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Forestry Best Management Practices Relationships with Aquatic and Riparian Fauna: A Review

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Abstract: Forestry best management practices (BMPs) were developed to minimize water pollution from forestry operations by primarily addressing sediment and sediment transport, which is the leading source of pollution from silviculture. Implementation of water quality BMPs may also benefit riparian and aquatic wildlife, although wildlife benefits were not driving forces for BMP development. Therefore, we reviewed literature regarding potential contributions of sediment-reducing BMPs to conservation of riparian and aquatic wildlife, while realizing that BMPs also minimize thermal, nutrient, and chemical pollution. We reached five important conclusions: (1) a significant body of research confirms that forestry BMPs contribute to the protection of water quality and riparian forest structure; (2) data-specific relationships between forestry BMPs and reviewed species are limited; (3) forestry BMPs for forest road construction and maintenance, skid trails, stream crossings, and streamside management zones (SMZs) are important particularly for protection of water quality and aquatic species; (4) stream crossings should be carefully selected and installed to minimize sediment inputs and stream channel alterations; and (5) SMZs promote retention of older-age riparian habitat with benefits extending from water bodies to surrounding uplands. Overall, BMPs developed for protection of water quality should benefit a variety of riparian and aquatic species that are sensitive to changes in water quality or forest structure.

Keywords: best management practices; forest operations; riparian species; silviculture; wildlife

1. Introduction

Forestry best management practices (BMPs) were developed and implemented to protect physical and chemical aspects of water quality relative to the Clean Water Act of 1972 [1–6]. Prior to development and implementation of forestry BMPs, adverse impacts from forest operations to aquatic environments included increases in water temperature, deposition of fine sediment and increases in concentrations of nutrients and other chemicals, altered loading of coarse and fine organic matter in streams as well as disruption in stream channel form [7,8]. BMP guidelines were developed in the 1970s and refined over time as new information and practices were developed [1,5]. Today forestry BMPs are widely adopted, implemented, and studied [9]. Furthermore, reviews of forestry BMP research conclude that properly applied forestry BMPs protect water quality and critical habitat [1,2,10,11]. Specifically, forestry BMPs address potential impacts of sedimentation, temperature change, and changes in chemical regimes by significantly reducing or eliminating sediment, nutrient, and other pollution inputs [1–3,6,8,10–12]. Following widespread BMP implementation in the United States, water quality impacts from forestry operations have been reduced by over 90% from operations in the pre-BMP era [2].

The water quality protections that forestry BMPs afford are believed to have positive effects on riparian and aquatic species, yet information about the specific effects that forestry BMPs have on wildlife, biodiversity, and other ecological functions have not been fully examined or synthesized. Over the past two decades, forest management research projects have incorporated surveys of species abundance, biological diversity, and measures of nutrient cycling/food chain interactions into monitoring protocols to more fully assess BMP effectiveness [13–15]. Overall, such projects have concluded that forestry BMPs conserve portions of affected forested ecosystems and provide protection for a variety of species. For example, Lockaby et al. [13] examined forest harvesting in Southern bottomland hardwoods and concluded that there would be few lasting effects on ecosystem processes "as long as best management practices are followed." The overall goal of our review is to document how forestry BMP implementation affects aquatic and riparian species.

2. Materials and Methods

Because the numbers of species that might be affected by sediment reductions due to BMP implementation are too numerous to summarize concisely, we focused our literature search on 322 faunal species included in a recent multi-species status assessment conducted by the U.S. Fish and Wildlife Service [16]. This list included all categories of vertebrate (fish, amphibians, reptiles, mammals, and birds) in the region as well as a broad cross-section of invertebrates (Table 1) that are potentially affected by sediment. These riparian and aquatic species were being considered for potential classification as threatened/endangered status in the southeastern United States. Throughout this manuscript, we elected to use the phrase "riparian and aquatic species," as some of these species migrate between the riparian and aquatic environments during different periods of the life cycle, with different activities, or as the riparian zones experience overbank flooding. Our initial search revealed that specific information relating the impact of BMPs on targeted individual species was limited due to the lack of natural history information and species-specific knowledge of habitat associations. Thus, we developed this review of BMP effect literature on information from species in the same genus or with similar ecologies, rather than restricting our search to individual species. In effect, this expanded the scope of the search to an evaluation of potential sediment effects on aquatic and riparian species in the region, not just those originally considered by the U.S. Fish and Wildlife Service. We examined research data regarding assessments of BMP effectiveness for protecting riparian and aquatic fauna during forest operations and supplemented this information with information regarding habitat relations, life histories, and home ranges. We used *Google Scholar* to access information and used combinations of keywords including species names, species groupings, species life histories, forestry best management practices, riparian forests, forest operations, water quality, and silviculture. We generally restricted the geographical setting to the southeastern U.S. However, we often expanded the locations of the search to fill gaps. Articles produced after the introduction of BMPs were targeted. The search provided over 300 peer-reviewed journal articles, theses/dissertations, and government publications, although we are reporting on only the most relevant and non-duplicative for the sake of brevity.

Peer-reviewed articles were given precedence, but other sources of information (theses, dissertations, government/technical publications) were used to help fill information gaps. We focused on studies performed in the southeastern United States and published after the passage of the Federal Water Pollution Control Act of 1972. We summarized information on the effects of BMPs by geographic location on faunal species (or genera) with the specific intent of developing overarching, comprehensive conclusions.

Table 1. Taxonomic groups and the number of species listed in the recent status assessment and the focus of the literature review.

Taxonomic Group	Number of Species
Crayfish	83
Fish	48
Mussels	48
Snails	44
Beetles	18
Amphibians	15
Dragonflies	14
Reptiles	13
Caddisflies	9
Stoneflies	8
Amphipods	6
Mammals	4
Butterflies	4
Birds	3
Isopods	2
Fairy shrimp	1
Moths	1
Springfly	1

3. Results and Discussion

3.1. BMP Implementation and Benefits to Riparian Ecosystems

The overwhelming consensus of the literature was that forestry BMP acceptance and implementation levels have increased dramatically since the 1970's, reaching over 90% in 2015, and that forestry BMPs are effective for reduction of nonpoint source pollution. Numerous reviews from regions across the U.S. have been conducted on forestry BMP effectiveness, and all have concluded that forestry BMPs are effective, e.g., [1–4,6,10,11,17]. Recently, Cristan et al. [9] conducted a survey of forestry BMP implementation across the United States and found that overall BMP implementation levels in the Southeast were slightly over 92%, which was an increase of approximately 8% since a previous study by the Southern Group of State Foresters in 2012. The combination of BMP effectiveness with widespread BMP acceptance and implementation levels provides compelling evidence that BMP programs protect water quality.

3.2. Sediment

Sediment is the most commonly identified nonpoint source pollutant associated with most designations of stream impairment in the United States [11,18]. Although forest operations are relatively minor contributors of sediment, accounting for about 7% of stream sediment impairment [18], sedimentation is the primary water quality concern associated with forest operations [1,4,5,19,20]. Unfortunately, studies of the specific relationships between the ameliorating effects of forest BMPs for sediment reduction on aquatic/riparian species are very limited. However, there is a significant body of work demonstrating the deleterious impacts of excess sediment on aquatic species.

Species that depend on aquatic respiration may experience lethal or sub-lethal respiratory impairment from the precipitation of suspended sediment on gills [21–24]. Sub-lethal effects of elevated sediment potentially include reduced immunity to disease, depressed growth rates, and impaired feeding and reproduction [22,23,25–33].

Sedimentation also has the potential to transform benthic substrate by homogenizing benthic environments, reducing habitat complexity and structural diversity and eliminating important microhabitats [21,30,32–36]. Dissolved oxygen levels also can be reduced by sediment loading [32,35–38]. Ultimately, high fine sediment loads can alter community composition and disrupt trophic level interactions [21,24,27,33,39–43]. Much of this information was developed from studies of sediment derived from land uses other than forestry or from sites without BMPs. These worst-case examples nonetheless emphasize the negative effects of sediment and suggest that any reduction in the rate or amount of sediment delivered to water bodies, as is the purpose of forestry BMPs, should be beneficial to aquatic species [1,2,13,15,44–47].

3.3. BMP Effectiveness

The literature also indicates that BMPs developed for forest roads, skid trails, stream crossings, and streamside management zones (SMZs) have greater potential to reduce sedimentation and also benefit riparian and aquatic species. Of all silvicultural activities, roads and skid trails have the largest potential to contribute excess sediment [48,49]; poorly designed and maintained roads and skid trails have been shown to increase soil erosion, regardless of harvest intensity [44,45,47]. Forestry BMPs for road and skid trails have consistently been shown to be effective for limiting sediment inputs [49–58]. Effective sediment control from forest roads involves appropriate design and template selection, minimization of road grade (particularly at stream crossing approaches), use of water control and retention structures, and achieving adequate cover or surfacing for travel surfaces [48].

Road and skid trail stream crossing approaches surfaced with grass, slash, or gravel are examples of highly effective BMPs that can slow or prevent sediment inputs to aquatic environments [59–63]. Changes in macroinvertebrate functional feeding groups and assemblages in streams associated with harvest treatments and forest road construction and maintenance activities implemented with BMPs are often indistinguishable from natural variations [64].

Forestry BMPs also include a number of water control and diversion methods to prevent sedimentation, particularly on roads and skid trails. Water turnouts and water bars can reduce stream water sedimentation by diverting water flow away from streams and into riparian filter strips, thereby reducing runoff velocity and allowing sediment to be deposited on land [11,58,61]. While stream crossings with a greater area will have greater erosion potential, water turnout and wing ditch BMPs will decrease the stream crossing approach length, thereby reducing the amount of potential sediment inputs [62]. In the Virginia Piedmont, Brown et al. [61] found that appropriate spacing of water control structures can reduce sediment loss. A continuous berm along the edge of a forest road in the Coastal Plain of North Carolina reduced sediment loss by an average of 99% [65]. Maximizing water bar surface roughness and increasing water bar frequency are also effective measures in reducing sediment delivery to streams [66]. Lang et al. [58] found that ditch BMPs can be used to effectively reduce sediment contributions from road ditches.

Streamside management zones and riparian buffers have consistently been shown to reduce sedimentation in aquatic environments [53,54,67]. On the Appalachian Plateau region of eastern Kentucky, Arthur et al. [68] found that in watersheds where BMPs (including riparian buffers) were applied, water yield, sediment flux, and nutrient inputs were similar to non-harvested watershed sites. Lakel et al. [53] found that SMZs trapped approximately 89–97% of watershed erosion before reaching streams. In the Georgia Piedmont, Ward and Jackson [69] found that SMZs were effective for trapping sediment from overland flow, averaging 81% efficiency [11]. Although SMZs applied to harvest units in the highly erodible bluff hills of the Gulf Coastal Plain in Mississippi were not effective in reducing overland flow, they reduced total suspended solid (TSS) concentrations due to the preservation of riparian characteristics [70]. Variability in results among studies may be attributed to differences in topography, geology/soils, and hydrology, but the results of this particular study were attributed to the formation of gullies that breached the SMZ [70]. BMP efficacy is dependent on site-specific characteristics (i.e., site history, disturbance or logging history, topography, slope, climate, etc.); studies consistently have shown the capacity for forestry BMPs to effectively prevent excessive sedimentation of aquatic environments [1–4,10,11,17].

3.4. Stream Crossings

In the absence of BMPs, both permanent [71] and temporary stream crossings have the potential to cause long-lasting effects on aquatic and riparian environments and organisms if not properly designed or maintained [72–75]. However, application of BMP technology at stream crossings can help substrate heterogeneity and stream flow regimes, and retain streambank integrity [72,76–78], all of which are important environmental characteristics for maintaining and conserving healthy aquatic and terrestrial riparian wildlife [71,79].

Stream crossing location and design are important aspects of forestry BMPs. Improper selection of stream crossings can cause changes in hydrology and sediment inputs, which in turn may influence population dynamics and in-stream and terrestrial habitat [72]. Maintaining stream channel morphology helps maintain ecological communities and populations of riparian species [72]. To safeguard aerial, terrestrial, and aquatic riparian wildlife, stream crossing designs need to consider river morphology, depth, velocity, stream flow, and scouring potential [80–83]. These considerations are vital to maintaining healthy wildlife populations; poorly designed stream crossings increase sedimentation, cause issues with aquatic organism passage, influence population dynamics, and contribute to loss of suitable habitat [72,76]. Legacy stream crossings installed prior to the era of BMPs may require replacement or remediation [57]. Although bridges, which usually can be installed to preserve natural channel shape, are a preferred stream crossing type, particularly over larger streams, other factors such as traffic requirements, structural loading capabilities, site features, and economic feasibility often favor use of other stream crossing types [48,83,84].

Culverts typically are the structure of choice for crossings in smaller streams. Culverts that are improperly sized for the watershed can have reduced capacity to pass water and sediment or accommodate fish passage [83]. Water velocity at the exit from culverts that are undersized for the watershed can exceed the capacity of the channel and cause greater downstream scour [85]. Increased velocity and potential culvert suspension could result in habitat and population fragmentation of aquatic species by creating a barrier to aquatic organism movement upstream [73,76,83,86]. Proper culvert size selection is a very basic BMP application [48]. By considering the benefits and potential impacts of stream crossing selection options at a particular site, land managers can select an appropriate stream crossing that will minimize potential ecological and environmental impacts [76,84].

Potentially negative effects of culverts are also contingent on other design parameters. With careful planning and knowledge of local options, selection of stream crossing types that allow adequate organism passage can be both cost-effective and ecologically compatible. Some designs, such as open-bottom culverts, can mimic natural channel shape and substrate and preserve natural hydrological attributes [76–78,83]. Although research on the effects of stream crossings on riparian and aquatic wildlife other than fish [86,87] are relatively limited [71,77,78], culvert BMPs and culvert design have been shown to influence mussels [88], crayfish [77,78], snails [89–92], and aquatic insects [93–96]. The complexity of culvert material, design, and placement and potential effects on a variety of aquatic organisms warrants further investigation. Current BMP effectiveness research suggests that minimizing the numbers of crossings, placement of stream crossings at sites that minimize channel disturbances, use of appropriately sized and installed culverts, and disconnecting sources of erosion from stream crossing approaches will benefit sediment-sensitive aquatic organisms [48,72,83].

3.5. Streamside Management Zones

SMZs, also known as riparian buffers, forest buffers, and filter strips, are a particularly important type of BMP because they provide a zone for water quality protection between managed lands and the stream [97–99]. For example, SMZs promote sediment and nutrient trapping by slowing and often preventing entry into aquatic systems [53,100]. Appropriately managed and designed SMZs moderate light infiltration, dampen or minimize aquatic and terrestrial temperature gradients, slow nutrient flow, maintain hypoheic and hydrologic function, and preserve riparian vegetative composition and structure [2,15,101–106].

However, SMZs also provide forest habitat for a variety of species and maintain structures important to faunal communities in the presence of forestry operations [27,40,47,107,108]. SMZs provide coarse woody debris and detritus inputs that serve as food and habitat structure for aquatic species [109–112] and critical microhabitat for riparian organisms for nesting, roosting, feeding, or breeding. Implementation requirements and subsequent success of an SMZ depends on the aquatic species of concern, and to what extent managers need to protect riparian and aquatic ecosystems from disturbance [47].

As different species of wildlife have different sensitivities to environmental changes, they also have differing requirements for optimal environments, including canopy composition, width of the riparian buffer, and patch length along the stream [34]. SMZs can be designed to address these habitat requirements. Alterations to aquatic and terrestrial temperature gradients could impact aquatic biota, restricting movement, limiting biological functions, and altering habitat suitability [20,47,113,114]. SMZs provide shade and relatively stable canopy composition and streambank stability; therefore, these riparian buffers help preserve terrestrial and aquatic temperature regimes in riparian areas, safeguarding and maintaining wildlife populations [2,15,102,114–118].

Canopy cover influences light and temperature regimes, which are important to many vertebrate species but also to other sensitive fauna such as dragonflies (Odonata) and moths and butterflies (Lepidoptera) [116,119–121]. Species preferences for light infiltration, solar radiation, and temperature regimes differ [47,122]. Although some species are sensitive to changes in these parameters, others may benefit from the manipulation and alteration of riparian vegetation [123]. Riparian zones can be managed to favor the life history for a particular species, but specific information for many threatened and endangered species is lacking and some species have conflicting life history needs. Thus, additional research is needed to ascertain how forestry riparian zones can be managed to best address various species' habitat requirements.

SMZs also provide a source for coarse woody debris, snags, tree cavities, and rotting logs [39,112]. These structures create diverse habitat and microtopography, benefiting a variety of riparian species [112,124] and species within the surrounding landscapes where these structures may be less abundant. The benefits of coarse woody debris in aquatic ecosystems depend on the amount and size of such debris [2,39,112]. Because coarse woody debris can increase habitat diversity, it is an essential component of eastern stream ecosystems, and is required by fish populations [39] and some turtles [124].

Woody debris is typically generated during harvesting operations, and riparian buffers can be managed to provide woody debris input into aquatic ecosystems [39,110–112,125,126]. Although additional nutrient inputs sometimes can enhance fish habitat in headwater streams, in some cases, these inputs could stimulate downstream eutrophication [2]. Fresh slash and debris inputs may elevate water temperatures and decrease dissolved oxygen in still or very slow-flowing water [2], although predictions are challenging due to complexity in natural ecosystems [2,127]. However, natural input of woody debris provided by SMZs should benefit aquatic and riparian wildlife by providing microhabitat and providing allochthonous organic matter to aquatic ecosystems [39,112].

States developed recommendations for SMZ widths primarily to address the goal of water quality protection, and most studies have found that these widths were adequate for protection against thermal, sediment, and nutrient pollution [53]. However, recommendations for SMZ widths typically were not designed specifically to meet objectives related to terrestrial wildlife species associated with riparian ecosystems. Appropriate riparian buffer characteristics for meeting objectives related to these species likely vary depending on site-specific vegetative, hydrologic, and geographic characteristics, adjacent forest structural conditions, and harvesting practices used in adjacent stands [128,129]. However, the literature generally indicates that habitat conditions for many riparian and aquatic species are positively affected by implementation of SMZs.

3.6. Macroinvertebrate Community Response to BMPs

Because BMPs protect water quality and in-stream structure, and provide heterogeneity of vegetation structure in riparian zones, implementation of BMPs has been shown to benefit aquatic biota and their habitat [130]. For example, from 2006 to 2010, DaSilva et al. [131] studied stream metabolic rates upstream and downstream from a loblolly pine (*Pinus taeda*) stand that was harvested with Louisiana's current BMPs. They quantified rates of net ecosystem productivity (NEP), gross primary productivity (GPP), community respiration (CR), and the GPP/CR ratio. No calculated metabolic rate was significantly changed by the timber harvest. Thus, the authors concluded that "timber harvests of similar intensity with Louisiana's current BMPs may not significantly impact stream biological conditions".

Bioassessment is a common technique for assessing biological integrity of streams [132] and has been used to characterize macroinvertebrates' response to timber harvests with forestry BMPs. Harvesting practices without properly implemented BMPs can negatively influence stream macroinvertebrate populations [133]; however, multiple studies in the Southeast have reported little to no change in aquatic macroinvertebrate community diversity following timber harvesting with BMPs [100,134–140]. Changes in invertebrate communities, when they do occur, generally reflect a shift from allochthonous to autochthonous food resources in streams draining harvested watersheds that is relatively short-lived (<5 years) due to rapid vegetation regrowth [7]. We briefly summarize results from several studies in the Southeast that have used bioassessment methods to study macroinvertebrate responses to BMPs.

Adams et al. [134] studied whether forestry BMPs effectively reduced harvesting impacts on stream habitat and macroinvertebrates in five physiographic regions in South Carolina. They found that most sites with BMPs scored high on rapid bioassessment protocols III (RBPs) established by the Environmental Protection Agency to assess stream health. Thus, the authors concluded that BMPs were effective in protecting macroinvertebrate assemblages.

Kedzierski and Smock [135] examined macroinvertebrate production and macrophyte growth in harvested and non-harvested sections of a low-gradient, sand-bottomed blackwater stream in the Virginia Coastal Plain. A section of the catchment had been clearcut three years prior to sampling and no additional harvesting occurred in the upstream area of the catchment. Macroinvertebrate production was higher in the stream reach of the harvested tract (103 g m^{-2}) than in the reach of the non-harvested tract stream (41 g m^{-2}). Production in the stream of the harvested tract was dominated by collector-filterers living on macrophytes as well as collector-gatherers. Other macroinvertebrate functional feeding groups showed little response to harvesting.

Vowell [136] evaluated Florida's BMPs for protecting aquatic ecosystems during intensive forestry operations that included clearcutting, mechanical site preparation, and machine planting. Sample streams were selected across Florida's major ecoregions. Stream condition index (SCI) bioassessments were conducted at points along each stream, above and below the treatment area. No significant difference in the SCI was observed between the reference and treatment stream segments. Vowell concluded that the proper implementation of forestry BMPs provides effective protection of aquatic resources.

Williams et al. [137] used stream survey data to evaluate timber harvesting influences on physical stream features and macroinvertebrate assemblages in three drainage basins in the Ouachita Mountains of Arkansas. Variability in macroinvertebrate assemblages was largely explained by drainage basin differences and year of sampling. The interaction between timber harvesting and drainage basins suggested that differences in physical stream features were important for determining the effects of logging within individual basins. Furthermore, harvesting did not influence diversity of macroinvertebrates in these small headwater streams. The authors suggest that natural variability in hydrology and in-stream physical features were the primary drivers of assemblage differences and not the effects of harvesting.

Carroll et al. [100] evaluated effectiveness of SMZs to protect water quality, aquatic habitat, and macroinvertebrate communities in low-order streams in north central Mississippi. Three replications of three SMZ treatments (clearcutting with no SMZ, clearcutting with an SMZ, and unharvested reference) were evaluated using response variables that included water quality, mineral soil exposure, and net soil deposition or erosion. One year following harvest, no differences in response variables between harvested sites with stream SMZs and reference streams were observed. Streams in harvested sites without SMZs had significantly higher stream temperatures and declining habitat stability ratings, but increased macroinvertebrate density compared to reference streams.

Vowell and Frydenborg [138] evaluated effectiveness of Florida's forestry BMPs for herbicide applications using methods similar to those used by Vowell [136]. Following a pretreatment assessment, study streams were re-sampled one and two years following herbicide applications to forests adjacent to streams. No significant differences in the Stream Condition Index were observed between reference and test portions of the streams that could be attributed to practices that included chemical applications.

Grippo and McCord [141] used bioassessment of benthic macroinvertebrates to evaluate effectiveness of Arkansas' silvicultural BMPs in protecting the water quality and biological integrity of streams adjacent to harvest areas. They found few significant differences in water quality or biological variables that could be associated with silviculture. Differences between upstream and downstream sites, when noted, were present before as well as after timber harvest. Differences in relative abundance variables (e.g., percent EPT) were typically location-specific and unrelated to silviculture activities.

Griswold et al. [139] conducted pre- and post-harvest sampling of benthic macroinvertebrates from four first-order streams draining the Dry Creek watershed in southwestern Georgia. They found differences in community structure between pre- and post-harvest periods, but responses of macroinvertebrates to harvest treatment and SMZ thinning were subtle. Relative abundance and total taxa all increased in the control and treatment sites after harvest, suggesting communities may have responded to increased streamflow due to increased rainfall during the study period. Overall, the macroinvertebrate communities appear to have been more strongly influenced by environmental factors (e.g., stream flow, water chemistry, and canopy cover) than by SMZ thinning and harvesting of adjacent stands.

McCord et al. [140] examined macroinvertebrate assemblages in six Arkansas low-order streams following harvesting with implementation of BMPs. Stream samples were collected above and below harvested tracts. BMP implementation rates on the harvested tracts ranged between 89% and 100%. Deficiencies in BMPs were generally limited to poorly designed erosion controls; however, no evidence of sedimentation was observed in any of the study stream reaches. Harvesting did not reduce taxonomic richness but did significantly influence several relative abundance metrics. Overall, Arkansas' forestry BMPs were effective in protecting water quality and biological integrity in five of the six study stream reaches examined.

Simpson et al. [142] used a Before-After-Control-Impact study design to assess effectiveness of Texas forestry BMPs for protecting water quality and biological integrity of four streams on intensively managed silvicultural sites in east Texas. Biological and physiochemical monitoring (both grab samples and stormwater samples) was conducted above and below treatment areas. The physiochemical data showed no statistically significant difference as a result of treatment. Following treatment, the biological data showed a shift in habitat quality at two sites and for fish at another site compared to the reference. Although change was detected, the treatment sites generally showed improved conditions for Aquatic Life Use Index (fish) and the Habitat Quality Index. Treatment had no negative effect on water quality and biology.

In addition to protecting water quality and biological integrity of aquatic ecosystems, BMPs also benefit riparian ecosystems. For example, SMZs in the southeastern U.S. provide habitat for species associated with mature deciduous forests and may provide travel corridors for some species, e.g., [123,143–146]. In intensively managed forest landscapes, SMZs promote spatial heterogeneity and enhance landscape conservation value, e.g., [147,148].

4. Conclusions

This literature review indicates that forestry operations in the pre-BMP era had the potential to negatively affect water quality and aquatic and riparian species, and that current forestry BMPs can help protect water quality and habitat conditions for a variety of riparian and aquatic wildlife during forestry operations. Although there are relatively few direct evaluations of the specific effects of forestry BMPs on individual aquatic or riparian species, the effects of forestry BMPs are likely beneficial for the following reasons.

Riparian and aquatic species in general benefit from reduction of anthropogenic pollutants. Forestry BMPs, which were specifically designed to limit sediment, nutrient, and other pollutant entry into streams, help protect habitat for many riparian and aquatic species. State forestry agencies report that forestry BMP implementation levels across the United States are above 90%, and within the Southeastern region overall implementation rates are about 92% [11]. Forestry BMPs specifically target roads, skid trails, and stream crossings, as these forest operations have greater potential to cause water quality problems if BMPs are not applied. Forestry BMPs have been shown in numerous research investigations and comprehensive reviews to protect water quality from sediment, nutrient, and chemical pollution. Thus, a wide variety of species that are negatively influenced by such pollutants should benefit from BMPs that protect water quality. The BMPs recommended by several of the southeastern states have been shown to protect water quality, and multiple studies have reported little to no change in aquatic macroinvertebrate community diversity following timber harvesting with BMPs. Therefore, BMPs should benefit individual aquatic and riparian species that are negatively influenced by sediment and other pollutants.

Stream crossings receive particular attention in forestry BMP guidelines in the southeastern United States for several reasons. Research indicates that stream crossings with inadequate or no BMPs are likely to provide direct connectivity of sediment generated from road systems to hydrologic networks. As a result, BMPs for stream crossings were developed to minimize effects on stream water quality and stream dependent organisms. Therefore, appropriate stream crossings, adherence to installation recommendations, and other properly implemented water quality BMPs will help protect aquatic and riparian species.

SMZs are an especially important type of BMP because managed riparian buffers provide habitat and water quality benefits for both riparian and aquatic organisms. Riparian buffers protect the stream from thermal pollution, which can negatively affect a host of species. Riparian buffers also provide leaf litter and woody debris, both of which are critically important to aquatic food chains, stream habitat, and stream structure and morphology. Riparian forests are zones where sediment, nutrients, and chemicals can be trapped and transformed by physical, soil and plant processes. Finally, SMZs provide habitats for species associated with riparian forests and potentially provide refugia for species affected by adjacent forest management activities. Current state SMZ recommendations or requirements maintain water quality and greatly reduce potential risks to aquatic and riparian species during forest management.

Although implementation of BMPs has been shown to benefit aquatic macroinvertebrate communities, information about the direct effects of forestry BMPs for forest operations on many individual aquatic and riparian faunal species is limited. Therefore, additional research investigating the responses of aquatic and riparian species and communities to modern forestry practices that include implementation of BMPs, is warranted.

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