

Effects of riparian vegetation removal on nutrient retention in a Mediterranean stream

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Abstract. We examined the effects of riparian vegetation removal on algal dynamics and stream nutrient retention efficiency by comparing $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$ uptake lengths from a logged and an unlogged reach in Riera Major, a forested Mediterranean stream in northeastern Spain. From June to September 1995, we executed 6 short-term additions of N (as NH_4Cl) and P (as Na_2HPO_4) in a 200-m section to measure nutrient uptake lengths. The study site included 2 clearly differentiated reaches in terms of canopy cover by riparian trees: the first 100 m were completely logged (i.e., the logged reach) and the remaining 100 m were left intact (i.e., the shaded reach). Trees were removed from the banks of the logged reach in the winter previous to our sampling. In the shaded reach, riparian vegetation was dominated by alders (*Alnus glutinosa*). The study was conducted during summer and fall months when differences in light availability between the 2 reaches were greatest because of forest canopy conditions. Algal biomass and % of stream surface covered by algae were higher in the logged than in the shaded reach, indicating that logging had a stimulatory effect on algae in the stream. Overall, nutrient retention efficiency was higher (i.e., shorter uptake lengths) in the logged than in the shaded reach, especially for $\text{PO}_4\text{-P}$. Despite a greater increase in $\text{PO}_4\text{-P}$ retention efficiency relative to that of $\text{NH}_4\text{-N}$ following logging, retention efficiency for $\text{NH}_4\text{-N}$ was higher than for $\text{PO}_4\text{-P}$ in both study reaches. The $\text{PO}_4\text{-P}$ mass-transfer coefficient was correlated with primary production in both study reaches, indicating that algal activity plays an important role in controlling $\text{PO}_4\text{-P}$ dynamics in this stream. In contrast, the $\text{NH}_4\text{-N}$ mass-transfer coefficient showed a positive relationship only with % of algal coverage in the logged reach, and was not correlated with any algal-related parameter in the shaded reach. The lack of correlation with algal production suggests that mechanisms other than algal activity (i.e., microbial heterotrophic processes or abiotic mechanisms) may also influence $\text{NH}_4\text{-N}$ retention in this stream. Overall, this study shows that logging disturbances in small shaded streams may alter in-stream ecological features that lead to changes in stream nutrient retention efficiency. Moreover, it emphasizes that alteration of the tight linkage between the stream channel and the adjacent riparian zone may directly and indirectly impact biogeochemical processes with implications for stream ecosystem functioning.

Key words: algal biomass, ammonium, disturbance, logging, Mediterranean stream, nitrate, nutrient retention, phosphate, primary production, riparian vegetation, riparian zone, uptake length.

Recent studies have highlighted the importance of the riparian zone in influencing stream structure and ecological function, both because of the riparian zone's intrinsic features as an ecosystem (Naiman et al. 1993) and because of its hydrologic interaction with the stream (Gregory et al. 1991). Riparian ecosystems often act as a sink for nutrients from runoff waters (Pinay et al. 1992, Haycock and Pinay 1993) because dissolved nutrients entering streams through surface and subsurface flowpaths can be partly removed by riparian vegetation and by micro-

bial processes in the riparian soil (Komor and Magner 1996). On the other hand, for streams with relatively low nutrient concentrations, a riparian deciduous forest can be a nutrient source to the stream (Mulholland 1992). The effectiveness of the riparian zone as a nutrient sink or source, however, depends on many factors, including the size of the riparian ecosystem and the flowpaths of water through it (Hill 1996). Although many studies have shown that riparian zones play an important role as lateral filters of nutrient loadings from upland sources, their role in modifying the magnitude of longitudinal nutrient transport and retention within the

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stream is less well known (but see Dahm et al. 1998).

Logging of riparian vegetation in small watersheds is a common practice, especially in Mediterranean regions where riparian ecosystems can be more productive than the upslope forest (Sterling 1996). This practice may cause changes in the magnitude of downstream nutrient export, in particular in 1st- and 2nd-order streams of temperate zones in which the canopy often shades the channel (Lake and Marchant 1990). In semiarid regions such as the Mediterranean, riparian corridors act as permanent wet zones because they increase humidity and moderate water temperature (Fisher 1995). Therefore, riparian logging in these regions may have a great effect on stream communities through changes in both water temperature and energy inputs (Statzner and Kohmann 1995). Riparian zones, especially in forested watersheds, influence energy input to streams in 2 ways: 1) supplying organic matter, and 2) reducing light availability and thermal energy to stream primary producers. Thus, removal of riparian forest reduces inputs of detrital organic matter, but increases light availability to the stream. Reduction of allochthonous inputs affects stream community structure (Wallace and Gurtz 1986, Haack et al. 1988, Behmer and Hawkins 1989, Wallace et al. 1997). Increases in light availability in the stream generally favor stream primary production (Hansmann and Phinney 1973, Triska et al. 1983); further, increases in stream primary production may result in a higher abundance of macroinvertebrate grazers (Allan 1995), which in turn can have a positive effect on bacterial activity and nutrient turnover rate (Newbold et al. 1982). All these changes in benthic community structure may directly or indirectly affect stream nutrient dynamics.

The objective of this study was to evaluate the short-term effect of riparian deforestation on stream nutrient transport and retention, and to examine the relationship between changes in nutrient dynamics and changes in algal biomass and production. The study was done in Riera Major, a small light-limited stream in a semiarid region of Spain (Guasch and Sabater 1995). To test the effect of riparian removal on stream nutrient dynamics, we compared retention efficiency of N and P between a reach in which riparian vegetation had been removed and an adjacent downstream reach that was left intact.

We were particularly interested in how nutrient retention efficiency in the logged reach would vary compared to the intact reach.

Study Site

Riera Major is a 2nd-order tributary of the River Ter 90 km north of Barcelona (northeastern Spain). The stream drains a 15.5-km² watershed dominated by igneous rocks (granodiorite), and spans an altitudinal range of 960 to 460 m above sea level with an average stream gradient of 5%. Stream discharge during low flow ranges from 30 to 100 L/s. Stream water temperature, before logging, ranged from 3 to 18°C (Martí 1995). The watershed is mostly forested, dominated by evergreen oak (*Quercus ilex*), with lesser coverage by chestnut (*Castanea sativa*) and Norway spruce (*Picea abies*). The riparian forest was dominated by mature (~50-y-old) alders (*Alnus glutinosa*), which formed a dense gallery along the stream channel. During winter 1995, 60% of the riparian corridor length was completely removed for commercial purposes. Some of the remaining riparian forest was logged the following winter. Trees and shrubs were harvested from the riparian zone (6–8 m wide on both sides), and all slash was removed from both the riparian zone and the stream channel. The adjacent terrestrial forest was left intact. No signs of siltation, erosion, or changes in channel morphology appeared in the stream during the study period probably because tree roots were not removed.

We selected a 200-m-long section of stream. This section had 2 clearly differentiated reaches: the upstream 100 m were completely logged (i.e., the *logged* reach), and the remaining 100 m were left intact (i.e., the *shaded* reach) until the winter of 1996 when the remaining riparian forest was removed. Both study reaches were characterized by step-pool morphology, and stream bed sediments consisted of sand, cobbles, and boulders. The hyporheic zone of the Riera Major is composed mainly of mobile coarse sand, ranging in depth from a few centimeters to 1 m (Butturini 1999). Several studies had been conducted in this stream section, prior to the removal of riparian trees, to examine nutrient dynamics (Martí and Sabater 1996, Butturini and Sabater 1998) and epilithic biofilm metabolism (Guasch and Sabater 1995, Sabater and Romaní 1996). Stream nutrient concentrations during

baseflow ranged considerably ($\text{PO}_4\text{-P}$: 7–23 $\mu\text{g/L}$, $\text{NH}_4\text{-N}$: 2–24 $\mu\text{g/L}$, $\text{NO}_3\text{-N}$: 128–602 $\mu\text{g/L}$). Consequently, the range of molar N:P ratio was broad (10.3–213.9), but mostly >16 , indicating potential $\text{PO}_4\text{-P}$ limitation (Martí and Sabater 1996). Before logging, a red encrusting alga (*Hildenbrandia rivularis*) was the dominant species in summer when riparian canopy was fully developed. Diatoms were abundant during winter and spring, and the filamentous green algae *Cladophora glomerata* only appeared during spring in locations where light intensity was relatively high (Guasch 1995).

Methods

Field sampling

We conducted 6 short-term additions of nutrients to the 200-m section of Riera Major from 2 June to 29 September 1995 to measure stream nutrient retention efficiency. The riparian canopy was fully developed along the 100-m shaded reach during this period, which allowed us to assess the impact of altered light availability during times of maximum insolation. We conducted 2 nutrient additions during the following summer (31 July and 4 September 1996) after deforestation of the shaded reach to verify the short-term effect of riparian vegetation removal on stream nutrient dynamics. All additions were done at midday.

For each nutrient addition, we added a solution containing $\text{PO}_4\text{-P}$ (as Na_2HPO_4), $\text{NH}_4\text{-N}$ (as NH_4Cl), and Cl^- (as NaCl), which was used as a conservative tracer, to the study section. The solution was added at the head of the section at a constant rate for 2 to 3 h. We defined 10 sampling sites that were equally distributed along the study section (5 sites in each reach). The addition of nutrients resulted in increases of 2 to 3 times the stream background concentrations ($\text{PO}_4\text{-P}$: 5.6–15.8 $\mu\text{g/L}$ and $\text{NH}_4\text{-N}$: 3.9–15.7 $\mu\text{g/L}$). Cl^- concentration increased ~ 3 mg/L over background. Once the addition started, increases in conductivity (WTW[®] conductivity meter) were continuously recorded using a Delta Logger[®] that was placed at the end of the section. Conductivity values were transformed to Cl^- concentrations using a regression curve (Butturini 1999). With the Cl^- concentration data, we used a mass-balance approach coupled with morphometric measures to obtain discharge

and average water velocity (Triska et al. 1989, Gordon et al. 1992). These parameters were needed for calculation of solute transport and retention (see detailed explanation in the data analysis section). Conductivity values were also used during the addition to determine when plateau conditions were achieved along the section. Duplicate samples for background concentrations of nutrients and Cl^- were collected at each sampling site before the addition started. Once plateau conditions were achieved, we collected water samples (4 replicates) in polyethylene syringes at each sampling site, and filtered the water immediately through glass microfibre filters (Whatman[®] GF/F, 0.7- μm pore size).

We measured water temperature and light intensity (PAR; Li-Cor[®] light sensor) at several locations along the study section on each addition date. The % of light reduction caused by the riparian canopy cover in the shaded reach was represented as the % of light intensity measured in the logged reach (i.e., full sunlight conditions). The % of algal cover in each reach was mapped by quantifying % coverage at transects every 10 m along the section. Algal biomass (as chlorophyll *a*) and primary production per unit area were measured on small unglazed ceramic tiles (0.64 cm^2), which were placed in the stream 4 to 5 wk prior to the study period. This time was sufficient to allow the biofilm community on the tiles to develop similarly to mature communities in the stream (Sabater and Romani 1996). Chlorophyll *a* per unit area was measured spectrophotometrically in triplicate tiles after extraction of pigments in 90% acetone (Jeffrey and Humphrey 1975). Primary production was measured using the $^{14}\text{C-HCO}_3^-$ incorporation technique (Hunding and Hargrave 1973). On each date, 9 tiles were randomly collected from each reach, placed in tubes filled with filtered stream water, and transported to the laboratory. One μCi of $\text{Na}^{14}\text{CO}_3\text{H}$ was injected into each tube, and the tubes were incubated for 2 h under constant shaking and at ambient stream temperature. Quenching and nonphotosynthetic uptake of C were determined respectively from substratum-killed tiles (2 replicates in 40% formaldehyde) and from substratum under dark conditions (2 replicates). The remaining 5 replicates were exposed under a saturating irradiance (210 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$). Photosynthetic uptake was estimated from incorporation of radioactivity in light-exposed substratum af-

TABLE 1. Comparison of physical, chemical, and biological parameters between the logged and the shaded reaches for the 1995 study period. Asterisks indicate statistical differences (*t*-test) between logged and shaded reaches on each date (* = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$). SRP = soluble reactive P.

Dates		Water temperature (°C)	Light intensity ($\mu\text{E m}^{-2} \text{s}^{-1}$)	NH ₄ -N ($\mu\text{g/L}$)	SRP ($\mu\text{g/L}$)
2 June	logged	12.4*	1200***	15.7	12.7
	shaded	11.2	62	13.7	13.6
23 June	logged	15.0*	1243***	6.3	5.9
	shaded	14.1	36	8.5	5.6
11 July	logged	20.0**	1363***	6.3	8.7
	shaded	18.5	59	8.6	7.7
26 July	logged	23.0*	1300***	9.0	9.9
	shaded	22.5	58	7.7	10.8
8 September	logged	18.0*	1210***	4.2	14.9
	shaded	17.4	42	5.6	12.1
29 September	logged	14.0*	497***	3.9	13.3
	shaded	13.3	32	4.6	15.8
Average (± 1 SE) over experimental duration	logged	17.1 \pm 1.6	1136 \pm 130	7.6 \pm 1.8	10.9 \pm 1.4
	shaded	16.2 \pm 1.7	48 \pm 5	7.6 \pm 1.3	10.9 \pm 1.5

ter correction for quenching and nonphotosynthetic C uptake. More precise details of these methods are described in Guasch (1995) and Sabater and Romani (1996).

Laboratory analyses

Filtered water samples were kept on ice and transported to the laboratory. Soluble reactive P (SRP) and NH₄-N were analyzed within a few hours after collection. Samples for NO₃-N and Cl⁻ analysis were preserved frozen until analysis (within ~1 wk). SRP was analyzed using the molybdenum-blue colorimetric method (Murphy and Riley 1962). NH₄-N was analyzed by the indophenol-blue colorimetric method (Solorzano 1969). Phenol was added in the field to the samples for NH₄-N analysis to improve analytical replication. NO₃-N and Cl⁻ were analyzed using the capillary electrophoresis technique (Waters®, CIA-Quanta 5000; Romano and Krol 1993).

Data analysis

Nutrient retention efficiency for each reach was estimated from the downstream decline in nutrient concentration at plateau conditions along each reach after correction for background nutrient concentration and dilution (Stream Solute Workshop 1990). Assuming that the ratio be-

tween nutrient uptake rate and downstream flux of added nutrients remains constant along each reach, the corrected nutrient concentration ($[N] = N_{\text{plateau}} - N_{\text{background}} / \text{Cl}^-_{\text{plateau}} - \text{Cl}^-_{\text{background}}$) will show a negative 1st-order exponential decay curve along the reach as described in the following equation:

$$d[N]/dx = K_L[N]. \quad [1]$$

The corrected nutrient concentration at each sampling site (x) is calculated by integration of equation 1:

$$N_x = N_0 e^{-(K_L x)} \quad [2]$$

where N_x and N_0 are the nutrient concentrations at plateau ($\mu\text{g/L}$), corrected for background concentrations and for dilution, at downstream and upstream sampling sites, respectively; x is the distance (m) between sampling sites; and K_L is the 1st-order downstream nutrient change coefficient (m^{-1}). K_L is the slope of the regression between ln-transformed corrected nutrient concentrations at each sampling site, and the distance of each sampling site from the addition site. The inverse of K_L is the nutrient uptake length (S_w , m), which is an estimate of the nutrient retention efficiency (Newbold et al. 1981). Shorter S_w indicates that nutrients are retained more efficiently than longer S_w . Because PO₄-P and NH₄-N uptake lengths were measured simultaneously on each addition date, we used

TABLE 1. Extended.

Chlorophyll <i>a</i> (mg/m ²)	Primary production (mg C m ⁻² h ⁻¹)	Algal cover (%)
55.8	19	12.4
50.0	18	8.2
864.5***	262**	15.9
76.8	74	11.2
270.5***	315**	35.9**
16.05	21	17.6
100.8***	1118**	46.5**
22.3	376	17.8
108.5*	142	28.4*
57.16	103	16.0
110.0*	93	36.4*
55.0	92	19.7
246.7 ± 121.3	324.9 ± 164.8	29.2 ± 5.3
46.2 ± 9.3	114.0 ± 54.3	15.1 ± 1.8

the S_w ratio (i.e., $S_{w[NH_4-N]}:S_{w[PO_4-P]}$; Martí and Sabater 1996) to compare retention efficiency of the 2 nutrients within each reach and among sampling dates. Ratios <1 indicate a higher efficiency for NH_4-N retention relative to PO_4-P , whereas values >1 indicate a higher PO_4-P retention relative to NH_4-N .

Spatial differences in uptake of a given nutrient were tested between the logged and shaded reaches. Using data from each addition date, we compared the slopes from the regression curves for each reach using a *t*-test (Flower and Cohen 1990) to determine whether nutrient retention efficiency (i.e., S_w) differed significantly (i.e., $p < 0.05$) between the 2 reaches on each particular date.

Temporal variation in nutrient retention efficiency is affected by temporal variation in stream discharge. Lower nutrient retention efficiencies are expected at higher discharges because of an increase in water velocity and stream depth and, therefore, less contact between the water column and the stream benthic biota (D'Angelo and Webster 1991, Valett et al. 1996, Butturini and Sabater 1998). To examine temporal trends in nutrient retention efficiency in the study reaches excluding discharge effects, we used the nutrient mass-transfer coefficient (V_f , cm/min). This coefficient is related to S_w as follows:

$$V_f = 1/S_w \cdot v \cdot h \quad [3]$$

where v is the average water velocity (m/min) and h is the average depth of the water column (cm) for each reach. The V_f is an estimate of how rapidly an element is being removed from the stream water to the benthic compartment (Stream Solute Workshop 1990).

On each date, replicate measures of temperature, light, nutrient concentrations, algal biomass and cover, and primary production were collected along each of the study reaches. We used *t*-test analyses on these data to assess statistical differences between reaches on individual dates for each of the parameters cited above. Taking data from all dates together, Pearson correlations were calculated between V_f for NH_4-N and PO_4-P , primary production, chlorophyll *a*, and algal coverage to examine the relationship between nutrient dynamics and algal abundance and production in the 2 reaches. Temporal trends in V_f were compared between nutrients for each particular reach and between reaches for each particular nutrient using Pearson correlations. Significant correlations between the 2 nutrients for a given reach suggested that dynamics of the 2 nutrients were controlled by similar processes. Likewise, significant correlations between reaches for a particular nutrient indicated that dynamics of that nutrient were controlled by similar processes in the 2 reaches; however, reaches may have differed in the rate of these processes. SYSTAT (SYSTAT, Evanston, Illinois) was used for all statistic analyses.

Results

Effects of logging on stream environmental conditions and primary producers

Water temperature and light irradiance were significantly higher in the logged than in the shaded reach on each addition date (Table 1). Differences in temperature between the 2 reaches ranged from 0.5 to 1.5°C. Light intensity in the shaded reach was only 4 to 21% of light intensity in the logged reach. Background concentrations of SRP and NH_4-N during the study period were relatively low and did not differ between reaches on any date; average (± 1 SE) concentration of SRP was 10.9 ± 1.0 μ g/L and of NH_4-N was 7.6 ± 1.1 μ g/L for the entire 200-m section (Table 1). In contrast, NO_3-N concentration was relatively high (785 ± 86 μ g/L).

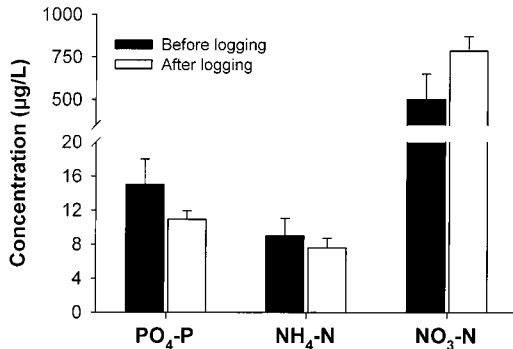


FIG. 1. Comparison of mean (+1 SE) concentrations of PO₄-P (as soluble reactive phosphorus), NH₄-N, and NO₃-N before and after removal of riparian vegetation. Data for the period previous to the logging are from Martí and Sabater (1996) and data for the period after logging were measured during this study. The 2 data sets were measured along the same 200-m stream section.

Comparison of nutrient concentrations from this study measured over the entire 200-m section to those from Martí and Sabater (1996) measured in the same stream section previous to removal of riparian vegetation illustrated that, after logging, concentrations of NH₄-N were similar, concentrations of NO₃-N were 1.6× higher, and concentrations of SRP were 1.5× lower (Fig. 1).

Algal biomass (chlorophyll *a*) in the logged reach was significantly greater than in the shaded reach on 5 out of 6 dates (Table 1). Differences between reaches were greatest in mid-summer, when chlorophyll *a* in the logged reach was at least 10× higher than in the shaded reach. Epilithic primary production ranged from 19 to 1118 mg C m⁻² h⁻¹ in the logged reach and from 18 to 376 mg C m⁻² h⁻¹ in the shaded reach. Primary production significantly differed between the 2 reaches on midsummer dates only, when primary production in the logged reach was from 3 to 15× higher than in the shaded reach (Table 1). Percentage of stream surface that was covered by algae was significantly higher in the logged than in the shaded reach except in June (Table 1). Average (±1 SE) % of algal cover for the study period was 29.2 ± 5.3 in the logged reach and 15.1 ± 1.8 in the shaded reach (Table 1). Differences in algal cover between the 2 reaches were greatest in July, when algal coverage in the logged reach was 2 to 2.6× higher than in the shaded reach.

Effects of logging on nutrient retention efficiency

$S_{w[NH_4-N]}$ values for the 1995 study period ranged from 67 to 253 m for the logged reach and from 128 to 368 m for the shaded reach (Fig. 2). Differences in $S_{w[NH_4-N]}$ between the 2 reaches were only significant in late June and July (Fig. 2), when uptake lengths were on average 2.3× shorter for the logged than for the shaded reach. $S_{w[PO_4-P]}$ ranged from 110 to 532 m for the logged reach and from 177 to 800 m for the shaded reach (Fig. 2). As with NH₄-N, $S_{w[PO_4-P]}$ tended to be shorter in the logged than in the shaded reach, and differences between reaches were significant on 3 out of the 6 dates (Fig. 2), when uptake lengths in the logged reach were on average 2.2× shorter than in the shaded reach. Overall, only additions done in July were significantly different between the 2 reaches for both nutrients (Fig. 2). In contrast, in September neither NH₄-N nor PO₄-P retention efficiency differed between the 2 reaches (Fig. 2). None of the additions done in 1996 after removal of the riparian vegetation from the shaded reach showed significant differences in nutrient retention efficiency between the 2 reaches (Fig. 2). The $S_{w[NH_4-N]}:S_{w[PO_4-P]}$ was <1 for the 2 reaches on all dates (Table 2).

$V_{f[NH_4-N]}$ values ranged from 0.21 to 0.76 cm/min in the logged reach and from 0.16 to 0.54 cm/min in the shaded reach (Fig. 3). On those dates when $S_{w[NH_4-N]}$ significantly differed between the 2 reaches, $V_{f[NH_4-N]}$ in the logged reach was 1.7 to 3.2× higher than in the shaded reach (Fig. 3). We did not find any significant correlation between the temporal pattern of $V_{f[NH_4-N]}$ in the logged and the shaded reach ($r = 0.18$, $p = 0.734$; Fig. 3). $V_{f[NH_4-N]}$ showed a positive relationship only with % of algal coverage in the logged reach ($r = 0.79$, $p = 0.050$), but was not correlated with any algal-related parameter in the shaded reach. $V_{f[PO_4-P]}$ values ranged from 0.13 to 0.47 cm/min in the logged reach and from 0.07 to 0.29 cm/min in the shaded reach. The temporal pattern of the $V_{f[PO_4-P]}$ was similar in the 2 reaches ($r = 0.90$, $p = 0.014$; Fig. 3). On those dates when the 2 reaches significantly differed in $S_{w[PO_4-P]}$, values of $V_{f[PO_4-P]}$ were 1.6 to 3× higher in the logged than in the shaded reach. $V_{f[PO_4-P]}$ was positively related to primary production in each reach ($r = 0.98$, $p = 0.001$ for the logged reach; $r = 0.96$, $p = 0.002$ for the shaded reach). Temporal patterns of $V_{f[NH_4-N]}$ and

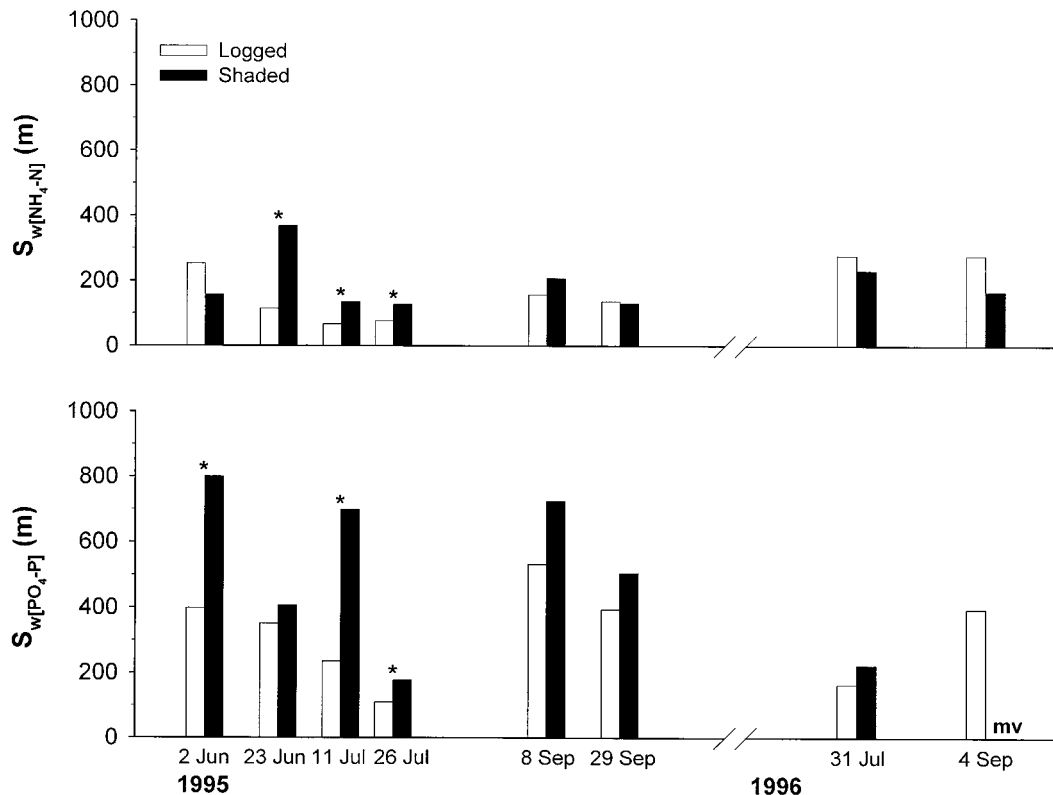


FIG. 2. Uptake lengths for $\text{NH}_4\text{-N}$ ($S_{w[\text{NH}_4\text{-N}]}$) and $\text{PO}_4\text{-P}$ ($S_{w[\text{PO}_4\text{-P}]}$) for the logged and the shaded reaches during the study period. Solute was added in 1996 after riparian vegetation was removed from the shaded reach. Asterisk indicates a significant difference ($p < 0.05$) in uptake lengths between the 2 reaches on each particular date. mv = missing value.

$V_{[\text{PO}_4\text{-P}]}$ were not significantly correlated in either of the 2 reaches ($r = 0.60$, $p = 0.207$ for the logged reach; $r = 0.15$, $p = 0.777$ for the shaded reach; Fig. 3).

TABLE 2. Nutrient uptake length ratios ($S_{w[\text{NH}_4\text{-N}]}$: $S_{w[\text{PO}_4\text{-P}]}$; see text for explanation) for the logged and the shaded reaches during the 1995 study period. Values < 1 indicate that $\text{NH}_4\text{-N}$ retention efficiency is higher than $\text{PO}_4\text{-P}$ retention efficiency.

Date	Logged reach	Shaded reach
2 June	0.64	0.20
23 June	0.32	0.91
11 July	0.28	0.19
26 July	0.69	0.72
8 September	0.30	0.29
29 September	0.35	0.26

Discussion

This study showed that a disturbance in the riparian zone (i.e., removal of riparian vegetation) has indirect effects on in-stream ecological features. Removal of riparian trees did not directly disturb either the stream morphology or the benthic community; instead, it represented a shift in the source of energy input to the stream. Light and temperature increased in the logged reach relative to the shaded reach. This shift may be of particular relevance in low-order and forested streams such as the Riera Major. Previous studies in this stream demonstrated that primary production was limited by light availability, especially during the summer-fall period, because of the dense canopy cover by riparian vegetation (Guasch and Sabater 1995). Accordingly, we observed an increase in algal

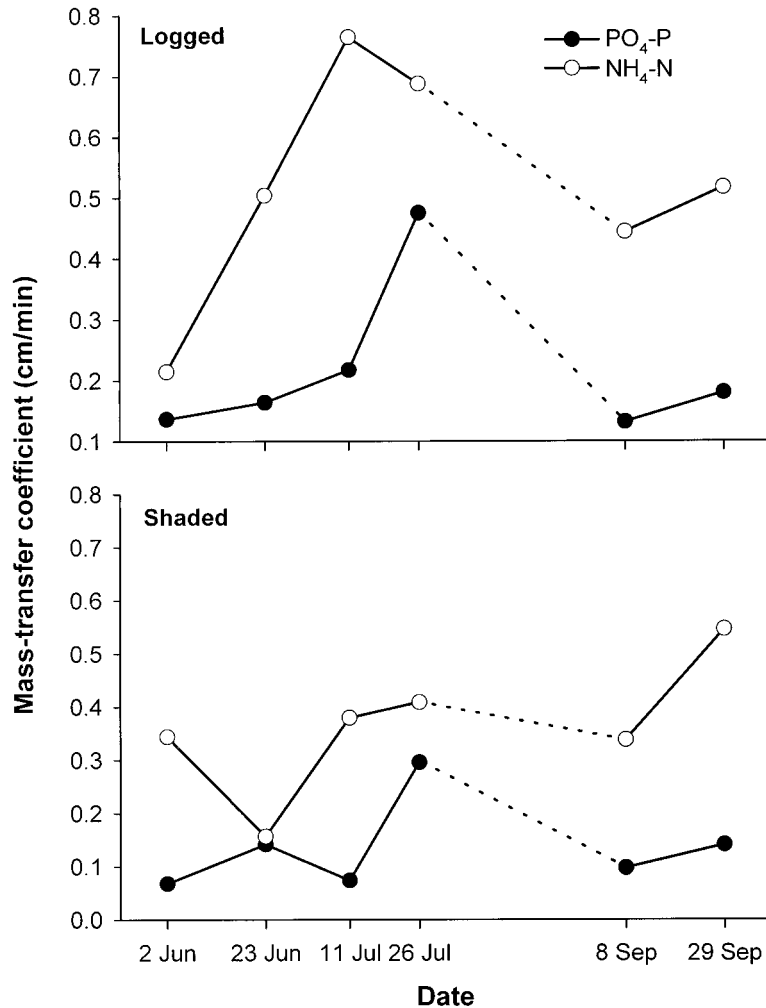


FIG. 3. Temporal variation of NH₄-N and PO₄-P mass-transfer coefficients (V_i) during the study period for the logged reach (top) and for the shaded reach (bottom).

biomass and primary production after removal of riparian trees. Other studies illustrated concomitant changes in algal community composition (Guasch and Sabater 1994, Sabater et al. 1998). These studies and our current results support findings from previous research showing the influence of riparian canopy cover on algae in small forested streams (Hansmann and Phinney 1973, Shortreed and Stockner 1983, Triska et al. 1983, Boston and Hill 1991, Leland 1995). Altering the riparian zone also impacts in-stream bacterial assemblages. Sabater et al. (1998) reported increased bacterial densities and exoenzyme activity in the logged reach of the Riera Major. These structural and functional

characteristics are interrelated, and it is interesting to note that ecological alteration within the logged reach was not the result of an in-stream disturbance, but was induced by structural changes in the adjacent riparian ecosystem.

Riparian vegetation removal also affected stream nutrient retention efficiency. Retention efficiency was higher in the logged than in the shaded reach. Only during midsummer did both reaches differ in retention efficiency for both nutrients. This fact coincided with the greatest differences between the 2 reaches in terms of biological parameters such as algal cover, chlorophyll *a* content, light intensity, and pri-

mary production. Changes in stream nutrient retention efficiency were probably influenced by these in-stream biological changes. In fact, the positive correlation between $V_{f[PO_4-P]}$ and primary production in the 2 reaches suggested that algal activity plays an especially important role in controlling PO_4-P dynamics in this stream. Therefore, observed increases in PO_4-P retention efficiency after logging could mostly be attributed to increases in algal abundance and activity. Mulholland (1992) also showed that algal activity plays a role in controlling P dynamics in another forested stream, at least during periods when light is not a limiting factor to algal growth.

On the other hand, temporal variation of $V_{f[NH_4-N]}$ in the logged reach was positively correlated with % of algal cover only, and no relationships were found in the shaded reach between $V_{f[NH_4-N]}$ and any of the parameters studied. The lack of correlation with primary production and the different temporal pattern between the 2 nutrients (i.e., no significant correlation between $V_{f[NH_4-N]}$ and $V_{f[PO_4-P]}$) in the 2 reaches suggest that mechanisms other than algal activity (e.g., nitrification, microbial uptake, microbial heterotrophic activities), or abiotic mechanisms (e.g., adsorption onto bed sediments) may also influence NH_4-N retention in this stream. Other studies have emphasized the importance of these processes in controlling NH_4-N dynamics in streams (Newbold et al. 1983, Richey et al. 1985, Rosenfeld 1989, Triska et al. 1989). This broad variety of processes is tightly associated to the biofilm community on rocks and sediments (Lock 1993, Freeman and Lock 1995, Battin and Sengschmitt 1999). In fact, Butturini and Sabater (1999) reported that 95% of NH_4-N was removed in the first 10 cm of stream bed sediments after a short-term addition of NH_4-N to the same study reach. Butturini and Sabater (1998) also found that 83% of the temporal variation in NH_4-N retention efficiency was explained by variation in water temperature after riparian logging, whereas before logging there was no significant relationship between these 2 parameters (Martí and Sabater 1996). Together, these results suggested that differences in NH_4-N retention efficiency between the 2 reaches could be influenced by changes in bacterial densities and activity because of increased water temperature and biofilm coverage after riparian logging.

Despite the effect of logging on stream retention efficiency for each particular nutrient, the effect was not as evident when considering the 2 nutrients together. In agreement with previous findings from this stream (Martí and Sabater 1996), $S_{w[NH_4-N]}:S_{w[PO_4-P]}$ was consistently <1 for both reaches on all addition dates. Therefore, only a relatively short time after disturbance to the riparian zone, Riera Major was still more efficient in retaining NH_4-N than PO_4-P .

Removal of riparian vegetation not only has an effect on light availability but also affects organic matter inputs to the stream. During summer in the study reach, allochthonous benthic detritus covered 10% of the stream bottom area before logging (Martí and Sabater 1996) and only 2% after logging (Butturini and Sabater 1998). This difference was mostly a result of continuous inputs of fresh leaves, but differences in stream benthic organic matter could have been even more pronounced during fall. Several studies have emphasized the role of dense riparian vegetation in favoring heterotrophic metabolism in shaded streams, and that energy budgets are dominated by the processing of allochthonous organic matter (Fisher and Likens 1973, Newbold et al. 1982). Effects of decreases in organic matter inputs from the riparian zone on stream functioning have been exhaustively examined in a recent leaf litter exclusion experiment conducted at Coweeta Hydrologic Laboratory, North Carolina. Elimination of litter inputs affected benthic community composition (Wallace et al. 1997) and altered the dynamics of stream dissolved organic C (Meyer et al. 1998). In contrast to our study, the Coweeta experiment emphasized the effects of decreasing organic matter inputs because canopy was kept intact and, thus, light availability did not change. Nevertheless, the 2 studies indicated that changes in stream energy inputs, both in quantity (less organic matter inputs) or in quality (organic matter vs light), influenced stream structure and function. However, it was difficult to assess effects caused by a decrease in organic matter input on stream nutrient retention in Riera Major because our work was conducted during summer, prior to leaf fall. Newbold et al. (1983) stated that NH_4-N retention efficiency is mostly attributable to biotic processes associated with mineralization of benthic organic matter. Likewise, Mulholland et al. (1985) showed that inputs of organic matter from adjacent riparian

zone enhanced P retention efficiency in Walker Branch, Tennessee. These 2 studies suggest that a decrease in organic matter input will reduce stream retention efficiency for both $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$. In our study, riparian trees were completely removed, so effects caused by decreases in organic matter inputs could be counterbalanced by those caused by increases in light availability.

Riparian zones play an important role in controlling nutrient fluxes from terrestrial to stream ecosystems (Gregory 1991, Pinay et al. 1992). Therefore, removal of riparian trees can also affect the in-stream flux of dissolved nutrients. The increase in stream $\text{NO}_3\text{-N}$ concentration after logging compared with the average concentration from the preremoval period (Martí and Sabater 1996) could, in part, be explained by the lack of a buffer zone along most of the stream length. However, other factors such as the inter-annual variation in stream hydrologic regime, characteristic of Mediterranean streams, could have also accounted for this change. The increase in $\text{NO}_3\text{-N}$ transport adds complexity to the overall effect of riparian tree removal on stream N transport and retention because it may counterbalance the relative increase in $\text{NH}_4\text{-N}$ retention efficiency. We did not measure $\text{NO}_3\text{-N}$ uptake length and cannot assess the overall effect of riparian logging on $\text{NO}_3\text{-N}$ dynamics.

In conclusion, large-scale studies by Likens et al. (1977), Vitousek and Melillo (1979), and Webster et al. (1983), among others, showed that watershed clear-cutting increases stream nutrient fluxes. These studies, together with that from Meyer et al. (1998), and our study show that disturbances either in the terrestrial forest or in the riparian zone affect stream nutrient dynamics by altering either stream nutrient fluxes or stream nutrient retention efficiency. Our study also emphasizes the tight interaction between streams and the adjacent terrestrial ecosystem, and shows that both the indirect and direct aspects of the riparian-stream linkage are relevant to stream ecosystem functioning.

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