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A Comparison of Forest Biomass and Conventional Harvesting Effects on Estimated Erosion, Best Management Practice Implementation, Ground Cover, and Residual Woody Debris in Virginia

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Abstract: Expanding markets for renewable energy feedstocks have increased demand for woody biomass. Concerns associated with forest biomass harvesting include increased erosion, the applicability of conventional forestry Best Management Practices (BMPs) for protecting water quality, and reduced woody debris retention for soil nutrients and cover. We regionally compared the data and results from three prior independent studies that estimated erosion, BMP implementation, and residual woody debris following biomass and conventional forest harvests in the Mountains, Piedmont, and Coastal Plain of Virginia. Estimated erosion was higher in the Mountains due to steep slopes and operational challenges. Mountain skid trails were particularly concerning, comprising only 8.47% of the total area but from 37.9 to 81.1% of the total site-wide estimated erosion. BMP implementation varied by region and harvest type, with biomass sites having better implementation than conventional sites, and conventional Mountain sites having lower implementation than other regions. Sufficient woody debris remained for BMPs on both harvest types in all regions, with conventional Mountain sites retaining twice that of Coastal Plain sites. BMPs reduced the estimated erosion on both site types suggesting increased implementation could reduce potential erosion in problematic areas. Therefore, proper BMP implementation should be ensured, particularly in Mountainous terrain, regardless of harvest type.

Keywords: energywood; site impacts; logging residues; Best Management Practices (BMPs); downed woody debris

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1. Introduction

Increased environmental concern and governmental policy changes have generated interest in alternative energy feedstocks. In 2022, 13.0% of the energy produced in the U.S. was derived from renewable sources [1]. While there are numerous other field crops used to produce bioenergy such as miscanthus, switchgrass, and various types of agricultural waste [2], 16.7% of renewable energy in the U.S. is produced from woody biomass [1]. Some projections suggest that renewable energy sources will supply the majority of electricity generated in the U.S. by 2050 [3]. For these reasons, increased demand for woody biomass appears likely. Sources of woody biomass vary from small-diameter short-rotation coppice plantations to stands of pulpwood-sized material used for pellets, but one of the most common is forest harvesting residues from conventional logging operations [2]. Forestry

Best Management Practices (BMPs) to protect water quality were established in the U.S. by states in response to the Clean Water Act [4,5], and have been shown to be effective at protecting water quality [6–10]. Some suggest that existing BMPs for conventional harvesting operations are sufficient to protect water quality during biomass harvests [11–13]. However, concerns have been expressed that intensive harvesting of forest biomass may result in negative site impacts and require additional protection measures [14–18].

In Virginia and other locations throughout the U.S., biomass harvests are typically integrated into conventional harvesting operations, occurring simultaneously [19]. However, there are differences between biomass and conventional harvests that could necessitate additional environmental protection measures. By definition, biomass harvests obviously reduce post-harvest residual woody debris (slash) [20–24]. Slash is commonly used as a cover BMP for erosion control, as well as limiting unauthorized site access [9,25–29]. Slash may also be used as a "soil armor" treatment to protect against soil compaction and rutting from forestry equipment [30–34]. Woody debris provides important ecosystem services, such as carbon storage and wildlife habitat [16,18]. Additionally, residual woody debris decomposes and supplies nutrients to regenerating forests; therefore, intensive harvesting of forest biomass may deplete nutrient reserves over time [17,35–39]. Biomass harvesting may also necessitate additional machine trafficking during increased biomass removal [40]. Similarly, changes in forest operational feature sizes, such as larger decks necessitated by chippers and chip vans, more expansive skid trail networks to accommodate higher volumes of harvested biomass, and decreased area in streamside management zones (SMZs) due to incentive to overharvest are of potential concern [22,41].

Barrett et al. (2016) [22] compared the post-harvest conditions of 10 conventional and 10 biomass harvest sites in the Piedmont of Virginia. Biomass harvests extracted significantly more heavy slash than conventional harvests, yet biomass harvest sites still contained woody material, and slash applications were used for cover BMPs on both harvest types. Estimated erosion rates were not significantly different for any of the operational features (decks, skid trails, haul roads, harvest areas, stream crossings, and SMZs), nor were there any significant differences in the access network areas between biomass and conventional sites. There were also no significant differences in BMP implementation rates, which were significant predictors of site-wide erosion rate estimates, indicating that BMPs were effective at controlling potential erosion on both conventional and biomass harvest sites [22].

Hawks et al. (2023) [24] and Garren et al. (2022) [23] conducted similar studies in the Coastal Plain and Mountains of Virginia, respectively. Hawks et al. [24] found significantly less area of light slash and piles and significantly more area of bare soil on biomass sites than on conventional sites. They also found a significantly lower amount of downed woody debris (DWD) on biomass sites than on conventional sites, confirming increased removal of woody biomass. Despite this, on biomass harvests, an average of 22.91 green tonnes/ha of DWD remained. Also, similar to Barrett et al. [22], slash was used for BMP purposes on both site types [24]. As in Barrett et al.'s [22] Piedmont evaluation, the Coastal Plain evaluation revealed no significant differences in estimated erosion rates, operational feature areas, or BMP implementation rates, which were again found to be significant predictors of sitewide erosion rate estimates [24].

Garren et al. [23] found similar results to Hawks et al. [24] and Barrett et al. [22] in the Mountains of Virginia. However, more significant differences between biomass and conventional sites were detected, likely due to the higher potential for negative site impacts from forest harvesting operations in topographically challenging mountainous regions [23]. Haul roads were significantly more erosive on biomass than conventional harvests, though estimated erosion rates for haul roads on both site types were relatively low compared with other studies in Mountainous areas (e.g., [42,43]). Skid trails on conventional sites contributed a significantly higher percentage to the total amount of site-wide estimated erosion than those on biomass sites, likely due to significantly lower BMP implementation rates for skid trails on these sites. Conventional sites also had significantly lower implementation rates for SMZs and sitewide. Similar to Barrett et al. [22], there was significantly less area in heavy slash on biomass sites than conventional sites. Consistent with Hawks et al. [24], there was also significantly less DWD remaining on biomass sites, though an average of 24.61 tonnes/ha remained available for BMP use. Additionally, as concluded in both other studies, there was no significant difference in the use of biomass for BMPs, and BMP implementation rates were significant predictors of estimated erosion rates, indicating that existing BMPs were effective on both site types at minimizing potential erosion [22,24].

The three independent research projects of Barrett et al. [22], Hawks et al. [24], and Garren et al. [23] provide valuable information regarding site impacts resulting from biomass harvesting operations within their respective physiographic regions. However, a comparison of the three studies would provide a comprehensive evaluation of site impacts and post-harvest conditions related to water quality from both biomass and conventional harvesting operations across the diverse physiography of Virginia. These three regions represent a majority of the topographic regions where forest harvesting occurs within the Southeastern United States, as well as many others globally. Therefore, the goal of this study was to analyze combined data from Barrett et al. [22], Hawks et al. [24], and Garren et al. [23] to provide a wholistic representation of post-harvest site conditions on both biomass and conventional forest harvesting sites that could inform diverse industry stakeholders in the Southeastern U.S. and around the world. Specific objectives were to: (1) quantify estimated erosion, operational feature areas, BMP implementation rates, visual ground cover, and downed woody debris on both biomass and conventional harvest sites across Virginia's Mountain, Piedmont, and Coastal Plain regions and (2) summarize and compare the results by harvest type from Barrett et al. [22], Hawks et al. [24], and Garren et al. [23] to provide a comprehensive evaluation of site conditions and BMP adequacy for protecting water quality following biomass and conventional forest harvesting operations.

2. Methods

To ensure consistency and comparability in data and results, the methodology used in Garren et al. [23] and Hawks et al. [24] was derived from Barrett et al. [22]. An overview of these methods is provided below. Detailed data collection methods for each region can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24].

2.1. Site Selection

Ten biomass harvests (Biomass) and ten conventional harvests (Conventional) were selected for each study within the Mountain (including the Blue Ridge, Ridge and Valley, and Appalachian Plateau) [23], Piedmont [22], and Coastal Plain [24] physiographic regions of Virginia [44] (Figure 1). County delineations for each region were based on Cooper and Becker (2007) [45] and therefore differed slightly from physiographic region boundaries provided by the Virginia Department of Environmental Quality [44]. Lists of forest harvests conducted within the year prior were obtained for each physiographic region from the Virginia Department of Forestry (VDOF). The lists were divided into Biomass and Conventional harvests based on input from local biomass-consuming mills and/or VDOF employees. Selected sites for each study were required to be clearcuts between 6 and 32 ha in size, harvested within at most one year of the site visit. Landowners were contacted in random order until 10 Biomass and 10 Conventional sites were chosen within each region. Biomass sites were confirmed upon arrival by visual inspection for wood chips on decks and other distinguishable features. Site forest types ranged widely, with most being either plantation pine, natural pine, or mixed hardwood stands.

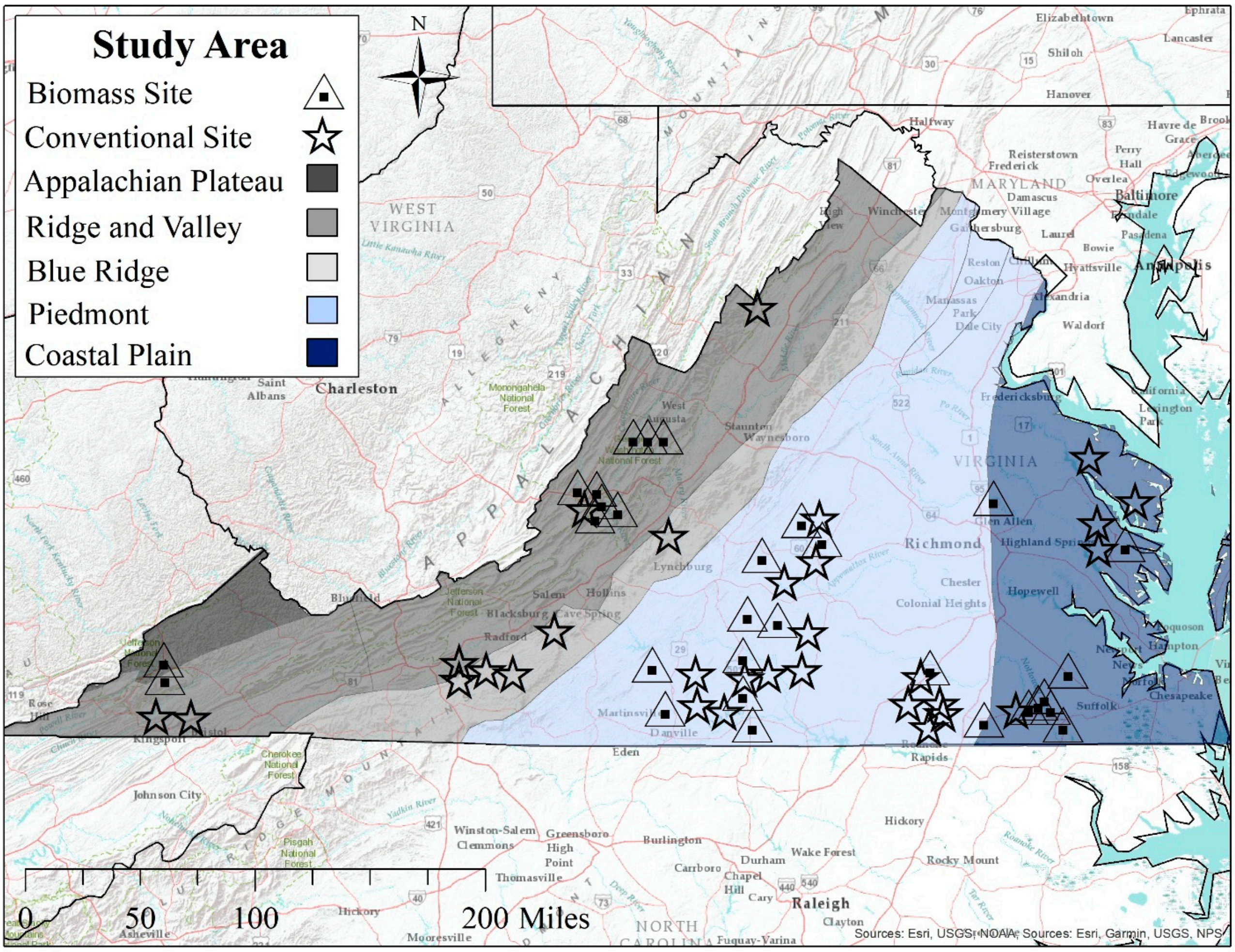

Figure 1. Approximate locations of Biomass and Conventional harvest sites in Virginia that were included in this study [44]. Notes: Site selection for each study was based on county boundaries provided by [45] and therefore differ somewhat from the physiographic region boundaries shown above. The map was created using ArcGIS® software (version 10.8.2) by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved.

2.2. Erosion Estimates

Erosion was estimated in all three studies using the Universal Soil Loss Equation (USLE) as modified for forests [46]. The equation is A = RKLSCP, where A is the soil loss per unit of area, expressed in tonnes/ha/year. Rainfall and runoff values (R) were obtained from Dissmeyer and Foster (1980) [46] and were 150 in the Mountains, 175 in the Piedmont, and 250 in the Coastal Plain. Soil erodibility factors (K) were based on soil type and were obtained from the USDA NRCS Soil Survey Geographic Database [47]. Slope length (L) and steepness (S) factors were measured using range finders, tape measures, pacing, and visual estimation for lengths and clinometers for slopes. Cover and management (C) and practice support factors (P) were derived from Dissmeyer and Foster [46]. Erosion estimates for operational features and sitewide weighted averages were completed using methods from Christopher and Visser (2007) [43]. Each site was subdivided into six operational features: access roads, decks/landings, skid trails, stream crossings, streamside management zones (SMZs), and clearcut harvest areas. Area estimates were measured using range finders, handheld GPS units, GIS software (version 10.8.2), tapes, and/or pacing.

2.3. BMP Implementation

BMP implementation was evaluated on each site using the VDOF BMP audit questionnaire. This questionnaire consists of 117 yes/no questions divided into 10 categories [48]. Scores were calculated by category and overall as a percentage of applicable questions that were answered "yes", which indicated the applicable BMPs were correctly implemented. Of the 10 categories, only 7 (roads, decks, skidding, stream/wetland crossings, SMZs, and harvest planning) were applicable to sites within all three studies.

2.4. Ground Cover

Ground cover was estimated visually using methods derived from Eisenbies et al. (2005) [49]. Ground cover categories included bare soil, litter, light slash (woody debris < 2.5 cm in diameter), heavy slash (woody debris $\geq$ 2.5 cm in diameter), piles of woody debris (>30 cm deep), and rocks. Additionally, Garren et al. [23] included grass/shrubs as a category to accommodate the larger amount of vegetation present due to the longer acceptable time window for post-harvest site visits of up to 1 year. In each study, data were collected at 10 randomly located sample plots within the harvest areas of each site. Each plot consisted of four 10 $\times$ 10 m quadrants, with one estimate made per quadrant, totaling 40 observations per site.

2.5. Downed Woody Debris

In addition to ground cover, DWD was estimated on sites by Garren et al. [23] and Hawks et al. [24] to provide an index of residual biomass. DWD was estimated using a methodology developed by Brown (1974) [50] and modified by Coates et al. (2020) [51]. Data were collected on 15 randomly located sample plots within the harvest areas of each site. Each plot consisted of three 15.24 m transects located based on random azimuths that radiated from the plot center, totaling a 45-degree angle. DWD data were tallied on each transect in four size class categories: <0.6 cm in diameter, $\geq$0.6–<2.5 cm in diameter, $\geq$2.5–<7.6 cm in diameter, and $\geq$7.6 cm in diameter. Equations from Coates et al. [51] were used to convert data into tonnes/ha of residual woody debris. An idealized measure of the spatial orientation of DWD on each site was determined by summing the tallies of woody debris and dividing this by the total length of transect the data were tallied on to determine pieces of DWD/m.

2.6. Data Analysis

Data from the Piedmont (Barrett et al. [22]), Mountains (Garren et al. [23]), and Coastal Plain (Hawks et al. [24]) were compiled and summarized. Uniformity in data collection methods ensured data were directly comparable. It is important to note that the three previous studies tested for differences between Biomass and Conventional harvests within their respective regions [22–24], whereas the current study tested for differences between physiographic regions on both Biomass and Conventional harvests. No statistical comparisons were made between Biomass and Conventional harvests in the current study. Data were analyzed in JMP Pro [52]. Shapiro–Wilk goodness-of-fit tests suggested some data were non-normal. Therefore, Kruskal–Wallis tests were conducted to test the null hypothesis that there was no difference in the parameters of interest between the Mountain, Piedmont, and Coastal Plain regions on either Biomass or Conventional sites. If the null hypothesis was rejected, Steel–Dwass tests were conducted for multiple comparisons to determine significant differences between regions. Chi-square tests were used to test for differences in slash usage for BMPs between regions due to the categorical nature of the data. If significant differences were detected, pairwise Chi-square tests with Bonferroni corrections were used for multiple comparisons while controlling the family-wise error rate. All hypothesis tests were conducted at an α = 0.1 significance level as suggested by Stefano (2001) [53] for operational data. Simple linear regressions were used to predict weighted average erosion rates on Biomass and Conventional sites based on overall BMP implementation rates. Data from all regions were combined for regression analyses, which were performed in Minitab [54].

3. Results and Discussion

The average tract size for the 60 sites (30 Biomass and 30 Conventional) was 16.1 ha, similar to other studies conducted within Virginia (e.g., [55–59]). There was no significant difference in tract size between Biomass (p = 0.3904) and Conventional (p = 0.1965) sites across regions at an average of 17.2 and 14.9 ha, respectively. The only significant difference reported in the other three studies was between Biomass and Conventional sites in the Mountains at an average of 20.7 and 12.7 ha, respectively.

3.1. Estimated Erosion Rates

Biomass sites in the Mountains were significantly (p = 0.0942) more erosive overall than those in the Coastal Plain, with average site-wide estimated erosion rates of 5.4 and 1.6 tonnes/ha/year, respectively. This trend is also present compared with Piedmont Biomass sites (Table 1). Skid trails on Mountain Biomass sites were significantly more (p = 0.0662) erosive than those in the Coastal Plain at 30.0 and 9.2 tonnes/ha/year, respectively. Finally, harvest areas on Biomass sites in the Mountains (p = 0.0662) and Piedmont (p = 0.0550) were significantly more erosive than those in the Coastal Plain (Table 1). Regarding Conventional sites, roads on Mountain sites were significantly less erosive than those on Piedmont (p = 0.0018) and Coastal Plain (p = 0.0031) sites at 1.3, 26.5, and 13.5 tonnes/ha/year, respectively. Otherwise, trends in estimated erosion rates on Conventional sites were similar to those on Biomass sites, with Mountain sites tending to have higher estimated erosion rates than Piedmont or Coastal Plain sites (Table 1). This was especially true for skid trails, with Conventional Mountain sites having a significantly higher (p = 0.0550) estimated erosion rate than Conventional Coastal Plain sites at 74.9 and 8.7 tonnes/ha/year, respectively.

Table 1. Potential erosion rate estimates by operational feature category for Biomass and Conventional sites compared by region.

Operational Feature	Estimated Erosion Rate (Tonnes/ha/Year)					
	Biomass			Conventional		
	Mountain	Piedmont	Coastal Plain	Mountain	Piedmont	Coastal Plain
	M [SE] (n)	M [SE] (n)	M [SE] (n)	M [SE] (n)	M [SE] (n)	M [SE] (n)
Roads	9.4 a [4.1] (10)	20.8 a [8.8] (5)	8.5 a [2.5] (8)	1.3 a [0.5] (10)	26.5 b [10.4] (8)	13.5 b [2.1] (7)
Decks	9.9 a [2.7] (10)	8.3 a [3.4] (10)	5.2 a [2.3] (10)	5.6 a [1.5] (10)	14.3 a [7.0] (10)	7.4 a [2.4] (10)
Skid trails	30.0 a [10.6] (10)	20.4 ab [7.7] (10)	9.2 b [3.6] (10)	74.9 a [24.6] (10)	24.2 ab [13.6] (10)	8.7 b [2.4] (10)
SMZs	0.0 a [0.0] (6)	0.2 a [0.1] (4)	0.0 a [0.0] (8)	0.7 a [0.7] (4)	0.2 a [0.1] (5)	0.2 a [0.2] (7)
Stream crossings	63.9 a [59.0] (4)	17.3 a [11.7] (3)	26.5 a [18.2] (5)	3.8 a [1.7] (4)	7.6 a [3.6] (2)	7.8 a [3.1] (4)
Harvest area	1.6 a [1.1] (10)	0.4 a [0.2] (10)	0.2 b [0.1] (10)	2.7 a [1.8] (10)	0.4 a [0.1] (10)	0.4 a [0.2] (10)
Overall	5.4 a [2.3] (10)	1.6 ab [0.6] (10)	1.6 b [0.7] (10)	12.1 a [4.4] (10)	1.8 a [0.8] (10)	1.3 a [0.3] (10)

Notes: Differing letters for means within operational feature categories (rows) and treatment (Biomass and Conventional) are significantly different at α = 0.10. Statistical comparisons between Biomass and Conventional treatments were not conducted in this study but can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24].

Elevated potential erosion rates for most operational categories in the Mountains demonstrate the substantial effect of steep slopes, as has been demonstrated elsewhere (e.g., [42,43,60–62]). The three prior studies reported similar estimated erosion rates between Biomass and Conventional sites within their respective regions and concluded that Biomass harvests do not result in increased erosion potential as compared with Conventional harvests. This study suggests that Mountain forest harvests result in elevated potential erosion rates when compared with Piedmont and Coastal Plain harvests, regardless of harvest type. Thus, as Dangle et al. (2019) [63], Hawks et al. (2022a) [64], and

Hawks et al. (2022b) [65] have suggested, proper BMP implementation is vital on Mountain harvests for reducing potentially excessive erosion and resulting impacts to water quality.

3.2. Operational Feature Areas

Biomass sites in the Mountain (p = 0.0017) and Coastal Plain (p = 0.0005) regions had a significantly higher percentage of total area in skid trails than those in the Piedmont at 10.6%, 10.9%, and 3.9%, respectively (Table 2). Biomass sites in the Coastal Plain had a significantly higher (p = 0.0370) percentage of total area in SMZs than Piedmont sites at 7.0% and 1.1%, respectively. Lastly, Piedmont Biomass sites had a significantly higher percentage of total area in clearcut harvest than Mountain (p = 0.0010) and Coastal Plain (p = 0.0010) sites at 93.0%, 81.8%, and 78.5%, respectively (Table 2). Conventional Mountain sites had a significantly (p = 0.0454) higher percentage of total area in decks than Conventional Piedmont sites at 2.6% and 1.3%, respectively. Similar to Biomass sites, Conventional Mountain (p = 0.0017), and Coastal Plain (p = 0.0022) sites had a significantly higher percentage of total area in skid trails than Piedmont sites (Table 2). Finally, Conventional Piedmont sites had a significantly higher percentage of total area in clearcut harvest area than Conventional Mountain (p = 0.0550) and Coastal Plain (p = 0.0247) sites (Table 2). Though some have expressed concerns that biomass harvests may result in more area in roads, skid trails, or decks and less area in SMZs [22,41], none of the three prior studies observed any significant differences in operational area percentages between Biomass and Conventional harvests. Rather, the results of the current study suggest that differences in operational areas on forest harvests are regionally based, as was observed in Horton et al. (2021) [66].

Table 2. Percentage of the total tract area occupied by operational feature category for Biomass and Conventional sites compared by region. There were n = 10 sites for each treatment within each region.

Operational Feature	Percentage of Total Tract Area					
	Biomass			Conventional		
	Mountain	Piedmont	Coastal Plain	Mountain	Piedmont	Coastal Plain
	M [SE]	M [SE]	M [SE]	M [SE]	M [SE]	M [SE]
Roads	0.8 a [0.2]	0.7 a [0.3]	1.4 a [0.5]	1.0 a [0.3]	0.9 a [0.4]	0.5 a [0.2]
Decks	1.9 a [0.4]	1.3 a [0.3]	2.0 a [0.2]	2.6 a [0.4]	1.3 b [0.2]	1.9 ab [0.4]
Skid trails	10.6 a [1.3]	3.9 b [0.5]	10.9 a [1.3]	10.9 a [1.4]	3.5 b [0.7]	10.1 a [0.7]
SMZs	4.9 ab [2.0]	1.1 a [0.5]	7.0 b [2.1]	1.9 a [0.7]	4.5 a [2.6]	7.4 a [2.4]
Stream crossings	0.0 a [0.0]	0.1 a [0.0]	0.3 a [0.1]	0.1 a [0.0]	0.1 a [0.1]	0.1 a [0.1]
Harvest area	81.8 a [1.9]	93.0 b [0.9]	78.5 a [2.3]	83.5 a [1.6]	89.6 b [2.6]	80.0 a [2.1]

Notes: Differing letters for means within operational feature categories (rows) and treatment (Biomass and Conventional) are significantly different at α = 0.10. Statistical comparisons between Biomass and Conventional treatments were not conducted in this study but can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24].

3.3. Contribution of Operational Features to Total Estimated Erosion Mass

Skid trails were the largest contributor to the total estimated erosion mass on Biomass sites across all three regions, despite the fact they comprised an average of only 8.47% of the total area (Table 3). Erosion mass estimates for skid trails on Mountain Biomass sites were significantly higher than those on Biomass sites in the Piedmont (p = 0.0942) and Coastal Plain (p = 0.0454) (Figure 2). Both Mountain (p = 0.0373) and Piedmont (p = 0.0199) Biomass sites had significantly higher harvest area erosion mass estimates than Coastal Plain Biomass sites (Figure 2), comprising 16.4%, 34.1%, and 11.7% of the total estimated erosion mass, respectively (Table 3). Finally, Mountain Biomass sites had higher overall estimated erosion masses than Piedmont and Coastal Plain Biomass sites at 132.5, 36.3, and 21.0 tonnes/year, respectively, though only significantly higher than Coastal Plain sites (p = 0.0454) (Figure 2).

Table 3. Percentage contribution to total estimated erosion by operational feature category for Biomass and Conventional sites compared by region. There were n = 10 sites for each treatment within each region.

Operational Feature	Percentage Contribution to Total Estimated Erosion					
	Biomass			Conventional		
	Mountain	Piedmont	Coastal Plain	Mountain	Piedmont	Coastal Plain
	M [SE]	M [SE]	M [SE]	M [SE]	M [SE]	M [SE]
Roads	6.2 a [3.1]	7.9 ab [4.8]	10.2 a [3.0]	1.7 a [1.2]	16.0 a [6.8]	7.4 a [2.8]
Decks	9.8 a [3.7]	6.8 a [1.7]	11.7 a [7.7]	7.4 a [4.1]	8.4 a [3.5]	11.8 a [3.7]
Skid trails	67.2 a [6.5]	48.7 a [8.4]	63.7 a [7.5]	81.1 a [5.5]	37.9 b [5.0]	59.4 c [8.4]
SMZs	0.3 a [0.2]	0.1 a [0.1]	0.2 a [0.1]	0.1 a [0.1]	0.7 a [0.4]	0.8 a [0.8]
Stream crossings	0.1 a [0.1]	2.4 a [2.3]	2.5 a [1.0]	0.0 a [0.0]	0.5 a [0.3]	0.4 a [0.3]
Harvest area	16.4 ab [5.3]	34.1 a [6.3]	11.7 b [4.5]	9.7 a [3.6]	36.6 b [6.5]	20.1 ab [7.5]

Notes: Differing letters for means within operational feature categories (rows) and treatment (Biomass and Conventional) are significantly different at $\alpha = 0.10$. Statistical comparisons between Biomass and Conventional treatments were not conducted in this study but can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24].

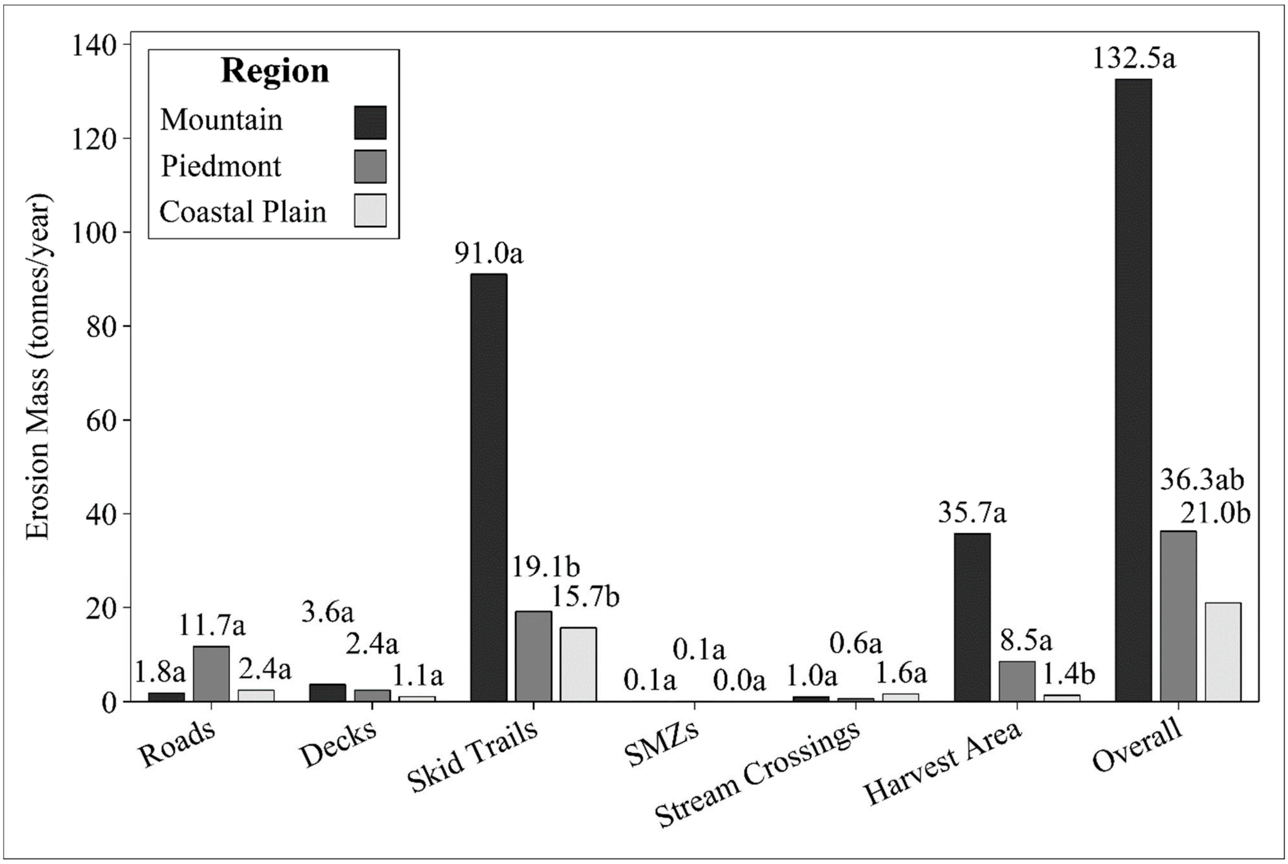

Figure 2. Estimated erosion mass by operational feature for Biomass sites compared by region. Notes: Differing letters for means within operational feature categories are significantly different at $\alpha = 0.10$. Standard errors can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24].

Similar to skid trails on Biomass sites, skid trails on Conventional sites made up an average of only 8.19% of the total area, yet they were the largest contributor to the total estimated erosion mass across all three regions (Table 3). However, skid trails on Conventional Mountain sites contributed a significantly higher percentage to the total estimated erosion mass than those on both Conventional Piedmont ($p = 0.0022$) and Coastal Plain ($p = 0.0942$) sites (Table 3). Similarly, erosion mass estimates for skid trails on Conventional Mountain sites were significantly higher ($p = 0.0454$) than those on Conventional Piedmont sites at

123.5 and 16.5 tonnes/year, respectively (Figure 3). Finally, skid trails on Conventional Coastal Plain sites contributed a significantly higher (p = 0.0550) percentage to total estimated erosion than Conventional Piedmont sites at 59.4% and 37.9%, respectively. Due to trends in estimated erosion rates (Table 1), total estimated erosion masses for roads exhibited similar trends, with roads on Conventional Mountain sites having significantly lower estimated erosion masses than Piedmont (p = 0.0108) and Coastal Plain (p = 0.0199) sites (Figure 3). Harvest areas on Conventional Piedmont sites contributed a significantly higher (p = 0.0160) percentage to total estimated erosion than those in the Mountains at 36.6% and 9.7%, respectively (Table 3). Total estimated erosion masses overall on Conventional sites exhibited similar trends to those on Biomass sites, though no significant differences were observed (Figure 3).

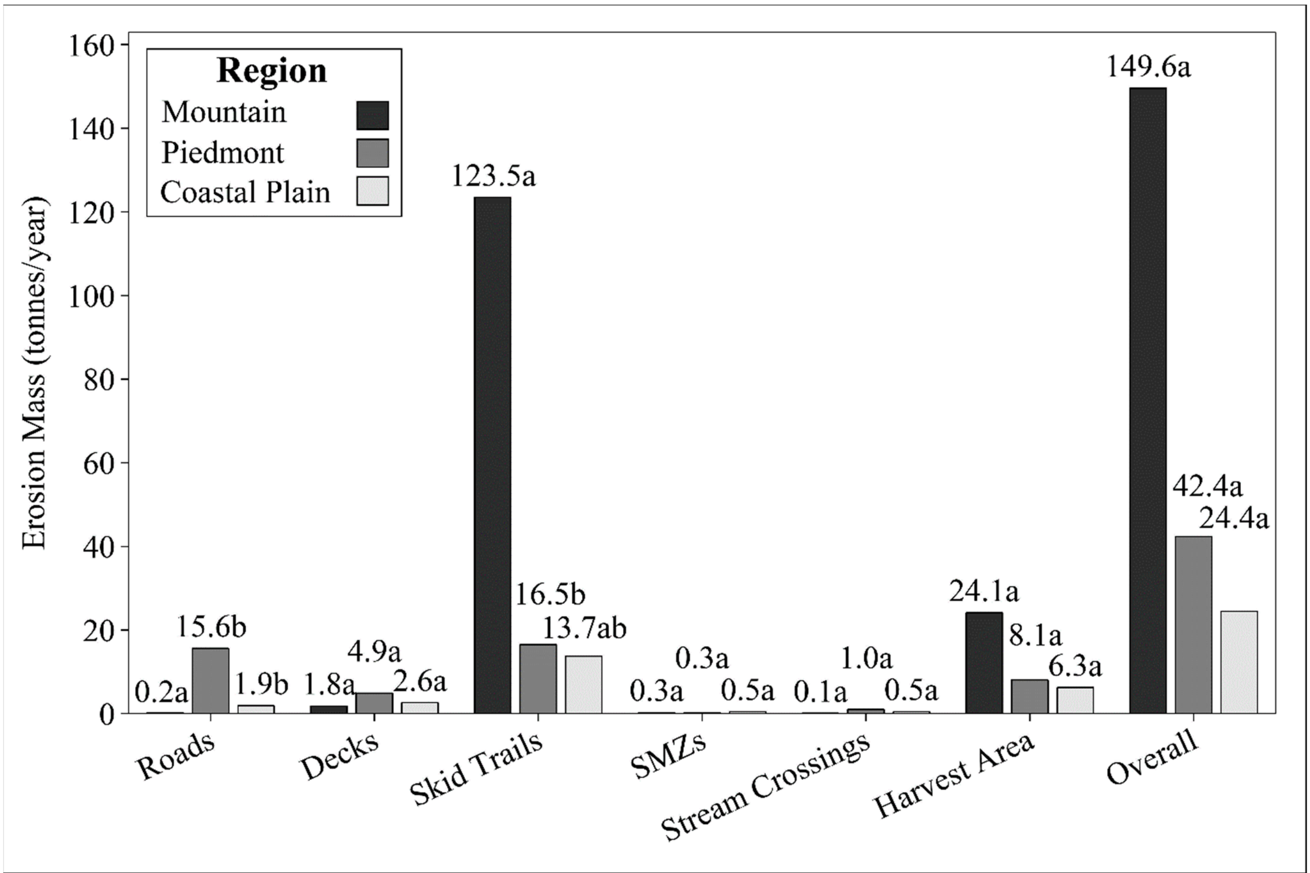

Figure 3. Estimated erosion mass by operational feature for Conventional sites compared by region. Notes: Differing letters for means within operational feature categories are significantly different at α = 0.10. Standard errors can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24].

Garren et al. [23] found that skid trails on Conventional sites constituted a significantly higher percentage of the total estimated erosion than those on Biomass sites at 81.1% and 67.2%, respectively. They also found significantly higher total estimated erosion masses from roads on Biomass sites than Conventional sites, though estimated erosion rates for both were low compared with other mountain studies (e.g., [42,43]). However, these were the only differences found among the three prior studies, and all three studies concluded that Biomass harvesting does not result in increased erosion potential compared with Conventional harvesting. Thus, these results suggest that, as with the estimated erosion rates and operational areas, differences in estimated erosion masses on forest harvests are largely due to climatic variables, physiographic region, topographic factors, and/or best management practice application, as has been demonstrated in numerous other studies (e.g., [42,61,64,65,67]), and are not due to harvest type.

3.4. BMP Implementation

Overall BMP implementation rates on Conventional Mountain sites were significantly (p = 0.0550) lower than those on Conventional Coastal Plain sites at 75.4% and 89.1%, respectively (Table 4). Skid trails on Conventional Mountain sites also had significantly (p = 0.0633) lower BMP implementation rates than Conventional Coastal Plain sites at 60.9% and 87.5%, respectively. This trend was also present for decks, with Conventional Mountain sites having an average implementation rate of 84.2%, compared with 95.6% on Conventional Coastal Plain sites (p = 0.0590). Finally, SMZs on Conventional Mountain sites had significantly lower BMP implementation rates than both Conventional Piedmont (p = 0.0027) and Coastal Plain (p = 0.0086) sites at 41.7%, 97.2%, and 83.4%, respectively, with Coastal Plain sites being significantly (p = 0.0997) lower than Piedmont sites, as well. Interestingly though, Piedmont sites had significantly lower harvest planning BMP implementation rates than both Mountain (p = 0.0848) and Coastal Plain (p = 0.0848) sites among Conventional Harvests, along with Mountain (p = 0.0868) sites among Biomass harvests (Table 4).

Table 4. BMP implementation rates by category for Biomass and Conventional sites compared by region.

BMP Category	Percentage BMP Implementation					
	Biomass			Conventional		
	Mountain	Piedmont	Coastal Plain	Mountain	Piedmont	Coastal Plain
	M [SE] (n)	M [SE] (n)	M [SE] (n)	M [SE] (n)	M [SE] (n)	M [SE] (n)
Roads	93.1 a [2.1] (10)	75.4 a [9.1] (5)	90.4 a [2.3] (8)	90.4 a [2.6] (10)	79.6 a [8.3] (8)	87.8 a [4.7] (7)
Decks	86.6 a [4.0] (10)	93.6 a [3.3] (10)	96.7 a [2.4] (10)	84.2 a [3.7] (10)	82.6 ab [5.2] (10)	95.6 b [1.8] (10)
Stream crossings	79.2 a [20.8] (4)	91.7 a [8.3] (3)	76.2 a [7.5] (5)	65.9 a [15.1] (4)	76.4 a [1.4] (2)	80.4 a [10.7] (4)
SMZs	74.0 a [11.2] (9)	82.3 a [8.4] (9)	85.0 a [4.1] (9)	41.7 a [6.8] (7)	97.2 b [7.9] (8)	83.4 c [5.8] (10)
Harvest planning	100.0 a [0.0] (10)	78.3 b [9.0] (10)	93.3 ab [4.4] (10)	100.0 a [0.0] (10)	80.0 b [8.2] (10)	100.0 a [0.0] (10)
Skidding	82.6 a [6.5] (10)	81.5 a [6.1] (10)	79.1 a [6.1] (10)	60.9 a [8.9] (10)	71.1 ab [8.0] (10)	87.5 b [4.9] (10)
Overall	86.2 a [4.1] (10)	85.2 a [4.8] (10)	87.5 a [2.8] (10)	75.4 a [4.7] (10)	81.3 ab [5.5] (10)	89.1 b [2.1] (10)

Notes: Differing letters for means within operational feature categories (rows) and treatment (Biomass and Conventional) are significantly different at α = 0.10. Statistical comparisons between Biomass and Conventional treatments were not conducted in this study but can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24].

The results suggest that BMP implementation rates tend to be lower on Conventional sites in the Mountains than on Conventional sites in the Piedmont or Coastal Plain regions, consistent with other studies (e.g., [63,65,68]). BMP audit questions not only address whether BMPs were present but also whether BMPs were originally installed and functioned properly. As demonstrated by the estimated erosion results, steep terrain in the Mountains inherently causes increased erosion potential in areas with increased runoff or bare soil as compared with sites in gentler terrain (e.g., [42,43,60–62]). Therefore, some BMPs, such as water bars or turnouts, may have a higher potential to fail or function improperly if not correctly implemented in the Mountains than in regions with gentler terrain. Additionally, Shaffer et al. (1998) [69] found that Mountain sites had a higher number of BMPs installed than Piedmont or Coastal Plain regions, leading to a higher median BMP cost per ha (USD 72.38) when compared to sites in Piedmont (USD 63.63) and Coastal Plain (USD 20.04). These results were corroborated by McKee et al. (2012) [70], who found average BMP costs for stream crossings of USD 655 in the Mountains compared with USD 445 and USD 533 in the Piedmont and Coastal Plain regions of Virginia, respectively. Thus, it is inherently more difficult and expensive to properly implement BMPs in the Mountains than in the Piedmont and Coastal Plain regions, potentially explaining the lower BMP implementation rates found on Conventional sites in the Mountains.

While BMP implementation rates were lower on Conventional Mountain sites than on Conventional sites in other regions, this trend was absent on Biomass sites, with no significant differences found among regions except for harvest planning (Table 4). Garren et al. [23] found that BMP implementation rates were significantly higher on Biomass sites than on Conventional sites in the Mountains for SMZs and skid trails, as well as overall. This trend was also supported by Barrett et al. [22], though the difference was not significant. Thus, the finding that Biomass sites may have higher BMP implementation rates than Conventional sites is supported by results in the current study. Loggers in the Mountains tend to be smaller scale than those in other regions [56,59], and entry into the biomass market requires a significant initial capital investment [19,59]. As Garren et al. [23] speculated, most biomass producers in the Mountains are likely larger companies that can take advantage of economies of scale and/or have the fiscal ability to enter the market and may be more likely to work with mills involved in forest certification programs. Therefore, these producers may have added incentive to properly implement BMPs. Some have expressed concern that biomass harvesting may incentivize overharvesting, particularly within the SMZ. However, BMP implementation rates were lower in SMZs on Conventional sites than in Biomass sites in the Mountains (Table 4), often because the SMZs on Conventional sites were not retained. Mountain loggers typically produce more sawtimber than loggers in other regions [56], which is a higher value than most other products, including biomass. Therefore, these results suggest that biomass harvesting does not incentivize overharvesting within the SMZ; rather, Conventional loggers in the Mountains may have more incentive to overharvest within the SMZ due to the larger amount of high-value sawtimber present.

3.5. Overall BMP Implementation Compared to Estimated Erosion Rates

Overall BMP rates were found to be significant predictors of site-wide weighted average erosion rate estimates on both Biomass ($p < 0.001$) (Figure 4) and Conventional ($p < 0.001$) (Figure 5) sites. The inverse relationship clearly indicates that estimated erosion rates decrease as BMP implementation increases. Additionally, R^2 values were higher in this study compared with others that have conducted similar analyses (e.g., [63,64,68]), indicating a relatively strong relationship on both Biomass and Conventional sites (Figures 4 and 5). BMPs have been shown to be effective at reducing potential erosion and protecting water quality in Conventional forest harvests in numerous studies (e.g., [5,6,9,10,65]). These findings corroborate these studies, as well as the findings of the three previous studies, confirming that existing BMPs are effective at reducing potential erosion on both Biomass and Conventional sites in Virginia.

3.6. Slash Usage for BMPs

There was no difference in slash usage as a BMP among regions on Biomass sites ($p = 0.7866$), with 83% of all biomass sites utilizing slash as BMPs on decks, skid trails, and/or stream crossings, compared with 77% of all Conventional sites. However, Conventional Mountain sites only utilized slash as a BMP on 60% of sites, compared with 100% in the Coastal Plain ($p = 0.0759$). Additionally, slash was used as a BMP for skid trails on significantly fewer Conventional Mountain sites ($p = 0.0102$) than Conventional Coastal Plain sites at 40% and 100% of sites, respectively. No significant differences in slash use for BMPs were detected between Biomass and Conventional sites in the three previous studies. These findings further confirm that differences in slash use for BMPs are regionally based and that BMP implementation trends are lower on Conventional Mountain sites than in other regions [63,65,68].

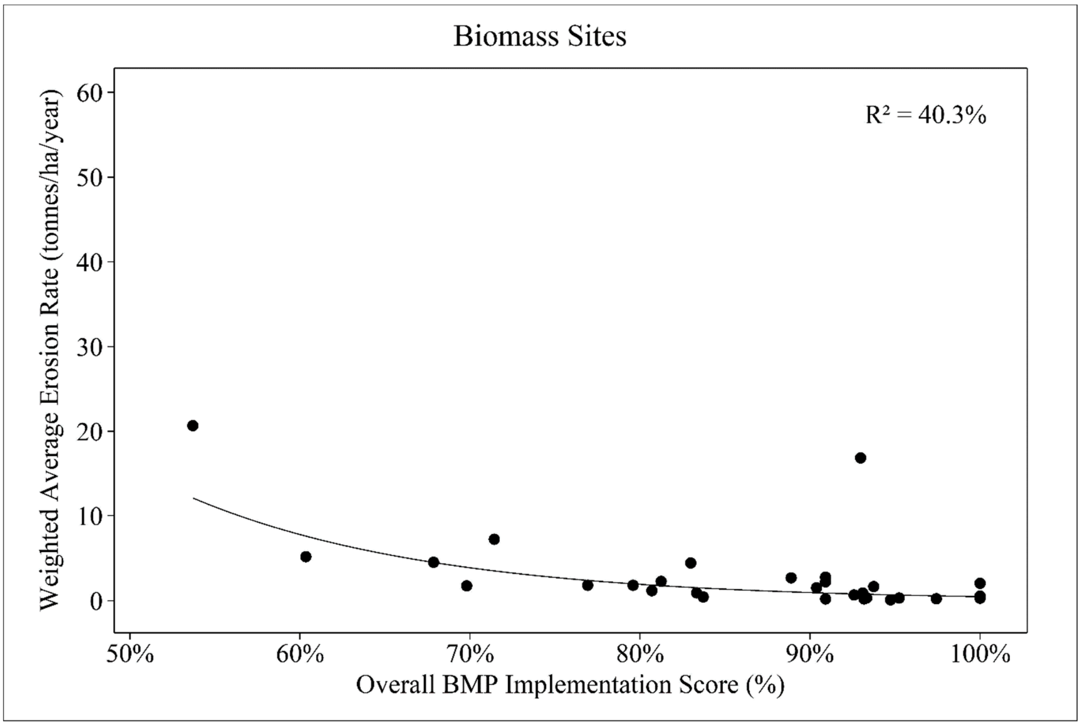

Figure 4. Overall BMP implementation percentage for all 30 Biomass sites as a predictor of the site-wide weighted average erosion rate estimate ($p < 0.0001$). The regression equation is log10(Weighted Average Erosion Rate Estimate) = 2.708 − 3.028 (Overall BMP Implementation Rate).

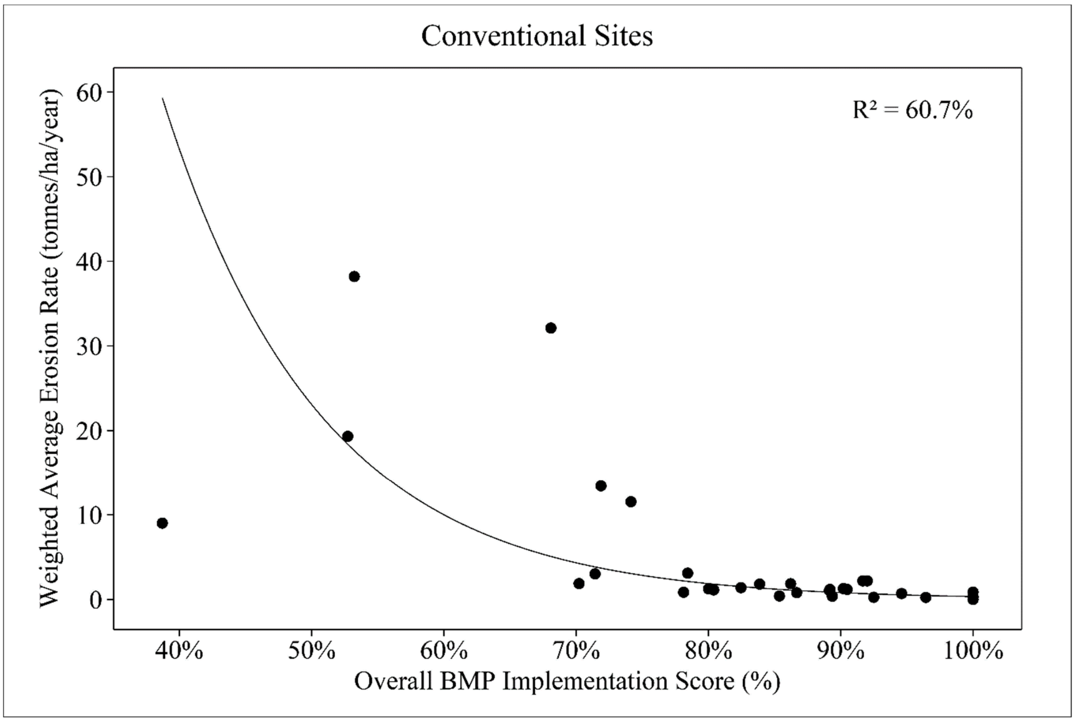

Figure 5. Overall BMP implementation percentage for all 30 Conventional sites as a predictor of the site-wide weighted average erosion rate estimate ($p < 0.0001$). The regression equation is log10(Weighted Average Erosion Rate Estimate) = 3.179 − 3.633 (Overall BMP Implementation Rate).

3.7. Harvest Area Ground Cover

Piedmont Biomass sites had a significantly higher (p = 0.0550) percentage of area in litter than Coastal Plain Biomass sites at 62.2% and 51.8%, respectively. Mountain Biomass sites had a significantly higher percentage of area in rocks than both Piedmont (p = 0.0011) and Coastal Plain (p = 0.0011) sites (Table 5). Regarding Conventional sites, those in Piedmont had a significantly higher percentage area in bare soil than those in the Mountain (p = 0.0033) or Coastal Plain (p = 0.0274) regions at 11.3%, 3.0%, and 5.6%, respectively. Conventional Piedmont sites also had a significantly higher (p = 0.0662) percentage area in litter than Conventional Mountain sites at 49.1% and 36.4%, respectively. Conventional Coastal Plain sites had a significantly higher percentage area in light slash than Conventional Mountain (p = 0.0048) and Piedmont (p = 0.0079) sites at 26.7%, 15.6%, and 17.9%, respectively. Finally, Conventional Mountain sites had a significantly higher percentage area in rocks than Piedmont (p = 0.0555) and Coastal Plain (p = 0.0022) sites (Table 5). It is important to note that Mountain sites had grass/shrubs as an additional ground cover category. Thus, significant differences in percentages for Mountain sites compared to Piedmont or Coastal Plain sites could be partially due to the diluting effect of the additional category.

Table 5. Percentage of the harvest area occupied by ground cover category for Biomass and Conventional sites compared by region. There were n = 10 sites for each treatment within each region.

Ground Cover	Percentage of Harvest Area					
	Biomass			Conventional		
	Mountain	Piedmont *	Coastal Plain *	Mountain	Piedmont *	Coastal Plain *
	M [SE]	M [SE]	M [SE]	M [SE]	M [SE]	M [SE]
Bare soil	4.6 a [1.2]	7.4 a [1.4]	9.5 a [1.6]	3.0 a [0.8]	11.3 b [1.6]	5.6 a [1.2]
Litter	45.4 ab [6.5]	62.2 a [1.9]	51.8 b [3.0]	36.4 a [4.4]	49.1 b [3.3]	48.4 ab [4.2]
Light slash	18.9 a [1.8]	17.4 a [0.7]	21.7 a [2.0]	15.6 a [1.3]	17.9 a [0.9]	26.7 b [2.2]
Heavy slash	14.8 a [1.2]	12.5 a [0.9]	16.8 a [1.7]	18.6 a [1.4]	18.5 a [1.6]	15.1 a [1.6]
Piles	2.0 a [1.0]	0.5 a [0.1]	0.3 a [0.1]	6.4 a [2.8]	2.7 a [1.0]	4.2 a [2.1]
Rock	1.6 a [0.4]	0.0 b [0.0]	0.0 b [0.0]	3.2 a [2.1]	0.5 b [0.4]	0.0 b [0.0]
Grass/shrubs	12.8 [3.0]	--	--	16.8 [4.6]	--	--

Notes: Differing letters for means within ground cover categories (rows) and treatment (Biomass and Conventional) are significantly different at $\alpha = 0.10$. Statistical comparisons between Biomass and Conventional treatments were not conducted in this study but can be found in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24]. * Barrett et al. [22] and Hawks et al. [24] did not report the amount of area occupied by the grass/shrubs category.

Both Barrett et al. [22] and Garren et al. [23] found significantly higher percentage areas of heavy slash on Conventional sites than on Biomass sites. Additionally, Barrett et al. [22] and Hawks et al. [24] found a significantly higher percentage area in piles on Conventional sites than on Biomass sites. Finally, Barrett et al. [22] found a significantly higher percentage area in litter on Biomass sites than on Conventional sites, while Hawks et al. [24] found a significantly higher percentage area in bare soil on Biomass sites than on Conventional sites. Thus, it appears that ground cover varies based on both harvest type and region. However, ground cover percentages followed the same general trends across harvest types and regions, having a low amount of bare soil, a large amount of area in litter, moderate amounts of light and heavy slash, and less area in piles and rocks. Additionally, ground cover and downed woody debris were estimated throughout the harvest area after BMPs had been installed and did not include woody debris used for BMPs in other operational features. Therefore, as concluded in the previous three studies, though there may be reduced amounts of woody debris on Biomass sites [17,21], sufficient woody debris is retained for BMP implementation regardless of site type or region.

3.8. Downed Woody Debris

DWD was estimated on Mountain and Coastal Plain sites in an effort to quantify residual Biomass [23,24]. There were several significant differences between Mountain and Coastal Plain sites in the <0.6 cm and ≥0.6 cm–<2.5 cm categories (Table 6). Generally, Mountain sites had more DWD < 0.6 cm, while Coastal Plain sites had more DWD ≥0.6 cm–<2.5 cm. However, these size classes comprise a very small amount of the total tonnes/ha of residual DWD (Table 6). Residual debris ≥ 2.5 cm in diameter has a far greater impact on total tonnes/ha of residual DWD. There were no significant differences between regions on Biomass sites for categories ≥ 2.5 cm, with Biomass sites in the Mountains and Coastal Plain having similar amounts of residual DWD at 24.61 and 22.91 tonnes/ha, respectively (Table 6). However, Conventional Mountain sites had significantly more tonnes/ha and pieces/m of residual DWD for every category ≥ 2.5 cm except total pieces/m (Table 6). Hawks et al. [24] only found slight differences in tonnes/ha and pieces/m of DWD ≥1–<7.6 cm, as well as tonnes/ha total in the Coastal Plain (Table 6). However, differences observed by Garren et al. [23] in the Mountains were more pronounced, with Conventional Mountain sites having significantly more tonnes/ha and pieces/m in every category ≥ 0.6 cm as well as total (Table 6). Thus, it appears that while there is significantly more DWD remaining on Conventional Coastal Plain sites than Biomass Coastal Plain sites, there is far more DWD remaining on Conventional sites in the Mountains compared with Mountain Biomass sites.

Table 6. Amount of residual downed woody debris by size category for Biomass and Conventional sites compared by region and treatment. There were n = 10 sites for each treatment within each region. Barrett et al. [22] did not sample woody debris; therefore, data were only available from the Mountain (MTN) and Coastal Plain (CP) regions.

Size Class	Amount of Woody Debris						Biomass vs. Conventional p-Values [a]	
	Biomass			Conventional				
	MTN	CP	p-Value [b]	MTN	CP	p-Value [b]	MTN [b]	CP [b]
	M [SE]	M [SE]		M [SE]	M [SE]			
<0.6 cm (tonnes/ha)	0.76 [0.06]	0.61 [0.03]	**0.0539**	0.85 [0.06]	0.58 [0.06]	**0.0113**	0.1620	0.7913
<0.6 cm (pieces/m)	7.78 [0.05]	6.30 [0.03]	**0.0890**	8.79 [0.06]	6.17 [0.06]	**0.0172**	0.2261	0.7913
≥0.6 cm–<2.5 cm (tonnes/ha)	5.94 [0.65]	7.06 [0.53]	**0.0890**	7.46 [0.50]	9.19 [1.13]	0.3847	**0.0376**	0.1620
≥0.6 cm–<2.5 cm (pieces/m)	3.18 [0.03]	3.87 [0.03]	**0.0452**	4.04 [0.03]	5.05 [0.06]	0.3075	**0.0587**	0.1620
≥2.5–<7.6 cm (tonnes/ha)	9.50 [1.14]	9.26 [0.92]	0.8501	17.98 [1.24]	11.97 [1.11]	**0.0036**	**0.0013**	**0.0962**
≥2.5–<7.6 cm (pieces/m)	0.66 [0.01]	0.66 [0.01]	0.7913	1.21 [0.01]	0.82 [0.01]	**0.0036**	**0.0013**	**0.0962**
≥7.6 cm (tonnes/ha)	8.41 [1.93]	6.01 [1.34]	0.3847	36.34 [5.37]	10.18 [2.64]	**0.0058**	**0.0028**	0.1620
≥7.6 cm (pieces/m)	0.10 [0.00]	0.07 [0.00]	0.3443	0.33 [0.00]	0.10 [0.00]	**0.0022**	**0.0013**	0.1040
Total (tonnes/ha)	24.61 [3.61]	22.91 [2.11]	0.7913	62.66 [5.75]	31.92 [2.99]	**0.0022**	**0.0006**	**0.0173**
Total (pieces/m)	11.71 [0.06]	10.89 [0.05]	0.4274	14.37 [0.08]	12.14 [0.10]	0.1859	**0.0312**	0.3847

[a] p-values for comparison between Biomass and Conventional treatments were obtained from Garren et al. [23] and Hawks et al. [24]. [b] p-values in bold are significant at $\alpha = 0.10$.

These findings can be explained in several ways. Loggers who harvest biomass have a market for harvesting residues, including small-diameter materials or materials with undesirable qualities for other products, giving them the incentive to utilize as much DWD as possible for biomass production. Therefore, it appears that biomass loggers in Virginia leave 22–25 tonnes/ha of residual DWD on-site, regardless of region (Table 6). This is higher than amounts reported in other locations by Fritts et al. (2014) [21] and Bessaad et al. (2021) [17] of 7.80 and 7.13 tonnes/ha, respectively. However, it appears that conventional loggers in the Mountains of Virginia leave nearly 2× the amount of DWD of those in the Coastal Plain at 62.66 and 31.92 tonnes/ha, respectively (Table 6), suggesting increased wood utilization on Conventional Coastal Plain sites. Pulpwood markets are less common in the Mountains than in the Piedmont or Coastal Plain regions [56,71]. Accordingly, pulpwood comprises a smaller percentage of Mountain loggers' total production on average [55,56]. Therefore, pulpwood-sized material is commonly left on-site in the absence of pulpwood or biomass markets. Additionally, sites in the Coastal Plain had more pine than those in the Mountains. Pines have straight stems with better form than typical hardwood species, allowing more of the stem to be utilized for other products. Thus, there is a larger amount of unutilized material available in the Mountains for biomass production [71].

4. Conclusions

This study found several significant differences in potential erosion between regions, while the previous three studies [22–24] found few between harvest types. This suggests that differences in erosion potential on forest harvesting sites are more likely regionally or topographically based than based on harvest type. Specifically, both Biomass and Conventional Mountain sites tended to be far more erosive than Piedmont or Coastal Plain sites, demonstrating the large effect steep slopes have on potential erosion from areas often lacking adequate cover, such as roads and skid trails.

BMP implementation rates on Conventional sites in the Mountains were lower than Conventional sites in other regions. Though Mountain sites often have a higher number of BMPs installed than sites in other regions [69], increased erosion potential observed in the Mountains may provide greater potential for BMPs such as water bars to fail or function improperly if inadequately installed. However, this trend was absent on Biomass sites in the Mountains. Furthermore, slash was used less as a BMP on Conventional Mountain sites than in other regions, with this trend being absent for Biomass sites as well. Some have suggested that the ability to harvest biomass might provide an incentive for overharvesting within SMZs, but the current results suggest the opposite: Conventional loggers in the Mountains may have more incentive to overharvest within SMZs, potentially due to the larger amount of high-value sawtimber present. Thus, this study, along with Garren et al. [23] and Barrett et al. [22], demonstrates improved BMP implementation on Biomass sites compared with Conventional sites. Regression analyses in this study, as well as the three prior studies, show that properly implemented BMPs are effective at reducing potential erosion rates on both Biomass and Conventional sites regardless of region. Therefore, higher erosion rates and resulting impacts on water quality in the Mountains could be controlled with properly implemented BMPs.

Trends in ground cover varied based on both region and harvest type, but sites were not devoid of woody debris, regardless of the region or harvest type. Both Garren et al. [23] and Hawks et al. [24] concluded that there was more residual DWD on Conventional sites than on Biomass sites. However, the current study reveals that there is nearly 2× more material remaining on Conventional Mountain sites than on Conventional Coastal Plain sites, likely due to the lack of pulpwood markets in the Mountains [56,71] and differences in species present. Thus, there appears to be a larger amount of unutilized material available for biomass production or BMP implementation on forest harvesting sites in the Mountain region. Regardless, an average of 22–25 tonnes/ha of DWD remained on Biomass harvests in Virginia after BMPs had been installed, which is higher than the amounts reported by studies in other locations [17,21], and slash was used as a BMP on the majority of both Biomass and Conventional sites in the three previous studies. Thus, there appears to be sufficient material remaining post-harvest for water-quality BMP applications on both Biomass and Conventional sites across all regions.

Numerous studies have documented the high potential for severe erosion in mountainous terrain [42,43,60–62], particularly on road network features, and have shown this can be successfully controlled through the proper implementation of forestry BMPs [42,63–65,72]. Results presented in Barrett et al. [22], Garren et al. [23], and Hawks et al. [24] support these findings and show that erosion rates on biomass harvests are similar to those on conventionally harvested sites, if not lower. However, despite this wealth of available literature, the current study suggests that BMP implementation in the Mountains is still deficient, particularly on skid trails and other road network features. To protect water quality, it is vitally important to ensure proper BMP implementation in mountainous regions regardless of harvest type; thus, any additional BMP guidelines developed to ensure water quality should focus on differences among regions and/or terrain.

It is important to reiterate that, though biomass harvests may have other environmental impacts such as insufficient nutrient retention, habitat quality reductions, reduced carbon storage, etc. [16,18], the sufficiency of parameters in the current study was evaluated with a focus on water quality. This was because qualitative and statistical comparisons between biomass and conventional harvests were made in this study and Barrett et al. [22], Garren et al. [23], and Hawks et al. [24], respectively. Forestry BMPs for conventional harvests were originally created by states in response to the Clean Water Act and are still primarily focused on protecting water quality [73]. Thus, a focus on water quality in the current study was required in order to make equal comparisons of site impacts and BMPs between biomass and conventional harvests. Other studies have discussed whether additional guidelines (often called Biomass Harvesting Guidelines or BHGs) should be established for biomass harvests to address environmental concerns beyond water quality (e.g., [15,16,18]). However, fewer studies have quantified and assessed the sufficiency of various site impact measures in relation to these other environmental concerns. Thus, future research is warranted to quantify and assess the sufficiency of site impact measures and residual woody debris quantities following forest biomass harvests for environmental concerns beyond water quality.

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