive to edaphic macrofauna and will accelerate the recovery of the stream segment's hydrological properties.
- The richness and singularity of entomofauna in Andean stream ecosystems prove that forested riparian buffers function as biodiversity islands and support efforts to restore these landscape elements.

6.5.3 Social Issues

- The main environmental service provided by riparian forests in headwaters is the maintenance of water quality for rural populations, urban areas, and agriculture. Clear measures are required to achieve their conservation and recovery in order to ensure their productive use.
- The vulnerability of riparian forests is a direct result of conservation and management decisions made by landowners. Preserving these landscape elements, their ecosystems, and their myriad services requires an increasing willingness of farmers to adopt environmentally friendly and sustainable agricultural practices and undertake the restoration of areas critical for biodiversity. Colombia and other Latin American countries need clear policies for headwater conservation. These policies must guarantee the sustainable use of resources and the continuity of environmental services.
- Incentives such as payment for environmental services and discounts in property taxes motivate farmers to conserve and restore forest remnants adjacent to aquatic environments.

Acknowledgements The authors gratefully acknowledge the support of Minciencias and the Colombian Autonomous Fund for Science, Technology and Innovation Francisco José de Caldas through contract 80740-006-2020, and the support to L.P. Giraldo through the scholarship for doctoral studies, call 567.

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