water

Review

Forestry Best Management Practices and Conservation of Aquatic Systems in the Southeastern United States

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Abstract: State-approved forestry best management practices (BMPs) are a practice or combination of practices that, when properly implemented, effectively prevent or reduce the amount of nonpoint source (NPS) pollution entering waterbodies, such as sediment. Although BMPs are voluntary in most states in the southeastern United States (U.S.), forest landowners operating under the auspices of a forest certification system are required to use BMPs, and forest-certified wood procurement organizations also require loggers who supply them with fiber to use BMPs. Current implementation rates are, on average, 93.6% throughout the southeastern U.S. We conducted a literature review to better understand potential effectiveness of BMPs to conserve aquatic resources and species in the southeastern U.S. Our review focuses on how BMPs reduce NPS pollutants, particularly sediment, fertilizers, and herbicides; how BMPs are monitored throughout the southeastern U.S.; and current implementation rates. Additionally, we discuss how state BMP monitoring programs, coupled with participation in forest certification programs that require routine third-party audits, provide assurance to federal and state agencies that BMPs protect aquatic resources and species. The U.S. Fish and Wildlife Service has recognized that working forests where management activities implement BMPs represent a clear, actionable, and scientifically sound approach for conserving at-risk aquatic species. However, there is a data gap in directly linking BMPs to the conservation of aquatic resources. Given the high diversity of aquatic species in the southeastern U.S., it is important to better understand this potential linkage.

Keywords: best management practices; BMPs; forestry; aquatic; forest certification; agencies; southeastern United States; forest management; voluntary practices; biodiversity

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1. Introduction

On 27 September 2011, a partial 90-day finding was published in the Federal Register on a petition to list 404 species in the southeastern United States (U.S.) as threatened or endangered with critical habitats (76 Fed. Reg. 59836). This list included over 300 aquatic or semi-aquatic species potentially affected by sedimentation. Streams in forested areas are known to have higher water quality than streams with water draining from other land uses, such as agriculture [1,2]. However, the petitioners questioned the methods used by state forestry agencies to reduce sediment delivery to streams, specifically the effectiveness of state-approved forestry best management practices (hereafter, BMPs) to protect water quality from pollutants (sediment, nutrients, and pesticides) and, ultimately, contribute to conserving these species. The term "best management practice" is occasionally used in reference to management measures designed to achieve a non-aquatic outcome, such as non-aquatic wildlife conservation. However, the most common and best recognized use in the forestry context is in reference to measures to protect water quality, which is the focus of our paper. Best management practices refer to a practice or combination of practices determined by a state or designated agency to be the most effective at controlling point and nonpoint source (NPS) pollutants to protect water quality, which can be assessed by measuring sedimentation, pesticides, and nutrients from fertilizers in aquatic systems [3]. More specifically, BMP recommendations focus on limiting accelerated erosion and visible sediment. Since the enactment of the Federal Water Pollution Control Act Amendments of 1972 (Clean Water Act; CWA), all 13 states in the southeastern U.S. (i.e., Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia) have developed BMPs. The U.S. Environmental Protection Agency (EPA) relies on BMPs and programs to monitor BMPs to control erosion and NPS pollution that may result from forest management activities [4] in response to the CWA. Best management practice development and monitoring by states aligns well with the water quality goals set forth in the CWA [5]. Although BMPs are often voluntary practices, it is important to note that they are regulatory or quasi-regulatory in some states and are required by forest certification programs (discussed below), and for landowners that sell wood to mills with certified fiber sourcing. It is also important to note that forest managers consider specific site conditions (e.g., the slope and wetness of the site) when implementing BMPs.

In the southeastern U.S., individual states have reported high BMP implementation rates and the mean rates of implementation for the region are 93.6% [6]. Today, the concept of BMP effectiveness has broadened to encompass the conservation of aquatic species. For example, in 2013, the Florida Legislature created Section 570.94, F.S., which authorized the Florida Department of Agriculture and Consumer Services (FDACS) to work collaboratively with the Florida Fish and Wildlife Conservation Commission (FWC) to enter into a Memorandum of Agreement to develop and adopt by rule voluntary BMPs for state-imperiled species of wildlife as a voluntary alternative to incidental take permitting. This approach used by Florida recognized that collaboration with, and participation by, private forest landowners is critical to species conservation in the state. State forest action plans also commonly include goals to protect water quality and conserve aquatic species.

The Southeast is the largest wood-producing region in the U.S. [7], with more than 107 million hectares of forestland, of which approximately 93 million hectares (86.9%) reside in private ownership (Table 1). Increasingly, the U.S. Fish and Wildlife Service (hereafter, Service), is collaborating with private forest landowners to conserve aquatic species across this region, including using a variety of partnerships and cost share programs (e.g., https://www.ncforestservice.gov/healthy_waters/costshare.htm, accessed on 7 June 2021). Although there have been reviews of BMP effectiveness [8] and relationships with aquatic fauna [9], forestry practices and BMP research continue to develop. Protecting streams from sedimentation is critical to ensure that many aquatic species, including at-risk species, have appropriate substrates to meet life history requirements [10,11]. Sedimentation can reduce primary production by impeding photosynthesis, reduce oxygen flow to fish eggs, and increase stress in aquatic filter feeding species, such as mussels [10]. Streamside management zones (SMZs) are just one component of BMPs, and beyond reducing the amount of pollutants entering waterways, these riparian buffers also provide overstory canopy cover to maintain water temperature and soil moisture, which is important for semi-aquatic species such as salamanders [12]. Furthermore, a comprehensive review of the literature to examine the value of BMPs for maintaining habitats for aquatic species and to identify information gaps has not been completed. Therefore, in this paper, we summarize the published literature using the following categories to discuss relationships between BMP implementation on actively managed forest landscapes in the southeastern U.S. and the conservation of aquatic resources and species: (1) components of BMPs; (2) importance of BMPs for chemical use; (3) forestry research demonstrating water quality and how that is related to habitat conservation for aquatic species; (4) effects of BMP use, monitoring, and forest certification programs; (5) federal agencies recognizing BMP effectiveness in the published rules; and (6) information gaps based on our review, specifically the direct relationship between BMP implementation and aquatic species responses.

Table 1. Hectares of public and private forestlands within the 13 southeastern states, the percentage (%) of forestlands designated to each category, and the known hectares certified to the Sustainable Forestry Initiative (SFI) with the percentage of certified public and private forestlands. Data were obtained from the United States Department of Agriculture Forest Service Forest Inventory and Analysis Program [1].

Landowner	Hectares	Percentage (%)	SFI Certified Hectares (%)
PUBLIC	**14,346,411**	**13.36**	**618,926 (4.31%)**
Federal	8,865,493	8.25	
U.S. Forest Service, National Forests	5,275,817	4.91	
U.S. Department of Defense	1,743,529	1.62	
U.S. Fish and Wildlife Service	834,598	0.78	
U.S. National Park Service	830,343	0.77	
U.S. Bureau of Land Management	6523	0.01	
Other	174,681	0.16	
State	4,076,934	3.80	
County and Municipal	1,373,054	1.28	
Other Local and Government	30,930	0.03	
PRIVATE	**93,070,900**	**86.64**	**8,448,309 (9.08%)**
Family Owned/Private Landowner	59,974,888	55.83	
Commercial	33,096,012	30.81	
Total	**107,417,311**		

[1] USDA Forest Service, Forest Inventory and Analysis Program, Mon Feb 22 17:16:52 GMT 2021. Forest Inventory EVALIDator web-application Version 1.8.0.01. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Northern Research Station. (Available only on the internet: http://apps.fs.usda.gov/Evalidator/evalidator.jsp, accessed on 5 May 2021).

2. Components of BMPs

State forestry BMP manuals include specific recommendations for several components of a forest landscape, including streamside management zones (SMZs), roads, and stream crossings. However, it is important to note that all these recommendations work in concert to reduce erosion and the potential for pollutant delivery to streams. These various recommendations provide a level of redundancy, and the effects of each component are difficult to tease apart, as any forest management approach following BMPs will include multiple recommendations from several components.

2.1. Streamside Management Zones

Retaining vegetated SMZs along watercourses is the most widely recognized BMP practice. In general, SMZs are buffers of forestland adjacent to streams or other bodies of water where management practices are modified or restricted to reduce sediment and other pollutants from reaching the stream and surface waters, provide shade, and maintain streambank stability. Reducing sediment and other pollutants from entering the associated waterway is important for aquatic species, such as fish and mussels, whereas the provided shade maintains the water temperature for cold-water species, such as trout (Salmonidae), and soil moisture for semi-aquatic species, such as salamanders. Factors that are used separately or in combination to establish appropriate SMZ widths include stream type (perennial streams that flow year-round, or intermittent streams that flow seasonally), stream width, adjacent upland factors (slope, soil), and the presence of cold-water species, typically trout. Best management practices in the southeastern U.S. generally allow selective harvesting within SMZs and recommend retaining 5.7 to 11.5 m^2 per hectare or 25% to 75% crown cover in SMZs for perennial and intermittent streams [13]. However, the BMPs for all states recommend using harvesting systems and techniques that limit the disturbance to soils and the forest floor and retain residual vegetation in SMZs [13].

Retaining SMZs and implementing other BMPs to control runoff and capture sediment, especially for roads and stream crossings, has been shown to maintain water quality during and after forest management activities [8,14–24]. Streamside management zones are 71–99% effective in reducing, if not eliminating, sediment delivery to streams [17,18,25,26]. For example, Lakel et al. [18] compared the effects of SMZ widths (30.5, 15.2, or 7.6 m) and thinning levels on sediment delivery to streams in Virginia's Piedmont region within 16 watersheds on sites that were clearcut and burned. Although harvesting increased erosion rates, sediment delivery was low with SMZs' efficiency for trapping sediment ranging from 84% to 97% and sediment delivery ratios ranging from 3% to 14%. Furthermore, reducing the basal area within SMZs via a thinning harvest did not significantly increase erosion and sediment delivery. Lang et al. [25] examined sediment breakthroughs of SMZs in the Virginia Piedmont to determine the frequency and potential causes of sediment delivery. Noting that the current state recommendations for SMZs reduce the risk of negative environmental outcomes for sediment in most situations, Lang et al. [25] observed sediment breakthroughs for improperly executed BMPs for stream crossings, during the reactivation of legacy agricultural gullies, and when there was soil disturbance from harvesting within or near SMZs.

2.2. Forest Roads and Stream Crossings

Forest roads, skid trails, and stream crossings are essential parts of forest management operations and may also provide access for recreational activities and fire protection. All BMPs in the region address BMPs for roads and stream crossings and recommend that properly planned, constructed, and maintained forest roads, trails, and stream crossings allow efficient and safe forest management activities and generally result in minimal effects on water quality [27]. However, roads and trails that are poorly located (e.g., adjacent to streams, within SMZs, on steep slopes, etc.) and which do not implement BMPs and/or receive necessary maintenance have the potential to deliver substantial amounts of sediment to streams [28]. For this reason, state BMPs recommend that managers locate roads and trails as far away from streams as possible. If roads or trails must be constructed through a SMZ, states generally recommend careful consideration of the site conditions and selection of BMPs necessary to control and capture resultant erosion.

Effective forest road systems exist along a "road use continuum" that consists of primary, secondary, and temporary roads, and each road type or road segment along the continuum is constructed using standards and BMP prescriptions according to that road's intended function [28]. In general, forest road BMPs are based on stormwater control methods, which are needed to accommodate the anticipated traffic weight and frequency. Furthermore, these roads are designed to multiple standards that consider road use, traffic, width, subgrade stability, road grades, cut slopes, fill slopes, drainage structures, surfacing, stream crossings, curvature, switchbacks, and road closure [28]. Improperly designed and installed road segments or road approaches to stream crossings can be significant sources for sediment delivery to streams. This is especially true for "legacy" forest roads, which are those forest roads constructed before the adoption of the CWA and development of state-approved BMPs. In the Virginia Piedmont, Brown et al. [29] evaluated the effectiveness of gravel surfacing to reduce sediment delivery at stream crossings. Annual sediment delivery rates from regraded legacy road approaches (from 34 to 287 Mg ha^{-1} $year^{-1}$) were, on average, 7.5 times higher than gravel approaches (10 to 16 Mg ha^{-1} $year^{-1}$).

Road drainage can have important effects on soil erosion and sediment delivery to streams [30] and poorly designed and maintained forest road ditches can directly link road erosion to streams [31]. To reduce potential erosion, states suggest that roads follow the contour of the land, have grades less than 10% where possible, and implement appropriate road and ditch BMPs to reduce the erosion potential. Lang et al. [31] evaluated the effectiveness of five roadside ditch erosion-control treatments (a bare ditch treatment and four commonly recommended treatments) to reduce sediment transport in the Ridge-and-Valley region of Virginia. Trapped sediment deposits indicated that median erosion rates were the greatest for rock check dams, followed by bare ditches, completely rocked ditches, grass seed, and grass seed with a single erosion control mat [31].The authors also noted that seeding with erosion mats in ditches involved lower implementation costs compared to ditches with rock check dams and fully rocked ditch segments [31]. Overall, forest access roads that follow BMP recommendations are typically not a primary source of sediment in streams [8]. However, poorly designed and maintained forest road networks can increase the hydrologic connectivity of roads to streams via the delivery of stormwater runoff through roadside ditches that connect directly to streams at crossings [32]. This direct hydrologic connection can adversely affect water quality through increased sedimentation from erosion of the road surface and transport from roadside ditches.

The U.S. Army Corps of Engineers (ACE) has responsibility for regulating the deposition or dredging of material into navigable waterways and waters of the U.S. and their associated wetlands under CWA Section 404(f). Because the construction of forest roads in wetlands usually requires placing road fill material (i.e., 'deposition' or 'discharge') or the excavation of soil (i.e., 'dredging'), the ACE has authority to regulate forest roads in wetlands or waters of the U.S. Forest roads constructed in wetlands are exempt from permitting under Section 404(f), if the road BMPs comply with those outlined in the Code of Federal Regulations.

Stream crossings can be sources of sediment entering streams [33]. Where crossings are necessary, they should be able to accommodate logging traffic in an effective and environmentally sensitive manner. The proper construction and maintenance of crossings will reduce soil erosion and sedimentation [34]. For example, Wynn et al. [35] conducted a survey in the Big Canoe Creek watershed of Alabama and found that of 366 stream crossing structures evaluated (340 paved and 26 unpaved), only 15 sites (4.1%), one of which was unpaved, were at high risk for sedimentation, whereas 79 sites (21%) were at moderate risk, and 272 sites (74.3%) were at low risk.

The construction of some stream crossings may require a permit and BMPs recommend that managers consult with appropriate state and federal agencies to ensure that planned activities follow all applicable state and federal regulations. Each southeastern state recommends preharvest planning and layout of road systems and harvest operations to minimize the number of stream crossings. Best management practices emphasize the importance of controlling water and sediment movement from stream crossing approach sections (i.e., sections of roads and skid trails that are connected and adjacent to crossing structures) [13,30]. Recommended practices include applying gravel on surfaces of approach sections and roadside ditches and installing water control structures that divert runoff water into vegetated areas before it reaches the crossing [36,37].

3. Importance of BMPs for Chemical Use

Fertilizers and Herbicides

Silvicultural chemicals (e.g., fertilizers and herbicides) have the potential to impact stream water quality through several mechanisms, including direct application to stream channels and water courses, transport by overland flow, spray drift, and leaching [38] Silvicultural chemicals in water bodies can have toxic effects on aquatic organisms and plants. Toxicity depends on concentrations, but also on the frequency and length of exposure [39]. Forestry practices rarely use chemicals (generally less than 3–5 times during an entire rotation), so exposures tend to be limited pulse events. Not surprisingly, herbicides affect aquatic plants more directly than aquatic organisms [38], but effects on aquatic plants may lead to indirect effects of herbicides at higher trophic levels. Similarly, fertilizers can alter aquatic plant production and therefore indirectly affect aquatic organisms [40].

Forest fertilization is commonly used by some forest owners to increase tree survival and growth [41]. In general, fertilizer applications are considered during two points in a timber rotation; at stand establishment or at the midpoint of a stand's rotation age (12–15 years).

Mid-rotation fertilization prescriptions of 168 to 224 kg N ha^{-1} plus 28 kg P ha^{-1} are common for loblolly (*Pinus taeda*) and slash pine (*P. elliottii*) stands in the southeastern U.S. [42]. Because young seedlings can use only relatively small quantities of nutrients (e.g., less than 10 kg N ha^{-1} for seedlings 2 years and younger; [43]), stand establishment treatments are applied at lower rates (e.g., 28–56 kg P ha^{-1} as diammonium phosphate) and typically only in response to a phosphorus deficiency [42]. Best management practices for fertilizer applications generally limit application rates (e.g., Florida Forestry BMPs recommend no more than 89 kg P ha^{-1} over any three-year period), prohibit direct application to waterbodies, and require the retention of SMZs for surface water features (e.g., perennial and intermittent streams and lakes) to reduce opportunities for nutrient pollution during and after application. Several states recommend that managers should account for site and weather conditions (e.g., soil type, slope, air temperature, precipitation, and wind speed and direction) to minimize the potential for fertilizer movement to streams via drift or runoff. The application of fertilizers to SMZs is generally not recommended. If SMZs are adjacent to application sites, they should be contiguous to reduce the potential for fertilizer to reach streams via drift or in runoff [44].

When conducted properly, forest fertilization poses little threat to stream water quality [45]. Streamside management zones provide a highly effective filter for surface water runoff, link subsurface water flow with the stream channel, and store sediment and nutrients [46]. Edwards and Williard [47] conducted a meta-analysis of three paired forested watershed studies in the eastern U.S. to calculate the percentage of reduction in nutrients achieved by implementing BMPs (i.e., BMP efficiencies). For nutrients, BMP efficiencies were higher for total N (60–80%) and P (85–86%), which included particulate and sediment-bound forms, than for NO_3 (12%). Overall, these results indicate that BMPs, when properly implemented, are highly effective in reducing sediment and nutrient loads from surface waters. Multiple studies have documented that BMPs reduce or prevent fertilizer transport to surface waters in southeastern U.S. Coastal Plain streams [40,48–51].

The use of herbicides and other pesticides in the U.S. is regulated under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and state pesticide laws. Best management practices typically note that pesticides must be used in accordance with legal requirements and that forest managers should seek guidance from experts. In most southeastern states, BMPs emphasize the importance of reading labels on herbicides and other pesticide products. The label defines the legal restrictions on application rates and other aspects of safe, efficient use. For herbicides, leaching through the soil profile and transport to streams via shallow groundwater and movement into streams through baseflow have typically not been observed in forested streams [39].

Two types of silvicultural chemical BMPs are designed to minimize the potential for the movement of herbicides away from treated areas and into neighboring waterways. The first addresses the process of herbicide application. These BMPs are often specified on the herbicide label and include items such as using spray nozzles that produce large-diameter droplets to limit drift, limiting applications to favorable weather and wind conditions, and conducting mixing and loading at locations distant from any waterbodies. The second type includes many of the same measures used to limit sediment movement. Vegetated buffer zones with large and small trees, shrubs, and herbaceous vegetation create screens that capture spray drift and keep it away from streams [52]. Vegetation inside a buffer zone slows the movement of runoff water and helps retain dissolved herbicides or herbicides adsorbed to soil particles within a buffer zone.

Recent studies have failed to find measurable levels of herbicides in streams adjacent to treated forest sites at the time of application when appropriate BMPs were used. For example, McBroom et al. [53] and Scarbrough et al. [54] investigated herbicides reaching waterways during and after forestry applications in Texas and Georgia, respectively. With operational forestry treatments, herbicides were detected as brief pulses during the first and second storm events, which occurred six to 23 days after application, indicating that operational drift control measures and BMPs were protective of waterways during application. McBroom et al. [53] further described the protection of riparian buffers during an aerial herbicide treatment. They found no mortality of sensitive tree species in an SMZ after application, indicating that overspray did not occur. Herbicides commonly used in forestry target plants, and do not appear to be harmful to aquatic species using operational application rates and methods [55]. Garlon 4 (triclopyr; Dow AgroSciences, Indianapolis, Indiana) and some surfactants have been classified as moderately to highly toxic to fish, which in worst-case scenarios (e.g., the highest recommended application used and accidental overspray) could lead to negative effects on sensitive aquatic species [55]. However, the overall risk to aquatic species from pesticides in forested systems appears to be minimal [38] because pesticides are used infrequently (usually 1–3 times across an entire 25–35+ year rotation) in managed forests and when properly implemented, through established BMPs, and spray technologies are protective of stream systems.

4. Forestry Research Demonstrating Water Quality and Habitat Protection for Aquatic Species

Several studies have reported on BMP effectiveness and have demonstrated that BMPs, when properly implemented, reduce, if not eliminate, the potential negative effects of forest management on water quality [8,13,27,30,56–61]. More specifically, the use of BMPs has been shown to slow runoff, remove sediment from overland flows, and maintain water quality during and after forest management activities [8,12,14,15,17,18,20,22,23,62].

Ruhlman [14] compared reference watersheds with partially harvested watersheds in Georgia's lower Piedmont and upper Coastal Plain. Harvested sites were clearcut, and site preparation consisted of herbicide application (Velpar®), a site preparation burn, and subsoiling. All applicable BMPs were implemented and a selective tree harvest occurred within the retained SMZs. Pre- and post-treatment monitoring of benthic macroinvertebrates and EPA Rapid Bioassessment Protocols (RBPIII) indicated no impairment from sediment, turbidity, and nutrients (e.g., NH_4-N, NO_3-N, and PO_4-P) following harvest, with taxa richness found to be higher in treatment watersheds. Biotic indices were in the excellent water quality class for the Piedmont/Coastal ecoregion [63] and EPT indices were also similar for the control and treatment watersheds.

Ruhlman [14] concluded that buffers provided by SMZ retention in association with forestry management activities allow for conditions to be similar to shaded reference streams. Furthermore, they concluded that properly applied BMPs were effective in protecting water quality and maintaining aquatic ecosystem health in small watersheds of the region.

Boggs et al. [22] conducted a six-year paired watershed study to test the effects of timber harvest with BMPs on water quantity and quality in the North Carolina Piedmont physiographic region using four headwater watersheds in Durham and Granville counties. Water quality parameters included total suspended sediment (TSS), total organic carbon (TOC), ammonium (NH_4-N), nitrate (NO_3-N), total phosphorus (TP), total Kjeldahl nitrogen (TKN), and stream temperature. The authors found that total stream discharge increased in treatment watersheds during the post-harvest period, leading to increases in total suspended sediment and nitrogen. Within two years, stormflow nitrate in the treatment watersheds declined, corresponding to regrowth of vegetation on the sites. Benthic macroinvertebrate sampling was conducting using methods outlined by the North Carolina Department of Environmental and Natural Resources (2012) Division of Water Resources, Biological Assessment Unit Qual4 method. To assess water quality conditions, a bioclassification class (excellent, good, good/fair, fair, or poor) was based on the average values from EPT taxa richness and biotic index [63]. Boggs et al. [22] concluded that temporary hydrologic changes associated with timber harvest using BMPs did not have a measurable effect on indicators of aquatic invertebrate community health or bioclassification rankings.

A recent study in Arkansas found that SMZs maintained according to state BMP guidance (i.e., minimum width of 10.7-m for non-ephemeral streams) provided conservation value for semi-aquatic and terrestrial salamanders, therefore maintaining community diversity in managed forests [12]. Guzy et al. [12] reported that SMZs likely provide protection from edge effects from forest harvest for semi-aquatic salamanders, corridors for terrestrial salamanders, and an area for hardwood trees to persist, which have been shown to provide favorable conditions for terrestrial and aquatic macroinvertebrate prey species. In the same landscape, Halloran et al. [62] studied the response of the post-metamorphic Ouachita dusky salamander (*Desmognathus brimleyorum*) for two years following a winter timber harvest using BMPs. Halloran et al. [62] observed no negative effects of timber harvest on the relative abundance and apparent survival of the Ouachita dusky salamander. Based on their findings, Halloran et al. [62] concluded that SMZs of at least 14 m on each side of a stream can mitigate potential negative forest harvest effects on juvenile and adult stream salamanders.

5. Effects of BMP Use, Monitoring, and Forest Certification Programs

5.1. Monitoring BMP Implementation

State agency staff in the southeastern US conduct random audits, independently of forest landowners, of recently harvested tracts to monitor BMP implementation. The periodicity of surveys varies among states but generally consists of monitoring and reporting every two to three years [4]. Based on the results of a survey of state forestry BMP programs, Cristan et al. [64] reported that all 50 states in the U.S. have programs in place that monitor multiple categories of practices, such as timber harvesting, forest road construction and maintenance, log landings, skid trails, SMZs, and stream crossings. In the southeastern U.S., the Southern Group of State Foresters (SGSF) introduced a framework to standardize BMP monitoring efforts among the 13 state agencies. A 2018 report summarizing state BMP implementation rates noted that all states in the region were in conformance with the framework. Furthermore, 67 statewide monitoring surveys had been conducted since its initial development in 1997 and 23 surveys were conducted in the last six years. Combining all BMP categories in all states and using 2019 state survey data [65], the average overall BMP implementation for the region was 94.3%, up from 92% in 2012. The most recent national assessments by Cristan et al. [64] and NASF [65] found that BMP implementation averaged 92%.

Although the overall site score and individual practice scores are important and serve as general indicators of BMP compliance, onsite BMP evaluations consist of detailed reports of many practices and are designed to highlight potential problems for post-harvest monitoring [4]. Implementation rates for BMPs can be used to understand trends and to identify areas where improvement should be considered. For example, identified deficiencies serve as the basis for what agencies emphasize during subsequent educational programs and refresher courses. However, reported statewide BMP implementation scores are not a direct measure of impacts to water quality during or after forest management. In fact, Dangle et al. [66] found that BMP implementation may be achieved through a variety of methods, while adequately controlling erosion. Because individual BMP practices may be of variable importance, redundant, or involve professional judgment to apply and evaluate, many states further categorize BMP violations that pose a significant risk to water quality.

The SGSF monitoring protocol recommends that states report any instances where a "significant risk to water quality" is observed [4]. A significant risk as "an existing on-the-ground condition resulting from failure to correctly implement BMPs that, if left unmitigated, will likely result in an adverse change in the chemical, physical or biological condition of a waterbody. Such change may or may not violate water quality standards" [4], (p. 8, monitoring protocol). Risks to water quality can be observed during random site inspections by state forestry staff or reported to the agency by the public. The presence of a significant risk triggers further investigation by state forestry agency inspectors, which leads to collaborative efforts among other state agencies and the forest landowner, logger, or contractor to perform corrective measures. After a reasonable period, a follow-up site evaluation is made to assess compliance with the recommended measures. Willful noncompliance with state agency recommendations typically results in a referral to the appropriate regulatory agency for enforcement action.

Generally, state forestry agencies report few significant risks to water quality during field audits. However, if a significant risk is noted during an audit, the auditor visually determines if active sedimentation is occurring or has occurred. In cases of observed impairment, a request is made to the logger and/or landowner to take immediate corrective measures to remediate the infraction, and other agencies may be made aware, depending on the severity of the situation. In the 2020 audit cycle, Virginia audited 240 tracts and reported that only two (0.83%) had at least one significant risk, and only one of those had an active sedimentation concern (M. Poirot, Virginia Division of Forestry, Personal Communication, 2021). In North Carolina, from 2012–2016, risks to water quality, assessed based on the amount of sedimentation, were rare (0.15%) when BMPs were properly implemented (36 out of 23,907 BMP implementation opportunities; [67]). In this context, properly applied refers to a BMP being implemented according to the state recommendations. Conversely, improperly applied suggests that the correct BMP was applied incorrectly (not according to state recommendations) or that the wrong BMP was implemented. Evaluators associated potential water quality risks with 30% of improperly implemented BMPs, which constituted less than 5% of all BMP implementation opportunities [67]. In other words, 70% of improperly implemented BMPs did not lead to water quality risks.

5.2. Assurance That BMPs Are Implemented

Forest Certification Ensures BMP Use on Certified Forestlands

Although BMP use is voluntary for most states in the southeastern U.S., their use is required by the three most common third-party forest certification standards in the U.S., the American Tree Farm System (ATFS)®, Sustainable Forestry Initiative (SFI)®, and Forest Stewardship Council (FSC)®, and for landowners that sell wood to mills that are certified according to the SFI Fiber Sourcing Standard. These forest certification standards require participants who manage forestland to meet or exceed BMPs. Forest management and fiber sourcing standards also encourage use of trained logging professionals and the support of logger training programs that include instructions for implementing BMPs [5]. Fiber sourcing standards require a primary producer, such as a sawmill or pulp mill, to verify that the fiber sourced by the facility was harvested in accordance with BMPs. Furthermore, forest certification program requirements have many additional, positive implications relative to water quality for non-industrial private landowners who supply wood to primary producers following fiber sourcing standards but may not be third-party certified themselves. Fiber sourcing requirements have been the key driver in the growth of logger training and landowner outreach programs. In Georgia, these education and outreach efforts strongly improved BMP implementation across all forest ownerships [68].

Currently, within the 13 states in the southeastern U.S., we are aware of at least 9,067,235 hectares certified to SFI and 1,894,657 hectares certified to FSC (Table 1); note that there may be some overlap where some hectares are certified to both SFI and FSC. Nonetheless, this is a conservative estimate as there are likely additional acres that are certified to ATFS but are not accounted for here. Additionally, all ownerships in the area are likely to be influenced by the SFI Fiber Sourcing Standard. For example, a recent study in Georgia concluded that the SFI Fiber Sourcing Standard contributed to increased BMP compliance rates within mill sourcing boundaries [68]. Although the percentage varied among mill types, certified mills accounted for 97% of wood consumed by the pulp and paper industry. Because most timber harvests result in multiple products, including pulpwood, the higher number likely reflects the influence of forest certification. While BMP implementation across all types of ownership in the southeast is high, certified lands provide additional assurance that high rates of implementation will continue into the future.

Certification programs require third-party audits to ensure BMP use by both forest landowners and wood procurement entities. In short, third-party audits consist of auditors randomly selecting recently harvested sites to assess BMP use. For SFI and FSC, audit summaries are publicly available on their respective websites. In addition to ensuring BMP use, forest certification programs ensure that forestland owners and wood procurement entities have measures in place to ensure the conservation of high-value forests and biodiversity. Englund and Berndes [69] presented seven principles with underlying specific criteria to assess sustainability standards, particularly in relation to biodiversity. These principles include (1) endangered species; (2) habitat destruction and fragmentation; (3) habitat degradation and modification; (4) overexploitation; (5) invasive species and GMOs; (6) energy use and GHG emissions; and (7) research, awareness, and education. Using these principles, SFI® and FSC® standards were found to be "stringent" from a biodiversity perspective [69]. Other authors have concluded that, overall, contemporary forest management coupled with forest certification has resulted in landscapes that support and contribute to the conservation of biological diversity [70,71].

6. Federal Agencies Are Recognizing the Effectiveness of BMPs

6.1. The EPA Has Noted That BMPs Protect Water Quality

The EPA has recognized that implementing BMPs ensures high-quality water flowing from managed forests. The 2005 EPA Stormwater Phase II Final Rule Fact Sheet noted that the contributions of forest management to sediment runoff are orders of magnitude lower than rates for other land uses. It noted that "sediment runoff rates from construction sites are typically 10 to 20 times greater than those from agricultural lands, and 1000 to 2000 times greater than those of forest lands" [72] (p. 1). Brown and Binkley [73] reached a similar conclusion based on a comprehensive review of the effects of the management of water quality in North American forests. Their review included discussions of pathogens, dissolved oxygen, nutrients, dissolved solids, sediment, toxics, temperature, and water quality protection programs and concluded that "the quality of water draining forested watersheds is typically the best in the nation, whether the forests are left untouched or managed" [73] (p. 21).

In addition, the EPA decided not to regulate stormwater discharges from forest roads under Section 402(p)(6) of the CWA (81 Fed. Reg. 43492–43510). Although the EPA's decision was based on several factors, the primary reason for the finding was that state, federal, regional, tribal government, and private forest landowners already had adequate BMP programs in place to address water quality issues because of discharges from forest roads. The EPA noted that (1) BMP programs are routinely monitored, improved, and updated when necessary; (2) BMP implementation rates are generally high; and (3) decades of research have documented that BMPs are effective in protecting water quality when properly implemented. Based on these findings, the EPA concluded that its primary role going forward would be to assist with "efforts to help strengthen existing programs" rather than "superimposing an additional federal regulatory layer" over other agencies and forest landowners (81 Fed. Reg. 43492).

6.2. U.S. Fish and Wildlife Service Has Noted That BMPs Contribute to Conservation of At-Risk Aquatic Species

According to a report by the National Commission on Science for Sustainable Forestry (NCSSF) "the most important challenge for maintaining and enhancing U.S. forest biodiversity is keeping current forestland in forest usage" [74] (p. 13). Thus, a key benefit of forest management in the conservation of at-risk species is the opportunity to manage forests to achieve landowner goals, including timber production, recreation, wildlife management, or other goals, combined or singularly, providing an incentive for owners and managers to retain forested conditions rather than convert forests to other land uses. When the Service identifies potential threats to a species, the agency is required to identify and report specific threats (the Service defines a threat as anything that is known to or reasonably could negatively affect individuals either directly or as a stressor) in the Federal Register and provide the public with an opportunity to comment on the accuracy of their threat assessment and the opportunity to propose potential remedies or conservation measures. In recent threatened and endangered species listing determinations, the Service has recognized that privately-owned, managed forests that implement BMPs can be an important component of conservation strategies for aquatic organisms (Table 2).

Table 2. Examples of proposed and final rules in which the U.S. Fish and Wildlife Service (Service) has recognized that state-approved forestry best management practices (BMPs) can be an important component of conservation strategies for aquatic organisms. Quoted text was obtained from the Federal Register (Fed. Reg.), which publishes proposed and final federal rulemakings such as Endangered Species Act listing determinations.

Common Name	Species Name	Date	Language
Suwannee moccasinshell	*Medionidus walkeri*	1 July 2021	The final designation of critical habitat for the Suwannee moccasinshell (*Medionidus walkeri*) in Florida and Georgia includes: "special management considerations or protection may be required within critical habitat areas to ameliorate these threats, and include (but are not limited to): . . . use of best management practices designed to reduce sedimentation, erosion, and stream bank alteration" (86 Fed. Reg. 34984).
Neuse Riverwaterdog	*Necturus lewisi*	9 June 2021	The final section 4(d) rule includes the following exception: "forestry-related activities, including silvicultural practices, forest management activities, and fire control tactics, that implement State-approved BMPs" (86 Fed. Reg. 30710). Within this rule, the Service further lists specific outcomes the BMPs must achieve for the exception to apply.
Panama City crayfish	*Procambarus econfinae*	15 April 2021	The proposed section 4(d) rule includes the following exception: "silvicultural (forestry) activities located in secondary soils that follow state best management practices (BMPs)" (86 Fed. Reg. 19859).
Suwannee alligator snapping turtle	*Macrochelys suwanniensis*	7 April 2021	In the proposed listing rule, the Service stated: "silviculture practices and forestry management activities that follow State-approved best management practices to protect water and sediment quality and stream and riparian habitat will not impair the species' conservation" (86 Fed. Reg. 18031).
Candy darter	*Etheostoma osburni*	7 April 2021	The final designation of critical habitat listed the "use of BMPs designed to reduce sedimentation, erosion, and bankside destruction" among activities that could ameliorate threats to essential features of critical habitats (86 Fed. Reg. 17962).
Trispot darter	*Etheostoma trisella*	30 September 2020	In the final ESA Section 4(d) rule, the Service indicated that silvicultural practices that implement BMPs for water quality are among activities which benefit the species by contributing to habitat protection (85 Fed. Reg. 61616) and named silviculture practices and forest management activities that implement BMPs as excepted activities (85 Fed. Reg. 61619).
Big Sandy crayfish and Guyandotte River crayfish	*Cambarus callainus and C. veteranus; respectively*	28 January 2020	In the proposed designation of critical habitats, the Service listed the "use of best management practices (BMPs) designed to reduce erosion, sedimentation and stream bank destruction" among activities that can ameliorate threats to critical habitat (85 Fed. Reg. 5076).
Candy darter	*Etheostoma osburni*	21 November 2018	In the final listing rule, the Service announced the endangered status for the species and proposed the designation of a critical habitat. The Service included changes in water chemistry, increases in water temperature, and excessive sedimentation and stream bottom embeddedness among a list of threats from which habitat features essential to the conservation of the candy darter may require protection. Subsequently, the Service explained "management activities that could ameliorate these threats include, but are not limited to: use of best management practices (BMPs) designed to reduce sedimentation, erosion, and bankside destruction; protection of riparian corridors and retention of sufficient canopy cover along banks; reduction of other watershed disturbances that release sediments, pollutants, or nutrients into the water . . . " (83 Fed. Reg. 59235).
Black Warrior waterdog	*Necturus alabamensis*	3 January 2018	The final listing rule stated: "modern forestry operations in Alabama have a certified BMP compliance of 98 percent and, therefore, mostly are not currently significant contributors to nonpoint source pollution. According to Alabama's BMPs for forestry, SMZs should be a width of 35 ft (50 ft for sensitive areas) from the stream bank, providing a level of protection to instream habitat. Recently, the forest industry has begun to self-regulate SMZs through a third-party certification program in which mills will not accept timber from foresters who do not comply with SMZ requirements" (83 Fed. Reg. 263).

Table 2. *Cont.*

Common Name	Species Name	Date	Language
Pearl darter	*Percina aurora*	20 September 2017	In a final listing rule, the Service stated that, "based on the best available information, the following actions are unlikely to result in a violation of section 9, if these activities are carried out in accordance with existing regulations, permit requirements, or certification programs; this list is not comprehensive: (1) Normal agricultural and silvicultural practices, including herbicide and pesticide use, which are carried out in accordance with existing regulations, permit and label requirements, and certified best management practices ... " (82 Fed. Reg. 43895). In the discussion of forestry, the pearl darter listing rule described positive effects of best management practices (BMPs) as follows. "Nonpoint source pollution is a localized threat to the pearl darter within the drainage, and is more prevalent in areas where certified best management practices (BMPs) are not utilized. The use of certified BMPs during land-altering activities can greatly reduce impacts to water quality. Certified BMPs, currently implemented by the forestry industry (e.g., Sustainable Forestry Initiative, Forest Stewardship Council, and American Tree Farm System), are helping to minimize or eliminate non-point source pollution during forestry activities. The Mississippi Forestry Commission (2016, entire) reports certified BMP implementation rates to be high in Mississippi for forestry activities, primarily due to the efforts of State forestry agencies and forest certification programs (Schilling and Wigley 2015, pp. 3–7)" (82 Fed. Reg. 43889).
Diamond darter	*Crystallaria cincotta*	22 August 2013	In a final rule designating the critical habitat, the Service listed the "use of best management practices designed to reduce sedimentation, erosion, and streambank destruction" among management activities that ameliorate threats (78 Fed. Reg. 52375).

7. Direct Effect of BMPs on Aquatic Macroinvertebrates

Because research quantifying the direct effects of BMPs on aquatic species of concern is challenging, aquatic macroinvertebrates are typically used as a surrogate for the monitoring of water quality. Warrington et al. [9] found that, despite limited data documenting relationships between BMPs and individual aquatic species, there is a significant body of research confirming that BMPs contribute to protecting water quality. The authors concluded that BMPs should benefit several riparian and aquatic species, particularly species that are sensitive to changes in water quality or forest structure [9]. With unlimited time and resources, it would be best to have studies that focus on individual aquatic species, but until these studies are feasible, we need to rely on indicators (e.g., macroinvertebrates and water quality; but see below).

As an example, Hensley et al. [40] examined nutrient export dynamics and stream biota in two watersheds dominated by loblolly pine in north Florida following fertilization. Over 54 months, they monitored stream discharge, nitrogen (TN, TKN, NO3-N, NH4-N) and phosphorus (TP, orthoP), and stream biota (benthic macroinvertebrates, phytoplankton chlorophyll a, periphyton, and vascular plants) prior to and following watershed-scale fertilizer applications. Their study, which condensed four years of scheduled fertilization into a single year, resulting in nutrient additions significantly larger than standard operational practices. Hensley et al. [40] found that the annual mass export of N and P remained unchanged, suggesting the landscape retention of additional loads. Likewise, they observed no systematic change in biological indicators [40]. Although some seasonal patterns in macroinvertebrate communities were observed, measurements of stream biota did not show the effects of fertilization. Additionally, Florida's stream condition index (SCI) scores calculated from benthic macroinvertebrates indicated "exceptional" or "healthy" stream conditions [40].

In contrast with long-lived aquatic species, benthic macroinvertebrates are more easily studied and are a well-established proxy for stream quality (as reviewed by [9,75]). Bioassessments, such as those using aquatic macroinvertebrates, are commonly used to evaluate the biological integrity of streams [76] and to characterize the responses of macroinvertebrates to timber harvests that implement BMPs [77]. Most states have bioassessment programs that use metrics based on the relative abundance of fish, macroinvertebrates, or periphyton taxa to assess stream condition. Benthic macroinvertebrates are often used as indicators of water quality because most of their life cycle is aquatic, they are logistically easy to collect and identify, and they have variable taxonomic tolerance to disturbance and pollution. Importantly, benthic macroinvertebrates are relatively stationary in streams, which means that they are exposed and respond to disturbances in the area in which they are found. Diverse benthic macroinvertebrate communities indicate a stable and diverse food web. In fact, the EPA suggests using bioassessments specifically for measuring improvements in aquatic conditions after BMPs are implemented, therefore recognizing them as the best available science for understanding/quantifying the effects of water quality on aquatic fauna [78].

8. Conclusions

Protecting streams from sedimentation and chemical contamination is critical to ensure that many aquatic species have appropriate substrates for life history requirements. Assurance of this outcome can be reasonably expected, based on an understanding of how contemporary forest practices are protective of streams and minimize NPS pollution. This is a critical component of water quality that can be (and has been) extensively studied and measured, as discussed in detail above. Furthermore, to ensure that BMPs are properly implemented, it is imperative to continue to support logger education and training programs.

We suggest that future research should focus on field experiments directly relating BMPs to aquatic species, particularly focusing on long-lived species when possible. There are challenges and high costs for such research. Warrington et al. [9] observed that there are limited data on these direct effects, particularly for long-lived aquatic species such as the Atlantic pigtoe (*Fusconaia masoni*). It is difficult to implement a study to examine BMP effectiveness on long-lived aquatic species because it requires decades of data collection to understand watershed hydrology and aquatic system response. For example, the Carteret 7 paired watershed experiment in eastern NC has been in place for nearly 30 years and new information is still emerging regarding how this small watershed functions hydrologically [79,80]. No two watersheds act similarly over time; therefore, long-term comparisons across watersheds (i.e., paired watershed studies with a before-after-control-impact design) are generally not effective. Coupling the inherent variability in watersheds due to rain events, soils, natural fluctuations, etc., with trying to understand long-term demographic responses of a long-lived species (which has its own stochasticity) may be a time- and resource-prohibitive endeavor. However, these challenges may decrease with time and advancements in technology and tools, such as eDNA [81]. An added challenge to future research is the fact that most forests are now found in landscapes with mixed land use. In landscapes with mixed land uses, future research should focus on delineating the roles of each land use and how they interact. For example, what is the role of forests in alleviating emerging contaminants (e.g., pharmaceuticals, pesticides, surfactants, endocrine disruptors, etc.) coming from surrounding land uses (e.g., urbanization, agriculture)? Similar to the above, there will be challenges involved in this research, but understanding how forestry BMPs affect emerging contaminants throughout a watershed could lead to the efficient control of emerging contaminants from our water systems [82]. Based on our review, BMPs are effective in protecting water quality and, therefore, habitats for aquatic species. Furthermore, our review highlights that we know more about BMPs (particularly in relation to sedimentation) and their effects on macroinvertebrates than other groups of aquatic organisms. More research focusing on the direct relationships between BMP implementation and aquatic species conservation (particularly on long-lived species such as fish and mussels) and how forestry BMPs protect water quality issues originating from other land uses is needed.

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References

1. Binkley, D.; Burnham, H.; Lee Allen, H. Water Quality Impacts of Forest Fertilization with Nitrogen and Phosphorus. *For. Ecol. Manag.* **1999**, *121*, 191–213. [CrossRef]
2. Binkley, D.; Ice, G.G.; Kaye, J.; Williams, C.A. Nitrogen and Phosphorus Concentrations in Forest Streams of the United States1. *JAWRA J. Am. Water Resour. Assoc.* **2004**, *40*, 1277–1291. [CrossRef]
3. SAF. *The Dictionary of Forestry*; Society of American Foresters: Bethesda, MD, USA, 2008.
4. SGSF. *Silvicultural Best Management Practices Implementation Monitoring: A Framework for State Forestry Agencies*; Southern Group of State Foresters, Water Resources Committee, 2007; p. 28. Available online: https://southernforests.org/water/SGSF%20Regional%20BMP%20Framework%20Protocol%20publication_2007.pdf (accessed on 2 June 2021).
5. NASF. *Protecting Water Quality through State Forestry Best Management Practices*; National Association of State Foresters: Washington, DC, USA, 2015; p. 8.
6. SGSF. *Implementation of Forestry Best Management Practices: 2018 Southern Region Report*; Southern Group of State Foresters, Water Resources Committee, 2018; p. 16. Available online: https://southernforests.org/water/SGSF%20Water%20BMP%20Report%20FINAL.pdf (accessed on 2 June 2021).
7. Oswalt, S.N.; Smith, W.B.; Miles, P.D.; Pugh, S.A. *Forest Resources of the United States, 2017: A Technical Document Supporting the Forest Service 2020 RPA Assessment*; U.S. Department of Agriculture, Forest Service: Washington, DC, USA, 2019; p. WO-GTR-97.
8. Cristan, R.; Aust, W.M.; Bolding, M.C.; Barrett, S.M.; Munsell, J.F.; Schilling, E. Effectiveness of Forestry Best Management Practices in the United States: Literature Review. *For. Ecol. Manag.* **2016**, *360*, 133–151. [CrossRef]
9. Warrington, B.M.; Aust, W.M.; Barrett, S.M.; Ford, W.M.; Dolloff, C.A.; Schilling, E.B.; Wigley, T.B.; Bolding, M.C. Forestry Best Management Practices Relationships with Aquatic and Riparian Fauna: A Review. *Forests* **2017**, *8*, 331. [CrossRef]
10. Relyea, C.D.; Minshall, G.W.; Danehy, R.J. Development and Validation of an Aquatic Fine Sediment Biotic Index. *Env. Manag.* **2012**, *49*, 242–252. [CrossRef] [PubMed]
11. Bryce, S.A.; Lomnicky, G.A.; Kaufmann, P.R. Protecting Sediment-Sensitive Aquatic Species in Mountain Streams through the Application of Biologically Based Streambed Sediment Criteria. *Jnbs* **2010**, *29*, 657–672. [CrossRef]
12. Guzy, J.; Halloran, K.; Homyack, J.; Willson, J.D. Influence of Riparian Buffers and Habitat Characteristics on Salamander Assemblages in Headwater Streams within Managed Forests. *For. Ecol. Manag.* **2019**, *432*, 868–883. [CrossRef]
13. NCASI. *Compendium of Forestry Best Management Practices for Controlling Nonpoint Source Pollution in North America*; National Council for Air and Stream Improvement, Inc.: Research Triangle Park, NC, USA, 2009.
14. Ruhlman, M. Effectiveness of Forestry Best Management Practices: Evaluating Water Quality from Intensively Managed Watersheds. In Proceedings of the 1999 Georgia Water Resources Conference, Athens, GA, USA, 30–31 March 1999; Hatcher, K.J., Ed.; University of Georgia Institute of Ecology: Athens, GA, USA, 1999; pp. 126–129.
15. Williams, T.M.; Hook, D.D.; Lipscomb, D.J.; Zeng, X.; Albiston, J.W. Effectiveness of Best Management Practices to Protect Water Quality in the South Carolina Piedmont. In Proceedings of the Tenth Biennial Southern Silvicultural Research Conference, Shreveport, LA, USA, 16–18 February 1999; Haywood, J.D., Ed.; United States Department of Agriculture Forest Service, Southern Research Station: Asheville, NC, USA, 1999; Volume General Technical Report SRS 30, pp. 271–276.
16. Carroll, G.D.; Schoenholtz, S.H.; Young, B.W.; Dibble, E.D. Effectiveness of Forestry Streamside Management Zones in the Sand-Clay Hills of Mississippi: Early Indications. *Water Air Soil Pollut. Focus* **2004**, *4*, 275–296. [CrossRef]
17. Ward, J.M.; Jackson, C.R. Sediment Trapping within Forestry Streamside Management Zones: Georgia Piedmont, USA. *J. Am. Water Resour. Assoc.* **2004**, *40*, 1421–1431. [CrossRef]
18. Lakel, W.A.I.; Aust, W.M.; Bolding, M.C.; Dolloff, C.A.; Keyser, P.; Feldt, R. Sediment Trapping by Streamside Management Zones of Various Widths after Forest Harvest and Site Preparation. *For. Sci.* **2010**, *56*, 541–551.
19. Clinton, B.D. Stream Water Responses to Timber Harvest: Riparian Buffer Width Effectiveness. *For. Ecol. Manag.* **2011**, *261*, 979–988. [CrossRef]

20. Fraser, N.; Jackson, R.; Radcliffe, D. A Paired Watershed Investigation of Silvicultural Best Management Practices Revisted: B.F. Grant Memorial Forest, Georgia. *For. Sci.* **2012**, *58*, 652–662. [CrossRef]
21. Witt, E.L.; Barton, C.D.; Stringer, J.W.; Bowker, D.W.; Kolka, R.K. Evaluating Best Management Practices for Ephemeral Stream Protection Following Forest Harvest in the Cumberland Plateau. *South. J. Appl. For.* **2013**, *37*, 36–44. [CrossRef]
22. Boggs, J.; Sun, G.; McNulty, S. Effects of Timber Harvest on Water Quantity and Quality in Small Watersheds in the Piedmont of North Carolina. *J. For.* **2016**, *114*, 27–40. [CrossRef]
23. Barrett, S.M.; Aust, W.M.; Bolding, M.C.; Lakel, W.A.; Munsell, J.F. Estimated Erosion, Ground Cover, and Best Management Practices Audit Details for Postharvest Evaluations of Biomass and Conventional Clearcut Harvests. *J. For.* **2016**, *114*, 9–16. [CrossRef]
24. Aust, W.M.; Carroll, M.B.; Bolding, M.C.; Dolloff, C.A. Operational Forest Stream Crossings Effects on Water Quality in the Virginia Piedmont. *South. J. Appl. For.* **2011**, *35*, 123–130. [CrossRef]
25. Lang, A.J.; Aust, W.M.; Bolding, M.C.; Barrett, S.M.; McGuire, K.J.; Lakel, W.A. Streamside Management Zones Compromised by Stream Crossings, Legacy Gullies, and Over-Harvest in the Piedmont. *JAWRA J. Am. Water Resour. Assoc.* **2015**, *51*, 1153–1164. [CrossRef]
26. Rivenbark, B.L.; Jackson, C.R. Concentrated Flow Breakthroughs Moving through Silvicultural Streamside Management Zones: Southeastern Piedmont, USA. *J. Am. Water Resour. Assoc.* **2004**, *40*, 1043–1052. [CrossRef]
27. Aust, W.M.; Blinn, C.R. Forestry Best Management Practices for Timber Harvesting and Site Preparation in the Eastern United States: An Overview of Water Quality and Productivity Research during the Past 20 Years (1982–2002). *Water Air Soil Pollut. Focus* **2004**, *4*, 5–36. [CrossRef]
28. Aust, W.M.; Bolding, M.C.; Barrett, S.M. Best Management Practices for Low-Volume Forest Roads in the Piedmont Region: Summary and Implications of Research. *Transp. Res. Rec.* **2015**, *2472*, 51–55. [CrossRef]
29. Brown, K.R.; Aust, W.M.; McGuire, K.J. Sediment Delivery from Bare and Graveled Forest Road Stream Crossing Approaches in the Virginia Piedmont. *For. Ecol. Manag.* **2013**, *310*, 836–846. [CrossRef]
30. NCASI. *Assessing the Effectiveness of Contemporary Forestry Best Management Practices (BMPs): Focus on Roads*; National Council for Air and Stream Improvement, Inc.: Research Triangle Park, NC, USA, 2012.
31. Lang, A.J.; Aust, W.M.; Bolding, M.C.; McGuire, K.J.; Schilling, E.B. Forestry Best Management Practices for Erosion Control in Haul Road Ditches near Stream Crossings. *J. Soil Water Conserv.* **2017**, *72*, 607–618. [CrossRef]
32. Clinton, B.D.; Vose, J.M. Differences in Surface Water Quality Draining Four Road Surface Types in the Southern Appalachians. *South. J. Appl. For.* **2003**, *27*, 100–106. [CrossRef]
33. Taylor, S.E.; Yoo, K.H.; Rummer, R.B.; Welch, R.A.; Thompson, J.D. What We Know—And Don't Know—About Water Quality at Stream Crossings. *J. For.* **1999**, *97*, 12–17. [CrossRef]
34. Morris, B.C.; Bolding, M.C.; Aust, W.M.; McGuire, K.J.; Schilling, E.B.; Sullivan, J. Differing Levels of Forestry Best Management Practices at Stream Crossing Structures Affect Sediment Delivery and Installation Costs. *Water* **2016**, *8*, 92. [CrossRef]
35. Wynn, E.A.; O'Neil, P.E.; McGregor, S.W.; Powell, J.R.; Gangloff, M. *Watershed Assessment of the Big Canoe Creek System for Recovery and Restoration of Imperiled Aquatic Species*; Geological Survey of Alabama: Tuscaloosa, AL, USA, 2016; p. 116.
36. Brown, K.R.; McGuire, K.J.; Aust, W.M.; Hession, W.C.; Dolloff, C.A. The Effect of Increasing Gravel Cover on Forest Roads for Reduced Sediment Delivery to Stream Crossings. *Hydrol. Process.* **2015**, *29*, 1129–1140. [CrossRef]
37. Lang, A.J.; Aust, W.M.; Bolding, M.C.; McGuire, K.J.; Schilling, E.B. Best Management Practices Influence Sediment Delivery from Road Stream Crossings to Mountain and Piedmont Streams. *For. Sci.* **2018**, *64*, 682–695. [CrossRef]
38. Tatum, V.L.; Jackson, C.R.; McBroom, M.W.; Baillie, B.R.; Schilling, E.B.; Wigley, T.B. Effectiveness of Forestry Best Management Practices (BMPs) for Reducing the Risk of Forest Herbicide Use to Aquatic Organisms in Streams. *For. Ecol. Manag.* **2017**, *404*, 258–268. [CrossRef]
39. Michael, J.L. Best Management Practices for Silvicultural Chemicals and the Science behind Them. *Water Air Soil Pollut. Focus* **2004**, *4*, 95–117. [CrossRef]
40. Hensley, R.T.; Decker, P.H.; Flinders, C.; McLaughlin, D.; Schilling, E.; Cohen, M.J. Fertilization Has Negligible Effects on Nutrient Export and Stream Biota in Two North Florida Forested Watersheds. *For. Ecol. Manag.* **2020**, *465*, 118096. [CrossRef]
41. Fox, T.R.; Jokela, E.J.; Allen, H.L. The Development of Pine Plantation Silviculture in the Southern United States. *J. For.* **2007**, *105*, 337–347.
42. Fox, T.R.; Allen, H.L.; Albaugh, T.J.; Rubilar, R.; Carlson, C.A. Forest Fertilization in Southern Pine Plantations. *Better Crop.* **2006**, *90*, 12–15.
43. Fox, T.R.; Lee Allen, H.; Albaugh, T.J.; Rubilar, R.; Carlson, C.A. Tree Nutrition and Forest Fertilization of Pine Plantations in the Southern United States. *South. J. Appl. For.* **2007**, *31*, 5–11. [CrossRef]
44. Secoges, J.M.; Aust, W.M.; Seiler, J.R. The Effectiveness of Streamside Management Zones in Controlling Nutrient Fluxes Following an Industrial Fertilizer Application. In Proceedings of the 15th Biennial Southern Silvicultural Research Conference, Hot Springs, AR, USA, 17–20 November 2008; Guldin, J.M., Ed.; Department of Agriculture, Forest Service, Southern Research Station: Asheville, NC, USA, 2013; Volume 175, pp. 405–410.
45. NCASI. *Patterns and Processes of Variation in Nitrogen and Phosphorus Concentrations in Forested Streams*; National Council for Air and Stream Improvement, Inc.: Research Triangle Park, NC, USA, 2001.

46. Correll, D.L. Buffer zones and water quality protection: General principles. In *Buffer Zones: Their Processes and Potential in Water Protection, Proceedings of the International Conference on Buffer Zones*; Haycock, N.E., Burt, T.P., Goulding, K.W.T., Pinay, G., Eds.; Quest Environmental: Harpenden, Hertfordshire, UK, 1999; pp. 7–20.
47. Edwards, P.J.; Williard, K.W.J. Efficiencies of Forestry Best Management Practices for Reducing Sediment and Nutrient Losses in the Eastern United States. *J. For.* **2010**, *108*, 245–249. [CrossRef]
48. Beltran, B.J.; Amatya, D.M.; Youssef, M.; Jones, M.; Callahan, T.J.; Skaggs, R.W.; Nettles, J.E. Impacts of Fertilization on Water Quality of a Drained Pine Plantation: A Worst Case Scenario. *J. Environ. Qual.* **2010**, *39*, 293–303. [CrossRef]
49. McBroom, M.W.; Beasley, R.S.; Chang, M.; Ice, G. Storm Runoff and Sediment Losses from Forest Clearcutting and Stand Re-Establishmnet with Best Management Practices in East Texas, USA. *Hydrol. Process.* **2008**, *22*, 1509–1522. [CrossRef]
50. Fromm, J.H.; Herrmann, R.B. *Jones 5 Fertilizer Runoff Monitoring–1992*; Southern Environmental Field Station: New Bern, NC, USA, 1996.
51. Campbell, R.G. *Water Quality Mid-Year Report*; New Bern Forestry Research Station: New Bern, NC, USA, 1989.
52. Thistle, H.W.; Ice, G.G.; Karsky, R.L.; Hewitt, A.J.; Dorr, G. Deposition of Aerially Applied Spray to a Stream within a Vegetative Barrier. *Trans. ASABE* **2009**, *52*, 1481–1490. [CrossRef]
53. McBroom, M.W.; Louch, J.; Beasley, R.S.; Chang, M.; Ice, G.G. Runoff of Silvicultural Herbicides Applied Using Best Management Practices. *For. Sci.* **2013**, *59*, 197–210. [CrossRef]
54. Scarbrough, S.L.; Jackson, C.R.; Marchman, S.; Allen, G.; Louch, J.; Miwa, M. Herbicide Concentrations in First-Order Streams after Routine Application for Competition Control in Establishing Pine Plantations. *For. Sci.* **2015**, *61*, 604–612. [CrossRef]
55. Tatum, V.L. Toxicity, Transport, and Fate of Forest Herbicides. *Wildl. Soc. Bull.* **2004**, *32*, 1042–1048. [CrossRef]
56. Ice, G.G.; Stuart, G.W.; Waide, J.B.; Irland, L.C.; Ellefson, P.V. Twenty-Five Years of the Clean Water Act: How Clean Are Forest Practices? *J. For.* **1997**, *95*, 9–13. [CrossRef]
57. Ice, G.; Schoenholtz, S. Understanding How Extremes Influence Water Quality: Experience from Forest Watersheds. *Hydrol. Sci. Technol.* **2003**, *19*, 99–108.
58. Ice, G. History of Innovative Best Management Practice Development and Its Role in Addressing Water Quality Limited Waterbodies. *J. Environ. Eng.* **2004**, *130*, 684–689. [CrossRef]
59. Ice, G.G.; Stednick, J.D. *A Century of Forest and Wildland Watershed Lessons*; Society of American Foresters: Bethesda, MD, USA, 2004; ISBN 978-0-939970-88-9.
60. Shepard, J.P.; Aust, W.M.; Dolloff, C.A.; Ice, G.G.; Kolka, R.K. Forest Best Management Practices Research in the Eastern United States: The State of the Science 2002. *Water Air Soil Pollut. Focus* **2004**, *4*, 1–3. [CrossRef]
61. Anderson, C.J.; Lockaby, B.G. The Effectiveness of Forestry Best Management Practices for Sediment Control in the Southeastern United States: A Literature Review. *South. J. Appl. For.* **2011**, *35*, 170–177. [CrossRef]
62. Halloran, K.M.; Guzy, J.C.; Homyack, J.A.; Willson, J.D. Effects of Timber Harvest on Survival and Movement of Stream Salamanders in a Managed Forest Landscape. *Ecosphere* **2021**, *12*, e03489. [CrossRef]
63. Lenat, D.R. A Biotic Index for the Southeastern United States: Derivation and List of Tolerance Values, with Criteria for Assigning Water-Quality Ratings. *J. North. Am. Benthol. Soc.* **1993**, *12*, 279–290. [CrossRef]
64. Cristan, R.; Aust, W.M.; Chad Bolding, M.; Barrett, S.M.; Munsell, J.F. National Status of State Developed and Implemented Forestry Best Management Practices for Protecting Water Quality in the United States. *For. Ecol. Manag.* **2018**, *418*, 73–84. [CrossRef]
65. NASF. *Protecting Water Quality through State Forestry Best Management Practices*; National Association of State Foresters: Washington, DC, USA, 2019; p. 5.
66. Dangle, C.L.; Aust, W.M.; Bolding, M.C.; Barrett, S.M.; Schilling, E.B. The Effectiveness of Forestry Best Management Practices at Skidder Stream Crossings in Virginia. *J. Soil Water Conserv.* **2019**, *74*, 199–208. [CrossRef]
67. Coats, W.A. *An Assessment of Forestry Best Management Practices in North Carolina, 2012–2016*; North Carolina Department of Agriculture and Consumer Services and North Carolina Forest Service: Raleigh, NC, USA, 2017; p. 48.
68. Dwivedi, P.; Tumpach, C.; Cook, C.; Izlar, B. Effects of the Sustainable Forestry Initiative Fiber Sourcing Standard on the Average Implementation Rate of Forestry Best Management Practices in Georgia, United States. *For. Policy Econ.* **2018**, *97*, 51–58. [CrossRef]
69. Englund, O.; Berndes, G. How Do Sustainability Standards Consider Biodiversity? *Wiley Interdiscip. Rev. Energy Environ.* **2015**, *4*, 26–50. [CrossRef]
70. Miller, D.A.; Wigley, T.B.; Miller, K.V. Managed Forests and Conservation of Terrestrial Biodiversity in the Southern United States. *J. For.* **2009**, *107*, 197–203.
71. Demarais, S.; Verschuyl, J.P.; Roloff, G.J.; Miller, D.A.; Wigley, T.B. Tamm Review: Terrestrial Vertebrate Biodiversity and Intensive Forest Management in the US. *For. Ecol. Manag.* **2017**, *385*, 308–330. [CrossRef]
72. USEPA. *Stormwater Phase II Final Rule—Small Construction Program Overview*; United States Environmental Protection Agency, Office of Water: Washington, DC, USA, 2005.
73. Brown, T.C.; Binkley, D. *Effect of Management on Water Quality in North American Forests*; United States Department of Agriculture Forest Service, Rocky Mountain Forest and Range Experiment Station: Fort Collins, CO, USA, 1994.
74. NCSSF. *Global Markets Forum Summary. Report of the National Commission on Science for Sustainable Forestry*; National Commission on Science for Sustainable Forestry: Washington, DC, USA, 2005.

75. Sumudumali, R.G.I.; Jayawardana, J.M.C.K. A Review of Biological Monitoring of Aquatic Ecosystems Approaches: With Special Reference to Macroinvertebrates and Pesticide Pollution. *Environ. Manag.* **2021**, *67*, 263–276. [CrossRef]
76. Hutchens, J.J.; Batzer, D.P.; Reese, E. Bioassessment of Silvicultural Impacts in Streams and Wetlands of the Eastern United States. *Water Air Soil Pollut. Focus* **2004**, *4*, 37–53. [CrossRef]
77. McCord, S.B.; Grippo, R.S.; Eagle, D.M. Effects of Silviculture Using Best Management Practices on Stream Macroinvertebrate Communities in Three Ecoregions of Arkansas, USA. *Water Air Soil Pollut.* **2007**, *184*, 299–311. [CrossRef]
78. Barbour, M.T.; Gerritsen, J.; Snyder, B.D.; Stribling, J.B. *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, 2nd ed.; United States Environmental Protection Agency; Office of Water: Washington, DC, USA, 1999.
79. Ssegane, H.; Amatya, D.M.; Muwamba, A.; Chescheir, G.M.; Appelboom, T.; Tollner, E.W.; Nettles, J.E.; Youssef, M.A.; Birgand, F.; Skaggs, R.W. Calibration of Paired Watersheds: Utility of Moving Sums in Presence of Externalities. *Hydrol. Process.* **2017**, *31*, 3458–3471. [CrossRef]
80. Ssegane, H.; Amatya, D.M.; Chescheir, G.M.; Skaggs, W.R.; Tollner, E.W.; Nettles, J.E. Consistency of Hydrologic Relationships of a Paired Watershed Approach. *AJCC* **2013**, *2*, 147–164. [CrossRef]
81. Coble, A.A.; Flinders, C.A.; Homyack, J.A.; Penaluna, B.E.; Cronn, R.C.; Weitemier, K. EDNA as a Tool for Identifying Freshwater Species in Sustainable Forestry: A Critical Review and Potential Future Applications. *Sci. Total Environ.* **2019**, *649*, 1157–1170. [CrossRef]
82. Talib, A.; Randhir, T.O. Managing Emerging Contaminants in Watersheds: Need for Comprehensive, Systems-Based Strategies. *Sustain. Water Qual. Ecol.* **2017**, *9–10*, 1–8. [CrossRef]