



Linkages among land-use, water quality, physical habitat conditions and lotic diatom assemblages: A multi-spatial scale assessment

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Abstract

We assessed the importance of spatial scales (catchment, stream network, and sample reach) on the effects of agricultural land-use on lotic diatom assemblages along a land-use gradient in the agricultural Willamette Valley Ecoregion of Oregon. Periphyton, water chemistry, and physical habitat conditions were characterized for 25 wadeable streams during a dry season (July to September, 1997). Additional water chemistry samples were collected in the following wet season (February 1998) to assess seasonal effects of land-use on stream water chemistry. Percent agricultural land-use in the study catchments ranged from 10% to 89% with an average of 52%. Partial canonical correspondence analysis (CCA) with the first axis constrained by % agricultural land-use showed that % agricultural land-use at 3 spatial scales explained between 3.7%–6.3% of variability in the diatom species dataset. Monte Carlo Permutation tests indicated that the variance explained by % agricultural land-use was only significant at the spatial scale of the stream network with 10- and 30-m band width ($p < 0.05$, 999 permutations). In addition to the effects of % agricultural land-use, partial CCAs with a forward selection option showed that water chemistry (e.g., SiO_2), reach-scale stream channel dimensions (e.g., width, depth, and slope), reach-scale in-stream habitats (substrates and filamentous algal cover in stream beds), and riparian vegetative buffer were all important with relation to diatom species assemblages. Percent of obligately nitrogen-heterotrophic taxa was the only diatom autecological metric that showed a significant but weak correlation with % agricultural land-use along the stream network ($r = 0.50$), but not at catchment or sample reach scale. Correlation between % agricultural land-use and water chemistry variables varied among the spatial scales and between seasons. Physical habitat variables (\log_{10} erodible substrate diameters and stream reach slope) were significantly correlated with % agricultural land-use along the stream network but not at catchment or sample reach scale. Our data suggest that spatial scales are important in assessing effects of land-use on stream conditions but the spatial scale effects may vary between seasons. Direct linkages between agricultural land-use and lotic diatom assemblages were weak during summer base-flow time regardless of the spatial scales. Summer sampling may underestimate the effects of catchment land-use on stream conditions in areas where seasonal patterns are so distinctive as in the Willamette Valley.

Introduction

One of the major challenges in water resource management is to identify environmental stressors and understand how these stressors affect aquatic ecosystems. Catchment land-use is a major stressor on stream ecosystems, especially in agricultural regions.

For example, agricultural land-use in the catchment can significantly modify both water chemistry (Johnson et al., 1997) and physical habitat conditions (Roth et al., 1996), which eventually decrease biological integrity in these streams (Karr & Chu, 1999). Despite the large amount of literature on the effects of land-use on stream ecosystems, it is still challenging to

quantify the relationships between land-use and biological integrity of stream ecosystems. One of the major problems is to identify comparable spatial and temporal scales for assessing such relationships (Allan et al., 1997; Harding et al., 1998; Arheimer & Liden, 2000).

Differences in lotic biotic assemblages with different evolutionary history and life spans may reflect environmental conditions of hierarchically organized stream habitats and associated human influences (e.g., channel unit, reach, and catchment) (Frissel et al., 1986). For example, Roth et al. (1996) reported that fish assemblages in Michigan streams were better related to catchment land-use. In contrast, others have found that macroinvertebrates and periphyton exhibit much stronger relationships to stream reach environmental conditions than to catchment variables (Richards et al., 1997; Pan et al., 2000). Regional climate/geology may set up ultimate constraints on overall regional periphyton species diversity. Stream reach-scaled determinants such as resources and abiotic stresses may largely control actual species membership in a stream reach biotic assemblage (Stevenson, 1997). Pan et al. (1999, 2000) reported that the regional/catchment determinants such as climate and geology alone poorly predicted stream reach periphyton assemblages. Approximately 64% of the variability in periphyton species richness among 12 New Zealand streams was explained by flood disturbance and nutrients (Biggs & Smith, 2002). Relative importance of the regional/catchment-level and stream reach-level determinants on periphyton assemblages is, however, not well assessed. Meanwhile, most of stream bioassessment programs aim to assess catchment-level stressors such as land-use on stream ecosystems. Better understanding of the relative importance of both regional/catchment and stream reach scale determinants on periphyton species assemblages is essential for interpreting changes in periphyton with relation to environmental stressors at different scales, which will eventually increase accuracy and precision of periphyton-based bioassessment.

This study was aimed at assessing the effects of agricultural land-use at multiple spatial scales (catchment, stream network, and sample reach) on stream diatom assemblages along a land-use gradient in an agricultural region. We sampled 25 wadeable streams in the Willamette Valley Ecoregion of western Oregon during summer base-flow. Major types of land cover/land use such as agriculture, forest, rural built-up, and riparian vegetative buffer were delineated

based on recent aerial photographs at catchment, along the entire stream network, and at sample reach scales (Fig. 1). In addition, water chemistry and physical habitat conditions were also characterized at each sample reach. We wanted to relate changes in diatom species assemblages to the major types of land-use, particularly % agriculture at the 3 spatial scales. We also wanted to assess the relative importance of the effects of agricultural land-use and other environmental variables such as water chemistry and physical habitat conditions on diatom assemblages at each spatial scale. In addition, we collected water chemistry samples from the same sites in the following wet season to see if the effects of agricultural land-use on stream water chemistry vary between dry and wet seasons.

Materials and methods

Study sites

The study was conducted in the Willamette Valley Ecoregion, a lowland area dominated by agriculture with some forest (foothills) and some urban areas (Clarke et al., 1991). The lowland, approximately 170 km long and 70 km wide, is a structural trough downfolded between the Coastal Range in the west and the Cascade Mountains in the east with modest relief (Uhrich & Wentz, 1999). Climate in the Pacific Northwest is characterized by distinct dry and wet seasons. Most of the annual precipitation ($\cong 75\%$) occurs from October through March with $< 5\%$ occurring during July and August (Uhrich & Wentz, 1999). Stream flow patterns are highly correlated with the annual precipitation patterns. We used the blue-line network on 1:100 000 scale USGS maps to identify every stream in the Willamette Valley with catchment areas between 10–100 km². We used this size range as our intent was to study streams big enough to support fish but small enough to be wadeable. As the objective of the study was to examine an agricultural land-use gradient, we dropped from consideration any streams that flowed through urban areas, had most of its catchment in the adjacent mountainous ecoregions or contained large impoundments. From the 49 streams remaining on the candidate list after this screening, 25 streams were selected at random for field sampling and aerial photo analysis (Fig. 2).

In the field, a sample reach was selected near the downstream end of each stream at a site where

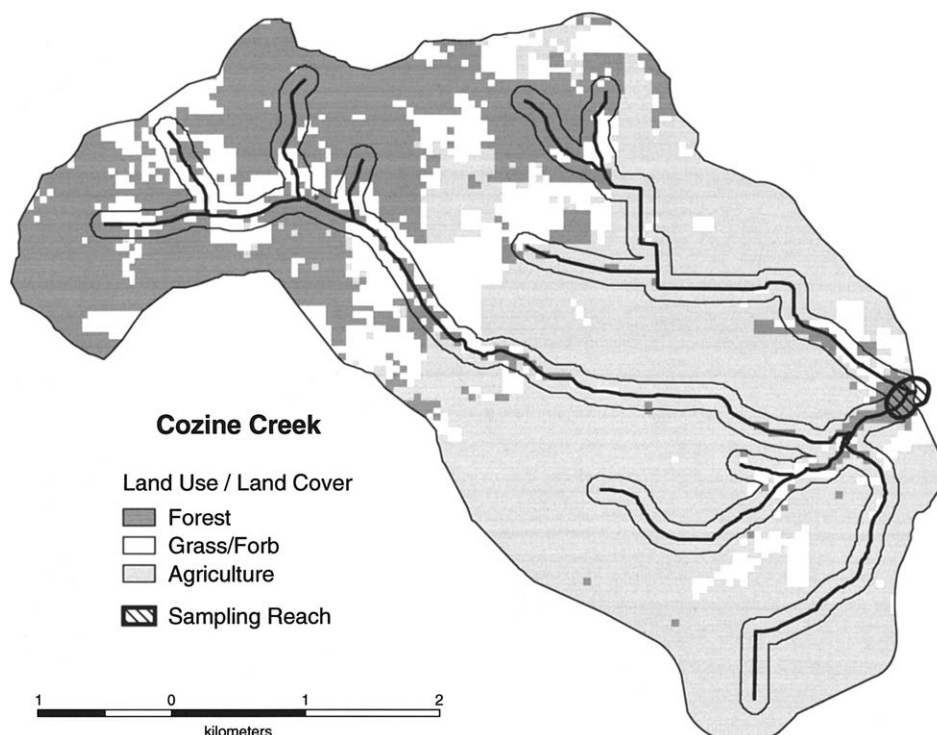


Figure 1. A map of Cozine Creek watershed showing 3 spatial scales used for characterizing land cover/land use (e.g. catchment, stream network showing only one bandwidth, and sampling reach) and major types of land cover/land use.

we were able to obtain access permission from local landowners. Sample reaches were each 40 times as long as the mean wetted channel width at the site (with a 150 m minimum) and ranged from 150 to 320 m. Eleven cross-section transects were set up on each sample reach by dividing the reach into 10 equal length intervals (includes a transect at the start and end of each reach). All samples were collected between July and early September 1997. Additional water chemistry samples were collected in Feb., 1998 from the same sites. However, periphyton samples were not collected due to field sampling difficulties (e.g., high flow).

Land-use characterization

Aerial photographs and a geographic information system (GIS) were used to determine land cover/land-use (LCLU) at 3 spatial scales (catchment, stream network, and sample reach) in each study stream (Schuft et al., 1999). For the network scale, LCLU was determined for band widths of 10, 30, and 150 m on both sides of the stream for the entire upstream stream network. The sample reach scale included band widths of 10 and 30 m on both sides of the 150–320 m

stream reach sampled in the field. Color-infrared aerial photographs (1: 24 000 scale) of study catchments were taken in mid-July, 1997, and these were scanned, spliced and georeferenced to make digital orthophotos with a minimum resolvable unit of about one meter. Catchment area boundaries, and the perennial and intermittent stream networks, as interpreted from 1:24 000 scale USGS topographic maps, were delineated on the digital orthophotos and digitized to create GIS coverages. The LCLU classification we used was a modification of that of Anderson et al. (1976) (for more details see Schuft et al., 1999; Moser et al., 2000). The LCLU categories include forest, shrub/scrub, grass/forb, agriculture, built-up (residential, industrial/commercial, transportation corridors or other built-up lands), barren land, water, and other. Agricultural land-use was further classified into 7 sub-categories (cropland, Christmas tree farm, etc.). Due to many zero values, redundancy among the variables, and the study objectives, 5 variables (% forest, % agriculture, % riparian vegetative buffer, % built-up, and % row crop) were used for our analyses. Percent of riparian vegetative buffer was a summation of % forest, shrub/scrub, and grass/forb within each defined

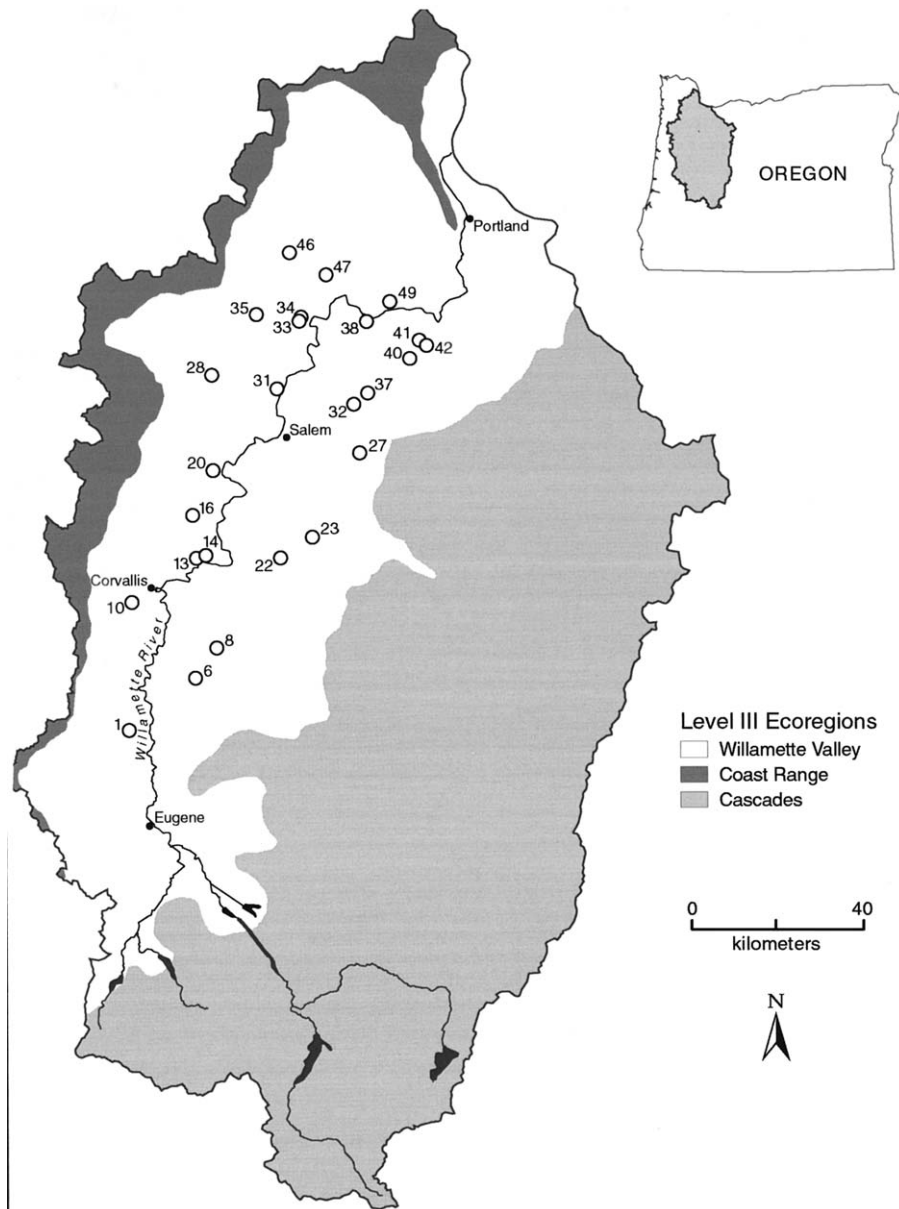


Figure 2. A map of the State of Oregon showing the Willamette Valley and a site map of the Willamette Valley showing Willamette Valley ecoregion and portions of Coastal Range and Cascades ecoregions, and sampling stream locations.

band width. Accuracy of the classification was verified by ground-truthing (Schuft et al., 1999). GIS analyses were used to calculate the area in each LCLU category at each spatial scale/band width. LCLU areas were converted to proportions for use in further data analyses.

Water chemistry

A container (4 l) and 2 syringe (60 ml) water samples were collected from the reach start point in the middle of the stream. Water from the syringe samples was analyzed for closed headspace measurements of pH and dissolved inorganic carbon (DIC), and the container samples were analyzed for major anions/cations and nutrients. Base cations were determined by atomic absorption. Anions were measured by ion chroma-

tography. Dissolved organic carbon (DOC)/DIC was determined using a carbon analyzer. Total nitrogen (TN) and total phosphorus (TP) were estimated by persulfate oxidation and colorimetry. Detailed information on the analytical procedures used for each of the analyses can be found in US EPA (1987).

Physical habitat

Vegetative cover over the stream was measured in 4 directions at each of the 11 cross section transects using a convex spherical densiometer. At each transect, the presence and the proximity of 11 categories of human activities in the riparian zone were estimated (i.e., row crops, pasture, dams and revetments, buildings, pavement, roadways, pipes, landfill or trash, parks/lawns, logging operations, and mining activities). Proximity-weighted riparian disturbance indices were calculated by tallying the number of riparian transects at which a particular type of disturbance was observed, weighting by its proximity to the stream, and then averaging over all transects on the reach (Kaufmann et al., 1999). Stream habitat characterization included thalweg depth measurements, mean wetted width, bank angle, slope, % of substrate embeddedness, and a systematic pebble count to characterize surficial substrates. Several metrics (e.g., \log_{10} erodible substrate diameters) were calculated. The erodible substrate diameter is defined as the critical mean diameter at bankfull flow. It was calculated from an estimate of shear stress during bankfull conditions. It is the mean value, within the reach, of the maximum size of substrate particle that is expected to be mobilized or 'eroded' and moved during bankfull flood conditions. Field methods and metric calculation, respectively, are described in more detail by Kaufmann & Robison (1998) and Kaufmann et al. (1999).

Periphyton

Periphyton samples were collected from each of the 11 transects and combined into a single composite sample. Periphyton was scraped off coarse substrates from a defined area of stream bed (12 cm^2) with a toothbrush and an area delimiter. For fine substrates, periphyton was suctioned into a 60-ml syringe. The samples were then preserved with 37% formalin. Detailed sampling and collection methods are described by Hill (1998). An aliquot of algal suspension from each sample was acid-cleaned and mounted in NAPHRAX[®] after repeated rinse with distilled water to identify and enumerate diatom species. A minimum

of 500 diatom valves was counted at $1000\times$ magnification using a Nikon E600 Eclipse microscope with a phase contrast. Diatom taxonomy mainly followed Krammer & Lange-Bertalot (1986–91) and Patrick & Reimer (1966, 1975).

Data analysis

We used multiple endpoints (species assemblages, autecological metrics, and diatom indices) to relate diatom assemblages with land-use patterns characterized at multiple spatial scales. Canonical correspondence analysis (CCA) was used to summarize diatom species assemblages and their relationships with environmental variables (ter Braak, 1995). A series of CCAs with different options were performed.

To identify a subset of environmental variables which were significant with relation to diatom species distribution patterns, CCA with a forward selection option was run on all environmental variables, which included all major land-use types (5 types) characterized at 3 spatial scales, water chemistry variables (17), and physical habitat variables (17). A subset of environmental variables was selected using a Monte Carlo Permutation test (999 permutations, $p < 0.05$). Detailed procedure and explanation for the Monte Carlo Permutation test can be found in ter Braak & Smilauer (1998). To better illustrate diatom species distribution patterns captured by the first 4 CCA ordination axes, the site scores of the first 4 CCA axes, surrogates of the species assemblages with recognizable distribution patterns, were correlated with diatom autecological metrics and indices. Diatom autecological metrics were calculated based on Lange-Bertalot (1979), Balhs (1993), and van Dam et al. (1994). The Trophic Diatom Index (TDI) was calculated following Kelly & Whitton (1995).

A total of 6 separate partial CCAs were performed to assess effects of agricultural land-use at each spatial scale on the diatom species assemblages. For instance, to assess the effects of agricultural land-use on diatom assemblages at the sample reach scale with 10-m band width, a partial CCA was performed with the first CCA axis constrained to % agricultural land-use characterized at this particular spatial scale. Significance of each agricultural land-use variable on the diatom species data was tested using the Monte Carlo Permutation test (999 permutations, $p < 0.05$). To assess relative importance of effects of agricultural land-use and other environmental variables such as water chemistry and physical habitat conditions on the diatom

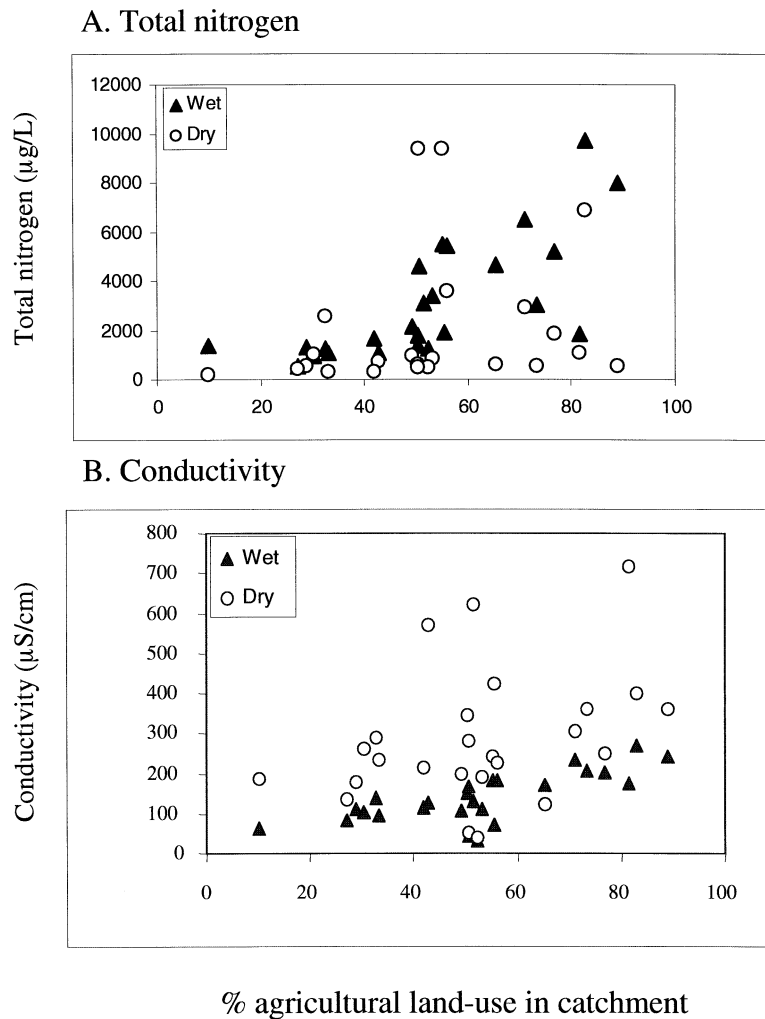


Figure 3. Changes in total nitrogen concentrations and conductivity along a % agricultural land-use gradient during a dry and a wet season. A. Total nitrogen, $r_{\text{dry}} = 0.22$ ($n = 23$, remove two sites with 2 highest values), $r_{\text{wet}} = 0.73$ ($n = 25$). B. Conductivity, $n = 25$, $r_{\text{dry}} = 0.36$, $r_{\text{wet}} = 0.73$.

species data, a total of 6 partial CCAs with a forward selection option were performed after the effects of agricultural land-use were ‘removed’ from the analyses (the agricultural land-use variables were treated as co-variables). A subset of environmental variables was selected. Significance of each selected environmental variable was tested using the Monte Carlo Permutation test (999 permutations, $p < 0.05$) at each spatial scale with different band widths.

Environmental variables were log-transformed except for pH and percentage variables. Percentage variables were square root transformed followed by arcsine transformation. Diatom species data were squared root transformed. Rare species were down weighted in

all CCAs. CCA was performed using CANOCO for Windows (version 4.0) (ter Braak & Smilauer, 1998).

Results

Land-use

Land-use showed considerable variability among and within catchments. Overall, catchment land-use was dominated by agriculture (mean = 52%, range = 10–89%), followed by forest (22%), among the 25 catchments. The land-use closest to the streams was most commonly dominated by forest with an average of 43% of the stream network within the 10-m

Table 1. Pearson correlation coefficients between % agricultural land-use in catchments, % agricultural land-use, forest and riparian vegetative buffer (e.g., forest, grass, shrub) along stream networks and sample reach. Bold number indicates a significant correlation at $p < 0.05$ ($n = 25$).

Spatial scales	Band width (m)	% agriculture	% forest	% riparian vegetation
Catchment			-0.88	
Stream network	10	0.54	-0.74	-0.69
	30	0.50	-0.63	-0.54
	150	0.84	-0.77	-0.82
Sample reach	10	-0.19	-0.10	-0.10
	30	-0.11	-0.06	0.07

band width being forested. Percent agricultural land-use increased as the band width increased at both the network and reach scale. Percent agriculture in the catchment was highly correlated with % agriculture at the stream network scale, especially the 150 m band width. However, % agriculture at the sample reach scale was not significantly correlated with % agriculture at the catchment scale (Table 1).

Water chemistry

Water chemistry was characterized by high spatial variability in nutrients and ionic strength among the 25 sites in both dry and wet seasons (Table 2). For example, total phosphorus (TP) concentrations varied from $12 \mu\text{g l}^{-1}$ to $6720 \mu\text{g l}^{-1}$ in the dry season and from 3 to $368 \mu\text{g l}^{-1}$ in the wet season. The median concentrations of the variables associated with ionic strength in the dry season were in general higher than those in the wet season while TN showed an opposite trend. The median concentration of TN in the wet season was 2 times higher than that in the dry season. Overall, higher winter TN was largely contributed by increases in $\text{NO}_3\text{-N}$. Mean % organic N in the wet season (15%) was much lower than that in the dry season (50%).

Correlation between % agricultural land-use and water chemistry variables varied among the spatial scales and between seasons (Fig. 3, Table 3). Catchment agricultural land-use was significantly correlated with ionic strength variables, chloride (Cl^-), and nutrients in the wet season (Table 3). The correlation was only significant with TP ($r = 0.40$) in the dry season. Percent of agricultural land along the stream network

was correlated significantly with ANC, conductivity, Cl^- , and DOC but not with nutrients in the dry season. The strength of the association also increased in the wet season (Table 3).

Physical habitat

Stream channel morphology and habitat conditions also varied considerably among the sampled sites. Wetted stream channel width ranged from 1.1 m to 10.5 m with a median of 4.4 m. Thalweg depth varied from 0.2 m to 0.9 m with a median of 0.4 m. Both wetted stream channel width and thalweg depth were significantly correlated with catchment area ($r_w = 0.55$, $r_d = 0.74$, $n = 25$). Stream substrates were dominated by fines (31%) and hardpan (29%). Percent of substrates as hardpan was significantly and negatively correlated with stream slope ($r = -0.51$). Mid-channel riparian canopy density varied from nearly absent (2.5%) to dense (98.8%). Riparian disturbance index values ranged from 0.4 to 3.3.

Correlation between % agricultural land-use and stream physical habitat variables varied among the spatial scales (Table 4). Log_{10} erodible substrate diameters were significantly correlated with % agriculture along the stream network (Fig. 4). The variable was not, however, significantly correlated with % agriculture, either at reach or catchment scales. Stream reach slope showed a similar pattern (Table 4). Both total riparian disturbance and riparian agricultural disturbance indices were significantly correlated with % agriculture at the reach-scale but not at catchment or stream network scales.

Diatom assemblages

A total of 159 diatom species and varieties were identified from the 25 sites. Species richness varied from 12 to 50 with an average of 35. Diatom assemblages were dominated by *Gomphonema parvulum* (Kütz.) Kütz., *Rhoicosphenia curvata* (Kütz.) Grun. ex Rabh., *Achnanthes lanceolata* (Bréb.) Grun., *A. deflexa* Reim., *Nitzschia palea* (Kütz.) W. Sm., *N. amphibia* Grun., and *Melosira varians* Ag.. The diatom assemblages were characterized by a high proportion of halophilous diatom species (mean = 72%), eutrophic diatom species (mean = 56%), and alkali-philous diatom species (mean = 51%). Approximately 41% of the diatoms identified were characterized as taxa tolerant of elevated nitrogen (N) levels and 25% were facultative N-heterotrophic species. Percent of pollution sensitive species ranged from 5% to 93%.

Table 2. Summary of selected water chemistry variables (median, range) in both dry and wet season (n=25) and Pearson correlation coefficients between two seasons.

Variables	Dry season		Wet season		<i>r</i>
pH	7.4 (7.0–8.8)		7.1 (6.4–7.5)		0.33
ANC ($\mu\text{eq l}^{-1}$)	1660	(299–5433)	692	(142–1448)	0.56
Conductivity ($\mu\text{S cm}^{-1}$)	249	(41–716)	129	(31–269)	0.39
SO_4^{2-} ($\mu\text{eq l}^{-1}$)	124	(7–338)	157	(13–326)	0.41
Cl^- ($\mu\text{eq l}^{-1}$)	384	(47–4039)	187	(46–553)	0.49
Total phosphorus ($\mu\text{g l}^{-1}$)	115	(12–6720)	120	(3–368)	0.26
Total nitrogen ($\mu\text{g l}^{-1}$)	864	(176–84438)	1899	(515–9731)	–0.02

Table 3. Pearson correlation coefficients between % agricultural land-use at different spatial scales and selected water chemistry variables measured in a dry and wet season. Bold number indicates a significant correlation at $p < 0.05$ ($n = 25$). ANC: acid neutralizing capacity, DOC: dissolved organic carbon, TN: total nitrogen, TP: total phosphorus.

Variables	Season	% agricultural land-use in					
		Reach		Network			Catchment
		10 m	30 m	10 m	30 m	150 m	
ANC	Dry	–0.43	–0.25	0.39	0.39	0.48	0.34
	Wet	–0.39	–0.23	0.35	0.33	0.55	0.45
Cl^-	Dry	–0.34	–0.14	0.52	0.53	0.34	0.01
	Wet	–0.44	–0.32	0.45	0.45	0.60	0.43
Conductivity	Dry	–0.38	–0.21	0.53	0.55	0.55	0.29
	Wet	–0.43	–0.32	0.39	0.37	0.66	0.59
DOC	Dry	–0.14	–0.02	0.14	0.56	0.45	0.25
	Wet	–0.15	0.22	0.63	0.62	0.66	0.27
TN	Dry	–0.13	–0.21	0.02	0.02	0.22	0.28
	Wet	–0.39	–0.43	0.13	0.07	0.51	0.76
TP	Dry	–0.39	–0.35	0.26	0.22	0.39	0.40
	Wet	–0.41	–0.20	0.46	0.43	0.55	0.42

Table 4. Pearson correlation coefficients between % agricultural land-use at different spatial scales and selected physical habitat variables. Bold number indicates a significant correlation at $p < 0.05$ ($n = 25$).

Variables	% agricultural land-use in					
	Reach		Network			Catchment
	10 m	30 m	10 m	30 m	150 m	
% filamentous algal cover	–0.11	0.21	0.35	0.40	0.30	0.14
% fine substrate	0.15	0.15	0.40	0.40	0.35	0.12
Erodible substrate diameter ^a	0.05	–0.20	–0.71	–0.73	–0.60	–0.30
Riparian disturbance ^b	0.70	0.70	0.05	0.07	–0.08	–0.11
Riparian ag. disturbance	0.51	0.68	0.21	0.25	0.04	–0.14
Stream reach slope (%)	–0.02	–0.21	–0.65	–0.67	–0.54	–0.17

^aErodible substrate diameter was \log_{10} transformed.

^bRiparian disturbance measures are indices calculated from observations made on-site at both banks on 11 transects.

Table 5. Summary of Canonic Correspondence Analysis (CCA) with a forward selection option. Variables were selected from all environmental variables (land-use, water chemistry, physical habitats) using the Monte Carlo permutation test (999 permutations, $p < 0.05$). The numbers in parenthesis next to eigenvalues are % of variability in diatom species dataset explained by the each CCA ordination axis. The other numbers are correlations of environmental variables with CCA ordination axes. Correlation between dominant diatom species, diatom metrics and CCA ordination axes were calculated only for showing and interpreting species patterns captured by each CCA axis. Bold number indicates a significant correlation at $p < 0.05$ ($n = 25$).

	Ordination axis			
	1	2	3	4
Eigenvalues (λ)	0.21 (10.5%)	0.18 (8.7%)	0.14 (6.8%)	0.12 (5.8%)
Diatom metrics				
Taxa richness	-0.64	-0.37	-0.29	0.23
% alkaliphilous taxa	-0.44	0.70	0.53	-0.09
% eutrophic taxa	-0.41	0.70	0.59	-0.23
% facultative N-heterotrophic taxa	-0.39	0.43	0.57	0.19
% halophilous taxa	-0.70	0.36	0.36	-0.35
% hypereutrophic taxa	-0.48	-0.62	-0.07	-0.07
% obligately N-heterotrophic taxa	-0.36	-0.65	0.09	-0.03
% pollution sensitive taxa	0.87	0.08	-0.13	-0.08
% pollution less tolerant taxa	-0.50	-0.23	-0.07	0.06
% polysaprobous taxa	-0.47	-0.62	-0.08	-0.09
Diatom species				
<i>Achnanthes deflexa</i>	0.93	-0.08	-0.28	-0.08
<i>A. lanceolata</i>	-0.15	0.02	-0.36	-0.25
<i>A. minutissima</i>	0.18	-0.18	-0.21	-0.09
<i>Cymbella minuta</i>	-0.09	-0.18	-0.23	-0.07
<i>Fragilaria capucina</i>	-0.20	-0.22	-0.20	-0.26
<i>Gomphonema parvulum</i>	-0.14	-0.15	-0.32	-0.15
<i>Melosira varians</i>	-0.12	-0.40	0.11	-0.02
<i>Navicula minima</i>	-0.39	0.23	0.07	0.01
<i>N. crptotenella</i>	-0.26	0.16	0.07	0.01
<i>Nitzschia amphibia</i>	-0.25	0.37	0.76	0.72
<i>N. palea</i>	-0.20	-0.16	-0.03	-0.27
<i>Rhoicosphenia curvata</i>	-0.10	0.32	-0.07	0.03
<i>Synedra ulna</i>	-0.29	-0.54	-0.02	0.31
Physical habitat				
Stream wetted width	0.56	-0.12	0.01	0.03
Thalweg depth	-0.06	-0.01	-0.27	-0.10
% filamentous algal cover	-0.06	0.07	0.67	0.41
% sand & fine substrates (<2 mm)	-0.41	0.05	-0.40	0.16
Water chemistry				
ANC	-0.57	0.12	0.34	0.30
pH	0.06	0.17	0.20	0.89
SiO ₂	-0.15	0.83	-0.15	-0.08

Percent silt tolerant species varied from 1% to 66% with an average of 35%.

CCA with a forward selection on all environmental variables identified 7 environmental variables that explained significant variance in the diatom species assemblages (Monte Carlo Permutation test, $p < 0.05$)

(Fig. 5, Table 5). The first two CCA axes explained 19% of variance among sites in the diatom assemblage data (Table 5). The first CCA axis was positively correlated with % of pollution sensitive taxa ($r = 0.87$), but negatively with diatom taxa richness ($r = -0.64$) and % halophilous taxa ($r = -0.70$) (Table 5). This

Table 6. Summary of partial Canonic Correspondence Analysis (CCA) results. In the partial CCA analyses, the first ordination axis was constrained by % of agriculture (3 different spatial scales with different buffer widths). The numbers in parenthesis are % variability in diatom species dataset explained by the first two CCA axes. P-values are the results of the Monte Carlo Permutation test (999 permutations) of the first CCA axis constrained by % of agriculture. Listed variables are selected in the order using a forward selection option with the Monte Carlo permutation test (999 permutations, $p < 0.05$).

Buffer width (m)	Spatial scale	Partial CCA			Variables selected by forward selection ($p < 0.05$)
		λ_1	λ_2	p -value	
10	Sample reach	0.08 (3.7%)	0.27 (13.4%)	0.76	SiO ₂ , NH ₄ , ANC, pH, % filamentous algal cover, % riparian buffer within 10-m band width around sampling reach
30	Sample reach	0.10 (5.0%)	0.27 (13.5%)	0.19	SiO ₂ , NH ₄ , ANC, pH, % filamentous algal cover, % riparian buffer within 30-m band width around sampling reach
10	Whole stream network	0.12 (6.0%)	0.26 (13.1%)	0.05	SiO ₂ , stream wetted width, thalweg depth, % riparian buffer within 30-m band width along the stream network
30	Whole stream network	0.13 (6.3%)	0.27 (13.2%)	0.02	SiO ₂ , stream wetted width, channel slope, % sand & fine substrates (<2 mm), % filamentous algal cover
150	Whole stream network	0.11 (5.5%)	0.26 (13.0%)	0.11	SiO ₂ , TN, channel slope, % fine gravel substrates (<16 mm), % filamentous algal cover, % riparian buffer with 30-m band width along the stream network
	Whole catchment	0.11 (5.5%)	0.27 (13.4%)	0.10	SiO ₂ , stream wetted width, % sand & fine substrates (<2 mm), % filamentous algal cover, % riparian buffer within 10-m and 30-m band width along the stream network

axis was significantly, but weakly correlated with water chemistry variables (e.g., acid neutralizing capacity ($r = -0.57$)) and physical habitat variables (e.g., stream wetted width ($r = 0.56$)). The second CCA axis was positively correlated with % alkaliphilous taxa ($r = 0.70$) and % eutrophic taxa ($r = 0.70$), but negatively with % obligately N-heterotrophic taxa ($r = -0.65$) and % polysaprobous taxa ($r = -0.62$). This axis was positively correlated with SiO₂ ($r = 0.83$). None of the first 4 CCA axes were significantly correlated with % agricultural land-use or other major types of land-use regardless of the spatial scales.

Partial CCAs showed that % agricultural land-use at different spatial scales explained between 3.7%–6.3% of variability in the diatom species dataset (Table 6). Monte Carlo Permutation tests indicated that the variance explained by % agricultural land use was only significant at the spatial scale of the stream network with 10- and 30-m band width. However, actual differences among the variability explained by % agricultural land use at different spatial scales were

small. In contrast, the % variability in diatoms explained by the second CCA axis was higher, ranging from 13.0% to 13.5% (Table 6). In addition to the effects of % agricultural land use, the partial CCAs showed that water chemistry (e.g., SiO₂), reach-scale stream channel dimensions (e.g., width, depth, and slope), reach-scale in-stream habitats (substrates and filamentous algal cover in stream beds), and riparian vegetative buffer were important with relation to diatom species assemblages (Table 6).

Percent obligately N-heterotrophic taxa was the only autecological metric that showed a significant correlation with % agricultural land-use and water chemistry (Cl⁻, $r = 0.46$). The correlation between this metric and % agriculture varied with spatial scales. A significant correlation ($r = 0.50$) was observed at the stream network scale (both 10- and 30-m band width), but not at the catchment or reach scales. The Trophic Diatom Index (TDI) was significantly and positively correlated with ANC ($r = 0.62$), conductivity ($r = 0.63$), and TP ($r = 0.51$).

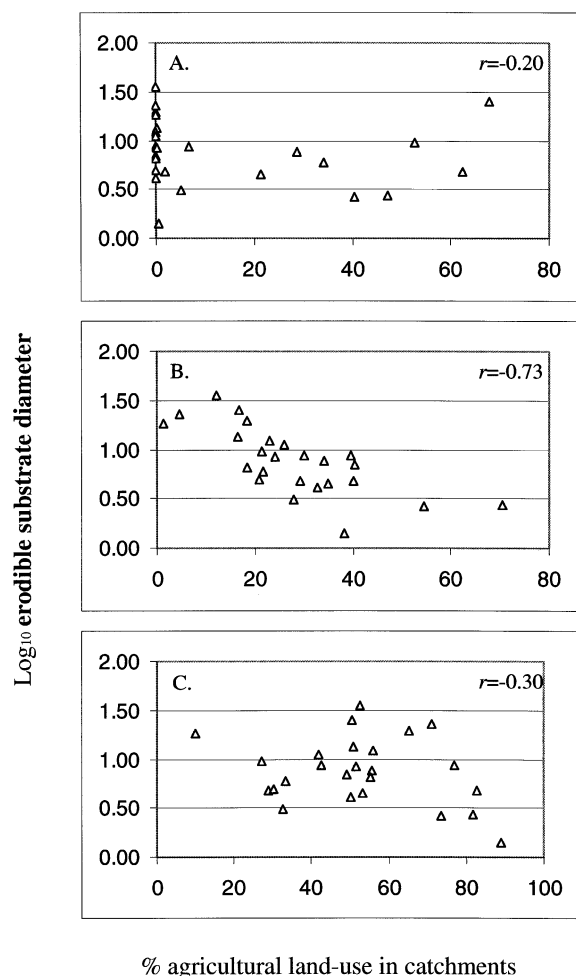


Figure 4. Comparison of the relationships between \log_{10} erodible substrate diameter and % of agricultural land use at 3 spatial scales. A. % agricultural land-use at the reach scale with 30-m band width. B. % agricultural land-use along the stream network with 30-m band width. C. % agricultural land-use at the catchment scale. A correlation coefficient >0.40 is significant at $p = 0.05$, $n = 25$.

Discussion

Effects of land-use on lotic diatoms and importance of spatial scales

Catchment determinants such as land-use may have direct and indirect effects on lotic diatom assemblages. Diatom assemblages clearly reflected agriculture-related impacts on sampled streams. For example, 72% of diatoms were halophilous taxa which may suggest that sampled streams may be enriched by minerals. However, our data showed that the direct linkage between agricultural land-use and lotic diatom assemblages was weak in the Willamette Valley

streams during the base flow period. CCA with a forward selection option on all environmental variables selected 7 variables of water chemistry and habitat conditions as being significantly related to diatom assemblages. None of land cover/land use variables was selected. Lack of a strong direct relationship between agricultural land-use and diatom assemblages during summer base flows may be attributed to our inability to measure the diatom/habitat and habitat/land-use relationships precisely so that noise overwhelms any diatom/land-use signal in our data. In this study, we sampled along a land-use gradient within the same ecoregion and river basin to minimize coarse-level confounding factors such as climate (Omernik, 1987). Percent agriculture in the catchment ranged from 10 to 89% with an average of 52% so the sites we selected covered a good range of the land-use gradient in the basin. However, the stream sites along this land-use gradient may still differ in site-specific factors such as hydrogeology. McFarland (1983) divided the Willamette Basin into 6 major hydrogeological units. The majority of our study sites were located in the basin-fill and alluvial aquifer while 3–5 sites were located in the Columbia River Basalt aquifer. The basin-fill and alluvial aquifers are a mixture of unconsolidated clay, sand, and gravel and are sensitive to contamination in areas with a shallow water table (Gonthier, 1985). The Columbia River Basalt aquifer is more permeable to water flow and with more dilute water chemistry.

An aggregated measure of land-use such as % agriculture in catchments may only represent the potential of land-use effects on streams. Spatial configuration of land-use such as agricultural patch shape and size, flow path between agricultural patches and streams, and localized activities may vary within and among catchments. Patch density in the catchment, for example, was one of the important factors in relating catchment land-use to stream water chemistry (Johnson et al., 1997). Kehmeier (2001) found that % agricultural land-use explained a significantly higher amount of variability in native fish biomass in the Willamette River basin streams when % agricultural land was weighted by flow path distance to streams.

Effects of water chemistry and physical habitat conditions on diatom assemblages

The potential effects of agricultural land-use on diatom assemblages may depend on variables such as water chemistry and physical habitat conditions measured at the sample reach scale. Changes in diatom

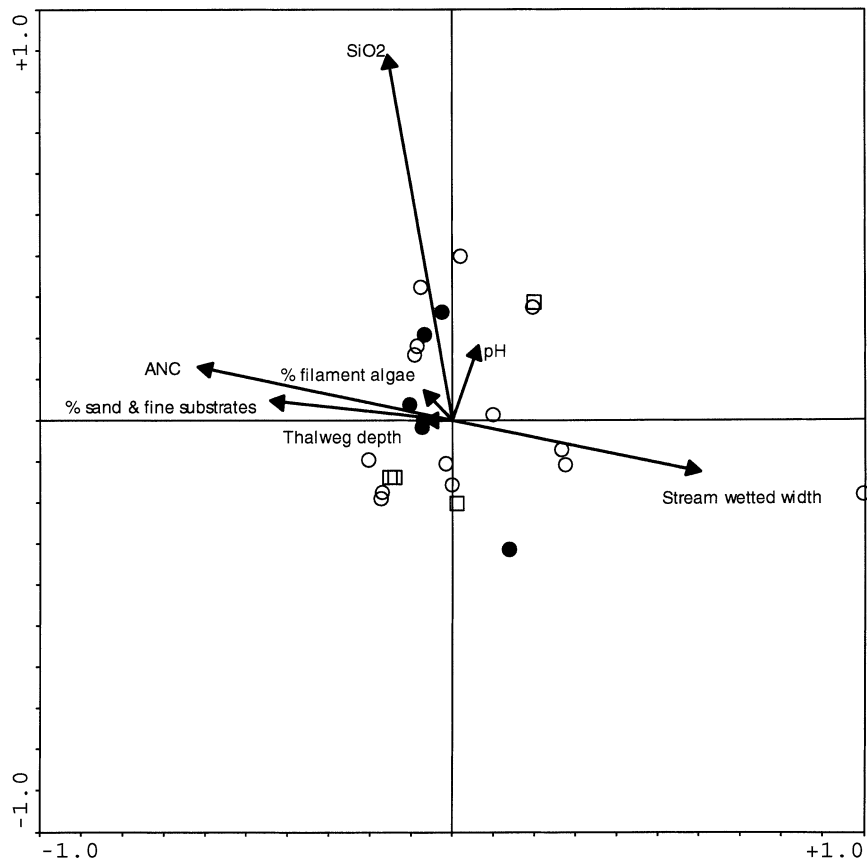


Figure 5. Canonical correspondence analysis (CCA) ordination diagram with 25 stream sites. Solid circles: sites with >70% agricultural land-use in catchments, open squares: sites with <30 agriculture in catchments, open circles: sites with % agricultural land-use in catchments between 30% and 70%.

assemblages were related to some water chemistry and physical habitat variables in our sampled Willamette Valley ecoregion streams. CCA showed that diatom taxa richness, % halophilous taxa, % pollution less tolerant taxa, % eutrophic taxa, % hypereutrophic taxa, % polysaprobous taxa, and % alkaliphilous taxa all decreased while % of pollution sensitive taxa decreased along the first CCA axis (Table 5). The changes of the diatom taxa and metrics along the first CCA axis were associated with ionic strength (ANC) and habitat conditions (stream wetted width, % sand & fine substrate). Effects of water chemistry and physical habitat conditions on diatom assemblages become more evident after variability in diatom species explained by agricultural land-use is removed. Partial CCAs with a forward selection option showed that water chemistry (e.g., SiO_2), reach-scale stream channel dimensions (e.g., width, depth, and slope), reach-scale in-stream habitats (substrates and filamentous algal

cover in stream beds), and riparian vegetative buffer were important to diatom species assemblages. Several researchers have found that changes in periphyton species were often related to ionic strength in the Pacific Northwest streams. Carpenter & Waite (2000) reported that agricultural stream sites and forested stream sites were separated along a conductivity gradient in the Willamette Valley. Conductivity was one of the key explanatory variables for lotic periphyton species assemblages in the Columbia Plateau, Washington, an agriculturally dominated region (Leland, 1995; Munn et al., 2002). Streams in this region are typically characterized by low ionic strength (conductivity, alkalinity) (Welch et al., 1998). Increases in ionic strength in streams may reflect changes in land-use and increases surface runoff. However, changes in diatom species assemblages in relation to stream habitat conditions have received less attention. Several studies have examined the effects of substrate

types on periphyton assemblages (see review by Cattaneo & Amireault, 1992; Burkholder, 1996). Most of these studies assessed substrate-specific effects, not substrate at a reach-level, on periphyton. But Kutka & Richards (1996) reported that changes in diatom assemblages were related to stream reach habitat conditions (% bank erosion, % canopy coverage, and bankfull width) in a Minnesota agricultural basin.

Effects of land-use on stream conditions and importance of temporal scale

We expected that high and frequent precipitation in the Pacific Northwest during the wet season may increase direct linkages between catchment land-use and stream conditions, and the stream conditions may better reflect cumulative effects of catchment land-use because the relative importance of land-use and other factors such as geology on stream water chemistry may be determined by hydrological connectivity between the catchment and streams (Blanchard & Lerch, 2000). Indeed, the Willamette River basin is characterized by a distinct change in climate and associated hydrological regimes between the dry and wet seasons. About 75% of annual precipitation occurs between October and March with <5% occurring during July and August (Uhrich & Wentz, 1999) and flows in the Willamette Valley streams are tightly coupled with precipitation. Bonn et al. (1995) estimated that low flow in the Willamette River basin streams during August and September only accounts for <2% of total annual streamflow. In their study on temporal changes of nutrients in 6 Willamette Valley streams, Bonn et al. (1995) reported that NO₃-N concentrations showed a relatively strong correlation with streamflow except at a site covered by 100% forest. Seasonal trends of nutrients became less pronounced for flow-adjusted nutrient data. Johnson et al. (1997) reported that surficial geology, but not land-use, was strongly correlated with stream water chemistry in the summer in Michigan catchments, whereas effects of land-use on stream water chemistry became more evident when the catchments and streams were more hydrologically connected in the fall. Arheimer & Liden (2000) also reported that catchment characteristics were better predictors of winter median nutrient concentrations. Bolstad & Swank (1997) reported that changes in water quality in relation to land-use were much more evident during a storm flow than a base flow period. Importance of the spatial scales in assessing effects of land-use on stream conditions becomes more evident

in the wet season in the Willamette Valley. Percent agricultural land explained more variance at larger spatial scales (e.g., the catchment and stream network with 150-m band width) and then decreased at the local scale (e.g., sample reach), indicating stream water chemistry during wet seasons is more a function of catchment-wide biogeochemical processes and land-use patterns.

Implication to stream bioassessment

Present periphyton diversity in streams may result from long-term cumulative effects of climate, catchment geology, and land-use (Stevenson, 1997). Harding et al. (1998) reported that catchment land-use in 1950s was a better predictor of present macroinvertebrate assemblages than present land-use patterns (1990s), suggesting the macroinvertebrate species pool has not fully recovered from previous land-use impacts despite recent changes in land-use patterns. To better relate biotic assemblages collected from a stream reach to environmental stressors such as catchment land-use in stream assessments, we need to consider both spatial and temporal scales in designing field studies and interpreting data (Allan et al., 1997; Lammert & Allan, 1999). Most stream bioassessment programs recommend sampling stream biota during the summer base flow time because of stable hydrological conditions and diverse biotic assemblages (Karr & Chu, 1999). Summer sampling may underestimate the effects of land-use on stream conditions in areas where seasonal patterns are so distinctive as in the Willamette Valley.

Systematic changes in diatom assemblages such as species replacement may reflect integrated changes of environmental conditions over time. Direct linkages between systematic changes in diatom assemblages and environmental changes may not be always evident on short-term time scales (e.g., weekly) until the two reach equilibrium. Allen et al. (1977) suggest that changes in species assemblages in a system may correspond to environmental changes at an annual scale. Catchments and stream water may be more tightly coupled during the wet seasons. However, high flow, low temperature, and high turbidity (low light) may not be favorable for periphyton growth in streams during the wet seasons. It is unclear how the wet season events (e.g., abundant nutrient supplies but with unfavorable habitat conditions) are linked to biotic assemblages and their distribution patterns during the following dry season. Our temporal data were very

limited in frequency and biotic responses. An integrated study between catchment hydrology and stream ecology over time may be needed to assess if such a linkage is important and to extract more information on changes in stream environmental conditions from biotic assemblages.

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