

## Diatom assemblages as indicators of timber harvest effects in coastal Oregon streams

JESSE NAYMIK<sup>1</sup> AND YANGDONG PAN<sup>2</sup>

*Environmental Sciences and Resources, Portland State University, Post Office Box 751,  
Portland, Oregon 97207 USA*

JESSE FORD<sup>3</sup>

*Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon 97333 USA*

**Abstract.** Spatially patchy and temporally varied cycles of timber harvest across a landscape may have subtle effects on stream conditions that are difficult, but important, to assess. The objective of our study was to examine the relationship between benthic diatom composition and timber harvest in coastal Oregon watersheds. Physical habitat conditions, water chemistry, and periphyton composition were characterized for 46 sites from 2 subbasins with different timber harvest intensities (0.3 km<sup>2</sup>/y vs 3 km<sup>2</sup>/y, between 1972–1998). Landscape variables including geology, vegetative cover types, and harvest intensity, were quantified for the watershed upstream of each sample point. Nonmetric Multidimensional Scaling analysis of periphyton composition showed that the 1<sup>st</sup> axis was primarily driven by *Achnanthes minutissimum* ( $r = -0.91$ ) whereas the 2<sup>nd</sup> axis was driven by *Nitzschia inconspicua* ( $r = 0.77$ ). The 1<sup>st</sup> axis was positively correlated with % of upstream area harvested between 1972 and 1998 ( $r = 0.54$ ) and water-quality variables such as total P (TP) (e.g.,  $r_{TP} = 0.74$ ). A subset comparison ( $n = 12$ ) between harvested (30% harvested 1972–1998,  $n = 6$ ) and unharvested (0% harvested 1972–1998,  $n = 6$ ) watersheds with similar geology (>80% basalts), broadleaf vegetative cover (8–35% broadleaf), and other reach-scale characteristics revealed higher total N, TP, turbidity, and conductivity in the harvested than the unharvested watersheds ( $p < 0.05$ ). Shannon diversity and species richness also were higher in the harvested group ( $p < 0.05$ ). Our data suggest that diatom assemblages may be useful in assessing the long-term impact of timber harvest within coastal Oregon watersheds.

**Key words:** periphyton, Nonmetric Multidimensional Scaling (NMDS), timber harvest, diatoms, bioassessment, *Achnanthes minutissimum*, red alder, Oregon coast range, stream.

In the coastal ecoregion of Oregon, conversion of forest to management for timber harvest is the greatest anthropogenic activity impacting streams and rivers (McClain et al. 1998). Approximately 263 to 324 km<sup>2</sup> have been clear-cut by the private forest industry in Western Oregon every year from 1975 to 1995, excluding nonindustrial clear-cutting and partial cutting (Lettman and Campbell 1997). Timber harvest and associated activities can have distinct effects on hydrology, water quality, and aquatic biota of stream ecosystems (Binkley and Brown 1993). However, it can be difficult to assess impacts of temporally variable and spatially patchy cycles of harvest occurring across the landscape. The

goal of our research was to determine if large-scale transformation of forest to management for timber harvest affected stream ecosystems in the Oregon coast range and, if so, whether benthic diatom assemblages could be used to assess these potential effects.

Diatoms are especially useful in assessing potential effects of timber harvest because they have well-described responses to environmental conditions and, specifically, to environmental variables that may change during land management for timber harvest (i.e., light, nutrients, sediment; Dixit et al. 1992, Biggs et al. 1998, Stevenson and Pan 1999). Community shifts such as prolific growth of green macroalgae, and replacement of previously dominant diatom species by lower abundances of other species, can occur in response to changing environmental conditions from harvest (Hansmann and Phinney 1973, Shortreed and Stockner 1983). For ex-

<sup>1</sup> Present address: Idaho Power Company, 1221 West Idaho Street, Boise, Idaho 83702 USA.

E-mail: jnaymik@idahopower.com

<sup>2</sup> E-mail addresses: pany@pdx.edu

<sup>3</sup> fordj@ucs.orst.edu

ample, 6 y after harvest, Lowe et al. (1986) observed higher abundances of 14 diatom species in a harvested stream compared with a reference stream, and attributed differences to increased light availability as a result of harvest.

However, assessing the potential effects of land use on streams over large spatial scales is difficult and is often confounded by landscape factors. Several studies have examined the relative importance of geology and land use on stream ecosystems in agriculturally dominated landscapes. In Michigan watersheds dominated by agriculture, Johnson et al. (1997) reported that surficial geology, but not land use, was strongly correlated with streamwater chemistry in summer, whereas effects of land use on streamwater chemistry became more evident when watersheds and streams were more hydrologically connected in autumn. Richards et al. (1996) found that geology was as important as land use in determining stream habitat for 45 central Michigan watersheds. In the Yakima River basin, Washington, Leland (1995) reported that drivers of periphyton communities were related to dominant rock type where timber harvest and grazing were the dominant land uses. To our knowledge, relationships among periphyton, timber harvest, and other landscape features (e.g., geology) at the larger subbasin, or smaller watershed, scale have not been explored in coastal Oregon forests.

We investigated linkages between benthic diatom assemblages, timber harvest, and other landscape features (i.e., geology, vegetative cover types) in coastal Oregon watersheds. The primary objective of our study was to characterize diatom distribution and quantify its relationship with timber harvest. A secondary objective was to examine other landscape features that may confound the relationship to timber harvest.

## Methods

### Study area

In this paper, we use "watersheds" to define smaller site-specific drainage areas, "subbasins" to define relatively larger drainage areas (i.e., Tillamook or Kilchis subbasins), and "basin" to define the largest drainage area (i.e., Tillamook Bay). This area is part of the coastal temperate rainforest with a mean annual temperature of 10.2°C, and annual rainfall averaging 254 cm,

the heaviest typically occurring from October through March (Follansbee and Stark 1998). The natural vegetation is distributed between 2 zones. The sitka spruce (*Picea sitchensis* Carr.) zone covers the lower regions (<150 m elevation) and is characterized by stands of sitka spruce, western hemlock (*Tsuga heterophylla* Sargent), western red cedar (*Thuja plicata* Donn), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), and grand fir (*Abies grandis* Lindl.), whereas the major hardwoods are red alder (*Alnus rubra* Bong), and bigleaf maple (*Acer macrophyllum* Pursh; Nelson et al. 1998). The western hemlock zone (>150 m elevation) consists of dense conifer stands of Douglas fir, western hemlock, and western red cedar, whereas hardwood species include red alder, bigleaf maple, black cottonwood (*Populus trichocarpa* Torr. and A. Gray), and Oregon ash (*Fraxinus latifolia* Benth.; Nelson et al. 1998). Current vegetation structure is primarily young coniferous and mixed (coniferous and broadleaf) forests, with dense successional monotypic broadleaf stands also common (Fig. 1; Follansbee and Stark 1998). The most prevalent broadleaf species in the northern Oregon Coast Range is red alder, primarily found in frequently or recently disturbed nearstream areas, landslide paths, or burned areas (Harrington et al. 1994, Nelson et al. 1998).

The western 2/3 of the Tillamook subbasin is primarily underlain by lower/middle Miocene and Oligocene/upper Eocene sedimentary rocks including fine- to coarse-grained marine siltstone, sandstone, and alluvium (Fig. 2; Walker and Macleod 1991). Upper/middle Eocene volcanistic basalts underlie the eastern portion of the subbasin. The Kilchis subbasin is almost entirely underlain by upper/middle Eocene basalts, with small portions of the lower subbasin comprised of siltstones and alluvium (Walker and Macleod 1991).

Strittholt and Frost (1995) noted that 1/3 of the land area in the Tillamook subbasin was harvested between 1974/1975 and 1992. More recently, cut rates in the Tillamook were ~280 ha/y resulting in ~12% of the entire subbasin cut from 1986 to 1992 (Strittholt and Frost 1995). In contrast, harvest in the Kilchis has been an order of magnitude lower than the Tillamook subbasin, with cut rates of 37 ha/y and 1.3% of the subbasin cut from 1986 to 1992 (Strittholt and Frost 1995).

Forest fires in 1933, 1939, and 1945 (termed

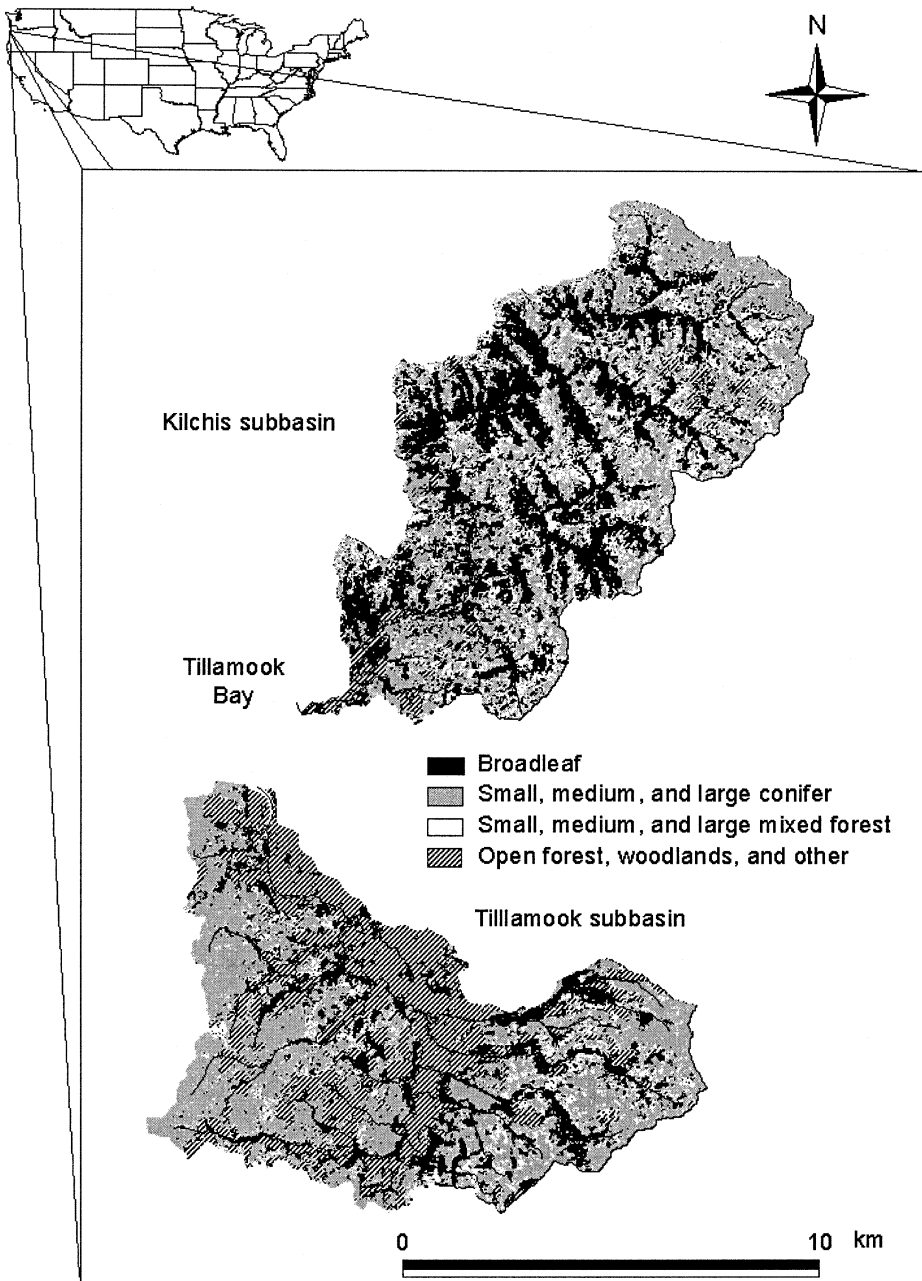


FIG. 1. Major vegetative cover types in the Tillamook and Kilchis subbasins from the 1996 Gradient Nearest Neighbor Vegetation Class map (CLAMS 1996). Broadleaf: >65% basal area hardwood, mixed: 20 to 65% basal area hardwood, conifer: <20% basal area hardwood.

the Tillamook Burn) burned portions, some repeatedly, of the Kilchis subbasin (Oregon Department of Forestry 1997). Heavy salvage logging with poor forest practices and down-

stream transport from splash dams followed the fires (Follansbee and Stark 1998). In contrast, the Tillamook subbasin was largely unaffected by the Tillamook Burn. Extensive

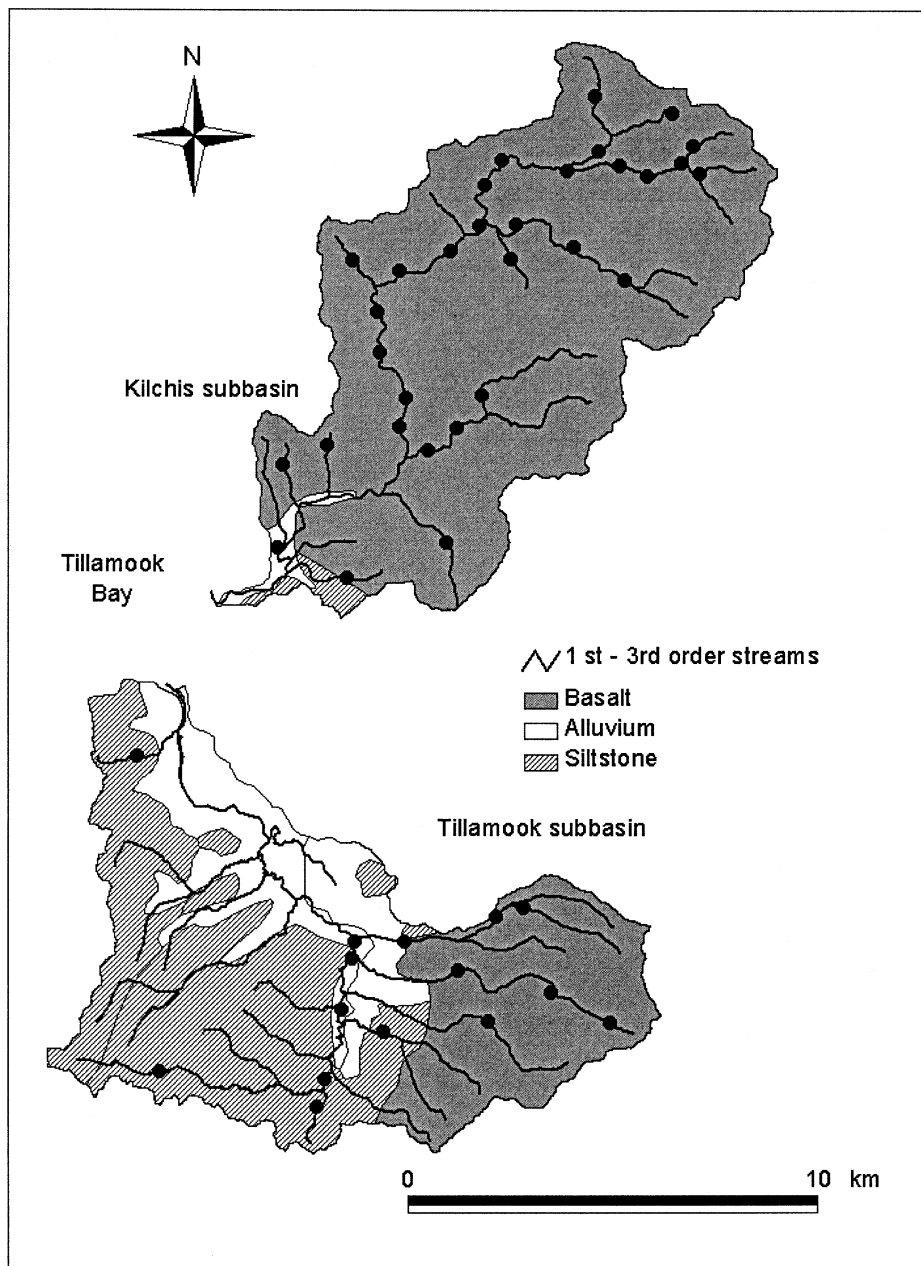


FIG. 2. Major geologic types and periphyton sampling sites in the Tillamook and Kilchis subbasins. Geologic p-types from Walker and MacLeod (1991) were classified into major lithologic types (i.e., siltstones, sandstones, basalts) from Johnson and Raines (1995). Dots represent periphyton sample locations in Ford and Rose (2000), which are the same locations used in our study.

dairy farming occurs in the lower-gradient portions of the Tillamook subbasin. Approximately 23% of the entire subbasin can be considered pasture lands for dairy farming (Strittholt et al.

1997). In contrast, dairy farming is present in the lower portions of the Kilchis subbasin but to a much smaller extent (6% of the subbasin; Strittholt et al. 1997).

TABLE 1. Spatial data layers used in landscape characterization. Format scale/resolution lists the format of spatial data as they were obtained.

Data layer	Format scale/resolution	Source
1972–1998 Western Oregon Stand Replacement Disturbance Map	Grid, 25 m	TM satellite imagery
1996 Gradient Nearest Neighbor Vegetation Class	Grid, 25 m	TM satellite imagery and plot data
1991 Geologic Map of Oregon	Coverage, 1:500,000	US Geological Survey (USGS)
Site-specific watersheds	Coverage, 1:25,000	Delineated from USGS Digital Raster Graphic images

#### Site selection

Study design and field sampling were conducted as part of multidisciplinary studies of stream conditions (Ford and Rose 2000). The procedures (described in Herlihy et al. 2000) involved a random sampling, balanced for stream order, of 1<sup>st</sup>- to 3<sup>rd</sup>-order stream networks (US Geological Survey [USGS], River Reach File version 3, blue lines on 1:100,000 maps), from which 67 candidate sites were identified. Only sites that were wadeable, had flowing water, could be accessed (with landowner permission), and had riffles and coarse substrate for periphyton collection were sampled (Ford and Rose 2000). As a result, a total of 46 study sites were sampled (15 in the Tillamook subbasin, and 31 in the Kilchis subbasin; Fig. 2).

#### Landscape characterization

Timber harvest, vegetative cover, and geology associated with the watershed upstream of each sample site were quantified using a Geographic Information System (GIS) with ArcInfo version 8 and ArcView, version 3.2, software (Table 1). Watersheds were delineated using ArcInfo (ArcEdit) by interpreting their boundaries on screen using contour lines from USGS Digital Raster Graphic images as guides (R. Comeleo, US Environmental Protection Agency, personal communication).

Areas harvested in the time periods available (1972–1977, 1977–1984, 1984–1988, 1988–1991, 1991–1995, and 1995–1998) from the 1972–1998 Western Oregon Stand Replacement Disturbance Map (Cohen et al. 1998), and geologic types from The Geologic Map of Oregon (Walker and Macleod 1991), were quantified for each watershed using overlay analysis in ArcInfo,

version 8. Geologic types were grouped into a major lithologic category (i.e., basalts, siltstones, or alluvium) using guidelines in Johnson and Raines (1995). The 1996 Gradient Nearest Neighbor Vegetation Class developed by the Coastal Landscape Analysis and Modeling Study ([CLAMS] 1996) was used to quantify vegetative cover types in each watershed.

#### Field sampling and laboratory analyses

Details of field sampling are given in Ford and Rose (2000) and Rose (2000). Briefly, sampling was conducted in the low-flow (June–August) seasons in 1998 and 1999. Physical habitat measures followed the protocol of Kaufmann and Robison (1998). A study reach 40 times the mean wetted channel width, or a minimum of 150 m for small streams, was established for each site and divided by 11 equally spaced transects. Mean reach length for our study was 282 m (range: 150–960 m). To estimate % shade, canopy cover was measured using a convex spherical densiometer held at the water surface from 4 directions (facing upstream, downstream, and towards each bank) at the center of each transect (for inchannel canopy cover), and from 1 direction (facing the bank) at the wetted edges of each transect (for riparian canopy cover) (Kaufmann and Robison 1998). In addition to estimating % shade at the water surface, shade from riparian trees was visually estimated on both banks at each transect as a % of a 10 × 10 m plot covered by canopy ≥ 5 m in height, and expressed as a mean % for the reach (riparian zone canopy). Substrate type was categorized visually as bedrock (> 4000 mm), boulder (250–400 mm), cobble (64–250 mm), coarse gravel (16–64 mm), fine gravel (2–16 mm), sand (0.06–2 mm), and fines (<0.06 mm), at 5 equally

spaced locations along each transect and expressed as a % for the reach. Ten depth and current velocity measurements (measured at 0.6 times the depth to determine mean velocity) were made across one transect within the reach using a Swofer 2100-C140 open stream current velocity meter.

Water quality was measured at one point within the reach prior to habitat characterization. Dissolved oxygen, conductivity, and temperature were measured using an YSI model 85 meter, and turbidity was measured with a Hach turbidimeter. Unfiltered water samples for total N (TN) and total P (TP) analysis were collected in acid-washed, 250 mL HDPE screw-top bottles. The methods of Qualls (1989) were followed for laboratory analysis of TN and TP.

For a given reach, one periphyton sample was taken from randomly selected coarse substrata at each transect where riffles were present. Periphyton was removed from a 12 cm<sup>2</sup> area on the surface of the rock using the toothbrush delimitter technique, composited for the reach, and preserved with 10% formalin (Hill 1998). Actual numbers of samples composited per reach varied (3–11) because of varying abundance of riffles and substrate type. Samples were homogenized in the laboratory and ~10 mL was oxidized overnight after adding an equal volume of concentrated H<sub>2</sub>SO<sub>4</sub>, and a microspatula of potassium dichromate (Patrick and Reimer 1966). After oxidation, samples were rinsed with deionized water until pH was ~7.0 and diatom frustules mounted on slides using Naphrax<sup>®</sup>. Diatom valves were identified and enumerated using a Nikon Eclipse E600 microscope (1000×) by scanning transects until 500 valves were counted. Diatoms were identified to the species level using Krammer and Lange-Bertalot (1986, 1988, 1991a, b, 2000) as primary references with supplemental information from Patrick and Reimer (1966, 1975).

#### *Data analysis*

Diatom distribution patterns were investigated using Nonmetric Multidimensional Scaling (NMDS; Clarke 1993). Only species occurring with >1% relative abundance at ≥2 sites were included in the analysis (total of 34 species). NMDS was done with the Sorenson (Bray–Curtis) distance measure, 400 maximum iterations, 40 real runs, and 50 randomized runs for the

Monte Carlo permutation procedure. The dimensionality of the best solution as determined by NMDS in PC-ORD (B. McCune and M. J. Mefford. 1999. PC-ORD. Multivariate analyses of ecological data, version 4, MjM Software Design, Gleneden Beach, Oregon) was retained (i.e., 2-dimensional solution).

Selected environmental variables were log<sub>10</sub>-transformed or arcsine-square root transformed (for proportional data) to produce near-normal distributions (Zar 1999). Statistical differences in environmental variables or species relative abundances among groups of study watersheds were tested using *t*-tests on transformed values. Appropriate tests for normality were conducted using SigmaStat (1993, version 1.0, SPSS Science, Chicago, Illinois) and when assumptions were not met, Mann–Whitney Rank Sum tests were conducted. An alpha level of 0.05 was used for all statistical tests.

*Subset site selection.*—A subset of watersheds (*n* = 12) with contrasting timber harvest intensity, but with similar environmental features, was selected to further investigate relationships among timber harvest, water quality, and diatoms, with minimum confounding factors such as geology and stream size. Six sites each were selected from harvested and unharvested sites based on a series of similar criteria: geology (>80% basalt), timber harvest (>10% harvested from 1972–1998 for the harvested group), % broadleaf (deciduous) vegetative cover (8–35%), stream size (mean wetted width >2.5 m, total watershed area >1.8 km<sup>2</sup>, 1<sup>st</sup>- or 2<sup>nd</sup>-order streams), gradient (slope <7%), and canopy cover (inchannel cover >80%). A total of 6 sites from the unharvested group and 7 sites from the harvested group met the above criteria. One site was randomly selected and removed from the harvested group to even sample size for the comparison.

## **Results**

#### *Relationship of timber harvest to diatoms and environmental variables*

A total of 72 diatom species was identified from the Tillamook and Kilchis subbasins. Shannon diversity and species richness were both significantly higher for watersheds in the Tillamook than the Kilchis subbasin (*p* < 0.001; Table 2). The most common species in both sub-

TABLE 2. Comparison of medians (and ranges) for diatom community measures and common species for the Tillamook ( $n = 15$ ) and Kilchis ( $n = 31$ ) subbasins.  $p$ -values are the results of  $t$ -tests. NS = not significant at  $p = 0.05$ .

Variables	Subbasin		$p$
	Tillamook	Kilchis	
<b>Community measures</b>			
Shannon diversity	2.0 (1.1–2.7)	1.3 (0.5–2.6)	<0.0001
Species richness	18 (13–30)	13 (7–23)	<0.0001
<b>Species (%)</b>			
<i>Achnantheidium minutissimum</i>	25.0 (10.1–53.5)	63.4 (6.4–87.8)	<0.01
<i>Achnanthes pyrenaicum</i>	12.9 (0–73.8)	9.0 (0–22.0)	NS
<i>Planothidium lanceolatum</i>	3.2 (0–25.3)	1.0 (0–47.0)	NS
<i>Gomphonema minutum</i>	3.8 (0–16.1)	3.6 (0–18.2)	NS
<i>Cocconeis placentula</i>	1.2 (0–15.6)	0.4 (0–23.0)	NS
<i>Achnanthes suchlandtii</i>	0 (0–40.4)	0 (0–8.5)	NS
<i>Rhoicosphenia abbreviate</i>	1.6 (0–16.9)	0.4 (0–15.2)	NS
<i>Nitzschia inconspicua</i>	1.4 (0–24.0)	0.8 (0–51.0)	NS

basins was *Achnantheidium minutissimum* Kützing (median relative abundance = 46%, range 6–88%), which occurred in all watersheds but was twice as abundant in Kilchis watersheds (median = 63%) as in Tillamook watersheds (median = 25%,  $p < 0.01$ ; Table 2). Other common species included *Achnanthes pyrenaicum* Hustedt, which showed the opposite pattern to *A. minutissimum*, with often higher relative abundances in Tillamook watersheds (median = 13, range = 0–74%) than Kilchis watersheds (median = 9, range = 0–22%). *Nitzschia inconspicua* Grunow and *Planothidium lanceolatum* Brébisson ex Kützing also were common.

A 2-dimensional solution was obtained for the NMDS ordination that explained 86% of the variance in the diatom distance matrix (Fig. 3). Variance was partitioned between the 1<sup>st</sup> ( $r^2 = 0.58$ ) and 2<sup>nd</sup> ( $r^2 = 0.28$ ) axes. Both axes explained significantly more variance than would be expected by chance based on Monte Carlo permutation tests ( $p = 0.02$ , 50 permutations). Axis 1 was primarily driven by *A. minutissimum* ( $r = -0.91$ ), whereas axis 2 was driven by *N. inconspicua* ( $r = 0.77$ ). Distribution of watersheds throughout the ordination plot showed no clear division between the Tillamook and Kilchis subbasins (Fig. 3).

The % of the watershed harvested from 1972 to 1998 was positively correlated with NMDS axis 1 ( $r = 0.54$ ). Correlations of timber harvest

increased in strength and significance as cumulatively more past harvest was included (Table 3). Water-quality variables including TN, TP, turbidity, and conductivity were significantly correlated with axis 1, along with % fine sediment and riparian zone canopy (Table 3). Neither inchannel nor riparian canopy cover variables were correlated with axes 1 or 2 (Table 3).

Water-quality variables related to diatom distribution from NMDS were generally positively correlated with timber harvest for a number of time classes (Table 4). Correlations of streamwater TP and turbidity with timber harvest increased in strength as more past harvest was included. Compared with other water-quality variables, the correlation between streamwater TN and timber harvest was weak (% timber harvest 1972–1998,  $r = 0.31$ ; Table 4).

#### *Vegetative cover and geology related to diatoms and environmental variables*

Percent broadleaf vegetative cover was correlated with streamwater TN concentration for all watersheds together ( $r = 0.63$ ), although relationships were stronger for watersheds in the individual subbasins (Tillamook:  $r = 0.85$ , Kilchis:  $r = 0.69$ ; Fig. 4). Percent broadleaf cover was unrelated to intensity of harvest from 1972 to 1998 ( $r = -0.08$ ). In contrast, mixed-forest cover was related to harvest intensity from 1972

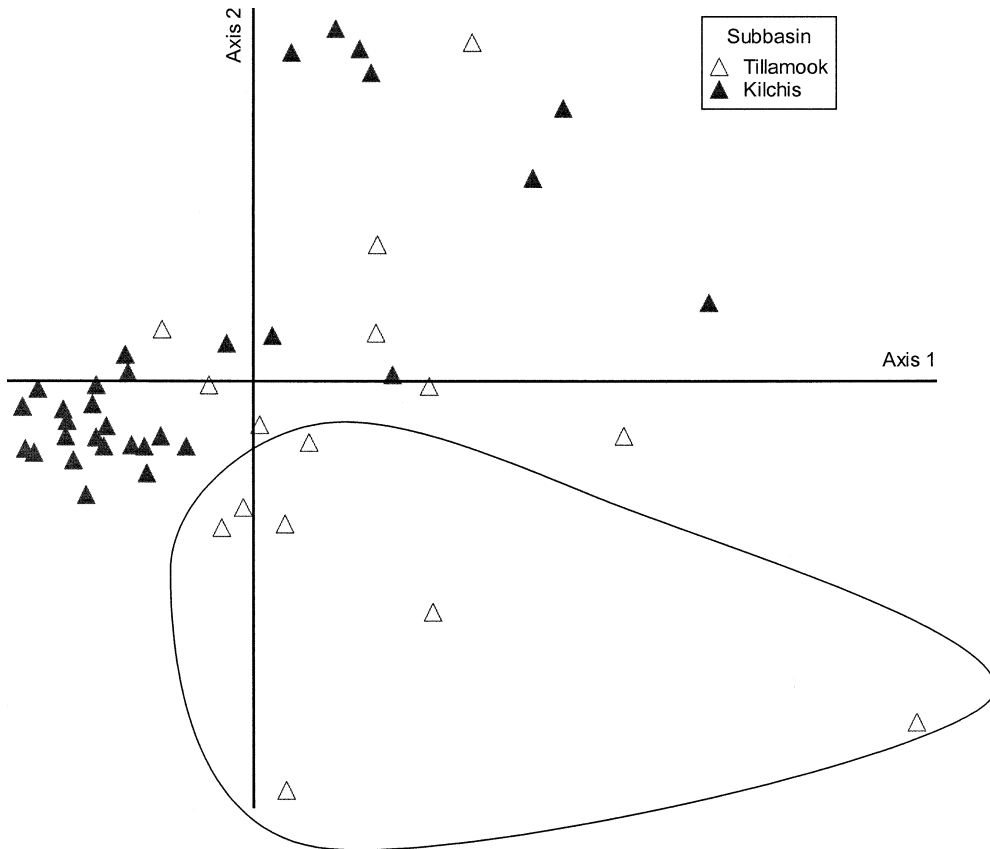


FIG. 3. Nonmetric Multidimensional Scaling plot showing ordination of sites based on species assemblages (sites in species space). Sites with watersheds dominated by siltstone and mixed (siltstone, basalts, alluvium) geologies are grouped inside the shape, whereas basalt-dominated watersheds are outside.

to 1998, but only for Tillamook watersheds ( $r = -0.80$ ; Fig. 5); there was no relationship between mixed-forest cover and harvest intensity in Kilchis watersheds ( $p > 0.05$ ). All Kilchis watersheds were dominated by basalts, whereas Tillamook watersheds exhibited diverse geology (Table 5): 3 were mixed siltstones/basalts/alluvium (mean siltstones = 59%, mean basalts = 34%, mean alluvium = 7%), 4 were dominated by siltstones (100%), and 8 were dominated by basalts (>82%). Inspection of the dominant geologic types in the NMDS plot showed that watersheds with siltstone and mixed geologies occupied the bottom of the plot (Fig. 3).

*Subset (watershed) analysis: accounting for confounding factors*

In our subset analysis, harvested ( $n = 6$ ) and unharvested ( $n = 6$ ) watershed groups

showed differences in water quality and diatom composition. Water-quality variables that correlated with diatom distribution from NMDS were all significantly higher in the harvested than in the unharvested group (Table 6). Shannon diversity and species richness also were higher for the harvested group ( $p < 0.05$ ; Table 6). Significantly higher relative abundances of *Cocconeis placentula* Ehrenburg, and *Rhoicosphenia abbreviate* Agardh occurred in the harvested group (Table 6). Median relative abundances of *A. minutissimum* were lower in the harvested than unharvested group, although differences were not significant. No significant differences were seen in the criteria used for site selection (i.e., mean wetted width, canopy cover, % slope, stream-flow watershed area, or % broadleaf vegetative cover; Table 6).

TABLE 3. Pearson correlation coefficients ( $r$ ) for selected environmental variables and timber harvest with axis 1 and 2 from Nonmetric Multidimensional Scaling (NMDS). Significant correlations are in bold ( $p < 0.05$ ).

Variable	NMDS axis	
	1	2
<b>Water quality</b>		
Total N (mg/L)	<b>0.62</b>	0.25
Total P ( $\mu\text{g/L}$ )	<b>0.74</b>	0.21
Turbidity (NTU)	<b>0.50</b>	<b>0.52</b>
Conductivity ( $\mu\text{S/cm}$ )	<b>0.57</b>	0.19
<b>Physical habitat</b>		
Mean wetted width (m)	-0.55	-0.28
% fine sediment	<b>0.62</b>	-0.18
Riparian zone canopy (%)	-0.69	0.27
Canopy cover (% inchannel)	0.08	0.13
Canopy cover (% riparian)	-0.05	0.03
<b>Timber harvest</b>		
% harvested 1995–1998	0.11	-0.19
% harvested 1991–1998	0.13	-0.15
% harvested 1988–1998	<b>0.32</b>	-0.32
% harvested 1984–1998	<b>0.47</b>	-0.31
% harvested 1977–1998	<b>0.54</b>	-0.26
% harvested 1972–1998	<b>0.54</b>	-0.26

TABLE 4. Pearson correlation coefficients ( $r$ ) between selected water-quality and physical habitat variables, and % watershed harvested (in different time classes). One watershed was removed with unique turbidity (58.9 NTU), total P (126.59  $\mu\text{g/L}$ ), and % fine sediment values (100%) having a strong influence on correlations ( $n = 46$  for all variables except turbidity, TP, and % fine sediment,  $n = 45$ ). Significant correlations are in bold ( $p < 0.05$ ).

Variable	Harvest time class					
	1995–1998	1991–1998	1988–1998	1984–1998	1977–1998	1972–1998
<b>Mean % harvested</b>						
Tillamook subbasin	2.5	9.7	16.7	22.5	29.1	31.5
Kilchis subbasin	0.2	0.4	0.7	1.1	2.1	2.4
Overall	0.9	3.4	5.9	8.1	10.9	11.9
<b>Water quality (June–August 1998–1999 data)</b>						
Total N (mg/L)	0.17	<b>0.31</b>	0.25	<b>0.33</b>	<b>0.32</b>	<b>0.31</b>
Total P ( $\mu\text{g/L}$ )	<b>0.43</b>	<b>0.52</b>	<b>0.57</b>	<b>0.65</b>	<b>0.69</b>	<b>0.68</b>
Turbidity (NTU)	<b>0.57</b>	<b>0.63</b>	<b>0.76</b>	<b>0.77</b>	<b>0.77</b>	<b>0.78</b>
Conductivity ( $\mu\text{S/cm}$ )	0.23	<b>0.39</b>	<b>0.48</b>	<b>0.51</b>	<b>0.49</b>	<b>0.47</b>
<b>Physical habitat (June–August 1998–1999 data)</b>						
% fine sediment	0.27	<b>0.31</b>	<b>0.51</b>	<b>0.56</b>	<b>0.56</b>	<b>0.58</b>
Riparian zone canopy (%)	0.11	0.07	-0.22	-0.37	-0.45	-0.47
Canopy cover (% inchannel)	0.09	0.06	0.06	0	0	-0.01
Canopy cover (% riparian)	0.11	0.03	-0.01	-0.10	-0.09	-0.09

## Discussion

### *Diatom distribution patterns*

Comparison of periphyton taxonomic composition among 46 sites with varying harvest intensity in coastal Oregon showed that diatom distribution was related to timber harvest and water-quality measures. Ordination analysis revealed that change from species-poor communities to relatively species-rich communities (axis 1 of NMDS ordination) was driven by abundance of *A. minutissimum* ( $r = -0.91$ ), considered to be an early successional species, typical of recently disturbed or stressful environments (Biggs et al. 1998). *Achmanthidium minutissimum* competes successfully at low resource/high physical stress levels and is replaced by other species when resources (e.g., inorganic nutrients and light) become more abundant or habitat becomes more stable (Biggs et al. 1998). Our observation that the 1<sup>st</sup> axis of the NMDS ordination was driven by decreasing abundance of *A. minutissimum* and increasing abundance of *R. abbreviate*, a species associated with higher nutrient availability (Van Dam et al. 1994, Leland 1995, Biggs et al. 1998), indicates increasing nutrients along this axis. *Nitzschia inconspicua*, listed as preferring higher nutrient availability

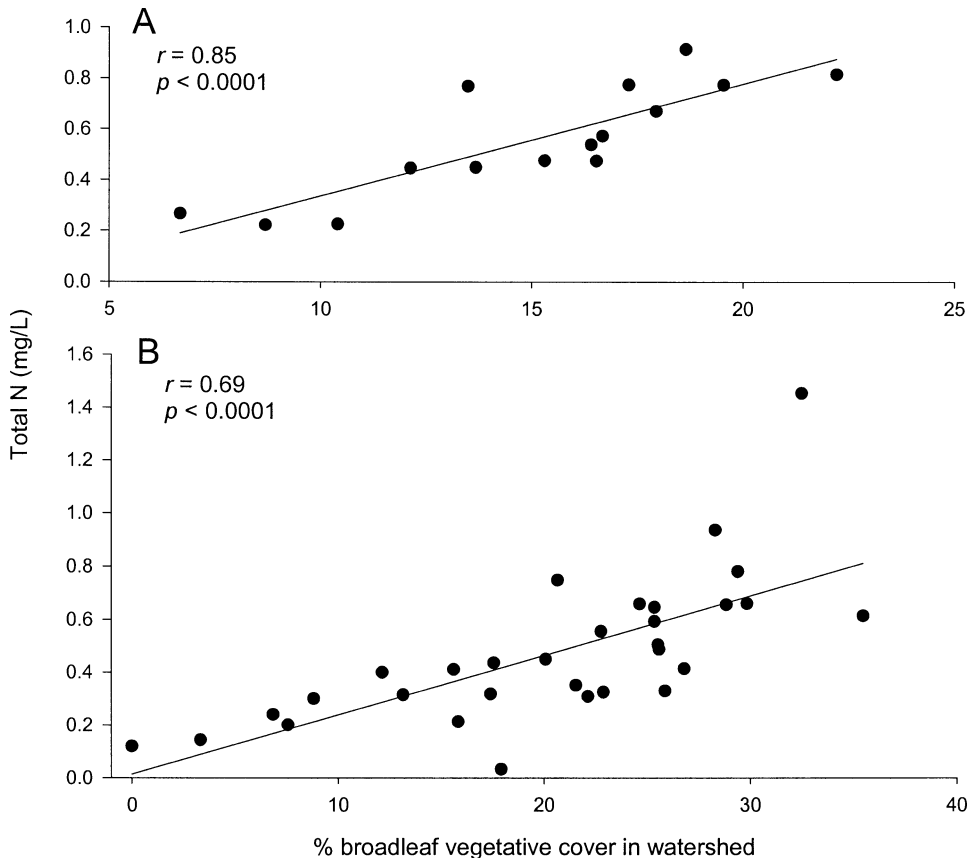


FIG. 4. Relationship between % broadleaf vegetation in the watershed and stream total N concentration. A.—Tillamook watersheds ( $n = 15$ ). B.—Kilchis watersheds ( $n = 31$ ).

by Van Dam et al. (1994), was the only species strongly influencing change along the 2nd axis ( $r = 0.77$ ). Pringle (1990) noted increasing biovolume of *Nitzschia* species and significantly less biovolume of *A. minutissimum* after 19 d of nutrient enrichment in a Michigan stream. Based on the autecology of the species driving the ordination analysis, nutrient availability may be the primary mechanism controlling species distribution patterns in the Tillamook and Kilchis subbasins.

Differences in species richness and Shannon diversity among watershed groups also were consistent with nutrient availability being an important mechanism in controlling diatom species distribution in coastal Oregon watersheds. Stevenson (1984) noted diatom species richness and diversity can increase or decrease in response to increased nutrient supply, and that changes in these indices are valuable indi-

cators of water quality. Holopainen and Huttunen (1992) noted that phytoplankton species richness increased 3-fold following harvesting and associated nutrient increases. In our study, higher richness, diversity, TN, and TP in the Tillamook subbasin and harvested subset suggest response of the diatom community to nutrient availability in these subbasins.

#### *Effects of timber harvest on diatom distribution*

Diatom community measures, specific diatom indicator species, and water-quality measures were higher in the Tillamook subbasin and the harvested subset than the Kilchis subbasin and unharvested subset. Previous studies, mostly using paired watersheds, have also shown diatom communities changed as a result of harvest. For example, a paired-watershed study conducted 1 y after 100% clear-cutting as part of

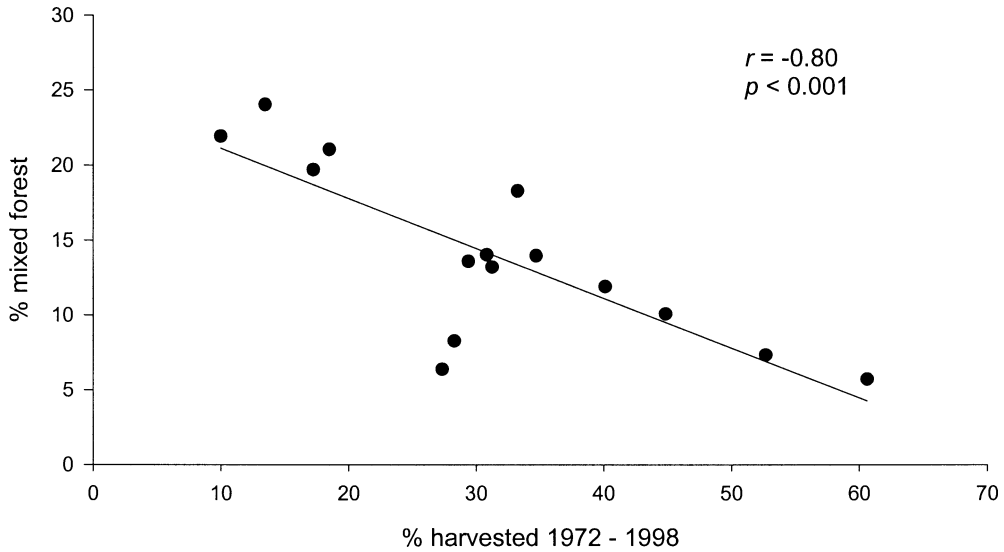


FIG. 5. Relationship between % mixed forest cover in the study watersheds ( $n = 15$ ) and timber harvest from 1972 to 1998 for the Tillamook subbasin.

the Alsea Watershed Study in coastal Oregon showed that the previously dominant species *Achnanthes lanceolata* (= *Planothidium lanceolatum*) was replaced by *Cocconeis placentula*, *Eunotia arcus*, and *Achnanthes minutissima* (= *Achnantheidium minutissimum*) (Hansmann and Phinney 1973). However, watershed disturbance from logging in that study was intense and re-

sponse of the algal assemblage may represent an extreme case. Increased growth of filamentous macroalgae altered algal community structure after progressive logging (~34% of watershed harvested) in coastal British Columbia (Shortreed and Stockner 1983). Comparison of algal assemblages in a reference watershed and a watershed clear-cut 6 y previously showed

TABLE 5. Medians (and ranges) of selected landscape variables for watersheds in the Tillamook ( $n = 15$ ) and Kilchis ( $n = 31$ ) subbasins. Dominant geology refers to watersheds dominated by >82% of one rock type. Percent harvested refers to the proportion of the watershed area harvested during the time frame. Watersheds with mixed geology were, on average, siltstones (59%), basalts (34%), and alluvium (7%).  $p$ -values are results of  $t$ -tests. NS = not significant at  $p = 0.05$ .

Variable	Subbasin		$p$
	Tillamook	Kilchis	
<b>Harvest intensity</b>			
% harvested 1972–1998	31 (10–61)	1 (0–20)	<0.0001
% harvested 1988–1998	16 (1–30)	1 (0–6)	<0.0001
<b>Vegetative cover (1996)</b>			
% broadleaf	17 (7–22)	22 (0–36)	<0.05
% mixed forest	14 (6–24)	31 (14–30)	<0.0001
<b>Watershed area (km<sup>2</sup>)</b>			
	7.6 (1.5–73.8)	15.7 (0.1–100.4)	NS
<b>Dominant geology (number of watersheds)</b>			
Basalt	8	31	
Siltstone	4	0	
Mixture (basalt, siltstone, and alluvium)	3	0	

TABLE 6. Comparison of medians (and ranges) of reach, landscape, water quality, and diatom community characteristics for subset selected from the Tillamook (harvested,  $n = 6$ ), and Kilchis (unharvested,  $n = 6$ ) subbasins. Dominant geology is >82% basalt in all 12 watersheds,  $p$ -values are results of  $t$ -tests. NS = not significant at  $p = 0.05$ .

Variable	Stream group		$p$
	Harvested	Unharvested	
<b>Water quality</b>			
Total N (mg/L)	0.73 (0.45–0.92)	0.36 (0.21–0.62)	<0.01
Total P ( $\mu\text{g/L}$ )	9.18 (6.54–17.83)	3.90 (1.22–8.05)	<0.01
Turbidity (NTU)	1.1 (0.5–2.3)	0.2 (0.2–0.4)	<0.01
Conductivity ( $\mu\text{S/cm}$ )	62.9 (47.6–90.1)	49.3 (46.7–57.5)	<0.05
<b>Diatom assemblage</b>			
Shannon diversity	1.9 (1.7–2.6)	1.3 (1.0–1.9)	<0.05
Species richness	16 (13–27)	12 (11–14)	<0.01
<i>Achmanthidium minutissimum</i>	32.6 (18.6–53.5)	65.2 (15.4–73.6)	0.09
<i>Cocconeis placentula</i>	10.5 (0.7–15.5)	1.3 (0.0–2.2)	<0.05
<i>Rhoicosphenia abbreviata</i>	7.6 (1.1–16.9)	0.9 (0.4–5.6)	<0.05
<b>Stream reach/landscape</b>			
Mean wetted width (m)	5.6 (2.7–6.6)	5.9 (4.0–9.8)	NS
Canopy cover (% in-channel)	90.6 (81.8–94.8)	91.2 (82.5–92.9)	NS
Canopy cover (% riparian)	95.3 (86.4–98.4)	94.9 (93.6–96.3)	NS
Slope (%)	3.6 (1.6–6.8)	2.3 (1.5–5.0)	NS
Streamflow ( $\text{m}^3/\text{s}$ )	0.12 (0.03–0.18)	0.09 (0.04–0.19)	NS
Watershed area ( $\text{km}^2$ )	7.6 (3.8–13.6)	10.2 (3.1–21.5)	NS
% broadleaf vegetative cover	19 (13–22)	19 (8–35)	NS

that 14 diatom species were more abundant in the clear-cut stream, with 8 of the 14 species found exclusively in the clear-cut stream (Lowe et al. 1986). Experimental nutrient additions to the reference stream resulted in no significant change in composition, leading Lowe et al. (1986) to conclude that assemblage differences between the reference and harvested streams were a result of increased light availability in the harvested stream.

The reported responses of diatom assemblages to the typically intense harvest in paired-watershed studies are somewhat different from our study because our results showed more variable diatom distribution, and the relationship to harvest was not as clear. These differences occurred, at least in part, because in our study harvesting was spatially patchy and temporally variable, and thus represented a “press disturbance” (sensu Bender et al. 1984), with multiple small effects accumulating to affect stream conditions. These effects may be subtle and we would not expect relatively short-term responses (e.g., increased N export) to be a strong signal in our subbasins. The integrated response of

the diatom community and longer-lasting effects (e.g., sediment delivery from roads) may be expected to show a stronger signal. Our finding that diatom assemblages are responsive to a patchy and temporally varied stressor makes diatoms a useful tool for assessing impacts such as timber harvest.

Streamwater TP showed the strongest correlation ( $r = 0.74$ ) with the 1<sup>st</sup> NMDS axis on Fig. 3 and was also positively correlated with % harvest. Turbidity was also positively correlated with % harvest and both TP and turbidity were correlated with one another ( $r = 0.70$ ), indicating P was associated with suspended sediment particles. Binkley and Brown (1993) noted that harvest is unlikely to increase streamwater P concentrations unless management practices (e.g., slash burning and road construction) cause increased sediment delivery to streams. However, Lamontagne et al. (2000) reported TP export increased for 3 y following harvest and was directly related to the proportion of the watershed harvested. The correlation of both TP and turbidity with % harvest in our study may indicate sediment delivery from forest roads in

the Tillamook and Kilchis subbasins, whereas increasing strength of TP and turbidity correlations as past harvests were included in the analysis may signal the effect of a greater number of older roads and stream crossings. Sediment delivery to streams from roads may be greater for roads built before adoption of construction rules codified in Oregon's Forest Practices Act (1971) and its 1983 revision. Increased correlation of % harvest with the 1<sup>st</sup> NMDS axis as more historical harvests are added also may indicate changing harvest practices since 1971 and their cumulative effects on stream conditions.

Our results showed a weak correlation of streamwater TN with % harvest ( $r = 0.31$ ) but a strong positive relationship with % broadleaf vegetative cover. Increased export of N in the form of  $\text{NO}_3^-$  is frequently observed following timber harvest (Shortreed and Stockner 1983, Harr and Fredriksen 1988). Harr and Fredriksen (1988) noted a six-fold increase in nitrate concentrations persisting for six years following clear-cutting of 25% of an Oregon watershed. Dahlgren (1998) also reported streamwater  $\text{NO}_3^-$  concentrations remained elevated for 6 y in streams draining clear-cut watersheds compared to reference streams, and also in the mainstem river to which both clear-cut and reference streams flowed. In our study,  $\text{NO}_3^-$  measurements were not available to help explain why N export expressed as TN was not strongly related to area harvested, although interpretation was further complicated by temporally variable cycles of harvest resulting in nearly  $\frac{1}{2}$  of the harvest occurring  $\geq 10$  y. In addition, our results represented only a snapshot of stream conditions (i.e., June–August) and are thus limited in detecting effects of harvest on nutrient export. However, strong correlation of % broadleaf with TN ( $r = 0.85$ , in the Tillamook) and none with % harvest ( $r = -0.08$ , overall) may indicate that N export is controlled by near-stream broadleaf vegetation (i.e., red alder, a species with N-fixing ability) that has not been affected by modern harvest after the Forest Practices Act required riparian buffer strips. Mixed and pure broadleaf stands, predominantly of red alder, are very common in near-stream and recently disturbed areas of the northern Coast Range, Oregon (Fig. 2; Pabst and Spies 1999, Ripple et al. 2000). High rates of N fixation and leaf-fall, and large accumulations of

N in soil under red alder stands can lead to increased leaching of N to streams (Binkley et al. 1992, Wigington et al. 1998). Binkley et al. (1982) noted mean streamwater  $\text{NO}_3^-$  concentrations from a red alder/Douglas fir-dominated watershed were 16 times higher than a conifer-dominated system. Our results suggest the effects of timber harvest on N export may be masked by the influence of nearstream alder stands on N cycles. Li and Gregory (1995) noted that N can be limiting to benthic algae in streams draining volcanic geology in the Oregon Coast Range. Therefore, it may be difficult to use benthic algae to assess effects of harvest if the limiting nutrient is controlled by nearstream vegetation rather than harvest intensity.

#### *Factors confounding effects of timber harvest*

Strong correlation between TN and % broadleaf cover, variable geology in the Tillamook, the presence of pasture lands in the Tillamook, and fire history in the Kilchis all represent confounding factors that make it difficult to isolate the effects of timber harvest on water quality and diatom composition. Geology is an ultimate regional factor controlling diatom species distribution (Stevenson 1997). NMDS analysis revealed patterns possibly related to diverse geology in the Tillamook subbasin. Leland (1995) found that drivers of periphyton communities were related to dominant rock type where timber harvest and grazing were the dominant land uses. Although occurring nearly 5 decades ago, fire history and intensive salvage logging in the Kilchis subbasin also may complicate harvest effects. Because of this history, none of the Kilchis watersheds in our study can be considered truly reference sites.

Our subset comparison, where 6 harvested and 6 reference watersheds of similar geology, % broadleaf vegetative cover, stream size, watershed size, slope, and canopy cover were compared, gave similar results to the subbasin comparison: TN, TP, turbidity, and conductivity as well as Shannon diversity and species richness all were significantly higher in the harvested than unharvested watersheds (Table 6). However, in contrast to the subbasin comparison, relative abundances of 2 species preferring higher nutrient availability (*C. placentula* and *R. abbreviate*; Van Dam et al. 1994) were significantly higher in the harvested watersheds.

In conclusion, spatially patchy and temporally varied cycles of harvest may have subtle and cumulative effects on important stream conditions, although such effects may be difficult to detect. Our results showed the composition of benthic diatom assemblages is a useful metric to assess potential effects of harvest in the coastal Oregon ecoregion. However, we found other landscape features not directly related to harvest (e.g., % broadleaf cover of the watershed, geology) also were potentially important in controlling diatom distribution. Accounting for these confounding factors appeared to strengthen the relationship between forest harvest and diatoms.

### Acknowledgements

Cathleen Rose sampled physical habitat and water chemistry as part of her MSc thesis, with assistance from Tarita Carruthers, Nicole Wolters, Lara Scott, and Kurt Mizze. Lara Scott, Randy Comeleo, and Gary Rule helped obtain and understand GIS data. Chris Walker, Christine Weilhoefer, and Brian Bowder provided laboratory assistance, and Miguel Estrada assisted with computer issues. We also thank Alan Yeakley and Ric Vrana for their thoughts and recommendations on the study. This study was partly supported by a US Environmental Protection Agency grant #R-825751-01 to Oregon State University as part of the NSF/EPA Science to Achieve Results (STAR) program.

### Literature Cited

- BENDER, E. A., T. J. CASE, AND M. E. GILPIN. 1984. Perturbation experiments in community ecology: theory and practice. *Ecology* 65:1–13.
- BIGGS, B. J. F., R. J. STEVENSON, AND R. L. LOWE. 1998. A habitat matrix conceptual model for stream periphyton. *Archiv für Hydrobiologie* 143:21–56.
- BINKLEY, D., AND T. C. BROWN. 1993. Forest practices as non-point sources of pollution in North America. *Water Resources Bulletin* 29:729–740.
- BINKLEY, D., J. P. KIMMINS, AND M. C. FELLER. 1982. Water chemistry profiles in an early- and a mid-successional forest in coastal British Columbia. *Canadian Journal of Forestry Research* 12:240–248.
- BINKLEY, D., P. SOLLINS, R. BELL, D. SACHS, AND D. MYROLD. 1992. Biogeochemistry of adjacent conifer and alder-conifer stands. *Ecology* 73:2022–2033.
- CLAMS (COASTAL LANDSCAPE ANALYSIS AND MODELING STUDY). 1996. (Available from: [www.fsl.orst.edu/clams/](http://www.fsl.orst.edu/clams/)) (Accessed October 2001).
- CLARKE, K. R. 1993. Non-parametric multivariate analysis of changes in community structure. *Australian Journal of Ecology* 18:117–143.
- COHEN, W. B., M. FIORELLA, J. GRAY, E. HELMER, AND K. ANDERSON. 1998. An efficient and accurate method for mapping forest clearcuts in the Pacific northwest using Landsat imagery. *Photogrammetric Engineering and Remote Sensing* 64:293–300.
- DAHLGREN, R. A. 1998. Effects of forest harvest on stream-water quality and nitrogen cycling in the Casper Creek Watershed. Pages 45–53 in R. R. Ziemer (technical coordinator). USDA Forest Service General Technical Report PSW-GTR-168. Pacific Southwest Research Station, US Forest Service, US Department of Agriculture, Albany, California.
- DIXIT, S. S., J. P. SMOL, J. C. KINGSTON, AND D. F. CHARLES. 1992. Diatoms: powerful indicators of environmental change. *Environmental Science and Technology* 26:23–33.
- FOLLANSBEE, B., AND A. STARK (EDITORS). 1998. Kildhis watershed analysis. Tillamook Bay National Estuary Project, US Environmental Protection Agency, Garibaldi, Oregon. (Available from: <http://www.tcwr.org/html/reportsq-t.htm>)
- FORD, J., AND C. E. ROSE. 2000. Characterizing small subbasins: a case study from coastal Oregon. *Environmental Monitoring and Assessment* 64:359–377.
- HANSMANN, E. W., AND H. K. PHINNEY. 1973. Effects of logging on periphyton in coastal streams of Oregon. *Ecology* 54:194–199.
- HARR, R. D., AND R. L. FREDRIKSEN. 1988. Water quality after logging small watersheds within the Bull Run Watershed, Oregon. *Water Resources Bulletin* 24:1103–1111.
- HARRINGTON, C. A., J. C. ZASADA, AND E. A. ALLEN. 1994. Biology of Red Alder (*Alnus rubra* Bong). Pages 3–23 in D. E. Hibbs, D. S. DeBell, and R. F. Tarrant (editors). The biology and management of red alder. Oregon State University Press, Corvallis, Oregon.
- HERLIHY, A. T., D. P. LARSEN, S. G. PAULSEN, N. S. URQUHART, AND B. J. ROSENBAUM. 2000. Designing a spatially balanced, randomized site selection process for regional stream surveys: the EMAP Mid-Atlantic pilot study. *Environmental Monitoring and Assessment* 63:95–113.
- HILL, B. H. 1998. Periphyton. Pages 119–131 in J. M. Lazorchak, D. J. Klemm, and D. V. Peck (editors). Environmental monitoring and assessment program—surface waters: field operations and methods for measuring the ecological condition of Wadeable streams. EPA/620/R-94/004F. US Environmental Protection Agency, Washington, DC.

- HOLOPAINEN, A.-L., AND P. HUTTUNEN. 1992. Effects of forest clear-cutting and soil disturbance on the biology of small forest brooks. *Hydrobiologia* 243/244:457–464.
- JOHNSON, B. R., AND G. L. RAINES. 1995. Digital map of major bedrock lithologic units for the Pacific Northwest: a contribution to the Interior Columbia River Basin Ecosystem Management Project. U.S. Geological Survey Open-file Report 95-680. US Geological Survey, Portland, Oregon.
- JOHNSON, L. B., C. RICHARDS, G. E. HOST, AND J. W. ARTHUR. 1997. Landscape influences on water chemistry in Midwestern stream ecosystems. *Freshwater Biology* 37:193–208.
- KAUFMANN, P. R., AND E. G. ROBISON. 1998. Physical habitat assessment. Pages 77–118 in J. M. Lazorchak, D. J. Klemm, and D. V. Peck (editors). Environmental monitoring and assessment program—surface waters: field operations and methods for measuring the ecological condition of Wadeable streams. EPA/620/R-94/004F. US Environmental Protection Agency, Washington, DC.
- KRAMMER, K., AND H. LANGE-BERTALOT. 1986. Bacillariophyceae. 1. Teil: Naviculaceae. In H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer (editors). *Süßwasserflora von Mitteleuropa*, Band 2/1. VEB Gustav Fisher Verlag, Stuttgart, Germany.
- KRAMMER, K., AND H. LANGE-BERTALOT. 1988. Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer (editors). *Süßwasserflora von Mitteleuropa*, Band 2/2. VEB Gustav Fisher Verlag, Jena, Germany.
- KRAMMER, K., AND H. LANGE-BERTALOT. 1991a. Bacillariophyceae. 3. Teil: Centrales, Fragilariaceae, Eunoziaceae. In H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer (editors). *Süßwasserflora von Mitteleuropa*, Band 2/3. VEB Gustav Fisher Verlag, Stuttgart, Germany.
- KRAMMER, K., AND H. LANGE-BERTALOT. 1991b. Bacillariophyceae. 4. Teil: Achnantheaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema. *Gesamtliteraturverzeichnis Teil 1–4*. In H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer (editors). *Süßwasserflora von Mitteleuropa*, Band 2/4. VEB Gustav Fisher Verlag, Stuttgart, Germany.
- KRAMMER, K., AND H. LANGE-BERTALOT. 2000. Bacillariophyceae, Part 5. English and French translation of the keys. In B. Büdel, G. Gärtner, L. Krienitz, and G. M. Lokhorst (editors). *Süßwasserflora von Mitteleuropa*, Band 2/5. Spektrum Akademischer Verlag Heidelberg, Germany.
- LAMONTAGNE, S., R. CARIGNAN, P. D'ARCY, Y. T. PRAIRIE, AND D. PARÉ. 2000. Element export in runoff from eastern Canadian Boreal Shield drainage basins following forest harvesting and wildfires. *Canadian Journal of Fisheries and Aquatic Sciences* 57(Supplement 2):118–128.
- LELAND, H. V. 1995. Distribution of phytobenthos in the Yakima River Basin, Washington, in relation to geology, land use, and other environmental factors. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1108–1129.
- LETTMAN, G. J., AND D. CAMPBELL. 1997. Timber harvesting practices on private forest land in western Oregon. Forest Resources Planning Program, Oregon Department of Forestry, Salem, Oregon. (Available from: Oregon Department of Forestry, Forest Resources Planning Department, 2600 State St., Salem, Oregon 97310 USA.)
- LI, J. L., AND S. V. GREGORY. 1995. Effects on aquatic biota. Pages 1–53 in R. L. Beschta, J. R. Boyle, C. C. Chambers, W. P. Gibson, S. V. Gregory, J. Grizzle, J. C. Hagar, J. L. Li, W. C. McComb, T. W. Parzybok, M. L. Reiter, G. H. Taylor, and J. E. Warila (editors). Cumulative effects of forest practices in Oregon: literature and synthesis. Oregon Department of Forestry, Salem, Oregon. (Available from: Oregon Department of Forestry, 2600 State Street, Salem, Oregon 97310 USA.)
- LOWE, R. L., S. W. GOLLADAY, AND J. R. WEBSTER. 1986. Periphyton response to nutrient manipulation in streams draining clearcut and forested watersheds. *Journal of the North American Benthological Society* 5:221–229.
- MCCLAINE, M. E., R. E. BILBY, AND F. J. TRISKA. 1998. Nutrient cycles and responses to disturbance. Pages 347–372 in R. J. Naiman, and R. E. Bilby (editors). *River ecology and management: lessons from the Pacific Coastal Ecoregion*. Springer-Verlag, New York.
- NELSON, S., B. FOLLENSBEE, AND R. HINZMAN. 1998. Introduction: a diverse and dynamic coastal landscape. Pages 1–12 in R. Hinzman, S. Nelson, and J. Booth (editors). *Tillamook Bay environmental characterization: a scientific and technical summary*. US Environmental Protection Agency, Garibaldi, Oregon. (Available from: <http://www.tcwrc.org/html/reportsq-t.htm>)
- OREGON DEPARTMENT OF FORESTRY. 1997. From the Tillamook Burn to Tillamook State Forest. Oregon Department of Forestry, Tillamook, Oregon. (Available from: Oregon Department of Forestry, 2600 State St., Salem, Oregon 97310 USA.)
- PABST, R. J., AND T. A. SPIES. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, U.S.A. *Canadian Journal of Forestry Research* 29:1557–1573.
- PATRICK, R., AND C.W. REIMER. 1966. The diatoms of the United States. Vol. 1. Monographs of the Academy of Natural Sciences of Philadelphia 13.
- PATRICK, R., AND C.W. REIMER. 1975. The diatoms of the United States. Vol. 2, Part 1. Monographs of

- the Academy of Natural Sciences of Philadelphia 13.
- PRINGLE, C. M. 1990. Nutrient spatial heterogeneity: effects on community structure, physiognomy, and diversity of stream algae. *Ecology* 71:905–920.
- QUALLS, R. G. 1989. The biogeochemical properties of dissolved organic matter in a hardwood forest ecosystem: their influence on the retention of nitrogen, phosphorus, and carbon. PhD Dissertation, University of Georgia, Athens, Georgia.
- RICHARDS, C., L. B. JOHNSON, AND G. E. HOST. 1996. Landscape-scale influences on stream habitats and biota. *Canadian Journal of Fisheries and Aquatic Sciences* 53(Supplement 1):295–311.
- RIPPLE, W. J., H. T. HERSHEY, AND R. G. ANTHONY. 2000. Historical forest patterns of Oregon's Central Coast Range. *Biological Conservation* 93:127–133.
- ROSE, C. E. 2000. Environmental variables as predictors of fish assemblages in the Tillamook Basin, Oregon. MSc Thesis, Oregon State University, Corvallis, Oregon.
- SHORTREED, K. S., AND J. G. STOCKNER. 1983. Periphyton biomass and species composition in a coastal rainforest stream in British Columbia: effects of environmental changes caused by logging. *Canadian Journal of Fisheries and Aquatic Sciences* 40:1887–1895.
- STEVENSON, R. J. 1984. Epilithic and epipelic diatoms in the Sandusky River, with emphasis on species diversity and water pollution. *Hydrobiologia* 114: 161–175.
- STEVENSON, R. J. 1997. Scale-dependent determinants and consequences of benthic algal heterogeneity. *Journal of the North American Benthological Society* 16:248–262.
- STEVENSON, R. J., AND Y. PAN. 1999. Assessing ecological conditions in streams and rivers with diatoms. Pages 11–40 in E. Stoermer and J. P. Smol (editors). *The diatoms: applications to environmental and earth sciences*. Cambridge University Press, Cambridge, UK.
- STRITTHOLT, J. R., AND P. A. FROST. 1995. Landscape change in the Tillamook Bay Watershed. Tillamook Bay National Estuary Project, US Environmental Protection Agency, Garibaldi, Oregon. (Available from: <http://www.tcwrc.org/html/reportsq-t.htm>)
- STRITTHOLT, J. R., R. J. GARONO, AND P. A. FROST. 1997. Spatial patterns in land use and water quality: a GIS mapping project. Earth Designs Consultants, Corvallis, Oregon. (Available from: [www.earthdesign.com](http://www.earthdesign.com)) (Accessed October 2001).
- VAN DAM, H., A. MERTENS, AND J. SINKELDAM. 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherlands Journal of Aquatic Ecology* 28:117–133.
- WALKER, G. W., AND N. S. MACLEOD. 1991. Geologic map of Oregon. US Geological Survey, Portland, Oregon (Available from: <http://geology.wr.usgs.gov/docs/geologic/or/oregon.html>)
- WINGTON, P. J., M. R. CHURCH, T. C. STRICKLAND, K. N. ESHLEMAN, AND J. VAN SICKLE. 1998. Autumn chemistry of Oregon coast range streams. *Journal of the American Water Resources Association* 34: 1035–1049.
- ZAR, J. H. 1999. *Biostatistical analysis*. 3<sup>rd</sup> edition. Prentice-Hall, Upper Saddle River, New Jersey.

*Received: 4 June 2003*

*Accepted: 15 June 2005*