United States Environmental Protection Agency

EPA841-R-10-002
May 12, 2010

Guidance for Federal Land Management in the Chesapeake Bay Watershed

Chapter 4. Forestry

Nonpoint Source Pollution
Office of Wetlands, Oceans, and Watersheds
U.S. Environmental Protection Agency

Chapter 4. Forestry

Contents

1 Nonpoint Source Pollution and the Chesapeake Bay: Forests in Perspective

The Chesapeake Bay Program has published a report on the health of the Chesapeake Bay almost annually since 1999 (CBP 2009a). In that report the program provides information on the primary sources of nitrogen (N), phosphorus (P), and sediment—the pollutants of most concern in the Chesapeake Bay. The list of largest contributors of nutrients to the Bay in the annual reports invariably has included agriculture, atmospheric deposition, wastewater, and urban/suburban lands. The 2007 report also includes septic systems as a primary contributor.

Of the states in the Chesapeake Bay watershed, only Virginia notes silviculture as a source contributing to water quality impairment. Virginia lists silviculture as a probable source of impairment for 14.8 miles of rivers and streams, or 0.069 percent of the total river and stream miles reported (USEPA 2008). Silviculture was not listed as a source of impairment to any other waterbody types.

Forest harvesting and other silvicultural activities, therefore, are generally not identified in state reports as having a significant adverse effect on the Chesapeake Bay. Forests play an important role in helping to protect water quality in the Bay. Some excerpts from the reports about the importance of forests in the Chesapeake Bay are provided below.

- Forests protect and filter drinking water for 75 percent of the Bay watershed's residents and provide valuable ecological services and economic benefits including carbon sequestration, flood control, wildlife habitat and forest products. Retaining and expanding forests in the Chesapeake Bay watershed is critical to our success in restoring the Chesapeake Bay. Forests are the most beneficial land use for protecting water quality, due to their ability to capture, filter and retain water, as well as absorb pollution from the air (CBP 2008).
- In addition to preserving the watershed, well-maintained forest buffers naturally absorb nutrients and sediments, thus improving water quality in neighboring streams. Riparian forest buffers also provide a source of large, woody material input to streams that helps form and maintain important fish habitat and provide for channel stability (CBP 2008).
- Scientific findings clearly show that well-managed forests are the most beneficial land use for clean water. Experts agree that healthy forests are directly linked to the health of rivers in the Chesapeake Bay watershed and, ultimately, the Bay. Large areas of healthy forest and streamside forests are essential to keeping nutrient and sediment pollution out of the rivers and Bay (CBP 1999).

A relatively new EPA initiative—the Healthy Watersheds Initiative—augments the Agency's well-established watershed approach with proactive, holistic, aquatic ecosystem conservation and protection. EPA recognizes the numerous benefits that healthy watersheds provide. For instance, forested watersheds protect aquifer recharge zones and surface water sources and reduce water treatment costs: For every 10 percent increase in forest cover in an aquifer's source area, chemical and treatment costs decrease by 20 percent. Healthy watersheds also provide benefits like habitat for fish, amphibians, birds, and insects; recreational opportunities such as fishing, water-based recreation, and tourism; and vast carbon storage capabilities. Healthy watersheds are also less vulnerable to floods, fires, and other natural disasters, which reduces costs to communities.

The Healthy Watersheds Initiative includes both assessment and management approaches that encourage states, local governments, watershed organizations, and others to take a strategic, systems approach to conserve healthy components of watersheds. The initiative combines understanding of the biological, chemical, and physical condition of waterbodies with watershed functional attributes, such as hydroecology, geomorphology, and natural disturbance patterns and, thus, helps us manage watersheds as integrated systems that can be understood through the dynamics of essential ecological attributes.

Forested watersheds are well recognized to provide water quality benefits. The full suite of the economic values of forested watersheds is difficult to quantify, however. Forest cover intercepts rainfall, protecting soils from erosion; the roots of trees and forest litter covering a forest floor prevent soil erosion; trees absorb water, delaying the input of stormwater runoff to streams; and forest vegetation absorbs nutrients that could otherwise be lost to surface waters through surface runoff and groundwater. All these water quality services provided by forests are valuable to society, but their dollar value varies by the location of the forest (e.g., Is it in a watershed that provides municipal drinking water?), species and sizes of trees, condition of the forest, climate, rainfall characteristics, and soil characteristics (e.g., erodibility, nutrient content) (CWP no date). The water quality protection service of an acre of forest, therefore, cannot be assigned a single dollar value. Studies have estimated the value of forest conservation (Table 4-1), resulting in a range of $25 million to $6 billion of capital costs that have been avoided through watershed protection.

Table 4-1. Avoided costs of constructing filtration plants through watershed protection

Metropolitan area	Avoided costs
New York City, NY	$1.5 billion spent on watershed protection over 10 years to avoid at least $6 billion in capital costs and $300 million in annual operating costs
Boston, MA	$180 million (gross) avoided cost
Seattle, WA	$150-200 million (gross) avoided cost
Portland, OR	$920,000 spent annually to protect watershed in avoiding a $200 million capital cost
Portland, ME	$729,000 spent annually to protect watershed has avoided $25 million in capital costs and $725,000 in operating costs
Syracuse, NY	$10 million watershed plan is avoiding $45-60 million in capital costs
Auburn, ME	$570,000 spent to acquire watershed land is avoiding $30 million capital cost and $750,000 in annual operating costs

Source: CWP No date

Forests, especially well-managed forests, are a key element in any state, local, or federal water quality protection program. It is estimated that between 50 and 75 percent of the population of the United States relies on forest lands for good quality water (Neary et al. 2009). Forests and forested land—whether in a rural setting, along streams on agricultural land, intermixed with other land uses in suburban settings, or in urban locations—possess characteristics that other soil types do not that make them act as natural filters for stormwater and one of the least expensive and most effective means of protecting water quality. (Further information about the benefits of trees and forests in urban settings is provided in Chapter 3 of this guidance [Chapter 3: *Urban and Suburban*]). These characteristics include high levels of organic matter on the forest floor that intercepts rain drops, and soil porosity from root growth and decay, cracking from freeze/thaw and wetting/drying processes, animal burrowing, and other natural processes. Much rain water is thus stored in the forest soil and its delivery to streams is primarily via groundwater flow; surface runoff is rare in forest settings. Good water quality is a result of the nutrient uptake and cycling and contaminant sorption processes that occur as water passes through the soil before reaching stream networks (Neary et al. 2009).

One strategy that states use to achieve well-managed forests is training programs for licensed loggers. Such logger training programs are run by state departments of forestry, universities, or nonprofit forestry groups, and they are critical to the effective use of best management practices (BMPs) on harvest sites. The New York Logger Training is a cooperative effort of timber harvesters, forest industry, government, educators, and foresters working together to deliver resources that allow loggers to learn environmentally sound practices and improved skills (NYLT 2010). The Sustainable Forestry Initiative Program in Pennsylvania has developed a comprehensive training program for loggers. A variety of courses cover topics from basic compliance with local, state, and federal laws; to in-depth discourses on business management, wildlife, forest management, and ecology; BMPs for erosion control; and others (Loggertraining

2010). In West Virginia, the West Virginia Division of Forestry provides workshops on BMPs for practicing loggers (WVDOF 2010). The logger training program in Virginia is referred to as the SHARP (Sustainable Harvesting and Resource Professional). To achieve SHARP Logger standing, participants must complete a core program of 18 hours of classroom and field training (Virginia Tech 2010). Of those 18 hours, 6 hours cover sustainable forestry, and 6 hours are devoted to BMPs. The *Sustainable Forestry* session combines classroom sessions with field exercises. Participants review the principles of sustainable forestry, and then tour a forest site to observe examples of forest ecology and silviculture. The *Harvest Planning and Best Management Practices* session includes visiting a forested site, discussion of how to use topographic maps, and training on the essential elements for an environmentally sound harvest plan.

Another important development in forest management is the increasing acceptance and use of sustainable forest management techniques through third-party forest certification programs. Forest certification began to become established in the mid- to late-1990s and is gaining attention, participation, and acceptance (Mercker and Hodges 2007). Forest certification programs often offer a more robust approach to preharvest planning activities and offer a host of economic and sustainability benefits. One of the principles of sustainable forestry is to protect waterbodies and riparian zones and to conform to BMPs to protect water quality (SFI 2010). The most commonly cited benefits of forest certification programs are market access, credibility, and improved forest management. A second potential benefit from certification is assurance that landowners are managing their property in the most sustainable way possible. A third-party audit provides a system for validating sustainable management claims. That could assure public agencies and the general public that the landowner is engaged in long-term forest management (University of Florida 2007). On a per-acre basis, direct costs will generally increase as ownership size decreases and can vary from less than $1/acre to many dollars per acre (University of Florida 2007).

As described fully in the *Riparian* chapter of this document, forested riparian buffers can provide some measure of flow regulation under certain watershed conditions. A primary way in which buffers reduce flow velocity is by creating physical barriers that slow down the flow and allow infiltration of water into soil. They also maintain streamside soils in a condition to absorb water by virtue of their extensive root systems and organic litter production that provide the soil structure necessary for a large quantity of infiltration. Rainfall and runoff intensity, soil characteristics, hydrologic regime, and slope of the buffer and runoff source area are some of the factors that determine a forested riparian buffer's ability to regulate stream flow. A narrow forested buffer on a steep, nonvegetated slope has little ability to regulate flow, whereas a wide forested buffer on a gentle, vegetated slope could help reduce peak flow levels and provide for dry season flow.

Leaders of the Chesapeake Bay Program clearly recognize the importance of forests and forested riparian areas to the Bay's health. For example, the current Federal Leadership Committee strategy is to protect 2 million acres of lands throughout the watershed currently identified as high conservation priorities at the local, state, and federal level (including 695,000 acres of forest land of highest value for maintaining water quality) by 2025 (Federal Leadership Committee 2010). An original goal of 2,010 miles of forest buffer restoration by 2010 was achieved ahead of time, and a new goal to restore forests along at least 70 percent of streams and shorelines in the Bay watershed was set in 2003. The Bay was to have at least 10,000 shoreline miles forested by 2010 (CBP 2009b). The progress as of 2009 was 6,901 miles. A federal implementation plan was developed as part of the initiative. For federally managed lands—approximately 1.9 million acres of the 2.2 million acres of federal lands in the Chesapeake watershed are forested—this plan focused on protecting existing forests from development, incorporating forest conservation into land use planning, and working with forest landowners to promote forest conservation.

Research in N saturation shows that young forests capture more N from atmospheric inputs. Old forests generally do not *leak* N unless there is a large input source of N, such as from atmospheric pollutants (Kyker-Snowman no date). The retention of atmospheric N in forested watersheds is directly influenced by species composition and many factors that can change that composition, e.g., natural succession, climate change, forest management practices, forest pest infestations (Lovett et al. 2002). Undisturbed and properly managed forested ecosystems have considerable capacity to retain and efficiently cycle reactive N and prevent it from entering waterways. If, however, a forested system experiences a disturbance—such as widespread removal of vegetation—its ability to retain N is diminished. Implementing sound forest management practices can minimize such effects (SUNY 2010).

Deforestation is the long-term conversion of forest to another land use or the long-term reduction of the tree canopy cover below a 10 percent threshold. Chesapeake Bay Program land analyst scientists have a very good idea where deforestation will occur in the coming years in the Bay watershed. Forests that are vulnerable to development and that without action would be expected to be developed are critical to protecting the Bay watershed. Preventing the loss of those forests is referred to as *avoided deforestation*, and it has been used as a measure of credit for more than 10 years.

The nutrient reduction efficiency of avoided deforestation can be considerable because of the difference in nutrient loading to the Chesapeake Bay between a natural forest versus typical development. Bay scientists ran a model to compare N contributions to the Bay under the scenario that all high-value, vulnerable forests are lost versus those forests remaining protected. The model predicted that if the forests are protected, 3.1 million pounds of N would be prevented from flowing into the Bay.

The focus on forestry in the Bay is on preserving forests, maintaining forested shorelines and streambanks, and restoring forests near Bay waters and throughout the Bay watershed where they have been removed.

The lessons from the above-mentioned reports and initiatives—and the message to be gained from this guidance—are the following:

- Forests and forested buffers are extremely important to maintaining and improving water quality in the Chesapeake Bay.
- Maintaining well-managed, protective forested riparian buffers in a condition that conserves or enhances their ability to trap pollutants; protect the water quality of the Bay; and provide high-quality habitat for aquatic species is vitally important.
- Most forests in the Bay watershed are privately owned (approximately 80 percent) (Blankenship 2006). The objectives and motivations of private landowners must be considered in determining what BMPs should be recommended to successfully engage forest owners in maintaining their forests for the future. The Chesapeake Bay Program estimates that as much as 35 percent of the region's private forests are vulnerable to development (CBP 2004).

2 Forestry Practices for Water Quality Protection

2.1 Introduction

The effects of forestry activities on surface waters are of concern because healthy, clean waters are important for aquatic life, drinking water, and recreational use. Surface waters and their ecology can be affected by inputs of sediment, nutrients, and chemicals, and by alterations to stream flow that can result from forestry activities. The purpose of implementing measures and BMPs to protect surface waters during and after forestry activities is to protect important ecological conditions and characteristics of the surface waters in areas with roads and logged, forested areas. Such conditions vary with waterbody type, but, in general, the ecological conditions that implementation measures and BMPs are intended to protect include the following:

- General water quality, by minimizing inputs of polluted runoff
- Water temperature, by ensuring an adequate amount of shade along shorelines and streambanks
- Nutrient balance, by providing for an adequate influx of carbon and nutrients that serve as the basis of aquatic food chains
- Habitat diversity, by ensuring that inputs of large organic debris to the aquatic system are appropriate for the system
- Hydrologic processes, by limiting disturbances to ground cover, overland flow, and stream flow patterns, both seasonal and annual

Logging a forested area can affect all those ecological conditions to some extent. Preharvest conditions might consist of canopy, subcanopy, and herbaceous vegetative layers; a thick litter layer; a complex of tree, shrub, and herbaceous roots surrounded by uncompacted soils; 70–100 percent shade at ground level; nutrient cycling between vegetation and soils; and a vegetation-buffered hydrologic process. Post-harvest, the canopy and subcanopy are reduced; the litter layer is removed in some areas and compacted in others; roots of removed vegetation decompose; sunlight penetration to the ground is increased; nutrient absorption by vegetation is reduced; and more rainfall reaches the ground, less rain water evaporates back to the atmosphere, and runoff increases. Those changes can lead to increased water, sediment, and nutrient delivery to streams, but the post-harvest effects can be minimized through the use of appropriate BMPs during and immediately after a harvest, followed by regular BMP maintenance. Forestry activities and their potential effects on forest hydrology and water quality (through nonpoint source pollution) are discussed below.

Sediment

Sediment deposited in surface waters is addressed in this document because of its potential to affect in-stream conditions and aquatic communities. Sediment is the pollutant most associated with forestry activities. Soil is lost from the forest floor by surface erosion following ground disturbances typically associated with a forest harvest (e.g., use of heavy machinery, skidding, truck traffic), or through mass wasting (e.g., landslides on steep slopes induced by loosened soil from decomposed tree roots after a harvest).

In undisturbed forests, surface erosion generally contributes minor quantities of sediment to streams and the quantity of surface erosion depends on factors mentioned earlier, such as soil type, topography, and amount of vegetative cover (Spence et al. 1996).

Rill erosion and channelized flow occur where rainwater and snowmelt are concentrated by landforms, including berms on roads and roadside ditches. They cause erosion most severely where water is permitted to travel a long distance without interruption over steep slopes because the combination of distance and slope tends to increase the volume and velocity of runoff. Sheet erosion, or overland flow, occurs occasionally on exposed soils where the conditions necessary for it exist—including saturated soil or a rainfall intensity that is greater than the ability of soil to absorb the water—but it is not common on forest soils because the forest floor and associated litter layer have a very high infiltration capacity.

Nutrients

Nutrients, such as N and P in soil and plant material, are primary chemical water quality constituents. They can enter waterbodies attached to sediments, dissolved in the water, or transported by air. Forest harvesting can locally increase nutrient leaching from the soil through its disruption of the cycling of nutrients between the soil and overlying vegetation, although the effect generally subsides to near precutting levels within 2 years of a harvest, provided that all appropriate post-harvest measures are taken to revegetate the site. Excessive amounts of nutrients can stimulate algal blooms or an overgrowth of other types of aquatic vegetation. That can, in turn, lead to an increase in the amount of decomposing plant material in an aquatic system and increased turbidity and biological oxygen demand. The latter effect can decrease dissolved oxygen concentrations, with potentially detrimental effects to aquatic biota. Chapter 3, section I *(Forest Chemical Management)* of EPA's 2005 guidance *National Management Measures to Control Nonpoint Sources of Pollution from Forestry* (USEPA 2005), discusses methods for minimizing the adverse effects of forestry activities on nutrient balances.

Organic debris, discussed below, can be an important source of nutrients in an aquatic environment. Streamside Management Areas (SMAs) play an important role in organic debris inputs and maintaining nutrient balances in aquatic forest ecosystems.

Organic Debris

Organic debris—primarily composed of leaves, twigs, branches, and fallen trees—is an important element of water quality because it provides nutrients and stream structure that are important to supporting aquatic life. The presence of organic matter in the form of woody debris is one of the primary influences on the microbial denitrification process. It ranges in size from suspended organic matter in water to fallen trees. Large, woody debris, or LWD, can be whole trees or tree limbs that have fallen into streams. It contributes to the physical habitat diversity essential to support aquatic life. As a structural element, LWD influences the movement and storage of sediment and gravel in streams and stabilizes streambeds and banks. Small, organic litter—primarily leaves in deciduous forests and cones and needles in coniferous forests—is an important source of nutrients for aquatic communities. It usually decomposes over a year or more, depending on the forest type.

When streamside vegetation is removed—especially when riparian canopy trees are removed—inputs of organic debris decrease and the amount of sunlight reaching the water increases. For a stream that might have relied primarily on sources of nutrients external to the stream (fallen debris), vegetation removal can force the stream to rely primarily on in-stream sources (such as algal growth and in-stream vegetation), which might not be present in low-order streams.

Organic debris generated during forestry activities include residual logs, slash, litter, and soil organic matter. Such materials can perform some of the same positive functions as naturally occurring LWD and organic litter. If their abundance in a stream is substantially greater than normal, however, they can also block or redirect streamflow, alter nutrient balances, and decrease the concentration of dissolved oxygen as they decompose and consume oxygen.

In 2005 EPA published *National Management Measures to Control Nonpoint Sources of Pollution from Forestry* (USEPA 2005). Little has changed with respect to the commonly accepted best practices of protecting surface waters from inputs of sediment and nutrients during and after forestry activities since that guidance was published. The 2005 guidance was based on a comprehensive review of both the scientific literature and state forestry practices at the time. A review of state forestry practices and the recent literature indicates that the information in the 2005 guidance is still as relevant today as it was when it was published.

Recent research on forest harvesting has focused on better understanding how some BMPs work (and why they fail) and on methods that can be used to reduce the cost and effort involved in forest planning and harvesting. One of the greatest risks to water quality from forestry activities come from having unprotected streams. SMAs have proven to be an important component of water quality protection in forested areas, and recent research has focused on understanding the width requirements and vegetative and soil characteristics that give SMAs their water-quality protection abilities.

The other major risk to water quality from forestry activities comes from sediment-laden runoff from areas disturbed by forestry activities, especially roads, landings, and skid trails. Not surprisingly, those have also been the focus of the bulk of the research over the past 5 years. Road building and timber removal are among the most costly aspects of forest harvesting, and much research has focused on reducing the costs of forest harvest planning, road building, and timber removal.

Below is a review of the implementation measures from EPA's 2005 guidance, with minor changes made to a few. Some of the implementation measures are not updated in this guidance because the 2005 guidance adequately identifies and discusses the best practices for protecting water quality from forestry activities. For those implementation measures that are updated, the relevant sections below provide a brief overview of the BMP-specific guidance provided in EPA's forestry guidance, some recommendations suggested by the recent research that could help improve on the advice provided in the 2005 guidance, and a brief review of some recent research relating to the recommendations.

2.2 Preharvest Planning

Implementation Measure F-1:

Perform advance planning for *timber harvesting* and *forest road systems* that includes the following elements, where appropriate:

1. Identify the harvest area and road layout and areas to be avoided during harvest and road construction (for example, waterbodies, wetlands, protected species locations and habitat, and highly erosive soils). Avoid locating roads, landings, and skid trails on steep grades and in SMAs. Use electronic and paper topographic and soil maps and a handheld global positioning system unit to facilitate marking the features, and mark them in a highly visible manner before the harvest.
2. Consider all water quality-related factors when planning the harvest and road system. Factors to consider include soil moisture conditions when the harvest and heaviest traffic will occur, BMPs for erosion control during and after the harvest, and existing water quality conditions in all potentially affected waterbodies.
3. Design roads to withstand the anticipated amount of traffic during the anticipated season of harvest such that ruts will not form and the effectiveness of road surface drainage features will not otherwise be compromised.

4. Design road drainage structures to discharge runoff in small quantities to off-road areas that are not hydrologically connected to surface waters.
5. Design the road layout to minimize the number of stream crossings.
6. For fish-bearing streams, design stream crossings to permit fish passage.

The Preharvest Planning implementation measure is to ensure that all forestry activities are planned with water quality considerations in mind and conducted to minimize the delivery of nonpoint source pollutants to streams and other surface waters. Road system planning is an essential part of this implementation measure. Two basic tenets of road planning are to minimize the number of road miles constructed and to locate roads so as to minimize the risk of water quality effects. Those two tenets of road planning are excellent and important guidelines for forest road network planning. Although the drive to reduce costs is what has led to much recent research on how road planning can be improved, minimizing costs can also be good for water quality because the fewer road miles and skid trails that are developed to harvest an area, the less water quality is likely to be adversely affected.

More than any other aspect of forest harvesting and management, forest roads have been identified as a major source of sediment delivered to streams and wetlands in forests. Soil sediment delivered to streams affects public resources such as water quality, aquatic and wildlife habitat, and riparian resources. Soil sediment causes problems when three components—source, resource, and delivery—are combined. Roads that are not eroded do not have the source to cause sediment problems. Roads that are far from streams do not have the resource to cause sediment problems. Roads that have adequate drainage structures to deliver the sediment onto stable forest floors do not deliver the sediment to the stream.

Forest roads have an important role in managing forest resources. They need to be constructed in such a way that forestry workers and machines can gain access to operational sites and carry out operations safely and efficiently. On the other hand, forest roads are at risk of road surface erosion and are subject to cut-and-fill slope failures. Therefore, it is important that forest road design incorporates consideration of cost efficiency *and* the appropriate management of water and soil.

Best Management Practices

1. If feasible, consider using a combination of geographic information system (GIS) data, Light Detection and Ranging (LiDAR) data, and one of the many computer optimization techniques modified for use in natural resources and forest harvest planning to determine road layouts, road and skid trail combinations, and landing locations that will

minimize the amount of road construction or skid distance, or both, expose the least amount of forest soil, and minimize the risk of water quality degradation from harvesting.

GIS data are widely available today for many areas of the country, and where they are not available, they are easy to collect quickly using a handheld global positioning system (GPS) device. LiDAR is a remote sensing technique that is rapidly being incorporated as a common technique in natural resources planning. Forest harvest planning, including road network layout and determining a best combination of roads and skid trails for an area is a field where computer optimization is being used with increasing success.

Designing a road network and determining an ideal combination of roads and skid trails to minimize cost and maximize water quality protection is difficult because so many possible layouts exist. Computer optimization techniques permit forest planners to analyze many more possibilities than manual techniques and can arrive at an optimum solution using any desired set of weighed factors.

Discussion

The location and operation of forest machinery, and the design and construction of forest roads are important issues in forest planning and account for up to 55 percent of production costs (Epstein et al. 2006). A major challenge of any forestry operation is designing an operation that minimizes the costs of road construction, installing and operating harvest machinery, and transporting timber, while at the same time protecting the forest environment. Forest planners are increasingly using computerized approaches to forest planning to reduce costs, collect the information necessary to plan a harvest, find road and landing layouts that minimize forest disturbance, and determine how best to manage existing road networks.

Aruga et al. (2005b) used two computer optimization techniques (the genetic algorithm and Tabu search) in combination with linear programming and compared the results obtained with the computer approaches to a manually designed forest road profile. They found that the profiles designed by computer cost less than the manually designed profile, that using such optimization techniques found good solutions for road system layout in a reasonable amount of time, and that more road profile alternatives could be evaluated in less time using computers. Aruga et al. also looked at the effect of the number of road profile control points (used in the optimization programming) on construction costs, and their results indicate that increasing the number of control points reduces the construction costs. That results from the forest road profile becoming closer to the ground profile—and the earthwork volume then being reduced—as the number of control points is increased (Aruga et al. 2005b).

LiDAR is a commercially available remote sensing system that is used in natural resources applications. LiDAR is a laser system that calculates the 3-dimensional (3D) coordinates of objects from reflections on the earth's surface (Akay et al. 2009). Various forestry activities can be performed rapidly and efficiently using LiDAR remote sensing technology. From the scans, various structures of individual trees, including crown width, diameter, volume, and height, can be estimated. The last scan can provide a very high-quality Digital Elevation Model (DEM) with approximately 1-meter (m) spatial resolution and about 10 to 20 centimeter (cm) height accuracy (Akay et al. 2009), which is useful for road and landing layout planning.

Forestry activities can sometimes be done more quickly and less expensively using LiDAR than using ground-based systems for wide-scale areas. LiDAR is one of the fastest growing technologies in the natural resources field and it is expected to provide higher resolution and more accurate data as the technology and GIS technologies advance (Akay et al. 2009). Of course, the use of technologies such as LiDAR and GIS must be balanced against the current availability of information about a forest stand, the cost of the technology, and the size of intended harvest. Small harvest operations, such as those typical of nonindustrial private forest landowners, might not benefit as much from the use of the technologies as would larger, corporate forest owners.

Aruga (2005) emphasizes the importance of using DEM and LiDAR data over something such as computer assisted drawings (CAD), which are widely used to draw road plans, road profiles, and cross sections, and to calculate earthwork volumes. But when planning a complicated road system for accessing numerous locations that might not be accessible from existing roads, CAD is not well suited to finding the best alignment with the lowest total road cost that is made up of construction, maintenance, user, social, and environmental costs. For such a complicated calculation, Aruga (2005) recommends using a high-resolution DEM derived from LiDAR data, which is then used to optimize horizontal and vertical alignments of forest roads. Where primary and secondary access routes are required, road intersection points are selected manually, from which the computer program using the DEM and LiDAR data generates alternative horizontal and vertical road alignments. The DEM generates ground profile and cross sections and calculates earthwork volumes for curved roadways. It also estimates construction and maintenance costs. The optimization model used by Aruga (2005) can find the best solution taking all the factors into account, and it helps forest engineers design a forest road by evaluating many alternatives (Aruga 2005).

Aruga et al. (2005a) also used a program to optimize forest road alignments but combined it with a method for predicting surface erosion and sediment delivered to streams, again using a high-resolution DEM. Because the program generates forest road alignments using a high-resolution DEM, it can calculate factors required by standard methodology to predict soil sediment delivered to streams. Aruga et al. (2005a) investigated the effects of road surface materials, culvert distance to stream, and out-sloped roads on total road costs and soil sediment delivered to streams. Using the model, Aruga et al. (2005a) found that using lower-quality rock surfacing on forest roads reduced total costs, but the amount of soil sediment from lower-quality rock surfacing was 1.5 times more than that on a higher-quality rock surface, and recommend that lower-quality rock surfacing not be used near streams. They also found that placing near-stream culverts 15 m upstream and using an out-sloped road template significantly reduces total road cost and soil sediment. Using the model permitted Aruga et al. (2005a) to successfully optimize forest road alignments, which reduced total road cost and soil sediment.

Other researchers have also been investigating the use of computer programming for forest planning. Epstein et al. (2006) used a mixed-integer programming system, PLANEX, that incorporates many parameters like the technical characteristics of machinery operation, road construction, transport and harvest costs, exit points, and economic variables that restrict the harvest. GIS was used in the process to provide timber volumes, topographic information, and information on the existing road network. Forestry companies have applied the technology and have reported that its advantages include operation designs that use fewer roads, which translates into lower total costs and the environmental benefits that come from less ground disturbance (Epstein et al. 2006).

Numerous authors have investigated the use of computer programs to find optimal road layouts for forest harvesting. Najafi et al. (2008) developed a method to evaluate forest road network variants using a systematic grid layout. They collected terrain condition and stand data at grid points using GIS and prepared maps of forest potential for road construction and maps of forest capacity for harvesting on the basis of the data they collected. A primary objective of the work was to determine whether the environmental impacts and costs of road network development could be reduced using GIS technologies. They determined that the method can be used to evaluate road networks easily, precisely, and in detail, with very little cost incurred to gather the grid point data (Najafi et al. 2008).

Ghaffarian et al. (2007) used an optimization program to find an optimal layout for a forest harvested by skidder in northern Iran. The program showed which roads could be eliminated from the existing forest road network, thus reducing the potential for road failure and sediment runoff and road maintenance costs, while still permitting efficient forest harvest (Ghaffarian et al. 2007).

Chung et al. (2008) developed a road network optimization model and applied it to a 11,540-acre (4,760 hectare) forest in the upper part of the Mica Creek watershed in Idaho, an area owned by Potlatch Forest Holdings. The model is used to identify cost-efficient road networks for timber harvesting given cost constraints and with options for on-road transportation of logged timber on new roads and off-road timber transportation using skidders, taking into consideration terrain conditions and stream locations. Costs that are input to the model and that partially determine the outcome include timber volume, road construction cost, skidding cost, and stream crossing cost (Chung et al. 2008). The latter purposefully tends to favor fewer or simpler stream crossings.

The model selects the least-cost activity using costs of skidding versus road construction and timber volume. For example, if enough timber volume is in an area or road construction cost is low compared with skidding cost, the road building option is selected so as to decrease the average skidding distance. On the contrary, if timber volume is not large enough or road cost is high, the skidding option is selected because building a new road would not be economically feasible even though the average skidding distance increases. Such a process eventually generates a road network that most cost-efficiently serves the entire area of interest for the purpose of timber harvesting (Chung et al. 2008).

Rackley and Chung (2008) used NETWORK2000, a forest transportation planning model, to produce alternative road system layouts that simultaneously minimize transportation costs and overall sediment delivery using inputs of estimated sediment delivery. They applied the methodology to the Mica Creek watershed in northern Idaho, where 11 alternative road networks were developed. The results of the modeling effort indicates that incorporating environmental effects into transportation planning can generate alternative road networks that reduce a large amount of estimated sediment delivery at the expense of a relatively small increase in transportation costs (Rackley and Chung 2008).

It is important to be able to include all relevant factors in any computerized system for optimizing forestry operations, because while many methods of finding optimal landing locations and determining the best skidding distance have been developed, they simplify harvest units and do not consider many factors that influence landing, skid trail, and road location (Contreras and Chung 2007). Contreras and Chung (2007) used a computerized model to determine the optimal landing location for harvesting using raster-based GIS data. The model found skid trails from stump to candidate landing locations and selected the best location on the basis of minimizing total skidding distance and spur road costs. The model included harvest unit boundary shapes, volume distribution, obstacles, terrain conditions, and spur road construction as factors taken into account in the optimization task. Using the model, Contreras and Chung (2007) found a range of cost savings associated with the various factors to be from $0 to $9,443, with an average savings per factor considered of $1,788. Data needed for the model are easy to obtain because LiDAR and GIS can provide most of it (Contreras and Chung 2007).

LiDAR can also be used to obtain detailed information on a forest harvest area (Akay et al. 2009). A LiDAR data set for forested areas is generated by light pulses reflected from different levels of vegetation canopy, including the top of the vegetation surface (first return), intermediate surfaces (second and following returns), and the ground surface (last return). From the first and second returns, various structures of individual trees (crown width, diameter, volume, and height) can be estimated. Using the last return, LiDAR can provide a very high-quality DEM. LiDAR is one of the fastest growing technologies in the natural resources field, and it is expected to provide higher resolution and more accurate data as the technology and GIS technologies advance (Akay et al. 2009).

1b. Where the use of LiDAR and DEM are not feasible (for instance, because data are lacking or because their use is too costly), consider integrating the use of digital topographic maps and aerial photography with data collected using a handheld GPS unit for forestry planning.

A handheld GPS unit combined with freely available or low-cost digital topographic maps and aerial images is a method ideally suited to forest planning uses for small properties to determine harvest unit boundaries, road layouts, road and skid trail combinations, and landing locations.

LiDAR and DEM are expensive, technology-intensive tools for forestry operations that are suitable for use by large-scale forestry operations and government agencies, but they are beyond the reach of smaller forest owners. A handheld GPS receiver used in combination with digital topographic maps and a computer mapping program is technology that is within the reach of and suitable for small forestry operations, such as those typical of nonindustrial private landowners. A variety of functions related to forestry—including collecting and storing specific GPS points, paths, and routes, and transferring the stored information between the GPS unit and a computer—can be performed with a handheld GPS receiver. Distances and areas can be calculated in the field or afterward on a computer using a mapping program, and adjustments to boundaries and paths can be made in the computer and then transferred back to the GPS unit for later use in the field, if necessary. Using a simple GPS receiver, a landowner or forester could gather complete location information on a forest unit to be harvested, walk candidate access road and skid trail routes while collecting GPS locations, and then conduct final harvest planning in more detail on a computer using a free or commercially available computer digital mapping software package. Free software packages include USAPhotoMaps, Google Earth, EasyGPS, and GPS Utility, while commercial software is available for purchase if required to provide greater accuracy and up-to-date maps.

2.3 Streamside Management Areas (SMAs)

Implementation Measure F-2:

Establish and maintain an SMA along all (perennial and ephemeral) waterbodies. Avoid all activity inside SMAs along all waterbodies. SMAs should be wide enough to provide a preharvest level of shade to surface waters, detain and capture water and sediment runoff from the harvest site and roads, and a sustainable source of large woody debris for in-stream channel structure and aquatic habitat.

Section 3B of EPA's guidance, *National Management Measures to Control Nonpoint Source Pollution from Forestry* (USEPA 2005) presents EPA's recommendation for SMAs in areas affected by forestry activities such as harvesting and post-harvest site preparation. The 2005 guidance describes the implementation measure, discusses the benefits of SMAs, and presents BMPs that can be used to meet the intent of the implementation measure.

The recommendations of the 2005 guidance with respect to SMAs still hold. Forested areas along streams and rivers are considered vital for providing habitat, food, and shelter for wildlife and protecting water quality by reducing nutrient and sediment input from upland areas. The Chesapeake Bay Program Forestry Workgroup emphasized the importance of streamside areas when it developed the *2003 Directive for Expanded Riparian Forest Buffer Goals* (CBP 2003). The directive recommends that forest buffers exist on at least 70 percent of all shorelines and streambanks in the Chesapeake Bay watershed. An estimated 60 percent of the shorelines in the watershed are now forested. Protecting the forests along streams in areas harvested for wood products is one of the key components to achieving the goal of the 2003 directive.

Most states incorporate SMAs as a major component of their forestry practice guidelines, and the recommendations of the states for establishing and protecting SMAs in harvest areas to protect water quality have not changed since publication of the 2005 EPA guidance. A general rule for the width of an SMA is a minimum of 25 to 50 feet, with 5 feet of additional width added for each 1 percent of slope of the contributing land (Klapproth and Johnson 2000). Of course, state, federal, or other applicable guidelines or rules for SMAs must be followed where they are applicable. For instance, many states (e.g., Virginia, Kentucky, Georgia, North Carolina, and South Carolina) prescribe wider SMAs along waters that protect cold water fisheries (Hodges and Visser 2004).

The importance of SMAs for water quality protection is well-established. Over the past 5 to 7 years, researchers have been investigating the use of technology for improving the accuracy and ease with which variable-width SMAs can be established. Technology has also been applied to preventing concentrated runoff flows from entering and passing through SMAs to reach streams. Also, in response to landowner concerns over lost revenue by not harvesting in SMAs, researchers have investigated the extent to which thinning in SMAs might be permitted while still retaining the nutrient- and sediment-trapping capabilities of the SMA. Recommendations to augment the information on SMAs in the 2005 EPA guidance are provided below, and the findings of the recent research are summarized. For more information on SMAs, see Chapter 5 Riparian Area Management.

Best Management Practices

1. Use GIS data or digital topographic maps and a GPS unit to determine SMA boundaries.

Field-based determination of variable-width SMA boundaries is a time-consuming process that can sometimes be accomplished in less time using GIS data or digital topographic maps. The width of SMAs is measured horizontally from the streambank, and the slope of land often varies along a stream course, which requires an SMA with a width that varies with the slope. Using GIS data or digital topographic maps, slope, and distance to stream, boundary points for an SMA can be determined quickly and accurately. Those points can then be loaded onto a handheld GPS unit and taken into the field for marking before harvest.

2. Use high-resolution stream maps when planning SMAs to ensure that all streams are protected.

When planning for stream protection, it is important to use the highest resolution stream map available. Lower resolution maps might not indicate the location of lower-order and ephemeral streams. When SMAs are planned, if these streams are left unprotected, water quality could be seriously compromised during and after a harvest.

Discussion

SMAs are delineated along streams in forested areas before harvesting. Generally, the width of an SMA varies by the slope of the terrain perpendicular to a stream, with the width increasing as the adjacent slope increases. That is because additional distance is necessary to prevent more rapidly moving runoff from reaching a stream channel. The process of establishing a variable-width SMA involves extensive field mapping, which requires traversing streams, measuring side slopes, determining where the limits of the SMA should be, marking the boundaries for easy identification during the harvest, and transferring the boundaries to aerial photos and retransferring them to the forest planning map. Although a variable-width SMA is advantageous for water quality protection, such an involved process of establishing them complicates forest operation planning (Williams et al. 2003). Williams et al. (2003) discuss how managers can use GIS as an aid to forestry management planning by accurately mapping SMAs without the need for on-the-ground field determinations. Basically, the process involves using maps of stream-bottom position and the topographic information in a GIS database to accurately and quickly determine the boundary location of variable-width SMAs. Details of the GIS software approach to delineating and mapping variable-width SMAs are provided by Williams et al. (2003).

Baker et al. (2007) evaluated the influence of stream map resolution on measures of the stream network and explored how predictions of nutrient retention potential might be affected by the resolution of a stream map. They noted that stream network maps from a broad range of map resolutions have been employed in watershed studies of riparian areas and were concerned that map resolution could affect important attributes of riparian buffers determined from the maps—for instance, the connectivity between source lands and small stream channels could be missing on coarse-resolution maps. They found that using fine-resolution stream maps significantly increased estimates of stream order, drainage density, and the proportion of watershed area near a stream (Baker et al. 2007).

When Baker et al. (2007) used stream maps of decreasing resolution for the same area, estimates of the mean distance from streams to source areas and mean buffer width were reduced, and the areas found to be unprotected by streamside buffers increased. Increasing the stream map resolution revealed portions of river networks reaching out farther into landscapes and closer to watershed divides, dissecting the landscape more finely while simultaneously decreasing the average proximity of the stream channels throughout watersheds (Baker et al. 2007).

Measures of percent land cover within 100 m of streams were found to be less sensitive to stream map resolution, and overall, increasing stream map resolution led to reduced estimates of nutrient retention potential in riparian buffers (Baker et al. 2007). That study also demonstrated that stream map resolution can also affect a user's ability to determine whether sediment retention occurs in riparian zones. In some watersheds, switching from a coarse-resolution to a fine-resolution stream map completely changed the perceptions of the authors of a stream network from one that was well-buffered to one that was largely unbuffered.

Best Management Practice

1. Establish wider-than-recommended SMAs where an SMA of recommended width will not sufficiently protect water quality.

The width of SMAs is generally prescribed by state or local ordinance, but under some circumstances, it can be too narrow to adequately protect water quality. For instance, the litter layer in an SMA is critical to stopping sediment- and nutrient-laden runoff from reaching streams. If the litter layer is disturbed or lacking, an SMA might have to be wider than recommended to adequately stop runoff.

Similarly, sediment and nutrients can be trapped as runoff infiltrates into the soil. But if the soil in an SMA has poor infiltration, runoff that does reach the SMA is more likely to reach surface waters. Extending the width of an SMA where soils have poor infiltration provides extra distance between the sediment and nutrient source to surface waters within which runoff can be slowed and stopped to prevent water quality degradation.

Discussion

White et al. (2007), working in the Piedmont region of Georgia, noted that a large portion of sediment is removed in the first 2 m of forested filter strips whether they are disturbed or not. In their study, only 2–3 percent of the total sediment was removed in each meter beyond the first 2 m. Significant reductions also occur in finer, silt-sized sediment in undisturbed filter strips, and "it appears that it is within this size fraction that increased filter strip width is the most important." If fine sediment is a concern, according to White et al. (2007), a 16-m filter strip should be sufficient to reduce the 2- to 20- micrometer (μm) particle concentrations in runoff to near zero. Filter strips will have little effect on surface flow sediment concentrations, however, where delivered sediment is colloidal size. That points again to the importance of considering soil characteristics when determining the appropriate SMA width for water quality protection.

White et al. (2007) also recommend that forested filter strip width be based on soil infiltration characteristics. They also note a trend toward increased sediment retention with increased depth of the litter layer, so it is probable that using harvesting equipment in an SMA would affect the litter layer and reduce sediment retention. In areas where coarse sediment is of concern, narrow filter strips should provide sufficient opportunity for settling and should be effective even if relatively little runoff infiltrates the soil. They report that narrow filter strips can remove coarse-textured sediment (> 20 μm in diameter) and that filter strips 16-m wide should remove most 2- to 20-μm sediment from runoff water (White et al. 2007).

The study highlights the potential limitation of using only slope as a tool for prescribing SMA width during harvesting for nutrient control. There is a disconnect between guidelines for slope as a modifying factor for buffer width establishment and slope as a causal factor affecting riparian zone nutrient concentrations. Stand characteristics, particularly the presence of N-fixing species in riparian areas, can also be an important factor influencing soil N concentrations. Vegetation in the SMA and soil properties are important factors to consider when determining the width of an SMA for water quality protection purposes.

Best Management Practice

1. Follow preharvest plan when harvesting in SMAs where upland, soil, and vegetative or litter layer characteristics are such that sediment and nutrients would likely be intercepted before reaching streams in a thinned SMA.

Where water quality would not be compromised and site characteristics are such that runoff from harvest sites would be stopped adequately before reaching streams, thinning harvests could be permitted in SMAs. Where permitted, harvesting in SMAs should always be done using techniques that minimally disturb the litter layer or compact soils. Additionally, managers must consider factors other than water quality protection when determining whether to permit thinning in SMAs. For instance, adequate shade should be provided post-harvest to regulate stream temperature in streams home to temperature-sensitive fish species, such as trout. Also, an adequate number of trees to supply woody debris to the stream must be retained to ensure the ecological health of stream biota.

Discussion

Lauren et al. (2007) investigated the possibility that SMA thinning could accommodate both the landowner's desire to maximize timber revenue and the need to protect water quality. While it is established that uncut buffer zones between clear cuttings reduce export of nutrients, they also reduce harvested stock and harvest revenue, a common and justified concern of landowners. Thinning in buffer zones could increase the volume and revenue of a harvest, but the effect of thinning on nutrient export is not well known. Lauren et al. (2007) compared N export in a 90-m, unthinned buffer zone to that in a 10-m, thinned buffer zone and found that the N export decreased by 53.4 kilograms (kg) in the 90-m, unthinned buffer zone but by only 4.3 kg in the 10-m, thinned buffer zone. Interestingly, however, was their conclusion that a prescribed target for water quality protection (e.g., reduce N export from a watershed by 25 kg in 5 years) can be achieved with several management options or by combining different management schemes. For example, a buffer zone around a stream could be divided into subzones, such as an area in which clearcutting is permitted with restricted site preparation, another zone in which thinning is permitted without the need for site preparation, and a third, completely unmanaged zone. Rivenbark and Jackson (2004) also noted the possibility that SMAs consisting of subzones could be used to meet water quality goals. If the relative strengths of the types of zones for nutrient and sediment reduction are known for an area, for a given water quality protection goal, a mixture of zones in which different harvesting activities are permitted and required could be recommended depending on individual landowner needs and site characteristics (Lauren et al. 2007).

2.4 Forest Road Construction/Reconstruction and Forest Road Management

Implementation Measures:

F-3. Guard against the production of sediment when installing stream crossings. Maintain permanent stream crossings and associated fills and approaches to reduce the likelihood (a) that stream overflow will divert onto roads and (b) that fill erosion will occur if the drainage structures become obstructed.

F-4. Protect surface waters from slash and debris material from roadway clearing.

F-5. Expedite the revegetation of disturbed soils on unstable cuts and fills. Use temporary structures such as straw bales, silt fences, mulching, or other appropriate practices until an area is adequately stabilized.

F-6. Conduct maintenance practices, when conditions warrant, including cleaning and replacing deteriorated structures and erosion controls, grading or seeding road surfaces, and, in extreme cases, slope stabilization or removing road fills where necessary to maintain structural integrity.

F-7. Evaluate the future need for a road and close roads (including temporary spur roads and seasonal roads) that will not be needed. Road closure should include stabilizing closed roads and drainage channels against failure during storms, ensuring that runoff from a closed road will be directed away from the roadway, removing drainage crossings and culverts if there is a reasonable risk of plugging, and removing all temporary stream crossings.

EPA's 2005 forestry guidance emphasizes the importance of good road planning for preventing sediment delivery to streams in the Road Construction/Reconstruction and the Road Management implementation measures. Road construction remains one of the largest potential sources of forestry activity-produced sediment, and providing road and drainage crossing structures that minimize the potential for sediment delivery to surface waters from roads, landings, and skid trails is still an essential task for long-term water quality protection from forest roads.

Road planning and construction can be even more effective today by using advances made in computerized techniques to find the best layouts for roads that can reduce both costs and the potential for road runoff to reach streams.

Forest roads also need to be maintained to correct breakdowns in road drainage structures that can lead to sediment runoff and inputs to streams. When properly planned and constructed, forest road drainage prevents or minimizes the connection between road runoff and the stream network. When roads are left unmaintained, road drainage paths can lead to the stream network. Road drainage hydrologically connected to the stream network is a direct path for sediment input. Additionally, managers should analyze forest roads that are no longer needed, and determine whether returning them to vegetative cover would reduce the risk of sediment runoff.

Best Management Practices

1. Provide extra road drains, especially near streams and stream crossings, to minimize the creation of concentrated runoff flows

In addition to protecting the litter layer and extending SMAs in areas with poor soil infiltration, it is important to ensure that roads and skid trails near drainages and streams are kept hydrologically disconnected from the drainage network. Such a practice means that road segments near streams and stream crossings could need extra drainage structures installed and runoff directed away from streams to minimize the chance of sediment-laden runoff reaching a stream.

Discussion

Preventing concentrated runoff flow from reaching SMAs—or stopping concentrated flows within an SMA if they do reach it—is important to protecting water quality. Rivenbark and Jackson (2004) surveyed SMAs in the Georgia Piedmont to determine the efficacy of BMPs in preventing concentrated overland flow. Recording where flow broke through SMAs and where it did not break through to streams, they found that 50 percent of breakthroughs were at areas of convergence (swales) and gullies, and 25 percent were concentrated runoff from roads or skid trails. They determined that breakthroughs tend to occur in areas with a large contributing area, little litter cover, and steep slopes. They recorded some breakthroughs that traveled 100 feet before being filtered. More than half of breakthroughs traveled 50 feet before reaching stream channels and 14 percent traveled more than 100 feet before reaching streams, though 75 percent of breakthroughs were stopped within the first 20 feet of an SMA. Runoff travel distance before dispersal was not really related to slope, and breakthrough frequency did not differ between sites that were prepared post-harvest and sites that were clearcut and not prepared (Rivenbark and Jackson 2004).

Rivenbark and Jackson (2004) noted the importance of protecting the litter layer in an SMA to prevent concentrated flow from reaching the stream channel. In looking at concentrated flow, White et al. (2007) recorded significant formation of concentrated flow after runoff had traveled 6 m through forested filter strips. According to their study, removing the litter layer can have a major effect on overland flow travel time, especially on steeper slopes. On terrain of the same slope but with a disturbed and undisturbed litter layer, runoff from the terrain with the disturbed litter layer traveled 40 seconds per meter faster on 15–17 percent slopes and 12 seconds per meter faster on 5–7 percent slopes (White et al. 2007).

The effectiveness of SMAs in protecting water quality, therefore, could be improved by protecting the litter layer, dispersing road runoff better, introducing hydraulic resistance to likely flow paths, and widening SMA at key locations (Rivenbark and Jackson 2004). Additionally, the width of SMAs could be varied on the basis of physical features of the site. For instance, SMAs could be extended in sensitive areas, their width could be based on the potential hydrologic load of upland areas rather than being a set width, they could be wider where the contributing area is large and slopes are steeper, and a sub-SMA—a width beyond the primary SMA—could be established where clearcutting is allowed but ground cover is not disturbed and burning and herbicide use is prohibited. It could also be beneficial to stack logging slash along SMA boundaries to intercept and slow concentrated flows (Rivenbark and Jackson 2004).

2. Analyze the connectivity of a road network to streams (using computerized models and risk analysis, if feasible) to determine where the risk of sediment runoff to streams is greatest and where road maintenance efforts should be concentrated, or road sections should be removed or modified.

Within a forest road network, a small portion of the road surface generally contributes disproportionately to water quality deterioration. Finding out which road segments are responsible for water quality deterioration can best be accomplished with computerized techniques that can analyze a variety of information about individual road segments to determine those where maintenance or decommissioning will have the greatest effect.

Discussion

The computer programming methods mentioned above are best used to plan a forest road network before one has been constructed to minimize costs and environmental damage. Computerized techniques for managing existing forest road networks, including road maintenance for water quality protection and road decommissioning, are also being developed. Because runoff and sediment delivery is the dominant process by which water resources are affected by forestry activities, the concept of a forest road system's hydrological connectivity to a stream network has been the focus of much recent research. By managing runoff delivery pathways and the resultant pattern of hydrological connectivity of the road system to the stream network, the potential adverse effects of forest harvesting on in-stream water quality can be limited (Croke and Hairsine 2006).

Computer programming methods are not necessarily needed to analyze small forest road networks where main access roads lead off of public roads and feeder roads are either limited in number or lacking. Under such circumstances, field monitoring of road conditions performed at regularly scheduled intervals or after storms to check for signs of erosion and road failure should be sufficient to determine where road maintenance or road decommissioning is necessary to minimize water quality impacts.

The various links between site runoff, transport, and movement through an extensive forest system into the river system at a site can be difficult to quantify accurately partly because it is difficult to accurately measure the amount of sediment and attached nutrients delivered to, stored and remobilized within, and eventually transported from a river system (Croke and Hairsine 2006). A combined approach of reducing the source strength and enabling the delivery path to trap mobilized sediment, thereby reducing connectivity, is a sound approach to managing the sediment delivery problem.

Three types of runoff delivery pathways from forest roads exist: stream crossings, gullied pathways, and diffuse pathways (Takken et al. 2008). Sediment delivery to streams depends on source strength and the characteristics of the delivery path. Importantly, the degree of connectivity of a road to surface waters depends on catchment characteristics such as topography, road placement, drain spacing, and road and drainage density (Takken et al. 2008).

Takken et al. (2008) evaluated the risk of road-derived runoff delivery. They created risk assessment maps using road-stream hydrological connectivity to highlight hot spots and to evaluate procedures for road rehabilitation. Examining the relatively steep Albert River catchment in Australia, they found that diffuse overland flow could be minimized with additional road drains, particularly by adding more stream crossings per kilometer (km) of road where drainage area is large and roads are lower on the hillslope. Road segments that are highly connected to the stream network, however, were found to require the relocation of the road to manage sediment delivery to streams (Takken et al. 2008).

Croke et al. (2005) demonstrated that a strong association exists between runoff pathway and drain type. They found that most (90 percent) of gullied pathways were at culvert pipes that drain cut-and-fill roads, whereas miter drains and push outs were predominantly associated with dispersive pathways. They studied main access roads, feeder access roads, and minor access roads. Initial sediment concentrations at road outlets ranged from 2 grams per liter (g/L) to 15 g/L and were highest from well-used main access roads compared with less-frequently used feeder access and dump access roads. Road usage alone explained 95 percent of the variation in sediment concentrations in runoff from the road surfaces studied. Most (more than 50 percent) sediment in runoff from the road outlets was silt- and clay-sized material, but sediment concentrations in runoff plumes from main access roads had about 3.5 times higher concentrations of < 63-μm material than those from feeder access roads (Croke et al. 2005).

Croke et al. (2005) concluded that the potential effect of road-related sediment on in-stream water quality can best be assessed in terms of the nature and connectivity of the delivery pathway. Forest roads have a delivery pattern largely determined by runoff source strength and connectivity. *Connectivity* is the arrangement and location of drainage structures such as culverts and miter drains with respect to the natural drainage system in the catchment (Croke et al. 2005).

Examining the hydrological connectivity of a forest road network and stream system can help determine where best to focus efforts to reduce sediment and nutrient inputs to surface waters. Fu et al. (2007) developed and applied a road erosion and sediment transport model. In the areas in southeastern of Australia that they studied, approximately 21 kilotons (kt) and 35 kt of sediment were produced annually from road erosion. They found that less than 10 percent of the sediment produced was delivered to streams, and about half of the delivered sediment was derived from only 4 percent of the total road network (Fu et al. 2007).

Allison et al. (2004) conducted research to demonstrate that decision analysis can be used to organize the complex nature of forest road decisions using road deactivation as an example decision. Road segments that are candidates for deactivation were ranked using factors of interest, which in the case of this study was to reduce the susceptibility of roads to landslides and debris flows. The rankings distinguish between road sections that offer high expected benefit from those that offer moderate to low expected benefit. Allison et al. (2004) applied the analysis to an area with steep terrain, but it could be applied to any terrain type and with various factors of interest. They found in their case that 17 of 171, 100-m road segments accounted for 18 percent of the cumulative cost of deactivation but 98 percent of the cumulative expected net benefits from road deactivation. The results point out that some road segments have a higher benefit-cost ratio than others and that most of the total potential restoration benefit (reduced sediment delivery to streams, maintenance cost, and such) can be obtained from a small proportion of the total road network and potential cost (Allison et al. 2004).

Road decommissioning is expensive, and Eastaugh et al. (2007) assessed the outcomes of different forest road decommissioning options to determine whether costs and environmental impacts could be lowered. They present a method of quantifying the degree to which a road is hydrologically connected to a stream network and the likely effects of different configurations of road construction on water quality. Their method permits the quantification of road/stream connectivity without the need for extensive parameterization, which reduces both the time and cost of implementing the method. They noted that several models exist for predicting road-derived sediment production and delivery, but those models suffer from the practical disadvantage of being highly parameterized, requiring a large number of input data that are often difficult to obtain or accurately estimate. In contrast, the method used by Eastaugh et al. (2007) uses a high-resolution DEM based on 1-m spaced LiDAR measurements to represent catchment topography. The road morphology data necessary for the evaluation was collected during an intensive field survey using a GPS receiver to record the location of road edges, culvert locations, and drain outlets from the road surface (Eastaugh et al. 2007).

Eastaugh et al. (2007) applied the model to an actual road decommissioning and replacement project in southeast Australia. For the application, road areas and drainage outlets were surveyed in the field, and flow paths to streams were derived from a 1-m resolution LiDAR-based DEM. The results of the application demonstrated that the road decommissioning project examined would have been unlikely to reduce runoff to the stream network and that the overall effect of the decommissioning would likely have been a net *reduction* in stream water quality from *increased* sedimentation (Eastaugh et al. 2007).

Best Management Practices

1. Avoid having traffic on forest roads when road water content is high.

Truck traffic on forest roads when the water content of the road is high leads to deformation of the road surface, which redirects runoff and reduces the effectiveness of drainage structures.

2. Use aggregate on forest roads near stream crossings.

Sediment runoff from roads surfaced with an aggregate chosen to withstand the intended traffic load can be much less than from unprotected roads or roads with an aggregate of insufficient quality to handle the traffic load. It is especially important to protect and maintain roads near streams and stream crossings.

Discussion

Suspended sediment makes up 96 percent of the total sediment load from runoff, and a practical option to limiting it in runoff is to reduce the generation rate by surfacing roads adequately with aggregate and maintaining road drainage so it functions as intended (Sheridan et al. 2006).

Sheridan et al. (2006) investigated the effect of truck traffic intensity on runoff water quality from unsealed, gravel-surfaced forest roads. In their studies, traffic explained 36 percent of the variation in erodibility, pointing to the importance of adequately surfacing and maintaining forest roads. Under wet-road conditions, it is common for the cross-sectional profile of a road to become deformed by longitudinal rutting caused by traffic. That compromises lateral road drainage and concentrates flows along the road surface, bypassing drainage structures and leading to rilling of the road surface and high sediment generation rates (Sheridan et al. 2006). The results of Sheridan et al. (2006) indicate that surfacing a road adequately and maintaining it in good condition can reduce sediment production.

Roadside ditches and other drainage features often produce finer sediment than natural conditions, and roads with only marginal-quality aggregate containing low-durability fine particles can produce 4 to 17 times more sediment than those with good-quality aggregate (Witmer et al. 2009). Witmer et al. (2009) recommend that because of limited budgets and the need for cost-effective water quality protection, a priority listing of unpaved road-stream crossings is needed before restoration and sedimentation reduction strategies can be implemented.

Witmer et al. (2009) addressed the problem of determining where to focus road rehabilitation efforts by developing a sedimentation risk index (SRI) for unpaved road/stream crossings to help managers determine which road-stream crossings should receive priority for restoration and sedimentation reduction. The SRI created by Witmer et al. uses 12 metrics to weigh factors involving soil erodibility, road sedimentation abatement features, and steam morphology alteration to arrive at a final index score for each stream crossing. All types of stream crossings—round culvert, box culvert, and bridge—can be included, and they found no significant difference in SRI scores among crossing structure type, indicating that one type is not necessarily better when it comes to less sediment production than others. Limited budgets make prioritizing unpaved road crossings a key means for efficient sedimentation abatement, and the SRI or a similar rating scheme can be used to make water quality protection more effective (Witmer et al. 2009).

2.5 Timber Harvesting

Implementation Measures:

F-8. Install landing drainage structures to avoid sedimentation to the extent practicable. Disperse landing drainage over stable side slopes. Protect landing surfaces used during wet periods. Locate landings outside SMAs.

F-9. Conduct harvest and construct landings away from steep slopes to reduce the likelihood of slope failures.

F-10. Protect stream channels and significant ephemeral drainages from logging debris and slash material.

The goal of the Timber Harvesting implementation measure in the 2005 guidance is to minimize the likelihood of water quality effects resulting from timber harvesting. Precautions taken during preharvest planning to minimize road and skid trail miles, and follow the contour of the land to the extent feasible, are important aspects of protecting the forest floor from disturbance. Using equipment well suited to the topography and forest type to limit erosion and sedimentation during harvesting operations is also important.

When conducting a harvest, it is important to pay attention to the potential for soil disturbance from the operation. Doing so can result in improved water quality protection. Disturbances to forested watersheds can have severe adverse effects on soil and soil nutrients. Road construction and skidding associated with forest harvesting can cause serious soil disturbance that can increase suspended sediment in streams. It is vitally important that the forest floor be protected from disturbance to the maximum extent feasible during all aspects of harvesting.

Best Management Practice

1. When constructing roads, landings, and skid trails, and during harvesting, use methods that maximize protection of the forest floor to the extent feasible.

Most sediment and nutrient runoff from forest harvest sites originates in areas where the forest floor has been disturbed and the soil has been exposed, disturbed, or compacted. Protecting the litter layer and soils of the forest floor where it is possible (that is, where it need not be disturbed for road construction or skidding) is vital to ensuring the protection of water quality. Although roads and skid trails are generally maintained or protected after a harvest to limit sediment runoff, disturbed areas beyond these can go unnoticed and not receive the rehabilitation that roads and skid trails do to prevent sediment runoff. Unintentionally disturbed areas also are not usually provided with runoff control features, so any runoff originating from them could drain unchecked to streams and rivers.

Discussion

Protecting the forest floor outside the SMA is important to protecting the water quality of forested streams. Surface erosion generally does not occur in an undisturbed forest because of the infiltration capacity of the litter layer and forest soils (Hotta et al. 2007). Following that logic, in an unharvested forest where the source area of suspended sediment is limited to the stream, suspended sediment transport should correspond well with water discharge. Certain forest practices, such as constructing forest roads and skid trails and serious soil surface disturbances such as those caused by skidder activity and plowing, are known to increase suspended sediment yields.

Most studies have investigated the effects of the practices associated with harvesting rather than the harvesting itself. Hotta et al. (2007) investigated whether harvesting would increase suspended sediment yields if harvesters took appropriate measures to prevent surface disturbance, including using skyline logging treatments and piling branches and leaves at selected locations in the watershed. They performed the study in an experimental watershed in a steep-sloped forest near Tokyo, Japan. Hotta et al. (2007) measured suspended sediment yield from areas harvested using such methods and found that annual suspended sediment yields did not increase despite post-harvest increases in annual water yields. They found that after harvesting, there were no increases in suspended sediment yields concurrent with heavy rainfall events, when most suspended sediment was normally transported in the watershed. They concluded that post-harvest increases in suspended sediment yields can be controlled by using careful harvesting techniques (Hotta et al. 2007).

2.6 Site Preparation

Implementation Measure F-11:

Protect surface waters during site preparation by

1. Selecting a method of site preparation and regeneration that is suitable for the site conditions.
2. Conducting mechanical tree planting, ground-disturbing site preparation activities, and bedding on the contour of sloping terrain and outside SMAs and ephemeral drainages.
3. Protecting surface waters from logging debris and slash material, including locating windrows far enough from drainages and SMAs to limit the entry of material into surface waters during high-runoff conditions.
4. Suspending operations during wet periods if equipment begins to cause excessive soil disturbance that will increase erosion. Conduct bedding operations in high-water-table areas during dry periods of the year.

The Site Preparation and Forest Regeneration implementation measure in the 2005 guidance discusses how important it is to revegetate harvested areas to minimize erosion and runoff from disturbed soils that could degrade water quality. Vegetative cover on disturbed soils reduces erosion and slows runoff, and roots stabilize soils. Minimizing disturbance to the forest floor litter layer during all phases of forestry activities—from road construction to site preparation operations—minimizes soil compaction and detachment, which helps maintain infiltration and slow runoff. Such factors, in turn, reduce erosion and sedimentation after site preparation is complete.

Where soil and the litter layer have been disturbed, and in instances where it would not prevent the regrowth of planted trees or natural regeneration, protecting the soil by applying wood chips or slash could be a viable method to both protect the soil and prevent the loss of N from the soil to surface waters.

Best Management Practice

1. Apply wood chips or slash to disturbed areas after a harvest to reduce nutrient runoff.

N as nitrate is commonly leached from a forest after clearcut harvesting because the N cycle is disrupted when vegetation that would normally use the N is removed. The amount of nitrate that is made available for leaching depends on the amount of vegetation removed (generally, selective cutting or diameter-limit harvesting do not result in nitrate leaching), vegetative characteristics of the forest, and the time elapsed since the harvest. Nitrate leaching generally decreases as vegetation regrows on the clearcut site. Applying wood chips derived from logging slash can significantly reduce nitrate leaching after a harvest during the time when vegetation is re-establishing itself. The wood chips are thought to immobilize much of the nitrate in the forest floor.

Discussion

N as nitrate is a pollutant that can be released after forest harvest, especially after clearcutting. Soil temperature can also be increased, which can increase microbial activity, organic matter decomposition, and inorganic N production. Homyak et al. (2008) tested whether applying wood chips derived from logging slash after harvesting would immobilize nitrate and thus reduce its flux to streams. They applied wood chips to the soil surface in a stand of northern hardwoods that was patch clearcut in the Catskill Mountains, New York, and found that between 19 and 38 kg of nitrate per hectare were immobilized in the first year after harvesting, depending on the quantity of wood chips applied, which contributed to water quality protection. They suggest that additional research on wood chip application as a new BMP after harvesting is warranted, particularly in regions that receive elevated levels of atmospheric N deposition (Homyak et al. 2008).

Immobilizing nitrate in the forest floor by either leaving some logging slash on the ground or by adding woody material after logging might be a feasible way to reduce nitrate flux to streams and limit water quality impacts. Other studies in Japan, the Mediterranean, New Hampshire, and the Appalachian Mountains have shown similar results (Homyak et al. 2008).

2.7 Fire Management

Implementation Measures:

F-12. Prescribed and wildland fire should not cause excessive erosion or sedimentation because of the combined effect of partial or full removal of canopy and removal of ground fuels and the litter layer, to the extent practicable.

F-13. All bladed firelines, for prescribed fire and wildfire, should be stabilized with water bars or other appropriate techniques if needed to control excessive sedimentation or erosion of the fireline.

F-14. Consider the potential nonpoint source pollution consequences on watercourses of wildfire suppression and rehabilitation activities, while recognizing the safety and operational priorities of fighting wildfires.

The Fire Management implementation measure in the 2005 forestry guidance emphasizes the importance of using prescribed fire in a way that does not remove the litter layer so that erosion is not a problem after a fire. Recent research examines the mechanism by which fire can protect a forest from erosion or expose it to erosion and emphasizes the importance of fire management to protect a forest from post-fire erosion.

Best Management Practice

1. Ensure that prescribed fires are burned at a low enough intensity and at a burn rate such that the litter layer that remains behind is sufficient to protect the forest floor from erosion after the fire. Also, do not set prescribed fires or allow prescribed fires to burn in SMAs.

The presence of a litter layer on the forest floor is key to reducing and avoiding sediment runoff. A low-intensity prescribed fire is more likely to leave an intact litter layer and reduce nutrient runoff after a fire than a high-intensity fire.

Discussion

The importance of protecting the forest litter layer during forestry operations was stressed earlier. Because exposure of bare forest soils is the critical link to sediment and nutrient runoff, it is equally important to maintain the litter layer during and after a prescribed fire.

Studies have shown that low-severity prescribed fire removes the upper forest floor layer (the Oi layer of the soil O horizon) but retains a large proportion of the portions of the O horizon below that (the Oe and Oa horizon layers) (Knoepp et al. 2009). Those layers protect surface soils from potential erosion and represent a large reservoir of plant nutrients.

Knoepp et al. (2009) investigated N responses on sites in subwatersheds that drained a first-order stream in the Blue Ridge Physiographic province of the southern Appalachian Mountains. All prescribed fires were done in the dormant season and were low to moderate intensity. All sites lost a significant amount of forest floor mass due to burning: 82 to 91 percent of the Oi layer and 26 to 46 percent of the Oe + Oa layer. Soil NH_4-N concentrations increased immediately after burning in the top 5 cm of surface soils only but returned to pre-burn levels by mid-summer. Burning had no measurable effect on soil solution inorganic N concentrations. No inorganic N was lost from the sites (Knoepp et al. 2009).

Elliot and Vose (2005) conducted low- to moderate-intensity and low-severity prescribed burning to restore shortleaf pine/mixed-oak forest (Elliot and Vose 2005). Fires of a low intensity in the study were ones that left the Oe and Oa layers intact but reduced the uppermost litter layer (Oi), exposed little soil, and had heat penetration only near the soil surface. They measured soil solution and stream water nutrient concentrations and stream water sediment concentration (TSS). Soil solution and stream water (N) did not increase after burning on any of the sites, and they found no differences in TSS between the burn and control streams. No detectable differences between control and burned sites for concentrations of PO^4, SO^4, Ca, Mg, K, or pH in soil solution or stream water were found, either. The results suggest that low-intensity, low-severity fires can be conducted and used as a management tool without negatively affecting water quality (Elliot and Vose 2005).

2.8 Revegetation of Disturbed Areas

Implementation Measures:

F-15. Revegetate disturbed areas (using seeding or planting) promptly after completing the earth-disturbing activity. Local growing conditions will dictate the timing for establishing vegetative cover.

F-16. Use mixes of species and treatments developed and tailored for successful vegetation establishment for the region or area. Native species are generally preferred, although nonnative species can be acceptable as long as they are noninvasive.

F-17. Concentrate revegetation efforts initially on priority areas such as disturbed areas in SMAs or the steepest areas of disturbance (e.g., on roads, landings, or skid trails) near drainages.

The 2005 forestry guidance describes the Revegetation of Disturbed Areas implementation measure, and the practices provided in the 2005 guidance are still the best advice for quickly restoring vegetation on disturbed forest areas. This chapter provides no additions to the information in the 2005 guidance. Revegetating disturbed areas is still important because it restabilizes the soil, reduces erosion, and helps prevent pollutants from entering surface waters. As knowledge of the ecological damage that can be caused by nonnative species has expanded after numerous unsuccessful introductions of nonnative species for erosion control or other purposes, it must be emphasized, however, that native species are preferred for revegetating disturbed areas and any species used, whether native or nonnative, should be noninvasive for the habitat into which it is to be introduced. Local or regional offices of a cooperative extension service can offer excellent advice on species selection for revegetation uses.

2.9 Forest Chemical Management

Implementation Measures:

F-18. Establish and identify buffer areas for surface waters. (This is especially important for aerial applications.) Conduct applications by skilled and, where required, licensed applicators according to the registered use, with special consideration given to effects on nearby surface waters. Carefully prescribe the type and amount of pesticides appropriate for the insect, fungus, or herbaceous species.

F-19. Before applying pesticides and fertilizers, inspect the mixing and loading process and the calibration of equipment, and identify the appropriate weather conditions, the spray area, and buffer areas for surface waters. Immediately report accidental spills of pesticides or fertilizers into surface waters to the appropriate state agency. Develop an effective spill contingency plan to contain spills.

The 2005 forestry guidance describes the Forest Chemical Management implementation measure. This chapter provides no additions to the information in the 2005 guidance. Chemicals used in forest management include pesticides (insecticides, herbicides, and fungicides) and fertilizers. Mixing, transporting, and applying the chemicals correctly and according to manufacturer directions, and disposing of containers properly will prevent water quality issues related to those substances to a great degree. For information relevant to forest chemical management, see the 2005 guidance.

2.10 Wetlands Forest Management

Implementation Measure F-20:

Plan, operate, and manage normal, ongoing forestry activities (including harvesting; road design, construction, and maintenance; site preparation and regeneration; and chemical management) to adequately protect the aquatic functions of forested wetlands.

The 2005 forestry guidance describes the Wetlands Forest Management implementation measure. This chapter provides no additions to the information in the 2005 guidance. The 2005 guidance discusses special harvesting methods for use in forested wetlands, road design and construction practices especially applicable to forested wetlands, wetland crossing practices, site generation and regeneration practices for use in forested wetlands, fire management practices for forested wetlands, and chemical management for working in forested wetlands. The information provided in the 2005 guidance is still EPA's official guidance for forestry work in wetland environments.

3 References

Akay, A.E., H. Oguz, I.R. Karas, and K. Aruga. 2009. Using LiDAR technology in forestry activities. *Environ. Monit. Assess.* 151:117–125. [Akay et al. 2009 -> 2009a]

Allison, C., R.C. Sidle, and D. Tait. 2004. Application of decision alanlysis to forest road deactivation in unstable terrain. *Environ. Manag.* 33(2):173–185.

Aruga, K. 2005. Tabu search optimization of horizontal and vertical alignments of forest roads. *J. For. Res.* 10:275–284.

Aruga, K., J. Sessions, and E.S. Miyata. 2005a. Forest road design with soil sediment evaluation using a high-resolution DEM. *J. For. Res.* 10:471–479.

Aruga, K., J. Sessions, and A.E. Akay. 2005b. Heuristic planning techniques applied to forest road profiles. *J. For. Res.* 10:83–92.

Baker, M.E., D.E. Weller, and T.E. Jordan. 2007. Effects of stream map resolution on measures of riparian buffer distribution and nutrient retention potential. *Landscape Ecology* 22:973–992.

Blankenship, K. 2006. *State of the Chesapeake forests: Public perception often fails to look at importance of forests beyond trees*. <http://www.bayjournal.com/article.cfm?article=2898>. Accessed April 22, 2010.

CBP (Chesapeake Bay Program). 1999. *The State of the Chesapeake Bay*. CBP/TRS 222/108. <http://www.chesapeakebay.net/content/publications/cbp_13006.pdf>. EPA 903-R99-013. Accessed February 8, 2010.

CBP (Chesapeake Bay Program). 2003. *Expanded Riparian Forest Buffer Goals*. Chesapeake Executive Council. Directive No. 03-01. <http://www.chesapeakebay.net/content/publications/cbp_12610.pdf>. Accessed February 8, 2010.

CBP (Chesapeake Bay Program). 2004. *Bay Watershed Forest Cover*. http://www.chesapeakebay.net/status_watershedforests.aspx?menuitem=19792. Accessed April 22, 2010.

CBP (Chesapeake Bay Program). 2008. *New Conservation Goals Aim to Protect More Chesapeake Forests*. http://www.chesapeakebay.net/forests.aspx?menuitem=14640. Accessed February 8, 2010.

CBP (Chesapeake Bay Program). 2009a. *Bay Barometer. A Health and Restoration Assessment of the Chesapeake Bay and Watershed in 2008*. CBP/TRS 293-09. EPA-903-R-09-001. <http://www.chesapeakebay.net/content/publications/cbp_34915.pdf>. Accessed February 8, 2010.

CBP (Chesapeake Bay Program). 2009b. *Bay Health and Restoration Assessment*. <http://www.chesapeakebay.net/indicatorshome.aspx?menuitem=14871>. Accessed February 8, 2010.

Chung, W., J. Stuckelberger, K. Aruga, and T.W. Cundy. 2008. Forest road network design using a trade-off analysis between skidding and road construction costs. *Can. J. For. Res.* 38:439–448.

Contreras, M., and W. Chung. 2007. A computer approach to finding an optimal log landing location an analyzing influencing factors for ground-based timber harvesting. *Can. J. For. Res.* 37:276–292.

Croke, J.C., and P.B. Hairsine. 2006. Sediment delivery in managed forests: a review. *Environ. Rev.* 14:59–87.

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.

CWP (Center for Watershed Protection). No date. *The economic connections between forests and drinking water: A pilot study in the Linganore Creek watershed, Maryland*. Center for Watershed Protection. Ellicott City, MD.

Eastaugh, C.S., P.K. Rustomji, and P.B. Hairsine. 2007. Quantifying the altered hydrologic connectivity of forest roads resulting from decommissioning and relocation. *Hydrol. Process*. 22:2438–2448.

Elliot, K.J., and J.M. Vose. 2005. Initial effects of prescribed fire on quality of soil solution and streamwater in the Southern Appalachian Mountains. *S. J. Applied For*. 29(1):5–15.

Epstein, R., A. Weintraub, P. Sapunar, E. Nieto, J.B. Sessions, J. Sessions, F. Bustamante, and H. Musante. 2006. A combinatorial heuristic approach for solving real-size machinery location and road design problems in forestry planning. *Operations Research* 54(6):1017–1027.

Federal Leadership Committee. 2010. *Strategy for Chesapeake Bay Watershed Protection and Restoration*. Chesapeake Bay Program, Annapolis, MD.

Fu, B., L.T.H. Newham, and J.B. Field. 2007. Modelling erosion and sediment delivery from unsealed roads in southeast Australia. *Mathematics and Computers in Simulation* 79:2679–2688.

Ghaffarian, M.R., and H. Sobhani. 2007. Modelling erosion and sediment delivery from unsealed roads in southeast Australia. *Croat. J. For. Eng.* 28(2):185–193.

Hodges, C., and R. Visser. 2004. *Comparison of Streamside Management Zone Requirements in the Southeast*. Virginia Polytechnic Institute and State University, Department of Forestry, Blacksburg, VA.

Homyak, P.M., R.D. Yanai, D.A. Burns, R.D. Briggs, and R.H. Germain. 2008. Nitrogen immobilization by wood-chip application: Protecting water quality in a northern hardwood forest. *For. Ecol. Manag*. 255:2589–2601.

Hotta, N., T. Kayama, and M. Suzuki. 2007. Analysis of suspended sediment yields after low impact forest harvesting. *Hydrol. Process*. 21:3565–3575.

Klapproth, J.C., and J.E. Johnson. 2000. *Understanding the science behind riparian forest buffers: Effects on water quality*. Pub. 420-151. Virginia State University, Virginia Cooperative Extension, Petersburg, VA.

Knoepp, J.D., K.J. Elliott, B.D. Clinton, and J.M. Vose. 2009. Effects of prescribed fire in mixed oak forests of the southern Appalachians: forest floor, soil, and soil solution nitrogen responses. *J. Torrey Bot. Soc*. 136(3):380–391.

Kyker-Snowman, T. No date. *Forests and water: Some principles of management*. <http://www.mass.gov/dcr/news/publicmeetings/forestry/Kyker-SnowmanForests%20and%20Water%20TSC%20visioning.pdf>. Accessed March 2, 2010.

Lauren, A., H. Koivusalo, A. Ahtikoski, T. Kokkonen, and L. Finer. 2007. Water protection and buffer zones: How much does it cost to reduce nitrogen load in a forest cutting? *Scand. J. For. Res*. 22:537–544.

Loggertraining. 2010. *Pennsylvania Timber Harvester/Forest Practitioner Training Program*. <http://www.loggertraining.com/pa.htm>. Accessed March 4, 2010.

Lovett, G.M., K. Weathers, and M. Arthur. 2002. Control of nitrogen loss from forested watersheds by soil carbon:nitrogen ratio and tree species composition. *Ecosystems* 5:712–718.

Mercker, D.C., and D.G. Hodges. 2007. Forest certification and nonindustrial private forest landowners: Who will consider certifying and why? *J of Extension* 45(4). <http://www.joe.org/joe/2007august/rb6.php>. Accessed March 2, 2010.

Najafi, A., H. Sobhani, A. Saeed, M. Makhdom, and M.M. Mohajer. 2008. Planning and assessment of alternative forest road and skidding networks. *Croat. J. For. Eng*. 29(1):63–73.

Neary, D.G., G.G. Ice, and C.R. Jackson. 2009. Linkages between forest soils and water quality and quantity. *Forest Ecology and Management* 258:2269–2281.

NYLT (New York Logger Training). 2010. *What is NYLT?* <http://www.nyloggertraining.org/home/>. Accessed March 4, 2010.

Rackley, J., and W. Chung. 2008. Incorporating forest road erosion into forest resource transportation planning: a case study in the mica creek watershed in northern Idaho. *Trans. ASABE* 51(1):115–127.

Rivenbark, B.L., and C.R. Jackson. 2004. Concentrated flow breakthroughs moving through silvicultural streamside management zones: Southeastern Piedmont, USA. *JAWRA* 40(4):1043–1052.

SFI (Sustainable Forestry Initiative). 2010. *SFI 2010–2014 Standard*. Sustainable Forestry Initiative, Inc., Washington, DC.

Sheridan, G.J., P.J. Noske, R.K. Whipp, and N. Wijesinghe. 2006. The effect of truck traffic and road water content on sediment delivery from unpaved forest roads. *Hydrol. Process*. 20:1683–1699.

Spence, B.C, G.A. Lomnicky, R.M. Hughes and R.P. Novitski. 1996. *An ecosystem approach to salmonid conservation*. TR-4501-96-6057. ManTech Corp, Corvalis, OR. Funded by National Marine Fisheries Service, U.S. Fish and Wildlife Service and the U.S. Environmental Protection Agency. Available from National Marine Fisheries Service, Portland, OR.

SUNY (State University of New York). 2010. *How does Forest Harvesting Affect Nitrogen in Streams?* State University of New York, College of Environmental Science and Forestry. <http://www.esf.edu/pubprog/nitrogen/default.htm>. Accessed March 2, 2010.

Takken, I., J. Croke, and P. Lane. 2008. A methodology to assess the delivery of road runoff in forestry environments. *Hydrol. Process*. 22:254–264.

University of Florida. 2007. Forest Certification Programs. <http://www.sfrc.ufl.edu/extension/florida_forestry_information/planning_and_assistance/forest_certification_programs.html>. Accessed March 2, 2010.

USEPA (U.S. Environmental Protection Agency). 2005. *National Management Measures to Control Nonpoint Sources of Pollution from Forestry*. EPA 841-B-05-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2008. *Virginia 2008 Water Quality Assessment Report*. U.S. Environmental Protection Agency, Office of Water, Washington, DC. <http://iaspub.epa.gov/waters10/attains_index.control?p_area=VA>. Accessed March 4, 2010.

Virginia Tech. 2010. *SHARP Logger Program*. <http://www.sharplogger.vt.edu/>. Accessed March 4, 2010.

White, W.J., L.A. Morris, A.P. Pinho, C.R. Jackson, and L.T. West. 2007. Sediment retention by forested filter strips in the Piedmont of Georgia. *J. Soil Water Cons.* 62(6):453–463.

Williams, T.M., D.J. Lipscombb, W.R. English, and C. Nickel. 2003. Mapping variable—width streamside management zones for water quality protection. *Biomass and Bioenergy* 24:329–336.

Witmer, P.L., P.M. Stewart, and C.K. Metcalf. 2009. Development and use of a sedimentation risk index for unpaved road-stream crossings in the Choctawhatchee watershed. *JAWRA* 45(3):734–747.

WVDOF (West Virginia Division of Forestry). 2010. *Logging*. West Virginia Division of Forestry, Charleston, WV. <http://www.wvforestry.com/>. Accessed March 4, 2010.