doi:10.2489/jswc.2022.00110

# Estimates of soil erosion and best management practice effectiveness at forestry stream crossings in North Carolina

A.J. Lang, W.A. Coats, T.A. Gerow Jr., and W.A. Swartley

**Abstract:** Approach ways of forest road and skid trail stream crossings can be direct pathways for sediment delivery to stream channels if not properly managed. Forestry best management practices (BMPs) can reduce erosion and sedimentation, but their effectiveness can vary by application. This study characterizes implemented stream crossing types and methods of access, and quantifies the effectiveness of BMPs implemented at 220 stream crossings in four ecoregions of North Carolina. We estimated soil erosion rate and quantity using the Universal Soil Loss Equation (USLE)-Forest methodology. Estimates of BMP effectiveness were explored by comparing on-site modeled estimates with modified modeled estimates that would be more discerning of no-BMP scenarios. Statewide, portable bridges and overland skid trails were the most frequently observed stream crossing type and access method, respectively. BMPs at stream crossings were properly implemented at a rate of 90.1%. Although increased BMP implementation scores were significantly associated with decreasing erosion estimates, the relationship was weakly correlated ($p < 0.0001$, $R^2 = 0.08$). There were no differences in modeled erosion rates by ecoregion ($p = 0.2671$). Statewide, overland skid trail crossings had lower modeled erosion rates than bladed skid trails ($p = 0.0432$) and haul roads ($p = 0.0002$). Erosion rates modeled at stream crossings when the tract had active operations were significantly higher compared to stream crossings on inactive/closed tracts ($p < 0.0001$). Most stream crossings observed (54%) had modeled erosion quantities less than 0.1 Mg crossing$^{-1}$ y$^{-1}$. Results show that most forestry-related stream crossings examined in this study across North Carolina adequately applied BMPs and reduced erosion potential.

**Key words:** best management practices—forest operations—North Carolina—soil erosion—stream crossings—Universal Soil Loss Equation

**Forestry best management practices (BMPs) implemented at stream crossings can reduce soil erosion to levels that are often compatible with water quality objectives of the Clean Water Act (Cristan et al. 2016).** However, forestry practices can result in short-term increases in sediment production (Yoho 1980). In the United States, the Clean Water Act requires states to develop programs to reduce nonpoint source pollution to the nation's waters. The silvicultural component of this effort is primarily accomplished through the development and implementation of BMPs. In this context, a BMP is "…a practice or combination of practices considered by a State [or authorized Tribe] to be the most effective means (including technological, economic and institutional considerations) of preventing or reducing the amount of pollution by nonpoint sources to a level compatible with water quality goals" (40 CFR 130.2[Q]). States have the leading role in developing appropriate BMPs, often collaborating with researchers, key stakeholders, and among themselves (Schilling et al. 2019). As an example, in the southeastern United States (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia), state forestry agencies primarily take the lead in implementing silvicultural nonpoint source pollution management programs. These programs include developing and revising BMPs, training forestry practitioners, participating in forest watershed research, advising landowners, providing technical assistance, and regularly examining silvicultural operations to assess the implementation of BMPs. The degree to which BMPs are implemented is often referenced as a surrogate for the protection of water resources from sedimentation (Cristan et al. 2016).

To foster consistency and repeatability of BMP implementation monitoring among these states, a procedural framework was developed and adopted by the Southern Group of State Foresters (SGSF 2007). The process for assessing BMPs includes a series of yes/no questions on whether the applicable BMP is properly installed, and a qualitative assessment of water quality risk. This process requires the evaluator to address each individual BMP on its own merit. While each state develops BMPs to meet its own needs, there are common BMP categories: harvesting, forest roads, stream crossings, streamside management zones, site preparation, firebreaks, and chemical application. Across these categories, the southeastern US region results indicate an overall BMP implementation rate of 93.6% (SGSF 2019).

Reviews of nonpoint source pollution from silvicultural operations often indicate that sediment is the most common water pollutant (Yoho 1980; Aust and Blinn 2004; Cristian et al. 2016). Streamside management zones (SMZs) can often provide enough sediment capture capacity and filtration to maintain water quality on managed forest lands (Ward and Jackson 2004; Lakel et al. 2010; Terrell et al. 2011). However, forest road and skid trail stream crossings bisect the SMZ, resulting in a pathway for sediment delivery from the road system to the waterway (Lang et al. 2015; Bowker et al.

**A.J. Lang** is a watershed and conservation staff forester, North Carolina Forest Service, Raleigh, North Carolina. **W. Alan Coats** is a geographic information systems analyst, North Carolina Emergency Management, Raleigh, North Carolina. **Thomas A. Gerow Jr.** is a water resources staff forester, North Carolina Forest Service, Raleigh, North Carolina. **William A. Swartley** is a forest hydrologist, North Carolina Forest Service, Raleigh, North Carolina.

Received July 20, 2021; Revised October 8, 2021; Accepted October 21, 2021; Published online April 19, 2022.

2020). Therefore, stream crossings and the associated road or skid trail approach ways are often cited in the literature as having the greatest potential for contributing nonpoint source pollution on silvicultural tracts (Lane and Sheridan 2002; Croke et al. 2005; Brown et al. 2013; Lang et al. 2015).

Forest road networks accelerate soil erosion beyond the naturally occurring rates of the surrounding forestland and can lead to increased sediment delivery (Yoho 1980). However, reductions in sediment delivery to waterways have been recorded when BMPs are applied to fit the site conditions (Aust et al. 2011; Morris et al. 2016; Rachels et al. 2020). Forest roads can be constructed using a wide range of standards (Walbridge 1997). Forest managers select road standards based on anticipated access needs (permanent or temporary); traffic volume, speed, and weight; size of areas to be accessed; available funding; and environmental protection requirements (Walbridge 1997; Edwards et al. 2016). When a permanent access road is constructed to a high operational standard, surface vegetation and topsoil are removed, with the subsoil often compacted, and/or supplemented by the addition of mechanically stable backfill soil or crushed stone (Walbridge 1997). Conversely, overland and bladed skid trails are constructed to lower operational standards due to their short duration of use and the ability of the logging tractors to traverse rougher terrain. These skid trails are the primary transportation routes used to extract forest products from the forest across the southeastern United States and are often abandoned or closed at the completion of the operation (Sawyers et al. 2012; Wade et al. 2012a; NCFS 2018). Forest roads and skid trails alter surface water flow paths by decreasing the soil hydraulic conductivity and modifying the composition of the forest floor (Brown et al. 2015). Increased runoff volume and velocity along these pathways increases soil erosion, which has been of research interest around the world (Fransen et al. 2001; Chappell et al. 2004; Sidle et al. 2004; Kreutzweiser et al. 2005; Croke et al. 2006; Jordán and Martínez-Zavala 2008; Anderson and Lockaby 2011).

BMP effectiveness at stream crossings on silvicultural tracts has been the focus of much research in the southeastern United States (Aust et al. 2015; Nolan et al. 2015; Morris et al. 2016; Boggs et al. 2017; Lang et al. 2017, 2018; Dangle et al. 2019a, 2019b, 2019c). Such studies have been directed toward intensive examinations of individual sites where soil erosion, soil deposition, sediment delivery to streams, and/or water quality parameters are measured and/or modeled. Variations among study results are common because soil erosion and sediment delivery rates differ based on terrain characteristics, weather events, and the type, amount, and timing of BMPs (Aust et al. 2015). Soil erosion models imperfectly incorporate these factors but provide a time-efficient and lower cost method to evaluate BMPs and road designs, although it is important to remember that such models have their limitations in determining broadly applicable conclusions (Fu et al. 2010).

The soil erosion modeling methodology of Universal Soil Loss Equation (USLE)-Forests (Dissmeyer and Foster 1984) has been used in similar research assessments of forest roads and skid trails (Sawyer et al. 2012; Wade et al. 2012b; Brown et al. 2013; Nolan et al. 2015; Lang et al. 2017; Vinson et al. 2017; Dangle et al. 2019a, 2019c). Other soil erosion models such as Water Erosion Prediction Project (WEPP) and the Revised USLE, version 2 (RUSLE2) have been used in similar studies, but no single model clearly produces more accurate results for forest roads and skid trails in the southeastern United States (Wade et al. 2012b; Brown et al. 2013; Lang et al. 2017; Vinson et al. 2017). These studies have generally shown the USLE-Forest to appropriately rank treatments according to erosion severity. The mathematical equations and table look-ups associated with USLE-Forest make it more user-friendly and easier to integrate into digital data collection systems as compared to RUSLE2 and WEPP desktop computer programs. While this study did not directly measure sediment yield to streams, USLE-Forest estimates of erosion along stream crossing approaches provide a quantitative metric and enhance the communication efforts of reporting BMP implementation coupled with effectiveness.

The literature indicates that stream crossings can be a sediment source on forest operations when BMPs are not implemented or implemented improperly. Despite high overall and stream crossing BMP implementation levels (93.6% and 92%, respectively) from the most recent southeastern report and research evidence of BMP effectiveness, there remains a demand for quantitative metrics to further understand sediment contributions during typical operational deployment of BMPs on managed forests (SGSF 2019). Modeled soil erosion estimates can be relatively easy to collect and can be used to assess BMP effectiveness.

The overall goal of this study was to estimate BMP effectiveness at stream crossing approach ways during a state-led forestry BMP implementation assessment in North Carolina. The specific objectives were to (1) assess stream crossing characteristics and BMP implementation, (2) estimate soil erosion on the stream crossing approach ways using the USLE-Forest model, (3) evaluate BMP effectiveness by comparing on-site modeled estimates with modified modeled estimates that reflect hypothetical no-BMP scenarios, and (4) provide a methodology for other state forestry agencies to assess BMP effectiveness at stream crossings.

## Materials and Methods

We sampled 434 approach ways to 220 stream crossings on 117 tracts across 73 counties and 4 ecoregions (Blue Ridge, Piedmont, Southeastern Plains, and Mid-Atlantic Coastal Plain) in North Carolina (figure 1). Sampled sites were a subset of 216 selected tracts evaluated for a coinciding statewide BMP implementation assessment conducted by the North Carolina Forest Service (NCFS) using the survey methodology developed by the Southern Group of State Foresters (SGSF 2007). Both projects were conducted simultaneously between December of 2018 and November of 2020. Selection criteria for the BMP implementation assessment project was broader in its objectives and encompassed a wider sample population than the stream crossing-focused project presented in this manuscript. Tract eligibility criteria for the BMP implementation assessment was that a tract must (1) be at least 4 ha in total size; (2) have an intermittent stream, perennial stream, or perennial waterbody within or adjacent to the tract boundaries; (3) be operationally active or active within the past six months; and (4) not have evidence of land use conversion. The presence of stream crossings was not a selection criterion in the BMP implementation assessment because forestry BMPs are applicable in other operational areas regardless if there are stream crossings present. All sampled tracts containing an intermittent or perennial stream crossing were assessed and included in the data used for this manuscript.

An iterative process, consisting of three main methods, was used to identify eligible tracts. For the first method, we used Landsat satellite imagery processed through the Southern Forest Area Change Tool (SouthFACT) (www.southfact.com) and Esri ArcGIS software to identify areas where the imagery detected a likely change (loss) of tree canopy cover. The resulting list of tracts was further narrowed using Esri ArcGIS software by removing sites without a mapped US Geological Survey (USGS) stream within 200 m of the tract boundaries. The tract list generated from this procedure served as a starting point for discussions with NCFS county staff. These tracts could be categorized into the following three situations by NCFS county staff: (1) staff had visited the site and could confirm whether it met study criteria, (2) staff were aware of the site, but had not yet performed an inspection and could not confirm study criteria, or (3) staff had no previous knowledge of the site. If 10 or more tracts met situation 1, they were numbered and randomly selected by the researchers who had not visited the sites nor had any prior knowledge of the forestry operation. If fewer than 10 tracts met situation 1, then tracts from situations 2 and 3 and a list of NCFS inspected sites known to meet the study criteria, but not detected by SouthFACT, were added to the random selection list. In some cases, researchers examined a site only to find out that it did not qualify for the two study projects, in which case the next closest tract from the list was visited. For the second method, if the SouthFACT process yielded no suitable sites, researchers randomly selected from a list of NCFS inspected sites known to meet the study criteria only. The third method consisted of examining sites that were discovered opportunistically while traveling; fewer than 30 of those sites are included in this study's assessment. This site selection process was repeated statewide for each county.

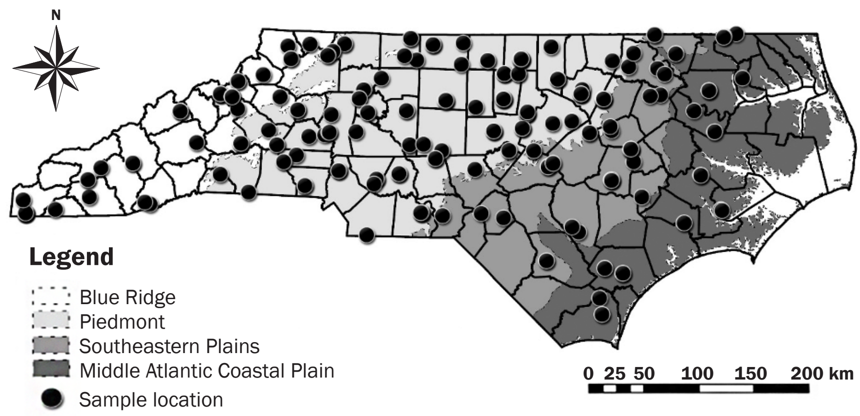
When on-site, researchers determined stream type (ephemeral, intermittent, or perennial) at crossing locations as part of the agency's responsibility to inspect forestry-related land-disturbing activities to determine compliance with the standards required by the state's Forest Practice Guidelines Related to Water Quality (FPG) (02 NCAC 60C) as part of the North Carolina Sedimentation Pollution Control Act. The BMP implementation questions for stream crossings (table 1), access type (overland or bladed skid trail or haul road), stream crossing type (bridge, culvert, ford, or pole), and soil erosion estimates were recorded using the Esri Survey123 (digital survey forms) and ArcCollector (digital mapping application) platforms on an Apple iPhone 8 (Apple, Cupertino, California) or a Google Pixel 3XL (Google, Mountain View, California) smartphone devices. The BMP implementation rate score for each BMP category was calculated as follows in equation 1:

$$\textit{BMP Implementation Rate (\%)} = \frac{(\textit{Number of Applicable BMPs Properly Implemented})}{(\textit{Total Number of Applicable BMPs})} \times 100\ . \quad (1)$$

If a BMP was determined by the researcher to be Not Applicable, then it was not included in the count. Soil erosion estimates were made at each intermittent and perennial stream crossing approach way using the USLE-Forest methodology (Dissmeyer and Foster 1984). Stream crossings primarily used as residential driveways or agricultural production were not assessed. The soil erosion modeling methodology has been used in similar research assessments of forest roads and skid trails (Sawyer et al. 2012; Wade et al. 2012b; Brown et al. 2013; Nolan et al. 2015; Lang et al. 2017; Vinson et al. 2017; Dangle et al. 2019a, 2019c). Stream crossing locations were recorded using the Esri ArcCollector application and integrated global positioning system (GPS) in the smartphone devices. Multiple pictures were taken with these devices from various angles to document the stream crossing conditions.

**Figure 1**

**Approximate locations of sampled stream crossing sites (117 tracts) and counties within North Carolina's ecoregions.**




The USLE has six components that are multiplied together to estimate soil loss ($A$) in units of ton per acre per year (Wischmeier and Smith 1978). English units can be converted to metric units (Mg ha$^{-1}$ y$^{-1}$) following the procedures described in Foster et al. (1981) (equation 2):

$$A = R \times K \times LS \times CP\ . \quad (2)$$

The six components are rainfall and runoff factor ($R$), soil erodibility factor ($K$), slope-length factor ($L$), slope-steepness factor ($S$), cover and management factor ($C$), and support practice factor ($P$).

The $R$ factor is provided in the USLE-Forest manual as an isoerodent map (Dissmeyer and Foster 1984). Lines from the isoerodent map were digitized into a shapefile and added into the Esri webmap for viewing on cellphone devices in the field. $R$ values ranged from 2,468 to 4,000 MJ mm ha$^{-1}$ y$^{-1}$ in the Blue Ridge, 2,723 to 4,766 MJ mm ha$^{-1}$ y$^{-1}$ in the Piedmont, 4,085 to 6,042 MJ mm ha$^{-1}$ y$^{-1}$ in the Southeastern Plains, and 4,425 to 6,468 MJ mm ha$^{-1}$ y$^{-1}$ in the Mid-Atlantic Coastal Plain. The $K$ factors were chosen from the USDA's Natural Resources Conservation Service (NRCS) Web Soil Survey erodibility values assigned to mapped soil series by soil horizon. The NRCS mapped soil series and associated $K$ values by soil horizon were also added into the Esri webmap for viewing on cellphone devices in the field. During assessments, a $K$ value was recorded based on soil horizon. If a soil horizon could not be readily

**Table 1**
North Carolina Forest Service Forestry Best Management Practices (BMP) implementation survey questions for stream crossings and approach ways to stream crossings.

| No. | Questions |
|---|---|
| 1 | Was the crossing site considered when selecting crossing type? |
| 2 | Was the stream crossing location designated using flagging, paint, or other suitable marking? |
| 3 | Was the crossing installed at a relatively straight stream section? |
| 4 | Was the crossing installed at a right-angle to the stream channel? |
| 5 | Was the stream depth, width, gradient, and capacity minimally altered? |
| 6 | Was the crossing constructed, installed, and removed during low-flow? |
| 7 | Was the temporary structure removed? |
| 8 | Was debris removed from the stream channel to meet state rules? |
| 9 | Were approach ways stabilized using appropriate materials? |
| 10 | Was the crossing area rehabilitated as soon as possible? |
| 11 | Were streambank edges and approach ways re-contoured to resemble natural conditions pre-installation? |
| 12 | Were BMPs to control, divert, and/or capture runoff/sediment along approach ways installed? |
| 13 | Was the approach way slope/grade minimized? |
| 14 | Was the crossing located at a narrow channel width? |
| 15 | Was the crossing located on firm, stable streambanks? |
| 16 | Were the bridges set on solid footing to support equipment? |
| 17 | Was the crossing located on high, level ground on each side? |
| 18 | Were bridge panels butted together? |
| 19 | Has equipment been kept out of the channel during installation and removal unless unavoidable? |
| 20 | Were logs, trees, or trucks/trailers over-hangs minimized? |
| 21 | Was fill material removed or prevented from entering the stream on the temporary culvert crossing? |
| 22 | Were the appropriate number/size of culverts used? |
| 23 | Do culvert extends at least 12 inches beyond the edge of the fill material? If shorter, are the inlet/outlet headwalls adequately protected? |
| 24 | Was 15 inch or larger culvert used? |
| 25 | Was the culvert placed in the center of existing or expected water flow? |
| 26 | Was/were the culvert(s) set with an appropriate downslope grade? |
| 27 | Is the height that water drops from the outlet of the culvert minimized? |
| 28 | Is there at least 12 inches of backfill material atop culvert? |
| 29 | Is backfill material packed down tightly and void of excessive debris? |
| 30 | Are the inlet/outlet of the culvert and fill material protected with suitable stabilization measures? |
| 31 | Does the crossing design allow floodwaters to flow overtop or around crossing as needed? |
| 32 | Were surface hardening materials used at the culvert and approach ways as needed? |
| 33 | Was the ford only used for truck access? |
| 34 | Was the ford installed at a location with relatively low streambanks? |
| 35 | Was the ford installed at location with solid and level stream bottom? |
| 36 | Was the ford installed at a straight section of stream channel? |
| 37 | Were geotextile fabrics as underlayment used as needed? |
| 38 | Were clean hardening materials used on vehicle traffic surfaces? |
| 39 | Were hardening materials evenly spread to avoid dips, humps, or ruts? |
| 40 | Was the ford installed to allow passage of natural streamflow, particularly for low-flow or dry periods? |
| 41 | Did the ford have permanent groundcover over at least 80% of the approach way area within the first 50 feet of the stream? |
| 42 | Can water flow through the pole crossing? |
| 43 | Was the integrity of the channel banks protected? (intact and stable) |
| 44 | Were de-limbed and topped logs used? |
| 45 | Were logs free of soil or other debris? |
| 46 | Were the logs large enough to stack loosely? |
| 47 | Was soil within or on top of the pole crossing avoided? |
| 48 | Was the pole crossing installed to an elevation higher than the adjacent channel or bank? |
| 49 | Were limbs, tops, slash, or other woody material atop the approach ways packed down? |
| 50 | Were pole crossing removed following use or when high-flows were expected? |

distinguished, the largest $K$ value per the observed soil series was selected. Soil erodibility range values for Blue Ridge, Piedmont, Southeastern Plains, and Mid-Atlantic Coastal Plain were 0.019 to 0.057, 0.018 to 0.066, 0.022 to 0.057, and 0.013 to 0.049 Mg ha h ha$^{-1}$ MJ$^{-1}$ mm$^{-1}$, respectively. Stream crossing approach length and width ($L$ factor) were measured using a logger's tape to the nearest 0.3 m, and slope with a clinometer to the nearest 1% ($S$ factor). Each approach way was delineated as the area between the streambank and nearest effective upslope water control structure that could disperse runoff away from the crossing. In the event that a failed or compromised water control structure was observed on the approach way, then the slope length was extended beyond that structure to an area upslope that was identified as being unlikely to contribute runoff to the stream crossing approach way. The $L$ and $S$ factors are evaluated together to create a $LS$ value. This value was calculated using the following equation 3:

$$LS = (\lambda/72.6)^m\ (65.41\sin^2\theta + 4.65\sin\theta + 0.065)\ , \quad (3)$$

where $\lambda$ = slope length (ft), $\theta$ = the slope angle (degrees), and $m$ = 0.2 for <1% slopes, 0.3 for 1% to 3% slopes, 0.4 for 3.5% to 4.5% slopes, and 0.5 for ≥5% slopes (Dissmeyer and Foster 1984).

The range of $LS$ values observed in the Blue Ridge, Piedmont, Southeastern Plains, and Mid-Atlantic Coastal Plain were less than 0.1 to 3.9, less than 0.1 to 2.8, less than 0.1 to 0.9, and less than 0.1 to 1.1 m m$^{-1}$, respectively. The $C$ and $P$ factors are also evaluated together by multiplying six $C$ and $P$ subfactors, which include (1) bare soil, residual binding, and soil reconsolidation; (2) canopy effect; (3) steps; (4) on-site storage; (5) invading vegetation; and (6) contour tillage. Percentage bare soil was estimated by walking along the approach way in a zig-zag pattern and recording the count of either bare soil or covered soil at each step. A minimum of 20 steps per approach way was used to calculate percentage bare soil (Brown et al. 2015; Lang et al. 2017). All other $C$ and $P$ subfactor values were recorded using table and figure prompts in the USLE-Forest methodology and visual estimates/observations (Dissmeyer and Foster 1984). These $R$, $K$, $LS$, and $CP$ estimates are multiplied together to create an estimate of erosion rate (ton per acre per year), which was then converted to megagram per hectare per year for each approach way. These potential erosion estimates were weighted by area and averaged to generate an overall potential erosion rate for each crossing site.

We also modeled a hypothetical "no-BMP" scenario for each crossing as a basis to compare against our observed erosion rates with actual BMP implementation. In the no-BMP scenario, $R$ and $K$ values from our observed data set remained the same. The $LS$ values were altered by doubling the measured approach length, while keeping the same percentage slope measure, and then recalculating $LS$ values. Doubling slope lengths was chosen partly for simplicity of evaluating and contextualizing the overall functionality of BMPs. Additionally, doubling slope lengths of our data set resulted in less than 2% of approach way lengths in excess of 122 m, which is the maximum length within the slope effect chart of the USLE-Forest manual (figure 3 of Dissmeyer and Foster 1984). Slope lengths in excess of 122 m tend to concentrate runoff and accelerate erosion beyond what the USLE-Forest model can estimate without extrapolating (Dissmeyer and Foster 1984). The $CP$ values were altered by assigning a value of one (i.e., multiplied by one and therefore eliminating the factor effects on model estimates). Forest operators have some control of both slope length and soil cover when executing forest operations. Road and skid trail slope lengths contributing runoff to streams are commonly shortened through implementation of water control structure BMPs such as waterbars, rolling dips, broad-based dips, and/or turnouts (NCFS 2006). Increasing ground cover on roads and trails using gravel/rock, grass seed, straw, slash, or other organic material also reduces erosion potential and is a commonly implemented BMP. Hypothetical model adjustments have been used in similar studies to reduce erosion rates for the assessment of improved BMP implementation (Nolan et al. 2015; Dangle et al. 2019a, 2019b, 2019c). The hypothetical adjustment used in this study is to assess BMP effectiveness. Although the "no-BMP" model estimate likely does not accurately reflect potential erosion without BMPs, it provides a simple, easily repeatable metric to approximate BMP effectiveness. We recognize that BMP effectiveness is often used in describing reductions in sediment delivery, or by assessing changes in physical, chemical, and biological water quality parameters (Anderson and Lockaby 2011; Cristan et al. 2016). Our use of BMP effectiveness relates to soil erosion reduction and was calculated using the following equation 4:

$$\mathit{BMP\ effectiveness}\ (\%) = \frac{(\mathit{No\ BMPs} - \mathit{With\ BMPs})}{\mathit{No\ BMPs}} \times 100 \quad (4)$$

where *No BMPs* is the hypothetical "no-BMP" soil erosion estimate using USLE-Forest (Mg h$^{-1}$ y$^{-1}$), and *With BMPs* is soil erosion estimate using USLE-Forest with all field observed parameters (Mg h$^{-1}$ y$^{-1}$).

JMP-Pro 15.2.0 was used to perform all statistical analyses (SAS Institute, Inc. 2019). Since the data did not meet parametric analysis assumptions, a combination of descriptive statistics and nonparametric analysis were used. Descriptive statistics were calculated for BMP implementation scores and soil erosion estimates and displayed by North Carolina ecoregions, crossing types, and access methods. Erosion estimates and BMP implementation scores were further evaluated with the nonparametric Kruskal-Wallis test, followed by multiple comparisons using the Steel-Dwass all pairs test (Ott and Longnecker 2016). We also used regression analysis to interpret the relationship between erosion rates with BMP implementation scores.

## Results and Discussion

***Stream Crossing Characterization.*** Researchers observed the characteristics of 220 stream crossings that were either on operationally active (34 crossings) or inactive/closed (186 crossings) tracts. Crossing types included portable bridges, culverts, fords, and poles. Portable bridges comprised 79.1%, 80.6%, and 53.3% of Piedmont, Southeastern Plains, and Coastal Plain stream crossings, respectively, and were the most common stream crossing overall (64.5%) (table 2). In the Piedmont, Southeastern Plains, and Middle Atlantic Coast Plain, portable bridges were the most frequently observed stream crossing structure on overland (90.3%, 90.5%, and 66.7%, respectively) and bladed (71.9%, 100%, and 100%, respectively) skid trails. However, in the Blue Ridge ecoregion, portable bridges were used only on 22.7% of all crossings and 26.5% of skid trail crossings. The lower percentage use of portable bridges

**Table 2**
**Distribution of stream crossing type and access method by ecoregion.**

| | | Bridge | | Culvert | | Ford | | Pole | | All crossing types | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ecoregion | Access Method | *n* | % within region | *n* | % within region | *n* | % within region | *n* | % within region | *n* | % within region |
| Blue Ridge | Bladed skid trail | 6 | 13.6 | 19 | 43.2 | 0 | 0.0 | 0 | 0.0 | 25 | 56.8 |
| | Overland skid trail | 3 | 6.8 | 5 | 11.4 | 0 | 0.0 | 1 | 2.3 | 9 | 20.5 |
| | Haul road | 1 | 2.3 | 4 | 9.1 | 5 | 11.4 | 0 | 0.0 | 10 | 22.7 |
| | Total | 10 | 22.7 | 28 | 63.6 | 5 | 11.4 | 1 | 2.3 | 44 | 100 |
| Piedmont | Bladed skid trail | 23 | 20.0 | 7 | 6.1 | 2 | 1.7 | 0 | 0.0 | 32 | 27.8 |
| | Overland skid trail | 65 | 56.5 | 3 | 2.6 | 3 | 2.6 | 1 | 0.9 | 72 | 62.6 |
| | Haul road | 3 | 2.6 | 5 | 4.3 | 3 | 2.6 | 0 | 0.0 | 11 | 9.6 |
| | Total | 91 | 79.1 | 15 | 13.0 | 8 | 7.0 | 1 | 0.9 | 115 | 100 |
| Southeastern Plains | Bladed skid trail | 6 | 19.4 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 6 | 19.4 |
| | Overland skid trail | 19 | 61.3 | 0 | 0.0 | 1 | 3.2 | 1 | 3.2 | 21 | 67.7 |
| | Haul road | 0 | 0.0 | 4 | 12.9 | 0 | 0.0 | 0 | 0.0 | 4 | 12.9 |
| | Total | 25 | 80.6 | 4 | 12.9 | 1 | 3.2 | 1 | 3.2 | 31 | 100 |
| Middle Atlantic Coastal Plains | Bladed skid trail | 2 | 6.7 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 2 | 6.7 |
| | Overland skid trail | 14 | 46.7 | 0 | 0.0 | 2 | 6.7 | 5 | 16.7 | 21 | 70.0 |
| | Haul road | 0 | 0.0 | 6 | 20.0 | 1 | 3.3 | 0 | 0.0 | 7 | 23.3 |
| | Total | 16 | 53.3 | 6 | 20.0 | 3 | 10.0 | 5 | 16.7 | 30 | 100 |
| Statewide | Bladed skid trail | 37 | 16.8 | 26 | 11.8 | 2 | 0.9 | 0 | 0.0 | 65 | 29.5 |
| | Overland skid trail | 101 | 45.9 | 8 | 3.6 | 6 | 2.7 | 8 | 3.6 | 123 | 55.9 |
| | Haul road | 4 | 1.8 | 19 | 8.6 | 9 | 4.1 | 0 | 0.0 | 32 | 14.5 |
| | Total | 142 | 64.5 | 53 | 24.1 | 17 | 7.7 | 8 | 3.6 | 220 | 100 |

in the Blue Ridge region has been documented in other similar studies (Nolan et al. 2015; Dangle et al. 2019a) and a logger survey (McKee et al. 2012). We suspect that this trend is partly a function of logging system/capability and cultural familiarity. Use of temporary bridges has been promoted through the NCFS Bridgemat Loan and Education Service since the mid-1990s (NCFS 2019) and in logger education programs throughout the southeastern United States. Although the initial purchase price of three steel panel bridges (>US$20,000) is high, they can be used for many years. The NCFS Bridgemat Loan and Education Service has steel panel bridge sets built in 2003 that have remained in service with modest maintenance costs through 2020. Portable bridges fabricated from timber beams are less expensive, but have a shorter lifespan and usually built-in shorter lengths.

Statewide, culverts were most frequently used on haul road crossings (59.4%). Culverts on permanent roads are often selected instead of bridges due to lower purchase price of the structure, less concern about traffic weight limitations, and ability to idealize fill height to reduce the overall slope-grade of the roadway. However, culverts tend to require more erosion control tactics to stabilize fill dirt overtop of the culvert, as compared with temporary bridges. Morris et al. (2016) examined sedimentation using three intensity levels of rainfall simulation on bridge, culvert, and ford stream crossings with three levels of increased erosion control tactics (referred to as BMP–, BMP, and BMP+ levels). That study found the highest sedimentation associated with the culvert stream crossing was measured during channel disturbance (i.e., culvert installation); however, the mean sediment reduction efficiency increased by 71% and 77% with standard BMP and BMP+ applications, respectively. In addition, culverts often restrict stream flow, particularly during flooding events, which may lead to channel scour and inhibit movement of aquatic life (Merrill 2005).

In our study, haul road stream crossings in the Blue Ridge, Piedmont, Southeastern Plains, and Middle Atlantic Coast Plain had culverts on 40.0%, 45.5%, 100%, and 85.7%, respectively. In the Blue Ridge region, culverts were the most frequently observed stream crossing structure for overland skid trails (55.6%) and bladed skid trails (76.0%). In a similar study conducted in Virginia, Dangle et al. (2019a) found pole crossings to be the most common crossing method on skid trails (50.0%), followed by bridge (34.6%) and culvert (15.4%). This difference may be attributed to our study criteria, which only examined crossings at intermittent and perennial streams. In North Carolina, pole crossings are only considered acceptable for ditches, ephemeral streams, and dry, intermittent streams (NCFS 2006).

Ford crossings accounted for 7.7% of all observed stream crossings and were primarily on haul roads (table 2). Ford stream crossings used for skidding (eight crossings) did not meet the standards of North Carolina's FPGs or BMP recommendations. It is notable that each of the eight ford crossings were on intermittent streams and none of them were in the Blue Ridge region. We believe this emphasizes the challenges associated with making in-field stream determinations, specifically between ephemeral and intermittent streams, as well as distinguishing between streams and hydrated ditches. On haul roads in the Blue Ridge region, fords (50%) were the most frequently observed stream crossing method. This may be partly attributed to the hard-bottom geology of streambeds in this region, which makes fording a more economical option.

Statewide, overland skid trails were the most frequently observed access method, accounting for 55.9% of all stream crossings and 65.4% of the skid trail stream crossings. From a BMP perspective, overland skid trails are preferred to bladed skid trails because soil disturbance is minimized, and they can be more easily stabilized afterwards. Wade et al. (2012a) examined erosion rates of bladed skid trails in the Virginia Piedmont in a designed study and found that their "water-bar-only" BMP treatment resulted in an average sediment production of 137.7 Mg $ha^{-1}$ $y^{-1}$. Comparatively, Sawyers et al. (2012) conducted a similar study examining only overland skid trails, and their "waterbar-only" BMP treatment resulted in an average sediment production of 24.2 Mg $ha^{-1}$ $y^{-1}$. In our study, overland skid trail stream crossings were most prevalent in the Piedmont (69.2%), Southeastern Plains (77.8%), and Middle Atlantic Coast Plain (91.3%), with bladed skid trails seen more often in the Blue Ridge region (73.5%). Bladed skid trails are frequently installed to create a lower-gradient trafficable pathway in steep terrain that would otherwise exceed machine capability.

**Table 3**

**Distribution of best management practice (BMP) implementation scores for stream crossings by ecoregion. Letters in the median column signify no significant differences using Steel-Dwass All Pairs test at α = 0.05.**

| Ecoregion | $n$ | Mean (%) | Median (%) | SD (%) | Min (%) | Max (%) |
|---|---|---|---|---|---|---|
| Blue Ridge | 44 | 88.7 | 94.4a | 13.4 | 42.9 | 100 |
| Piedmont | 115 | 90.7 | 100a | 16.5 | 20.6 | 100 |
| Southeastern Plains | 31 | 90.1 | 93.8a | 11.8 | 63.9 | 100 |
| Middle Atlantic Coastal Plains | 30 | 90.0 | 94.9a | 13.4 | 50.0 | 100 |
| Statewide | 220 | 90.1 | 100 | 14.8 | 20.6 | 100 |

***Best Management Practice Implementation Scores.*** The statewide mean BMP implementation score for stream crossings was 90.1% (table 3). This is similar to the nation-wide average of 91% and a southeastern US average of 92.4% as reported in a national survey of BMP implementation scores from state agencies (Cristan et al. 2018). Comparisons among ecoregions were not significantly different ($p > 0.1$). Compared to the previous NCFS BMP implementation assessment, our study had three more crossings (Coats 2018). There were 12.5% more bridge crossings and 7.7% fewer culverts observed. This may partially explain the 10% increase in BMP implementation score at stream crossings compared to the previous assessment (Coats 2018). Although southeastern states collect BMP implementation data in the same seven categories (including at stream crossings), the number of BMPs in a category varies. This is because each BMP implementation survey is based on the contents of the respective state's BMP manual. For example, North Carolina has 50 recommended BMPs for stream crossings (table 1), while Virginia has 18 (Dangle et al. 2019a). This is a notable difference among BMP implementation surveys throughout the United States.

Statewide BMP implementation score by stream crossing type indicate that bridges tend to score significantly greater than culverts ($p < 0.0001$), fords ($p < 0.0001$), and poles ($p = 0.0191$) (table 4). It is worth noting that there are fewer BMP specifications for using temporary bridges than for culverts, due to the greater ease with which portable bridges can be installed and their inherent enhanced performance since little to no soil disturbance or backfill is required. Bridging is a preferred temporary crossing method because it frequently results in smaller areas in need of stabilization following removal and minimizes alterations to the stream channel. However, Aust et al. (2011) compared stream crossing types in the Virginia Piedmont and concluded that all crossing types could maintain water quality when the most appropriate crossing structure is chosen for a given situation and applicable BMPs are implemented. Our findings support efforts of state forestry agencies and forest industry to encourage the use of portable bridging to minimize nonpoint source pollution at stream and ditch crossings on silvicultural tracts.

Statewide BMP implementation scores by access method indicate that overland and bladed skid trail crossings tend to score significantly greater than haul road stream crossings ($p < 0.0001$ and $p = 0.0322$, respectively) (table 5). Significant differences in the BMP score among access method were observed in the Piedmont and Middle Atlantic Coastal Plain ecoregions ($p < 0.05$) (table 5). Haul road stream crossings included in this study were believed to primarily serve silvicultural purposes. Although the data cannot indicate why haul road stream crossings scored less than skid trails, we suspect that permanent haul road stream crossings were subject to more frequent or prolonged traffic than skid trails. Some of the additional traffic likely includes nonsilvicultural uses. Traffic postharvest could potentially decrease soil cover and BMP implementation scores. Landowners may also be less willing to apply BMPs on haul roads due to cost or concerns about trafficability (from water diversions). Cover BMPs such as leftover logging slash can be used for skid trail closure at relatively low costs (Sawyers et al. 2012), while haul road cover BMPs such as gravel are costlier (Conrad et al. 2012).

***Modeled Erosion Rates.*** We used the USLE-Forest model to estimate soil erosion on stream crossing approach ways.

Statewide, culvert stream crossings had greater modeled erosion rates than bridge crossings ($p = 0.0002$) (table 6), while not significantly different from ford ($p = 0.3428$) and pole (0.0993) crossings. Within ecoregions, only the Piedmont displayed a similar pattern ($p < 0.0001$). Significant differences between culvert and bridge crossings may be partially explained by observed slope lengths. When examining all bridge and culvert approach lengths, the average and median values for bridges (10.5 m and 7.3 m, respectively) were noticeably shorter than culverts (24.8 m and 15.1 m, respectively). Aust et al. (2011) also found longer approach ways and higher erosion rates associated with culvert stream crossing, and attributed those findings to be a function of the standard to which the road was constructed and the BMPs for the approach ways, rather than what type of crossing was used. Our data support a similar conclusion. Road standards associated with bladed skid trails and many minimum-standard haul roads in steep terrain involve cut and fill operations that idealize the travel way and create longer, more gentle slope lengths as opposed to shorter and steeper slope lengths that often are found in high-relief topography.

Statewide, overland skid trail crossings had lower modeled erosion rates than bladed skid trails ($p = 0.0432$) and haul roads ($p = 0.0002$) (table 7). Designed experiments examining erosion rates on bladed skid trails (Wade et al. 2012a) and overland skid trails (Sawyers et al. 2012) indicate that bladed skid trails will erode at higher rates than overland skid

**Table 4**
**Distribution of best management practice (BMP) implementation scores for 220 stream crossings by ecoregion and stream crossing type. Values not followed by the same letter within a column specific to an ecoregion are significantly different using the Steel-Dwass All Pairs test at $\alpha = 0.05$.**

| Ecoregion | Crossing type | *n* | Mean (%) | Median (%) | SD (%) | Min (%) | Max (%) |
|---|---|---|---|---|---|---|---|
| Blue Ridge | Bridge | 10 | 91.1 | 97.2a | 11.0 | 73.3 | 100 |
| | Culvert | 28 | 86.6 | 92.1a | 15.0 | 42.9 | 100 |
| | Ford | 5 | 96.3 | 95.2a | 3.8 | 91.2 | 100 |
| | Pole | 1 | — | — | — | 84.6 | 84.6 |
| Piedmont | Bridge | 91 | 96.0 | 100a | 9.7 | 47.6 | 100 |
| | Culvert | 15 | 74.6 | 77.3b | 18.0 | 34.1 | 94.4 |
| | Ford | 8 | 66.4 | 64.4b | 24.8 | 20.6 | 100 |
| | Pole | 1 | — | — | — | 41.4 | 41.4 |
| Southeastern Plains | Bridge | 25 | 92.8 | 100a | 10.1 | 69.4 | 100 |
| | Culvert | 4 | 80.0 | 80.2a | 12.9 | 64.5 | 94.9 |
| | Ford | 1 | — | — | — | 63.9 | 63.9 |
| | Pole | 1 | — | — | — | 90.0 | 90.0 |
| Middle Atlantic Coastal Plains | Bridge | 16 | 97.7 | 100a | 5.0 | 81.2 | 100 |
| | Culvert | 6 | 83.3 | 83.1b | 11.1 | 71.4 | 95.0 |
| | Ford | 3 | 65.2 | 71.9b | 13.2 | 50.0 | 73.7 |
| | Pole | 5 | 88.5 | 91.3ab | 13.8 | 66.7 | 100 |
| Statewide | Bridge | 142 | 95.3 | 100a | 9.5 | 47.6 | 100 |
| | Culvert | 53 | 82.3 | 86.4b | 15.9 | 34.1 | 100 |
| | Ford | 17 | 74.8 | 73.7b | 22.3 | 20.6 | 100 |
| | Pole | 8 | 82.3 | 87.3b | 19.6 | 41.4 | 100 |

**Table 5**
**Distribution of best management practice (BMP) implementation scores for 220 stream crossings by ecoregion and access method. Values not followed by the same letter within a column specific to an ecoregion are significantly different using the Steel-Dwass All Pairs test at $\alpha = 0.05$.**

| Ecoregion | Access method | *n* | Mean (%) | Median (%) | SD (%) | Min (%) | Max (%) |
|---|---|---|---|---|---|---|---|
| Blue Ridge | Bladed skid trail | 25 | 88.4 | 92.9a | 12.7 | 59.0 | 100 |
| | Overland skid trail | 9 | 88.5 | 84.6a | 10.7 | 70.0 | 100 |
| | Haul road | 10 | 89.4 | 95.1a | 18.0 | 42.9 | 100 |
| Piedmont | Bladed skid trail | 32 | 89.3 | 100a | 17.1 | 34.1 | 100 |
| | Overland skid trail | 72 | 93.2 | 100a | 15.0 | 20.6 | 100 |
| | Haul road | 11 | 78.7 | 90.2b | 19.6 | 47.6 | 100 |
| Southeastern Plains | Bladed skid trail | 6 | 93.7 | 96.9a | 9.7 | 75.0 | 100 |
| | Overland skid trail | 21 | 91.0 | 84.1a | 11.7 | 63.9 | 100 |
| | Haul road | 4 | 80.0 | 80.2a | 12.9 | 64.5 | 94.9 |
| Middle Atlantic Coastal Plains | Bladed skid trail | 2 | 96.9 | 96.9ab | 4.4 | 93.8 | 100 |
| | Overland skid trail | 21 | 92.1 | 87.8a | 13.7 | 50.0 | 100 |
| | Haul road | 7 | 81.7 | 76.2b | 11.1 | 71.4 | 95.0 |
| Statewide | Bladed skid trail | 65 | 89.6 | 95a | 14.6 | 34.1 | 100 |
| | Overland skid trail | 123 | 92.3 | 100a | 13.9 | 20.6 | 100 |
| | Haul road | 32 | 82.8 | 90.4b | 16.7 | 42.6 | 100 |

trails when only waterbars are used. Logger training programs often include a discussion of this concept and emphasize the need to implement BMPs for ground cover stabilization in addition to water control structures. In our modeled erosion data for bladed skid trails, there are higher mean, median, and maximum erosion rates compared to overland skid trails for each ecoregion. However, when examining this data within ecoregions, we find no significant differences between overland and bladed skid trails ($p > 0.1$). The lack of significant differences within ecoregion may suggest that higher erosion rates of bladed trails are offset by selecting and implementing cover BMPs to reduce erosion rates.

Modeled erosion estimates among access methods within ecoregions were not significantly different except within the Piedmont ecoregion (table 7). Piedmont haul roads had significantly greater modeled erosion rates compared to bladed ($p$ = 0.0251) and overland ($p$ = 0.0010) skid trails. Our maximum erosion values for haul roads (191.9 Mg ha$^{-1}$ y$^{-1}$) are similar to maximum erosion rates observed in a legacy road study conducted in the Virginia Piedmont (Brown et al. 2013). Reopening of legacy roads frequently occurs as a result of undertaking forest management practices, and doing so may require significant improvements to road gradient, water diversion structures, and surfacing to minimize erosion potential. The Piedmont ecoregion is renowned for its highly eroded landscape and lends itself to erosion control challenges (Jackson et al. 2005) for all land-use activities.

For all crossing and access methods in our study, there were no differences in modeled erosion rates by ecoregion ($p$ = 0.2671) (table 8). However, erosion rates at tracts with active operations were significantly higher compared to inactive/closed tracts ($p$ < 0.0001), with modeled erosion estimates ranging from less than 0.1 to 381.4 Mg ha$^{-1}$ y$^{-1}$. Wide ranges within ecoregions were also observed (table 8). Although linear regression analysis of erosion rates and BMP implementation score were significant ($p$ < 0.0001), the coefficient of determination was low ($R^2$ = 0.08, $F$ = 19.89). Dangle et al (2019a) found that Virginia Department of Forestry BMP audit scores were better correlated with model erosion estimates when only questions pertaining to soil erosion were included in the regression analysis. Other combinations of our BMP implementation questions (i.e., excluding nonerosion related questions from analysis) and modeled erosion estimates were examined with regression analysis, but did not improve the coefficient of determination ($R^2$ < 0.08).

Data presented in this manuscript provide a basis from which future research can compare and improve upon the USLE-Forest model to better estimate soil erosion and sediment delivery from forestry stream crossings.

***Best Management Practice Effectiveness.*** Average predicted erosion rates for observed stream crossings increased by nearly 9× when USLE-Forest was adjusted to exclude soil cover practices and doubling the slope length (no-BMP scenario) (table 8). Using the no-BMP and observed BMP erosion estimates of the 220 stream crossings, BMP effectiveness ranged from 41.6% to 100% with an average of 88.2%. Estimated BMP effectiveness in the Blue Ridge ecoregion was significantly less than that of the Piedmont ($p$ < 0.0445), but not significantly different from the Southeastern Plains ($p$ = 0.6202) and Middle Atlantic Coastal Plain ($p$ = 0.9563). Although this method of estimating BMP effectiveness has its limitations, it adds a quantitative metric that can be used to readily compare across similar data sets.

Soil loss tolerance values (T factors) are estimates of the maximum average annual rate of soil loss that can occur without significantly affecting crop productivity at the site scale (Wischmeier and Smith 1978; USDA NRCS 2021). The USLE and T factor were developed to predict long-term, average soil losses under relatively fixed site, vegetation, and operational conditions (similar annually) for 20 or more years (Wischmeier and Smith 1978). The range of T factor values of the soil series in this study were between 2.2 and 11.2 Mg ha$^{-1}$ y$^{-1}$.

The estimated erosion rate on approximately 57% of our stream crossing data set was less than 11.2 Mg ha$^{-1}$ y$^{-1}$. Although

**Table 6**

**Summary statistics for Universal Soil Loss Equation estimates of erosion rates for 220 stream crossings by region and crossing type. Values not followed by the same letter within a column specific to an ecoregion are significantly different using the Steel-Dwass All Pairs test at $\alpha$ = 0.05.**

| Ecoregion | Crossing type | $n$ | Mean (Mg ha$^{-1}$ y$^{-1}$) | Median (Mg ha$^{-1}$ y$^{-1}$) | SD (Mg ha$^{-1}$ y$^{-1}$) | Min (Mg ha$^{-1}$ y$^{-1}$) | Max (Mg ha$^{-1}$ y$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Blue Ridge | Bridge | 10 | 81.4 | 22.1a | 139.3 | <0.1 | 381.4 |
| | Culvert | 28 | 23.5 | 15.3a | 24.4 | <0.1 | 102.3 |
| | Ford | 5 | 10.9 | 3.2a | 18.9 | 0.9 | 44.7 |
| | Pole | 1 | — | — | — | 0.8 | 0.8 |
| Piedmont | Bridge | 91 | 11.5 | 3.0a | 23.2 | <0.1 | 191.9 |
| | Culvert | 15 | 63.9 | 45.8b | 74.4 | 3.0 | 278.7 |
| | Ford | 8 | 16.4 | 15.1ab | 16.9 | <0.1 | 50.8 |
| | Pole | 1 | — | — | — | 11.3 | 11.3 |
| Southeastern Plains | Bridge | 25 | 20.1 | 5.6a | 27.1 | <0.1 | 93.9 |
| | Culvert | 4 | 24.4 | 6.8a | 39.8 | <0.1 | 83.8 |
| | Ford | 1 | — | — | — | 0.5 | 0.5 |
| | Pole | 1 | — | — | — | 0.5 | 0.5 |
| Middle Atlantic Coastal Plains | Bridge | 16 | 14.7 | 2.7a | 31.4 | 0.2 | 126.0 |
| | Culvert | 6 | 21.2 | 21.5a | 17.8 | 1.6 | 52.8 |
| | Ford | 3 | 35.8 | 37.1a | 29.5 | 5.6 | 64.6 |
| | Pole | 5 | 11.2 | 2.0a | 16.5 | 0.2 | 39.2 |
| Statewide | Bridge | 142 | 18.3 | 4.4a | 46.1 | <0.1 | 381.4 |
| | Culvert | 53 | 34.7 | 20.9b | 47.6 | <0.1 | 278.7 |
| | Ford | 17 | 17.3 | 5.6ab | 20.4 | <0.1 | 64.6 |
| | Pole | 8 | 8.5 | 2.0ab | 13.4 | 0.2 | 39.3 |

**Table 7**
Summary statistics for Universal Soil Loss Equation estimates of erosion rates for 220 stream crossings by ecoregion and access method. Values not followed by the same letter within a column specific to an ecoregion are significantly different using the Steel-Dwass All Pairs test at $\alpha = 0.05$.

| Ecoregion | Access method | *n* | Mean (Mg ha$^{-1}$ y$^{-1}$) | Median (Mg ha$^{-1}$ y$^{-1}$) | SD (Mg ha$^{-1}$ y$^{-1}$) | Min (Mg ha$^{-1}$ y$^{-1}$) | Max (Mg ha$^{-1}$ y$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Blue Ridge | Bladed skid trail | 25 | 34.1 | 15.9a | 74.2 | <0.1 | 381.4 |
| | Overland skid trail | 9 | 17.0 | 3.6a | 24.4 | 0.2 | 68.6 |
| | Haul road | 10 | 52.2 | 16.0a | 93.4 | 0.9 | 302.3 |
| Piedmont | Bladed skid trail | 32 | 27.8 | 5.0a | 58.3 | <0.1 | 278.7 |
| | Overland skid trail | 72 | 11.0 | 3.1a | 16.0 | <0.1 | 81.1 |
| | Haul road | 11 | 41.9 | 28.6b | 52.1 | 4.7 | 191.9 |
| Southeastern Plains | Bladed skid trail | 6 | 31.2 | 23.2a | 34.3 | 0.5 | 93.9 |
| | Overland skid trail | 21 | 15.0 | 4.6a | 23.7 | <0.1 | 76.1 |
| | Haul road | 4 | 24.4 | 6.8a | 39.8 | <0.1 | 83.8 |
| Middle Atlantic Coastal Plains | Bladed skid trail | 2 | 63.5 | 63.5a | 88.4 | 0.9 | 126.0 |
| | Overland skid trail | 21 | 11.2 | 3.6a | 16.9 | <0.1 | 68.6 |
| | Haul road | 7 | 23.4 | 22.1a | 17.4 | 1.6 | 52.8 |
| Statewide | Bladed skid trail | 65 | 31.6 | 11.9b | 63.0 | <0.1 | 381.4 |
| | Overland skid trail | 123 | 12.2 | 3.6a | 18.2 | <0.1 | 81.1 |
| | Haul road | 32 | 38.9 | 22.6b | 61.3 | <0.1 | 302.3 |

about 43% of our stream crossings exceeded the T factor for soils, it is important to recognize the context and scale of comparison. Soil disturbance from a timber harvest typically occurs on a less frequent temporal scale (i.e., rotation cycles) than most agricultural commodities. Most of the stream crossing soil loss estimates were modeled during active operations or within six months of operational activity. This is known to be the most vulnerable time for soil erosion on forestry sites. Many forest roads and skid trails that are not trafficked or are infrequently trafficked following the operation will usually erode at lower rates in future years. It is likely that in the absence of disturbance at these stream crossings, average soil erosion would decrease over time due to revegetation, annual leaf fall from adjacent vegetation in the SMZ, and soil reconsolidation (Bottinelli et al. 2014). Additionally, approach ways to stream crossings represent a small area relative to the size of the overall harvested tract. In our data set, stream crossing approach way areas were less than 1% of the total tract size. Although it was beyond the scope of this study to include estimates of erosion and percentage areas from other operational categories (e.g., roads, decks, skid trails, SMZs, and clearcut harvest areas), Barrett et al. (2012) report such estimates in the Virginia Piedmont. In an assessment of erosion rates on 20 clearcut tracts in the Virginia Piedmont, Barrett et al. (2012) found an average of 0.44 Mg ha$^{-1}$ y$^{-1}$ in harvest areas, which comprised an average of 91% of total tract area. We used percentage area found in their operational categories (roads, decks, skid trails, SMZs, and clearcut harvest areas) and associated erosion values to calculate an average erosion rate by tract. Substituting the stream crossing erosion rates presented in this manuscript, we find that at the tract scale, average overall erosion rates among all tracts were 1.6 Mg ha$^{-1}$ y$^{-1}$.

Averages of the erosion quantities for each crossing (erosion rate × stream crossing approach way areas) are presented for the observed and no-BMP scenarios by ecoregion in table 9. Approximately 54% of stream crossings had observed erosion quantities of less than 0.1 Mg crossing$^{-1}$ y$^{-1}$. The top 12% of stream crossings with the greatest erosion quantities accounted for over 80% of the total estimated erosion quantity from the 220 stream crossings. The values presented in table 9 are likely inflated because they represent the highest expected erosion quantities observed during a timber rotation. However, roads and trails that remain in-use for recreational or other purposes without maintaining functional BMPs may increase erosion rates (Miniat et al. 2019).

For some historical context, in 1975 the North Carolina Forest Service (Kea 1975) published findings from a rapid-assessment case study in which soil erosion rates were estimated on 18 silvicultural sites across the state using a modified Musgrave soil erosion equation. That equation used similar parameters as the USLE-Forest. That case study found an average statewide soil erosion rate >222 Mg ha$^{-1}$ y$^{-1}$ on skid trails and >78 Mg ha$^{-1}$ y$^{-1}$ on spur roads, with an average estimated sediment deposition of >81 Mg ha$^{-1}$ y$^{-1}$ into waterways. The maximum erosion rate found during that study was 1,316 Mg ha$^{-1}$ y$^{-1}$ from un-stabilized skid trails on a tract with 40% slope. This historical perspective illustrates the notable improvement in soil conservation being achieved today through the development, deployment, and institutionalization of BMPs within the forestry community.

In comparison to nonforestry land uses, mean and median soil erosion rates in this study are relatively low. For example, Potter et al. (2006) used a modified USLE for the Conservation Effects Assessment Project and found a mean estimated erosion rate of 3.6 Mg ha$^{-1}$ y$^{-1}$ upon agricultural lands in the southeastern United States. For an alternative comparison, the USDA NRCS (2000) cites a case study in Nashville, Tennessee, in which the RUSLE was used for a road construction site and resulted in an estimated erosion rate of 897 Mg ha$^{-1}$ y$^{-1}$. In addition, the *North Carolina Erosion and Sediment Control Planning and Design Manual* (North Carolina Sedimentation Control Commission 2013) notes that "the rate of erosion on a construction site varies with site conditions and soil types but is typically 100 to 200 tons per acre and may be as high as 500 tons per acre" (224 to 448 Mg ha$^{-1}$ and 1,121 Mg ha$^{-1}$, respectively).

**Table 8**

**Summary statistics for erosion rates and best management practice (BMP) effectiveness for 220 stream crossings by ecoregion. Values not followed by the same letter within a column are significantly different using the Steel-Dwass All Pairs test at α = 0.05.**

| Erosion rate/BMP efficiency | Mean | Median | SD | Min | Max |
|---|---|---|---|---|---|
| USLE-forest erosion rate with BMPs (Mg $ha^{-1}$ $y^{-1}$) | | | | | |
| Blue Ridge | 34.7 | 13.2a | 71.8 | <0.1 | 381.4 |
| Piedmont | 18.6 | 5.0a | 37.8 | <0.1 | 278.7 |
| Southeastern Plains | 19.4 | 5.6a | 27.8 | <0.1 | 93.9 |
| Middle Atlantic Coastal Plain | 17.5 | 6.3a | 26.7 | 0.2 | 126.0 |
| Statewide | 21.8 | 7.1 | 44.7 | <0.1 | 381.4 |
| Hypothetical USLE-forest erosion rate without BMPs (Mg $ha^{-1}$ $y^{-1}$) | | | | | |
| Blue Ridge | 244.9 | 132.3 | 293.4 | 11.6 | 1,397.7 |
| Piedmont | 193.8 | 139.2 | 182.5 | 10.8 | 1,003.7 |
| Southeastern Plains | 145.6 | 92.6 | 140.8 | 12.4 | 651.0 |
| Middle Atlantic Coastal Plain | 142.4 | 87.0 | 159.3 | 19.7 | 787.2 |
| Statewide | 190.2 | 128.5 | 203.8 | 10.8 | 1,397.7 |
| Estimated BMP effectiveness (%)* | | | | | |
| Blue Ridge | 84.1 | 87.5a | 16.4 | 43.0 | 100 |
| Piedmont | 90.6 | 94.5b | 12.0 | 50.8 | 100 |
| Southeastern Plains | 88.6 | 90.4ab | 12.3 | 53.6 | 100 |
| Middle Atlantic Coastal Plain | 84.9 | 92.9ab | 18.5 | 41.6 | 99.7 |
| Statewide | 88.2 | 93.6 | 14.2 | 41.6 | 100 |

*Estimated BMP effectiveness = hypothetical Universal Soil Loss Equation (USLE)-Forest erosion rate without BMPs (Mg $ha^{-1}$ $y^{-1}$) subtracted by USLE-Forest erosion rate with BMPs (Mg $ha^{-1}$ $y^{-1}$) then divided by hypothetical USLE-Forest erosion rate without BMPs (Mg $ha^{-1}$ $y^{-1}$).

## Summary and Conclusions

Soil erosion rates at forestry stream crossings can be significantly reduced through the implementation of BMPs. Our findings support the following conclusions:

1. Statewide, portable bridge and overland skid trails were the most commonly observed crossing type and access method, respectively. These findings complement the well-established logger training, outreach, and education efforts to promote forest operation methods that minimize soil disturbance. However, there continues to be opportunities to expand the use of portable bridges, especially in the Blue Ridge ecoregion.
2. Average BMP implementation rate at stream crossings statewide was 90.1%. However, North Carolina Forest Service BMP implementation audit questions for stream crossings are weakly correlated with erosion estimates and should be interpreted carefully when discussing sediment delivery from silvicultural operations.
3. The lack of significant difference in erosion rates among ecoregions support the concept that BMPs can be and are implemented to fit site conditions. In addition, the data suggest that even on relatively flat terrain of the Southeastern Plains and Mid-Atlantic Coastal Plain, there is a viable need for implementing erosion and sedimentation control BMPs at stream crossing approach ways.
4. Erosion rates modeled at stream crossings when the tract had active operations were significantly higher compared to stream crossings on inactive/closed tracts. Most stream crossings observed (54%) had modeled erosion quantities less than 0.1 Mg $crossing^{-1}$ $y^{-1}$. The top 12% of stream crossings with the greatest erosion quantities accounted for over 80% of the total estimated erosion quantity from the 220 stream crossings. This finding supports the efforts of state forestry agencies and forest industry to engage with forest operators during active operations to offer technical assistance and proactively address erosion and sedimentation control issues.
5. About 7% of stream crossings used a ford or pole for skidding access. This suggests that improved education and training on where to properly install fords and poles is needed. Well-constructed fords offer a permanent haul-road crossing option that can provide enhanced hydrological function as compared with culverts, but fords must be installed, used, and maintained correctly. Pole crossings can be used for skid trail

**Table 9**

**Modeled erosion quantity for 220 stream crossings as observed and modified to hypothetical "no-BMP" scenario.**

| Ecoregion | *n* | Observed average (Mg $crossing^{-1}$ $y^{-1}$) | No-BMP average (Mg $crossing^{-1}$ $y^{-1}$) | Difference (Mg $crossing^{-1}$ $y^{-1}$) |
|---|---|---|---|---|
| Blue Ridge | 44 | 1.61 | 5.75 | 4.15 |
| Piedmont | 115 | 0.66 | 3.89 | 3.23 |
| Southeastern Plains | 31 | 0.66 | 3.37 | 2.72 |
| Middle Atlantic Coastal Plains | 30 | 0.58 | 3.25 | 2.67 |
| Statewide | 220 | 0.84 | 4.10 | 3.27 |

Note: BMP = best management practice.

access, but may not be the best option for crossing intermittent and perennial streams.

6. Incorporating the USLE-Forest model into existing forestry BMP implementation monitoring proved to be efficient and effective, once the initial framework and data collection processes were set-up. State forestry agencies could include soil erosion estimates in their recurring BMP monitoring if they are adequately funded and trained to collect and interpret the data. Scaling-up erosion model estimation across the southeastern United States would provide a powerful tool to help link the deployment of forestry BMPs with tangible metrics associated with erosion and sedimentation control.

## References


Anderson, C.J., and B.G. Lockaby. 2011. The effectiveness of forestry best management practices for sediment control in the southeastern United States: A literature review. Southern Journal of Applied Forestry 35(4):170-177.

Aust, W.M., and C.R. Blinn. 2004. 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, and Soil Pollution: Focus 4(1):5-36.

Aust, W.M., M.C. Bolding, and S.B. Barrett. 2015. Best management practices for low-volume roads in the piedmont region: Summary and implications of research. Journal of the Transportation Review Board 2472(1):51-55.

Aust, W.M., M.B. Carroll, M.C. Bolding, and C.A. Dolloff. 2011. Operational forest stream crossings effects on water quality in the Virginia Piedmont. Southern Journal of Applied Forestry 35(3):123-130.

Boggs, J.L., G. Sun, and S.G. McNulty. 2017. The effects of stream crossings on total suspended sediment in North Carolina piedmont forests. Journal of Forestry 116(1):13-24. http://dx.doi.org/10.5849/jof.2016-059.

Bottinelli, N., V. Hallaire, N. Goutal, P. Bonnaud, and J. Ranger. 2014. Impact of heavy traffic on soil macroporosity of two silty forest soils: Initial effect and short-term recovery. Geoderma 217:10-17. http://dx.doi.org/10.1016/j.geoderma.2013.10.025.

Bowker, D., J. Stringer, and C. Barton. 2020. Influence of timber harvesting operations and streamside management zone effectiveness on sediment delivery to headwater streams in Appalachia. Forests 11:623. doi:10.3390/f11060623.

Brown, K.R., W.M. Aust, and K.J. McGuire. 2013. Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia Piedmont. Forest Ecology and Management 310:836-846.

Brown, K.R., K.J. McGuire, W.M. Aust, W.C. Hession, and C.A. Dolloff. 2015. The effect of increasing gravel cover on forest roads for reduced sediment delivery to stream crossings. Hydrological Processes 29(6):1129-1140.

Chappell, N.A., I. Douglas, J.M. Hanapi, and W. Tych. 2004. Sources of suspended sediment within a tropical catchment recovering from selective logging. Hydrological Processes 18(4):685-701.

Coats, W.A. 2018. An assessment of forestry best management practices in North Carolina 2012-2016. Raleigh, NC: Department of Agriculture and Consumer Services, North Carolina Forest Service.

Conrad, J.L. IV., W.S. Ford, M.C. Groover, M.C. Bolding, and W.M. Aust. 2012. Virginia Tech forest road and bladed skid trail cost estimation method. Southern Journal of Applied Forestry 36(1):26-32. http://dx.doi.org/10.5849/sjaf.10-023.

Cristan, R., W.M. Aust, M.C. Bolding, S.M. Barrett, and J.F. Munsell. 2018. National status of state developed and implemented forestry best management practices for protecting water quality in the United States. Forest Ecology and Management 418:73-84.

Cristan, R., W.M. Aust, M.C. Bolding, S.M. Barrett, J.F. Munsell, and E.B. Schilling. 2016. Effectiveness of forestry best management practices in the United States: Literature review. Forest Ecology and Management 360:133-151.

Croke, J., S. Mockler, P. Fogarty, and I. Takken. 2005. Sediment concentration changes in runoff pathways from a forest road network and the resultant spatial pattern of catchment connectivity. Geomorphology 68:257-268.

Croke, J., S. Mockler, P. Hairsine, and P. Fogarty. 2006. Relative contributions of runoff and sediment from sources within a road prism and implications for total sediment delivery. Earth Surface Processes and Landforms 31(4):457-468.

Dangle, C.L., W.M. Aust, M.C. Bolding, S.M. Barrett, and E.B. Schilling. 2019a. The effectiveness of forestry best management practices at skidder stream crossings in Virginia. Journal of Soil and Water Conservation 74(3):199-208. doi:10.2489/jswc.74.3.199.

Dangle, C.L., W.M. Aust, M.C. Bolding, S.M. Barrett, E.B. Schilling, and M. Poirot. 2019b. Characteristics, predicted erosion, and cost for different levels of forestry best management practices at skidder and truck stream crossings in the mountains, piedmont, and coastal plain of Virginia, USA. International Journal of Forest Engineering 30(2):76-86. https://doi.org/10.1080/14942119.2018.1527648.

Dangle, C.L., M.C. Bolding, W.M. Aust, S.M. Barrett, and E.B. Schilling. 2019c. Best management practices influence modeled erosion rates at forest haul road stream crossings in Virginia. Journal of the American Water Resources Association 55(5):1169-1182. https://doi.org/10.1111/1752-1688.12762.

Dissmeyer, G.E., and G.R. Foster. 1984. A Guide for Predicting Sheet and Rill Erosion on Forest Land. USDA Forest Service. Technical publication R8-TP 6. Atlanta, GA: USDA Forest Service.

Edwards, P.J., F. Wood, and R.L. Quinlivan. 2016. Effectiveness of best management practices that have application to forest roads: A literature synthesis. Gen. Tech. Rep. NRS-163. Newtown Square, PA: USDA, Forest Service, Northern Research Station.

Foster, G.R., D.K. McCool, K.G. Renard, and W.C. Moldenhauer. 1981. Conversion of the Universal Soil Loss Equation to SI metric units. Journal of Soil and Water Conservation 36(6):355-359.

Fransen, P.J.B., C.J. Phillips, and B.D. Fahey. 2001. Forest road erosion in New Zealand: Overview. Earth Surface Processes and Landforms 26(2):165-174.

Fu, B., T.H.N. Lachlan, and C.E. Ramos-Scharron. 2010. A review of surface erosion and sediment delivery models for unsealed roads. Environmental Modelling and Software 25:1-14.

Jackson, C.R., J.K. Martin, D.S. Leigh, and L.T. West. 2005. A southeastern piedmont watershed sediment budget: Evidence for a multi-millennial agricultural legacy. Journal of Soil and Water Conservation 60(6):298-310.

Jordán, A., and L. Martínez-Zavala. 2008. Soil loss and runoff rates on unpaved forest roads in southern Spain after simulated rainfall. Forest Ecology and Management 255:913-919.

Kea, J.B. 1975. A study of soil erosion and sediment production rates on selected forestry operations in North Carolina. Forestry Note No. 16. Raleigh, NC: North Carolina Forest Service.

Kreutzweiser, D.P., S.S. Chapell, and K.P. Good. 2005. Effects of fine sediment inputs from logging road on stream insect communities: A large-scale experimental approach in a Canadian headwater stream. Aquatic Ecology 39:55-66.

Lakel, W.A., W.M. Aust, M.C. Bolding, C.A. Dolloff, P. Keyser, and R. Feldt. 2010. Sediment trapping by streamside management zones of various widths after forest harvest and site preparation. Forest Science 56(6):541-551.

Lane, P.N.J., and G.J. Sheridan. 2002. Impact of an unsealed forest road stream crossing: Water quality and sediment sources. Hydrological Processes 16(13):2599-2612. http://dx.doi.org/10.1002/hyp.1050.

Lang, A.J., W.M. Aust, M.C. Bolding, S.M. Barrett, K.J. McGuire, and W.A. Lakel. 2015. Streamside management zones compromised by stream crossings, legacy gullies, and over-harvest in the piedmont. Journal of the American Water Resources Association 51(4):1153-1164.

Lang, A.J., W.M. Aust, M.C. Bolding, K. McGuire, and E.B. Schilling. 2017. Comparing sediment trap data with erosion models for evaluation of truck road stream crossing approaches. Transactions of the ASABE 60(2):393-408.

Lang, A.J., W.M. Aust, M.C. Bolding, K. McGuire, and E.B. Schilling. 2018. Best management practices influence sediment delivery from road stream crossings to mountain and piedmont streams. Forest Science 64(6):682-695. https://doi-org.prox.lib.ncsu.edu/10.1093/forsci/fxy019.

McKee, S.E., L.A. Shenk, M.C. Bolding, and W.M. Aust. 2012. Stream crossing methods, costs, and closure best management practices for Virginia's loggers. Southern Journal of Applied Forestry 36(1):33-37.

Merrill, M.A. 2005. The effects of culverts and bridges on stream geomorphology. Master's thesis, North Carolina State University.

Miniat, C.F., P.P. Clinton, and L.K. Everage. 2019. The effects of off-highway vehicle trails and use on stream water quality in the north fork of the broad river. Transactions of the ASABE 62(2):539-548. https://doi.org/10.13031/trans.13098.

Morris, B.C., M.C. Bolding, W.M. Aust, K.J. McGuire, E.B. Schilling, and J. Sullivan. 2016. Differing levels of forestry best management practices at stream crossings structures affect sediment delivery and installation costs. Water 8(3):92. doi:10.3390/w8030092.

Nolan, L., W.M. Aust, S.M. Barrett, M.C. Bolding, K.R. Brown, and K.J. McGuire. 2015. Estimating costs and effectiveness of upgrades in forestry best management practices for stream crossings. Water 7(12):6946-6966.

NCFS (North Carolina Forest Service). 2006. North Carolina forestry best management practices manual to protect water quality, 138. Raleigh, NC: Department of Agriculture and Consumer Services, North Carolina Forest Service.

NCFS. 2018. Harvesting timber using the shovel-mat logging method, 4. Raleigh, NC: Department of Agriculture and Consumer Services, North Carolina Forest Service.

NCFS. 2019. North Carolina Forest Service bridgemat loan and education service report: 2009-2017. Raleigh, NC: Department of Agriculture and Consumer Services, North Carolina Forest Service.

North Carolina Sedimentation Control Commission. 2013. Erosion and Sediment Control Planning and Design Manual, ed. M.D. Smolen. Raleigh, NC: North Carolina Sedimentation Control Comission, North Carolina DEHNR and the North Carolina Cooperative Extension Service.

Ott, R.L., and M. Longnecker. 2016. An Introduction to Statistical Methods and Data Analysis, 7th edition. Belmont, CA: Duxbury Press.

Potter, S.R., S. Andrews, J.D. Atwood, R.I. Kellogg, J. Lemunyon, L. Norfleet, and D. Oman. 2006. Model simulation of soil loss, nutrient loss, and change in soil organic carbon associated with crop production. Washington, DC: USDA Natural Resources Conservation Service, Conservation Effects Assessment Project.

Rachels, A.A., K.D. Bladon, S. Bywater-Reyes, and J.A. Hatten. 2020. Quantifying effects of forest harvesting on sources of suspended sediment to an Oregon coast range headwater stream. Forest Ecology and Management 466:118123. https://doi.org/10.1016/j.foreco.2020.118123.

SAS Institute Inc. 2019. JMP, Version 15.2.0. 1989-2019. Cary, NC: SAS Institute Inc.

Sawyers, B.C., M.C. Bolding, W.M. Aust, and W.A. Lakel. 2012. Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia Piedmont. Journal of Soil and Water Conservation 67(4):300-310. https://doi.org/10.2489/jswc.67.4.300.

Schilling, E.B., A.J. Lang, H. Nicholson, J. Nettles, T.A. Gerow Jr., and D. McInnis. 2019. Evolving silvicultural practices to meet sustainability objectives in forested wetlands of the southeastern United States. Wetlands 40:37–46. https://doi.org/10.1007/s13157-019-01152-z.

Sidle, R.C., S. Sasaki, M. Otsuki, S. Noguchi, and A.R. Nik. 2004. Sediment pathways in a tropical forest: Effects of logging roads and skid trails. Hydrological Processes 18(4):703-720.

SGSF (Southern Group of State Foresters). 2007. Silvicultural best management practices implementation monitoring: A framework for state forestry agencies. Southern Group of State Foresters Water Resources Committee.

SGSF. 2019. Implementation of forestry best management practices: 2018 southern region report. Southern Group of State Foresters Water Resources Committee.

Terrell, S.B., W.B. Summer, C.R. Jackson, M. Miwa, and D.G. Jones. 2011. Harvest, site preparation, and firebreak effects on hydrology and sediment transport in coastal plain headwater streams. Transactions of the ASABE 54(6):2117-2127.

USDA NRCS (Natural Resources Conservation Service). 2000. Erosion and Sedimentation on Construction Sites. Urban Technical Note No. 1. Auburn, AL: Soil Quality Institute, USDA NRCS. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053285.pdf.

USDA NRCS. 2021. Soil Erosion – About the Data. Washington, DC: USDA NRCS. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=stelprdb1041925.

Vinson, J.A., S.M. Barrett, W.M. Aust, and M.C. Bolding. 2017. Suitability of soil erosion models for the evaluation of bladed skid trail BMPs in the Southern Appalachians. Forests 8(12):482-500.

Wade, C.R., M.C. Bolding, W.M. Aust, and W.A. Lakel. 2012a. Comparison of five erosion control techniques for bladed skid trails in Virginia. Southern Journal of Applied Forestry 36(4):191-197.

Wade, C., M.C. Bolding, W.M. Aust, W.A. Lakel, and E.B. Schilling. 2012b. Comparing sediment trap data with the USLE-Forest, RUSLE2, and WEPP-Road erosion models for evaluation of bladed skid trail BMPs. Transactions of the ASABE 55(2):403-414.

Walbridge, T.A. 1997. The Location of Forest Roads. Blacksburg, VA: Walbridge and Associates.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses—A guide to conservation planning. USDA Agriculture Handbook 537. Washington DC: US Government Printing Office.

Yoho, N.S. 1980. Forest management and sediment production in the South—A review. Southern Journal of Applied Forestry 4(1):27-36.