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Regional Differences in Stream Water Nitrogen, Phosphorus, and Sediment Responses to Forest Harvesting in the Conterminous USA

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Abstract

Forest harvesting and management techniques were hypothesized to result in significant differences in stream water N (NO_3–N), P (total P [TP]), and total suspended sediment (TSS) responses among regions of United States. The objectives were (i) to determine the mean response periods after harvesting for each water quality variable, (ii) to compare the regional response yields, and (iii) to determine relationships among water quality, rainfall, and flow. Watershed-scale studies where best management practices were implemented provided a basis for water quality analyses. A mixed model was used to estimate the time from harvest to time when the harvested site yielded similar export as the reference site (response period). Normalized water quality yields were calculated as response yields (kg ha^{-1} yr^{-1}) times estimated response periods. Significant differences among yields were identified using ANOVA and Tukey test ($\alpha = 0.05$), and relationships between water quality and hydrologic variables were identified using multivariate analysis ($\alpha = 0.05$). The ratio of estimated mean response period for TSS to NO_3–N and TP, each individually, was approximately two. The mean normalized NO_3–N response yield was greater for the northern than the southern and/or western regions. Normalized NO_3–N and TSS response yields were greater for plantations than for other harvest types. The TSS export significantly increased with discharge from plantations. The literature-based response periods used in this study were not fully monitored, and soil surface manipulations after harvesting pose a significant influence on sediment export in the United States.

Core Ideas

- Publications on water quality responses to US forest harvesting were explored.
- The mean response period after harvesting for total suspended sediments (TSS) was 8.8 yr.
- The mean response period for NO_3–N and total P were 4.3 and 3.9 yr, respectively.
- The greatest NO_3–N response was 265.2 kg ha^{-1} for plantations in the northern region.
- The greatest TSS response was 17,756.6 kg ha^{-1} for plantations in the southern region.

Control of N, P, and sediment loss to water bodies is a concern to forest management in the United States. A variety of forest harvest techniques and postharvest operations as the best management practices are available to foresters, but their impact on water quality can vary widely (Abbas et al., 2011). Differences in climate, topography, soils, and plant communities have all been found to contribute to variability in water quality outcomes (Jurgensen et al., 1997; Berndes et al., 2003, Aust and Blinn, 2004; Miwa et al., 2004; LaFayette et al., 2012). For example, topography affecting heterogeneity of forests west of the Mississippi River in the southern United States (LaFayette et al., 2012) and soil recovery from disturbance depending on soil mineralogy, regional climate, and type of disturbance (Miwa et al., 2004) can possibly be linked to the varying water quality response. Indeed, Stednick (2010) documented regional variability in nutrient runoff to streams among regions, and that stream NO_3–N response to forest harvesting in northern hardwood forests may be greater than other regions in United States. Similarly, the effects of forest harvest residue removal were reported to depend on forest cover type and site characteristics by Premer et al. (2016), both of which may potentially affect regional nutrient responses. Elevated N and P concentrations, as a result of repeated fertilization of managed forests (Binkley et al., 1999; Groffman et al., 2004; Fox et al., 2007; Beltran et al., 2010), can stimulate growth of aquatic plants such as algae. Algal blooms reduce O_2 and visibility for aquatic organisms in water bodies. Thus, improved understanding of stream response to forest management options remains a priority of watershed studies in the United States.

Nitrogen cycling in forest ecosystems is complex, and, therefore, water quality outcomes related to forest management may be related to a variety of processes affecting the N cycle. Muwamba et al. (2015) compared export of N from pine forest sites subjected to bedding and root raking after harvesting and found that bedding resulted in increased N export in the southern coastal region, likely due to increased mineralization. In western North America, forest harvesting negatively affected soil mycorrhizae that play an important role in N cycling; the effect's magnitude was influenced by the extent of disturbance,

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Abbreviations: TP, total phosphorus; TSS, total suspended sediment(s).

soil ectomycorrhizal diversity, and rainfall distribution (Feller, 2005). Swank et al. (2001) and Lovett et al. (2002) associated changes in species composition to variability in NO_3–N yield from harvested forest watersheds in the southern region. Lovett et al. (2002) reported that N deposition is directly proportional to elevation and that stream water NO_3–N concentration is inversely proportional to elevation, and the authors attributed the patterns to diversity of vegetation and soils at higher elevations. Areas with greater precipitation and industries (e.g., the northeastern United States) were associated with greater atmospheric N deposition (Jurgensen et al., 1997).

Phosphorus loss from forested watersheds is highly modified by the properties of forest soils, which influence their role as a source or sink of P. Although sediment-bound P transport is generally seen as the principal pathway for watershed P loss, differences in edaphic properties influence sorption and desorption of P in forest soils. Because forest soils are often low in pH, Fe and Al are often cited as principal cations responsible for P sorption in forested ecosystems, such that practices influencing soil pH (e.g., liming) may increase the potential for dissolved P loss from soils (Rodgers et al., 2010; LaFayette et al., 2012; Muwamba et al., 2015). LaFayette et al. (2012) and Muwamba et al. (2015) hypothesized that acidification of soils in pine-dominated forest promotes greater sorption of P by Fe and Al.

Sediment delivery from forests varies as a function of topography, soil properties, extent of disturbance, and even elevation (Miller, 1984; Fulton and West, 2002; Neary et al., 2009). Aust and Blinn (2004) reported that forest harvesting and site preparation from steeper physiographic regions can increase erosion, sediment, and nutrient losses to streams. Binkley and Brown (1993) also reported that road construction and harvesting increased stream suspended sediment concentrations, with highly variable results among regions in North America. Shearing that involves opening the soil increases exposure of bare soil to erosion compared with sites subjected to clear-cut only (Douglass., 1977; Fulton and West., 2002). Grace and Carter (2001) and Grace (2004) documented that forests subjected to bedding store more runoff than sites not subjected to bedding in the southern region due to the deposition of transported sediment in the depressions between beds.

Compared with other land uses, forested streams have lower nutrients concentrations than crop-dominated areas due to greater fertilizer application rates and quality of mineralizable materials in agricultural systems. In a study by Gustafson and Wang (2002) in Vermont, USA, stream water concentrations of P and N were lower in forested regions than cropped regions due to greater nutrient enrichment in the latter. Golladay and Battle (2002) associated increase in solution inorganic N, P, and suspended sediment in coastal plain watersheds in southwestern Georgia with conversion of natural vegetation to agriculture land use. Allan (2004) also reported that increasing agricultural land use leads to greater nutrients loads, sediments loads, and storm flows in the neighboring streams than forested settings. The hydrologic, biogeochemical, topography, edaphic factors, vegetation species, and drainage areas affect water quality variables' export (Fig. 1).

Monitoring water quality changes after forest harvesting should continue until concentrations have reached levels of unharvested forests (Meals, 2001). For example, Amatya et al. (2006) analyzed water quality data until 9 yr after harvesting a coastal managed pine forest in 1995 and reported some nutrients returning to baseline levels after 4 yr since replanting in 1997. The entire monitoring period is called the true response period (Meals, 2001). Feller (2005) reported that the rate of afforestation and/or plant growth and prior N content also affect N response period after harvesting. There are only a limited number of studies that assess the temporal effects of forest harvesting on the true response period of nutrients and sediment. The objectives of this study were (i) to determine the mean response periods for each water quality variable to test the hypothesis that there will be differences in true response periods for N, P, and sediment; (ii) to compare the regional N, P, and sediment response yields after forest harvesting to test the second hypothesis that there will be differences in these responses to forest harvesting in the United States; and (iii) to determine relationships between water quality and rainfall and flow.

Materials and Methods

We conducted an extensive literature review to select published papers with studies that reported water quality responses to silvicultural practices on a watershed scale and where best management practices were followed during harvesting within the United States (Fig. 2, Table 1). We also acknowledge that there were publications that were not explored, which is also the reason for states that are not included in this paper.

The studies were grouped by (i) regions (north, south, and west) and (i) harvest types (plantations and other types of harvests). Plantation harvesting and establishment involved soil manipulation activities including shearing, bedding, raking, ripping, and herbicide and fertilizer application after harvesting (see supplemental material for expanded description of these activities). Other harvest types included thinning and harvesting without opening the soil with machinery. Information documented based on these publications included forest tree species, stand age, forest area, geographic location, precipitation, slope, soil series, harvest operations (Tables 1–5), baseline water quality parameters for the reference site, and changes in water quality following silvicultural operations.

Important definitions used in this study include: (i) treatment, defined as harvested site; (ii) control, defined as the reference or unharvested site; (iii) response period, defined as the number of years required for water quality variable in the treatment to return back to preharvest levels, or levels similar to the control; and (iv) response yield, defined as total load per unit area (kg ha^{-1}) of water quality variable of interest, delivered to a water body over the response period (yr), in excess of that of the reference condition. Water quality response (kg ha^{-1} yr^{-1}) was calculated as the total load normalized by the area (kg ha^{-1}) divided by the response period (yr).

Data Analysis and Estimation of True Response Period

Only 10% of the selected literature studies fully explored the true response period. The response periods for the rest of the studies were modeled, and 90% confidence intervals around the modeled mean were determined to illustrate the ranges of possible responses as uncertainties in estimates. The annual normalized response yields (or exports) for water quality variables and their respective confidence intervals for each year (kg ha^{-1})

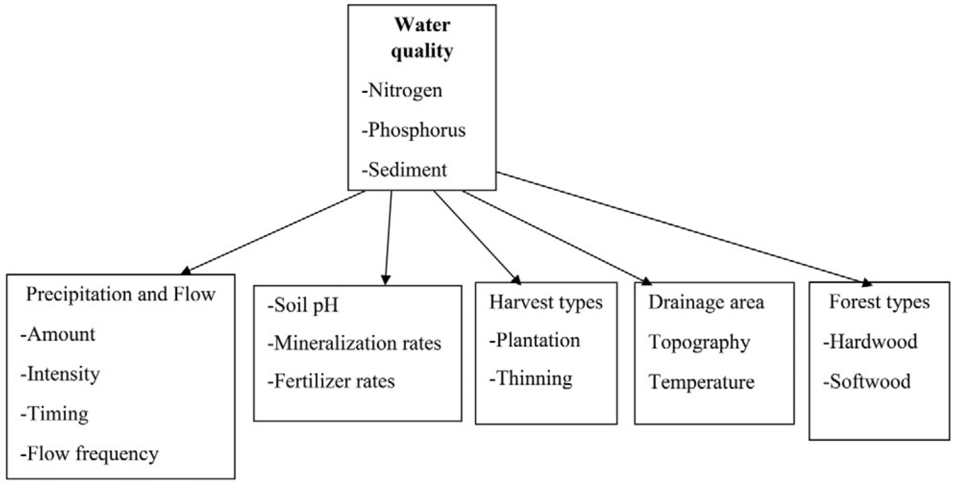

Fig. 1. Factors and processes that affect water quality responses in forest systems of the United States.

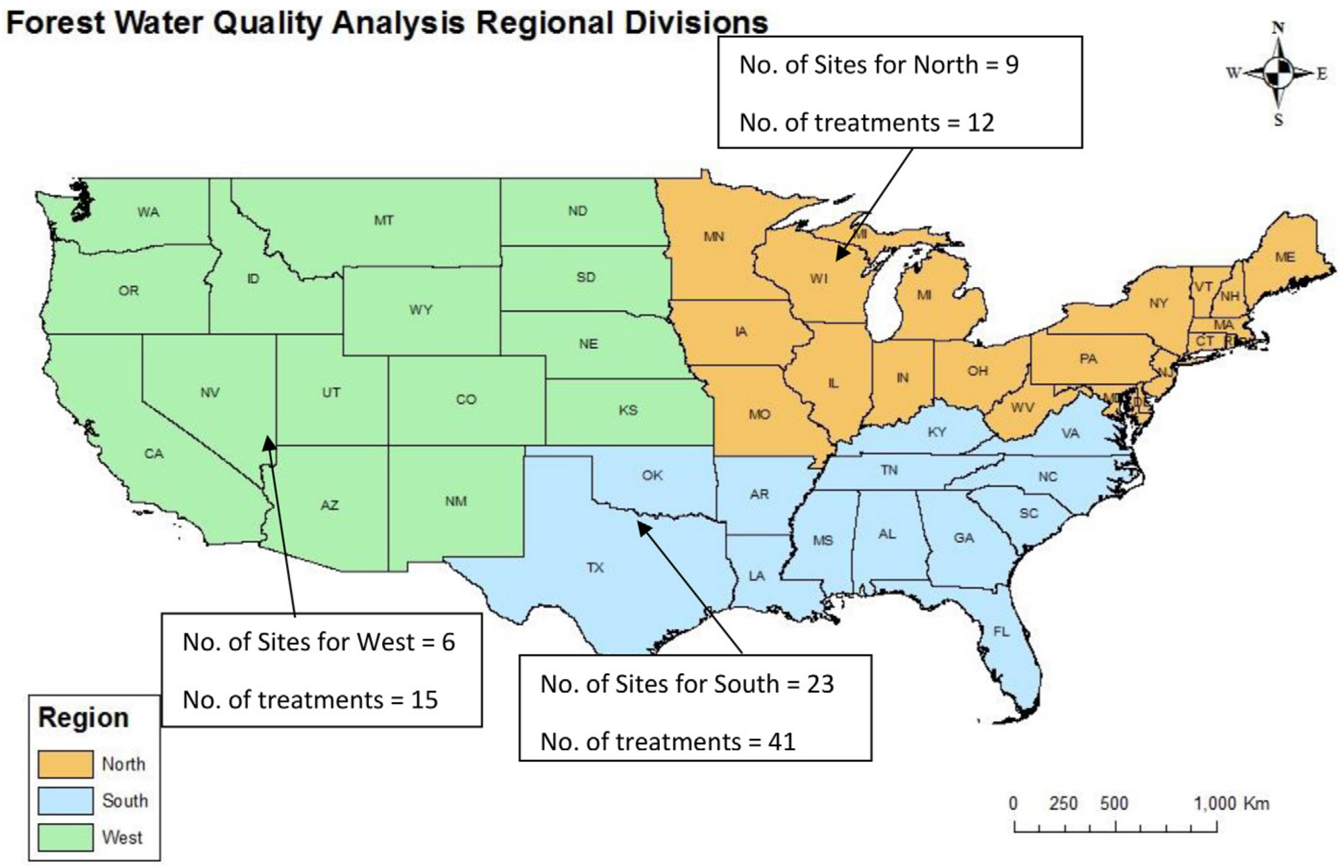

Fig. 2. Number of study sites in northern, southern, and western regions.

were plotted against year after harvest. An exponential function (Eq. [1]) below best described the available data.

$$Y = a^{-bX} \quad [1]$$

where Y is the water quality response (kg ha^{-1} yr^{-1}), a is a constant as the y intercept, b is the exponential decay rate, and X represents the year after harvest. Solving each equation for X, where the response curve intersects the reference condition, gives the modeled response period for each variable. The total response (kg ha^{-1}) yield was calculated as the product of mean response yield (kg ha^{-1} yr^{-1}) and modeled response period (yr). In addition to mean response yield, we calculated 90% confidence intervals for the mean for each harvest type, region, and response period. Differences in harvest type and regional differences in NO_3–N, total P (TP), and total suspended sediment (TSS) responses to forest harvesting were identified using ANOVA with a Tukey's test at a significance level at $\alpha = 0.05$. Data for reference (or preharvest) (kg ha^{-1} yr^{-1}) and postharvest (kg ha^{-1} yr^{-1}) were recorded as reference condition and response to harvest, respectively. For testing for significant differences, we multiplied literature based response yield data by the calculated true response periods to obtain the true response yields for regional and harvest type comparisons. For regions where there was not enough information for calculating response period (e.g., northern and western regions that did not have enough information for plantations), we used the calculated mean response period for the entire USA.

Multivariate analysis was used to identify the relationships between hydrologic variables (annual rainfall and flow) and water quality export variables. The relationships were developed for regions (north and south) and harvested types (plantations and other harvest types). For each region and harvest type, annual water quality export data were regressed with flow and/or rainfall. Relationships with $p < 0.05$ were considered significant. Statistical analyses were conducted using SAS 9.4 (SAS Institute, 2013).

Results and Discussion

Information Recorded from the Publications

There were adequate NO_3–N, TP, and TSS data as samples for statistical analyses (Table 1). A greater number of publications reported the response of NO_3–N and TSS to harvesting than TP (Table 1). The greater number of publications reporting NO_3–N than P variables was likely due to very low water P concentrations as a result of greater P sorption than N. A greater number of publications from the southern region reported the response of N, P, and sediment to harvesting than the northern and western

Table 1. Publications used to extract N (NO_3–N), P (total P [TP]), and sediment (SS) and site characteristics

Citation	Region	State	NO_3–N	TP	SS	Harvest type	Forest type
Briggs et al. (2000)	North	ME	x			Plantation	Softwoods
Likens et al. (1970)	North	NH	x			Plantation (N fertilized)	Hardwoods
Bormann et al. (1968)	North	NH	x			Other harvest	Hard and soft woods
Bormann et al. (1974)	North	NH	x			Other harvest	Hard and soft woods
Hornbeck et al. (1987)	North	NH	x			Other harvest	Hard and soft woods
Hornbeck et al. (1990)	North	NH,ME,CT	x		x	Other harvest	Hardwoods
Martin and Hornbeck (1994)	North	NH			x	Other harvest	Hardwoods
Wang et al. (2006)	North	NY	x			Other harvest	Hardwoods
Yanai (1998)	North	NH	x	x		Other harvest	Hard and soft woods
Amatya et al. (2006)	South	NC	x		x	Plantation (shear, bed)	Soft woods
Beasley (1979)	South	MS			x	Plantation (shear, bed)	Hard and soft woods
Beasley and Granillo (1988)	South	AR			x	Plantation (shear; burn)	Hard and soft woods
Beasley et al. (1986)	South	AR			x	Plantation (shear, herbicide)	Hard and soft woods
Blackburn et al. (1986)	South	TX			x	Plantation (shear)	Soft woods
Blackburn and Wood (1990)	South	TX	x	x		Plantation (shear, burn)	Hard and soft woods
Chang et al. (1982)	South	TX			x	Plantation (shear, root rake)	Hard and soft woods
Fox et al. (1986)	South	VA	x			Plantation (shear, disc)	Hard and soft woods
Grace (2004)	South	AL			x	Plantation (shear, rip, bed)	Soft woods
Grace and Carter (2001)	South	AL			x	Plantation (shear, rip, bed)	Soft woods
McBroom et al. (2002)	South	TX	x		x	Plantation (shearing)	Hard and soft woods
McBroom et al. (2008)	South	TX	x	x	x	Plantation (fertilizer; herbicide)	Soft woods
Miller (1984)	South	OK			x	Plantation (ripping)	Soft woods
Muwamba et al. (2015)	South	NC	x			Plantation (shear, root rake, bed)	Soft woods
Swank et al. (2001)	South	NC	x		x	Plantation	Hardwoods
Van Lear et al. (1985)	South	SC	x		x	Plantation	Soft woods
Wynn et al. (2000)	South	VA		x	x	Plantation (burn; herbicide)	Hard and soft woods
Amatya and Skaggs (2008)	South	NC	x		x	Other harvest	Soft woods
Arthur et al. (1998)	South	KY			x	Other harvest	Hard and soft woods
Aubertin and Patric (1974)	South	VA			x	Other harvest	Hard and soft woods
Beasley (1979)	South	MS			x	Other harvest	Hard and soft woods
Blackburn and Wood (1990)	South	TX	x	x		Other harvest (burn)	Hard and soft woods
Chang et al. (1982)	South	TX			x	Other harvest	Hard and soft woods
Fox et al. (1986)	South	VA	x			Other harvest (chop, burn)	Hard and soft woods
Grace (2004)	South	AL			x	Other harvest	Soft woods
Grace and Carter (2000)	South	AL			x	Other harvest	Soft woods
Grace and Carter (2001)	South	AL			x	Other harvest	Soft woods
Grace et al. (2006)	South	NC	x	x		Other harvest	Soft woods
McBroom et al. (2002)	South	TX	x		x	Other harvest	Hard and soft woods
Sanders and McBroom (2013)	South	TX			x	Other harvest	Soft woods
Brown and Krygier (1971)	West	OR			x	Other harvest	Hard and soft woods
Gravelle et al. (2009)	West	ID	x			Other harvest	Soft woods
Heede and King (1990)	West	AZ			x	Other harvest	Soft woods
Karwan et al. (2007)	West	ID			x	Other harvest	Soft woods
Martin and Harr (1989)	West	OR	x			Other harvest	Soft woods
Tiedemann et al. (1988)	West	OR	x			Other harvest	Hard and soft woods

United States (Table 1). The greatest percentage of harvested tree species in all the regions were hardwoods (Tables 2–5). The ranges for harvested stands were 15 to 70, 5 to 70, and 65 to 130 yr for northern, southern, and western regions, respectively (Tables 2–5). The average harvested area and stream flow yield were significantly greater ($p = 0.04$) for the northern region than for the southern region (Table 6).

Water Quality Response Periods

Across the literature analyzed in this study, postharvest measurement periods ranged from 1 to 13 yr (Table 6). The modeled mean response period for the entire United States was 8.8 yr for sediment, followed by 4.3 yr for NO_3–N and 3.9 yr for TP (Table 7, Fig. 3). The mean response period for TSS was significantly greater

Table 2. List of vegetation, soils, areas, and slopes for northern United States.

Harvest type	Soils	Vegetation types†	Drainage areas	Ages	Slopes
			ha	yr	%
Plantation	Coarse, loamy, mixed frigid Typic and Aquic Haplorthods	Sugar maple (H)	48		
		Yellow birch (H)	15.6		
		American beech (H)	15.6		
		White ash (H)			
		Eastern hemlock (H)			
		Eastern white pine (H)			
		Beech maple-birch (H)			
		Spruce fir (S)			
Other	Lithic and Typic Haplorthods	Sugar maple (H)	22	70	25
	Sandy-skeletal, isotic, frigid Typic Haplorthods	Yellow birch (H)	12	10	7.5
	Coarse-loamy, isotic, frigid Oxyaquic Haplorthods	American beech (H)	36	15	
	Loamy, isotic, frigid Lithic Haplorthods	White birch (H)	47	28	
	Coarse-loamy, isotic, frigid Aquic Haplorthods	*Quercus rubra* (H)	16		
	Coarse-loamy over sandy or sandy-skeletal, isotic over mixed, frigid Typic Haplorthods	*Quercus velutina* (H)	7		
	Aquic Haplorthod	*Quercus prinus* (H)	5.7		
	Aeric Haplaquept	*Betula lenta* (H)	22		
	Typic Fragiorthod	*Acer rubrum* (H)			
	Typic Dystrochrept	Red spruce (S)			
	Inceptisols	Balsam fir (S)			
		Eastern hemlock (S)			

† H, hardwood; S, soft wood.

Table 3. Soils, vegetation, areas, ages, and slopes for plantations in the southern United States.

Soils	Vegetation types†	Areas	Ages	Slopes
		ha	yr	%
Clayey, mixed, thermic Typic Hapludults	White oaks (H)	2.5	5	2
Ultisols (Lilbert, Tenaha, Rentzel, Briley, and Darco)	Southern red oak (H)	3.5	50	11
Typic Hapludults, clayey, kaolinitic, thermic and clayey, oxidic, mesic fine loamy siliceous, thermic family of Albic Glossic Natraqualfs	Hickories (H)	100	43	17
Fine loamy siliceous, thermic family of Albic Glossic Natraqualfs	*Tulipifera L* (H)	2.7	20	15
Fine-loamy, mixed, thermic Typic Umbraquults	*Quercus rubra L* (H)	3.1	34	57
Clayey, mixed, thermic Aquic Hapludults	*Quercus velutina L.* (H)	3.4	34	6
Typic Paleudult	*Quercus prinus L* (H)	3.55	40	9
Typic Dystrochrept	*Acer rubrum* (H)	2.9	40	13
Typic Halumbrept	*Pinus rigida* (H)	59.5	20	14.5
Ultic Hapludalf	Dogwood (H)	3.24		11.5
Typic Fragiudalf	Loblolly pine (S)	25		
Fine, montmorillonitic, thermic family of Vertic Hapludalfs	Sweetgum (S)	25		
Clayey, kaolinitic, thermic Rhodic Kanhupludults	Short leaf pine (S)	0.02		
Fine loamy, mixed, thermic, Typic Hapladults	Virginia pine (S)	0.8		
Loamy-skeletal, mixed, thermic Lithic Dystochrepts		3.5		
Loamy-skeletal, siliceous, thermic, Lithic Dystrochrepts		1.0		
Fine-silty, mixed, thermic Aquic Paleudalfs		2.7		
Clayey, mixed, thermic Aquic Hapludults		0.7		
		25		
		1.35		

† H, hardwood; S, soft wood.

Table 4. Soils, vegetation, areas, ages, and slopes for other harvest types in the southern United States.

Soils	Vegetation types†	Areas	Ages	Slopes
		ha	yr	%
Typic Hapludults, clayey, kaolinitic, thermic and clayey, oxidic, mesic	Oak (H)	1.53	50	17
Coarse-loamy, siliceous, thermic Typic Hapludults	Hickory (H)	0.02	43	2
Fine-loamy, siliceous, thermic Typic Hapludults	*L. tulipifera (H)*	7.9	20	6
Clayey, mixed, thermic Typic Hapludults	*A. rubrum* (H)	5.1	18	9
Ultisols (Lilbert, Tenaha, Rentzel, Briley, and Darco)	Sweetgum (H)	8.1	20	25
Fine loamy siliceous, thermic family of Albic Glossic Natraqualfs	Blackberry (H)	5.1	70	14.5
Clayey, mixed, thermic Aquic Hapludults	Beech (H)	98	70	11.5
Clayey, kaolinitic, thermic (Rhodic Manhapludult family)	Dogwood (H)	3.24	40	
Fine-loamy, mixed, mesic Typic Hapludults	Virginia pine (S)	25	40	
Loamy-skeletal, mixed, mesic Typic Dystrochrepts	Loblolly pine (S)	34	40	
Fine-loamy, mixed, mesic Typic Haplumbrepts	Short-leaf pine (S)	25	20	
Fine, montmorillonitic, thermic family of Vertic Hapludalfs		25	15	
Clayey, kaolinitic, thermic Rhodic Kanhupludults		2.7	33	
Fine loamy, mixed, thermic, Typic Hapladults		40		
Loamy-skeletal, mixed, thermic Lithic Dystochrepts		25		
Loamy-skeletal, siliceous, thermic, Lithic Dystrochrepts				
Calvin channery silt loams				
Belhaven series				

† H, hardwood; S, soft wood.

Table 5. List of vegetation, soils, and slopes for other harvest types in the western United States.

Soils	Vegetation types†	Areas	Ages	Slopes
		ha	yr	%
Typic Vitrandepts and Cryandepts	Douglas fir (S)	13	130	13.5
Fine-loamy, isotic, mesic Andic Humudepts	Vine maple (H)	15.4	130	22.5
Bohannon series	*Rhododendron* (H)	24.4	75	
Silt loam soil	*Salal* (H)	29.6	75	
Silty soils	Grand fir (S)	140	65	
Typic Haplorthods	Engelmann spruce (S)	175	65	
	Lodge pole pine (S)	70		
	Thuja plicata (S)	300		
	Larix accidentalis (S)	243		
	Alder (H)	140		
	Mixed conifer (S)	175		
	Western white pine (S)			
	Subalpine fir (S)			

† H, hardwood; S, soft wood.

Table 6. Average runoff coefficients (ROC = streamflow/precipitation), stream flow (with ranges in parentheses for the literature data), and average measurement periods for the literature data in the entire United States.

Harvest type	Region	*N*†	Mean harvested area	Mean ROC‡	Mean stream flow
			ha		mm yr^{-1}
Plantation (opening soil and fertilize)	South	23	16.8	0.17 (0.02–0.35)	201.2 (12.7–426.7)
Other (no soil opening and no fertilizer)	North	7	21.4	0.72 (0.51–0.87)	1304.2 (610.0–2322.0)
Other (no soil opening and no fertilizer)	South	11	12.8	0.26 (0.04–0.65)	336.6 (17.0–899.7)
Other (no soil opening and no fertilizer)	West	3	90.5	0.39 (0.01–0.64)	882.3 (6.8–1430.0)

Response variable§	No. of treatments	Measurement time	Measured treatment period
		——— yr ———	
NO_3–N	36	4.0	2.7
TP	8	5.0	2.2
TSS	37	4.8	2.3

† N, number of study treatments.

‡ ROC, runoff coefficient (flow/rainfall).

§ TP, total P; TSS, total suspended sediments.

($p = 0.02$) than for NO_3–N and TP. Most of the studies monitored water quality variables up to 3 yr after harvesting (Table 6).

The range of modeled response periods show the minimum and maximum number of years for the entire United States where water quality variable export can increase relative to the reference. Estimating the response yield using the literature-based treatment periods that are shorter than true response periods would lead to underestimation of water quality yield responses to forest harvesting. Based on the publications, we found that the studies did not explore the entire response periods, likely due to the timeframe of the projects.

Normalized Water Quality Yields

The yield response curves were described by a mixed model (Eq. [1]). The normalized response yield (kg ha^{-1}) for each region in Table 7 was calculated by multiplying the average mean yield (kg ha^{-1} yr^{-1}) and the mean estimated respective response period reported in Table 7. Literature sediment yield was significantly greater ($p = 0.01$) for plantations than other harvest types (Table 7). Nitrate-nitrogen response yield for the northern region was significantly greater ($p < 0.03$) than for the southern and western regions (Table 7). Greater ($p = 0.04$) sediment response to harvesting was reported in the southern region than in the western region (Table 7). There was a significant ($p = 0.04$) increase in TSS export with increase in discharge for plantations (hydrologic–water quality relationships are shown in Table 8). Nitrate-nitrogen and TP exports were not significantly ($p > 0.05$) related to rain and stream flow (Table 8).

Effects of Silvicultural Management Operations

The differences in the nature of forest management operations adopted in different regions, as shown in Table 1, could be among the reasons for regional differences in water quality variable export (Grace and Carter, 2001; Grace, 2004; Feller, 2005; LaFayette et al., 2012). In this study, for the northern and southern regions, NO_3–N export was greater for plantations

Table 7. Parameters for the mean and 90% confidence interval for water quality response curves, response periods, and average normalized response for the literature-based response yield data in the entire United States.

Response variable†	Region	Coefficient a	Coefficient b	R^2	*P* value	Response period
						yr
Sediment plantation 90% lcl	National	3,308.46	−1.17	0.98	0.0096	2.9
Sediment plantation mean	National	8,971.63	−1.01	0.79	0.0104	4.4
Sediment plantation 90% ucl	National	14,754.48	−0.98	0.98	0.0110	5.0
Sediment 90% lcl	National	104.54	−0.01	0.00	0.9488	0.0
Sediment mean	National	742.00	−0.22	0.66	0.0137	8.8
Sediment 90% ucl	National	1,288.38	−0.14	0.28	0.2850	18.2
NO_3^- 90% lcl	Northern	23.86	−1.34	0.61	0.1171	1.6
NO_3^- mean	Northern	31.77	−0.68	1.00	<0.0001	3.7
NO_3^- 90% ucl	Northern	44.26	−0.54	0.95	0.0054	5.2
NO_3^- 90% lcl	National	5.33	−1.47	0.89	0.0152	1.9
NO_3^- mean	National	3.86	−0.57	0.90	0.0245	4.3
NO_3^- 90% ucl	National	4.62	−0.39	0.73	0.0656	6.7
TP 90% lcl	National	0.01	−0.04	0.17	0.4849	0.0
TP mean	National	0.74	−0.61	0.78	0.0488	3.9
TP 90% ucl	National	1.46	−0.50	0.56	0.1461	6.1

	N_1‡	N_2§	Avg. normalized yield	
			Plantation¶	Other harvest types#
			kg ha^{-1}	
NO_3–N				
North	3	7	265.2	60.3
South	13	7	9.7	6.7
West	††	7	††	3.4
TP				
North	††	††	††	††
South	5	3	1.0	2.2
West	††	††	††	††
Sediment				
North	††	††	††	††
South	18	12	17,756.6	2,056.2
West	††	5	††	5,688.2

† lcl, lower confidence level; ucl, upper confidence level; TP, total P.

‡ N_1, number of treatments for plantation.

§ N_2, number of treatments for other harvest types

¶ Opening soil and fertilizer

No soil opening and no fertilizer).

†† Limited information for analyses.

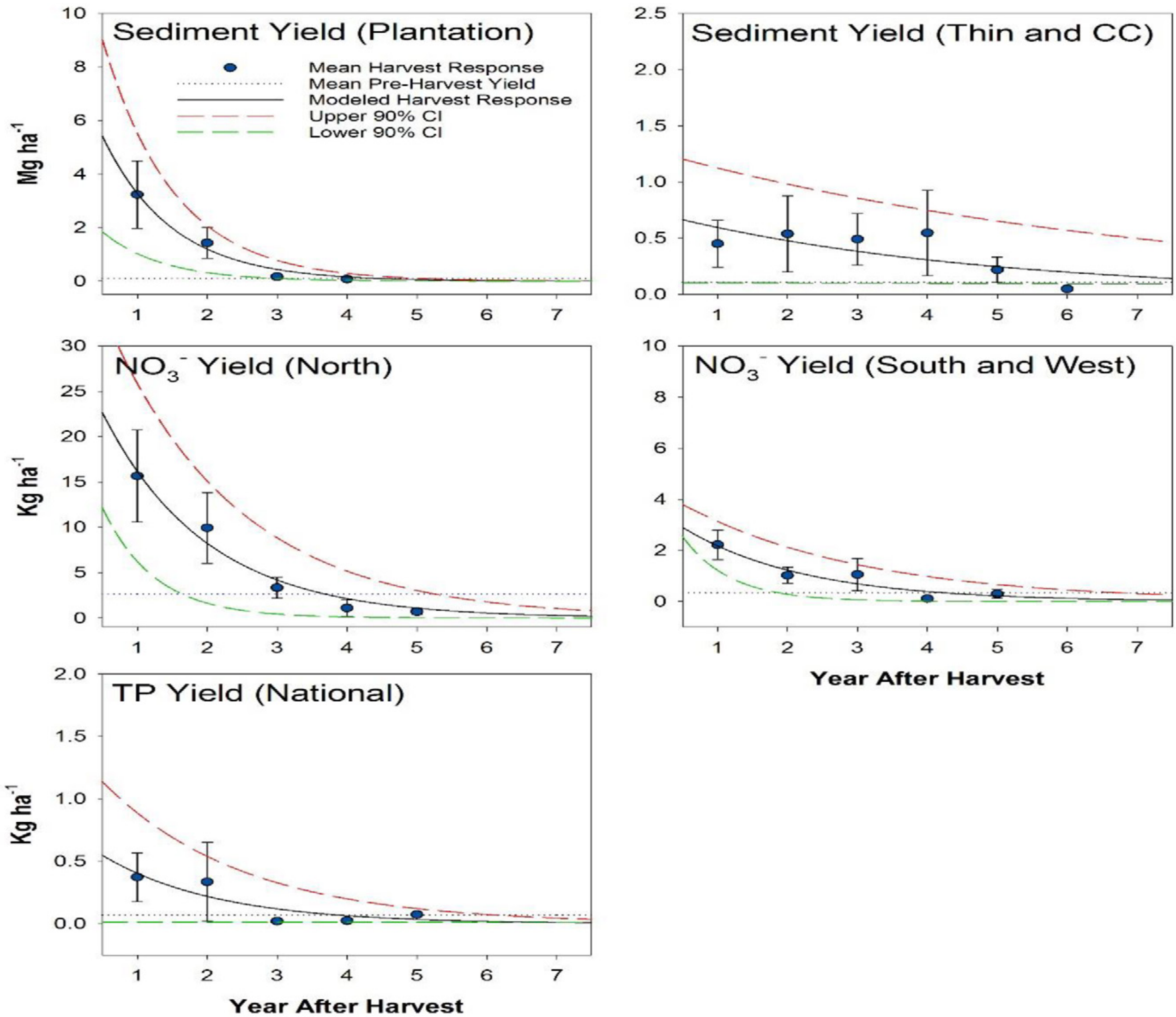

Fig. 3. Sediment, NO_3–N, and total P (TP) yield response curves generated from the results of the mixed model comparing regions and harvest types. Clear cutting only is represented by CC. Bars represent the upper and lower 90% confidence interval (CI) for each mean in each year.

than for other harvest scenarios (Table 7), likely due to the influence of intensive management operations. A number of studies have shown differences in responses of water quality to different forest management operations (Troendle et al., 2010; Muwamba et al., 2015). For example, N exports were greater in the first 2 yr after harvesting on sites that were subjected to shearing and bedding compared with sites that were subjected to shearing and root raking (Muwamba et al., 2015) in the southern coastal region, and the authors attributed the N increase to the influence of bedding. According to Feller (2005), clear-cutting plus slash burning recorded greater NO_3–N export than clear-cut only. Rapid growth of vegetation after planting reduced the effects of raindrop impacts, and herbicide use reduced canopy cover, leading to greater raindrop impacts (Douglass., 1977; Fulton and West., 2002; Stednick., 2010; Troendle et al., 2010). Sheared and bedded sites stored more runoff than sheared only sites after harvesting (Grace and Carter, 2001; Grace, 2004). Sediment export was greater for plantations than for other harvest types (Tables 3 and 4) in the southern region, likely due to subsoiling that reduces the soil detachment force. Additional nutrients through N and P fertilizer applications could also have contributed to greater N loads in plantations than other harvest systems

Table 8. Multivariate relationships between water quality and hydrologic variables for various regions (north and south) and treatments (plantations and other harvest types).

Variable	NO_3–N		Plantations		Other harvest types	
	North	South	NO_3–N	TSS†	NO_3–N	TSS
Precipitation‡	0.008 (0.60)	0.001 (0.62)	0.001 (0.81)	−1.78 (0.24)	0.013 (0.21)	0.46 (0.35)
Stream flow‡	0.012 (0.25)	0.003 (0.71)	0.001 (0.87)	12.0(0.001)	0.008 (0.17)	0.16 (0.67)
Intercept	−13.8	0.32	0.74	739.8	−16.2	−217.1
R^2	0.50	0.11	0.04	0.33	0.47	0.13

† TSS, total suspended sediments.

‡ Slope with *p* values in parentheses.

without postharvest fertilization (Binkley et al., 1999; Gurlevik et al., 2004; Fox et al., 2007; Beltran et al., 2010).

Effects of Plant Species Distribution

The regional distribution of plant species that depend on forest growers' choice and plant age also affect water quality responses to forest management (Finzi et al., 1998; Lovett et al., 2002; Flavel and Murphy., 2006; Fox et al., 2007). The C/N ratios that depend on the vegetation type affect nitrification rates, with decreasing C/N ratios leading to increasing nitrification rates (Finzi et al., 1998; Lovett et al., 2002). For example, conifers have greater C/N ratios than hardwoods (Lovett et al., 2002); therefore, ion concentrations in water will increase with hardwood dominance. In this study, regional hardwood dominance followed the trend north > south > west (Tables 2–5); NO_3–N export (Table 7) followed a similar trend. Lovett et al. (2002) also found a strong negative relationship between soil C/N ratio and nitrification rates in coniferous and hardwood northeastern US forests. Based on soil C/N correlations with NO_3–N export, Lovett et al. (2002) reported that forests dominated with sugar maple (*Acer saccharum* Marshall) and white ash (*Fraxinus americana* L.) experience more leaching of NO_3–N than forest dominated by red oak (*Quercus rubra* L.) and red maple (*Acer rubrum* L.) in the northern United States. Analyses in this study (Tables 2–5 and 7) also showed that plantations (where sugar maple and white ash were among the vegetation) recorded greater NO_3–N yield than other harvest types (where red oak and red maple were among the vegetation). Goodale et al. (2000) also identified a negative relationship between both dissolved organic C and percentage hardwood and dissolved organic N and hardwood cover in the forests found in the White Mountains of New Hampshire in the northeastern region.

The average age for the harvested forests in this study followed the trend west > south > north (Tables 2–5), and studies have shown the importance of age of forest materials on decomposition rates (Troendle et al., 2010; Jones et al., 2013). Mature conifer forests have also been reported to use more water than mature aspen forests, leading to less nutrient export (Jones et al., 2013). Stream flow response was also reported to be affected by species composition and the percentage change in vegetation density in the western region (Troendle et al., 2010), and in the eastern coastal plain (Jayakaran et al., 2014), with a potential to affect nutrient and sediment exports. Nitrate leaching was also reported to increase with decreasing C/N ratio in forests across Europe (Dise et al., 1998). According to Finzi et al. (1998), rates of decomposition are inversely proportional to C/N and lignin/N ratio, and the latter two ratios are lower for sugar maple, white ash, and red maple litter than in beech (*Fagus grandifolia* Ehrh.), red oak, and hemlock (*Tsuga Canadensis* Carr.) leaf litter. According to Flavel and Murphy (2006), young plant materials are more mineralizable than older materials due to less lignin and cellulose than the latter. The greater quality mineralizable plant species are likely to result in greater nutrient exports.

Effects of Climatic Variables and Drainage Areas

The regional differences in water quality responses were also associated with climatic variables and drainage areas. The watershed drainage area was reported to affect water quantity and quality (Klein et al., 2011; Cristan et al., 2016). For example, in our study, (i) the western region recorded greater average drainage area and total sediment yield than the south, and (ii) the northern region recorded greater average drainage area and total NO_3–N yield than the south (Tables 6 and 7). Goodale et al. (2000) identified positive relationships between dissolved organic N and hydrologic variables (precipitation and flow). Vaithiyanathan and Correll (1992) reported that P fluxes from watersheds are related to streamflow. For example, P export in other harvest types was greater than plantations of the southern region (Table 7), likely due to greater streamflow in the former. Feller (2005) observed association of increased nitrification and stream water NO_3–N fluxes with warmer summers.

Effects of Soils

The differences in soils (Tables 2–5), forest history, and atmospheric deposition for the different regions could also influence the forest nutrient dynamics. For example, Lovett et al. (2002) noted that soil C/N ratio can be affected by the historical disturbances of the forest sites. Christ et al. (2002) compared watersheds that receive almost similar N deposition and documented that those watersheds with greater pH, base saturation, and water-holding capacity, and lower C/N ratios are more susceptible to NO_3–N leaching and N saturation than those without. The depth of surface soil layer and soil sorbing components like Al, Fe, Ca, and pH affect P sorption and leaching leading to regional differences in P export after forest harvesting (Vaithiyanathan and Correll, 1992). Miwa et al. (2004) reported that the pH of the forest floor determines the decomposition process, with pH range of 6 to 8 favoring warm activity that may lead to greater nutrient exports and pH of 5.5 favoring aerobic cellulose-decomposing bacteria. The greater NO_3–N export in the northern United States than in the southern and western regions (Table 7) was likely partly due to greater atmospheric deposition as reported by Feller. (2005), Fenn et al. (1998), Carpenter et al. (1998), and Jaworski et al. (1997). According to Goodale and Aber (2001), regional differences in N deposition coupled with C/N ratio may partly explain the regional trends of N cycling.

Conclusions

The extensive literature review for this study revealed that water quality monitoring periods did not cover the full response periods in those published studies. The greater calculated true response period for total suspended sediment than for N and P indicates that studies related to sediment response to forest harvesting should aim to monitor for longer periods by opting for long-term research. Using literature reported water quality monitoring periods to calculate the true response yield after tree harvesting will therefore likely underestimate the effects of forest harvesting on water quality. For the regions explored in this study, drainage area normalized NO_3–N export was greater for the northern region than those reported for the southern and/or western regions. Greater NO_3–N and total suspended sediment exports were recorded for plantations than for other harvest types. Total suspended sediment export for plantations was the only water quality variable that significantly ($\alpha = 0.05$) increased with streamflow. Results of analysis using limited literature-based data in this study indicated that research activities and/or other studies related to water quality response to forest harvesting should aim to monitor until the recovery occurs (i.e., for whole response period); this will help in a thorough understanding of the mechanisms relating water quality responses to forest management operations, on top of climatic variables.

Supplemental Material

The supplemental material includes definitions of harvesting techniques, saw log removal, whole tree harvesting, and thinning. The definitions of post harvesting management operations for planting for regeneration, shearing, root raking, bedding, burning, herbicide application, fertilizer application, dozing, disking, and removal of harvested forest residuals were also included in the supplemental material.

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