ɘston transport in streams at Coweeta Hydrologic Laboratory, North Carolina, U. S. A.

J. R. WEBSTER and S. W. GOLLADAY

With 5 figures and 2 tables in the text

Introduction

)ne method of evaluating headwater stream efficiency is by evaluating the annual loss of ıic carbon (FISHER & LIKENS 1973). A stream with a high loss of particulate and dissolved ıic carbon would be considered inefficient compared to another stream with less loss and high :ation, i. e., respiration, within the stream. However, inefficiency in the use of organic carbon, :ially particulate organic carbon, is important since the transported particles, or seston, link l headwater streams with downstream reaches, providing an important food resource for ɑstream communities (e. g., SHORT & MASLIN 1977; BENKE & WALLACE 1980; VANNOTE et al.). Theoretically, seston concentrations should be related to stream power, i. e. the ability of a m to physically entrain material from the stream bed and to then keep it in motion (BAGNOLD ; SEDELL et al. 1978). Numerous studies have demonstrated a clear relationship between dis- ʒe, which is directly proportional to power, and the transport of seston during storms (e. g., r & LIKENS 1979; GURTZ et al. 1980). However, attempts to relate seston concentrations during storm periods to power or discharge have been largely unsuccessful (SEDELL et al. 1978; NAIMAN DELL 1979). This suggests that mechanisms other than physical entrainment are responsible for ın concentrations observed in streams during periods of stable discharge. In this study we col- d seston from a variety of small streams in a single area in order to better understand ıanisms determining seston transport and examined the effect of catchment disturbance on ın concentrations during non-storm periods.

Site description

'his work was conducted at Coweeta Hydrologic Laboratory, Macon County, North Caro- U. S. A. Samples were taken from twelve first and second order streams draining catchments ing from 8.9 to 85.8 ha (Table 1). Five of these streams drain catchments that have been undis- ed for approximately sixty years, and seven drain catchments that have received experimental :ments. All streams are located within the boundaries of the 2185-ha laboratory, and all streams ɔr have in the past been equipped with V-notch weirs for continuous discharge measurement.

Methods

ìeston samples were taken from a single site on each stream, just upstream of the weir ponding ı. More extensive samples were collected at eight points along the 1125-m length of the main ıch of Catchment 14 (C14) at intervals starting at 200 m but decreasing to 25 m at the headwa- Samples were taken at approximately monthly intervals. Twelve sets of samples were taken ı each catchment and nine sets of samples were taken along the length of C14. In addition, ples from C14 were collected periodically over six years. All samples were collected during non- m conditions. A minimum of three 1-liter grab samples were collected at each site and time.
ìamples were filtered with suction onto ashed and preweighed glass fiber filters (Gelman type . Filters were then over dried at 50 °C for at least 24 hr, desiccated (24 hr), weighed, ashed at °C for 20 min, rewetted to restore water of hydration, redried, desiccated, and weighed. From

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Table 1. Description of streams used in this study.

Stream	Catchment area (ha)	Average annual streamflow ($l \cdot s^{-1}$)[1]	Mid-catchment elevation (m)	Treatment
C6	8.9	2.5	802	Clearcut, 1958, slash burned; converted to grass, 1959; succession since 1967
C7	58.7	17.7	909	Commercial clearcut, 1977
C10	85.8	–	940	Commercial logging, 1942 through 1956
C13	16.2	4.7	819	Clearcut but no products removed, 1939 and 1962
C17	13.4	2.5	882	Clearcut but no products removed, 1940; recut annually trough 1955; white pine planted, 1956
C19	28.3	–	962	Understory vegetation cut, 1948–1949, 22% of basal area
C22	24.3	–	1 041	Alternate 10-m strips cut without removal, 1955
C2	12.1	–	858	Reference[2]
C14	61.1	19.0	861	Reference[2]
C18	12.5	3.1	849	Reference[2]
C21	24.3	–	996	Reference[2]
C34	32.8	–	1 030	Reference[2]

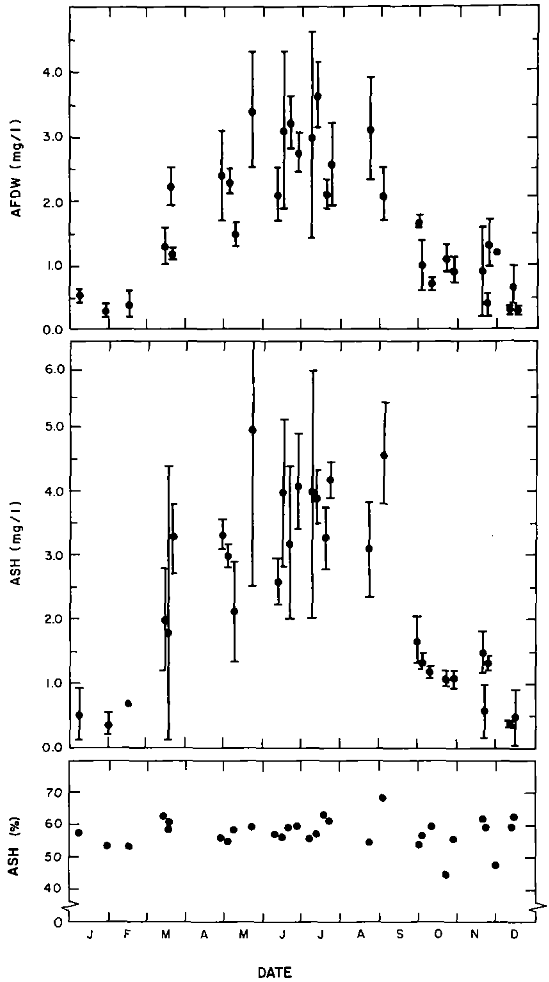
[1] Based on 20–40 years of record.
[2] Selective logging prior to 1930; chestnut blight, 1930's.

these weights, organic seston was determined as weight loss on ashing for ash free dry weight (AFDW), and inorganic seston was determined as weight of ash remaining.

Results

Based on samples taken over a six-year period from C14, non-storm organic (AFDW) seston concentrations peaked in summer and were lowest in winter (Fig. 1). Seasonal patterns in seston concentration are due in part to dilution because maximum non-storm discharge usually occurs in late winter — early spring and minimum discharge usually occurs in autumn (e. g., WEBSTER & PATTEN 1979). Highest transport (concentration x discharge) occurred in spring, and transport was lowest during autumn (Fig. 2). However, there was no relationship between organic seston concentration and discharge for samples taken from C14 during non-storm periods (Fig. 3). Inorganic (ash) seston concentration exhibited the same seasonal pattern and could not be related to discharge during non-storm periods (Figs. 1, 2, 3). The per cent ash in seston was very consistent over different dates and discharges (Figs. 1, 3).

We found statistically significant (analysis of covariance, $\alpha = .05$) downstream increases in both organic (AFDW) and inorganic (ash) seston concentrations in C14 (Fig. 4). The downstream increase in seston concentrations was greatest near the source. There was no statistically significant change in per cent ash downstream from the source.



1. Organic (AFDW) and inorganic
) particle concentrations in C14 du-
; non-storm periods. Samples were
:n over six years. Each point is the
.n of from two to nine samples
:n on the same date. Error bars are
6 confidence intervals for dates
:n more than two samples were
:n.

Catchment disturbance resulted in significant differences among organic and in-
anic seston concentrations and per cent ash in the seston of the twelve streams (anal-
; of variance, $\alpha = .05$). Organic and inorganic seston concentrations and per cent ash
re highest for streams draining C6 and C7, the two most recently disturbed catch-
nts, and were lowest for C22 and C19, the two catchments which have had the longest
ie to recover and which were disturbed the least. Among the disturbed catchments
re was a general decrease in seston concentration and per cent ash with increasing time
ce disturbance (Table 2). There was considerable variation among the five reference
ams: the stream draining C2 always had highest organic and inorganic seston concen-
tions and highest per cent ash, while C21 was always lowest (Table 2). The other refer-
:e streams were intermediate.

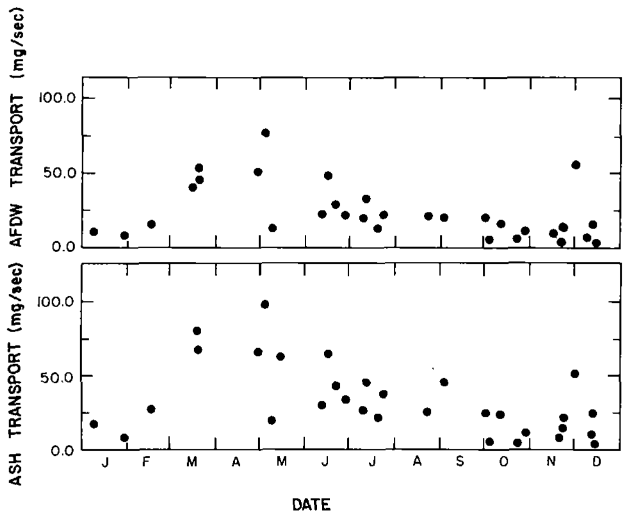


Fig. 2. Organic (AFDW) and inorganic (ash) particle transport (concentration × discharge) in C14 during non-storm periods. Samples were taken over six years. Each point is the mean of from two to nine samples.

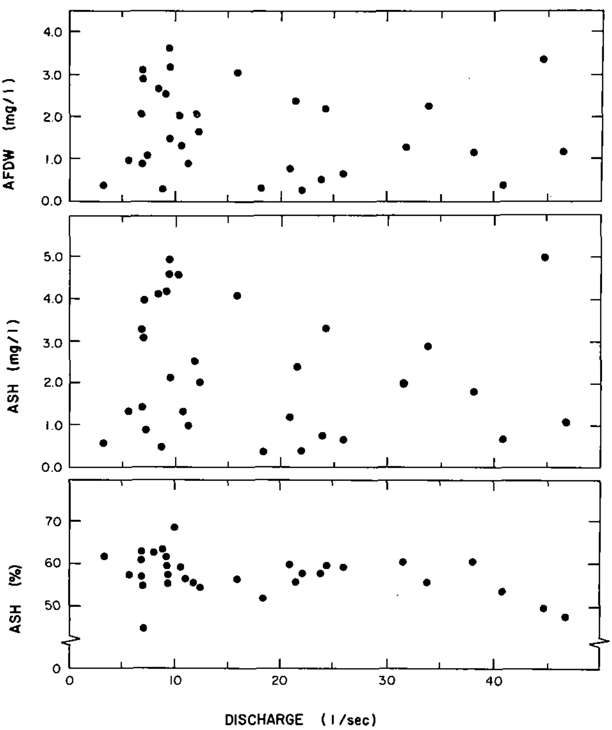


Fig. 3. Relationships of organic (AFDW) particle concentration, inorganic (ash) particle concentration, and per cent ash of seston with discharge. Each point is the mean of from two to nine samples taken from C14 over six years. All samples were taken during non-storm periods. Correlation coefficients (r values) were −0.17, −0.19, and −0.20, respectively with N = 31 in each case.

:. Means[1] (X̄) and standard errors of the means[1] (SE) for organic (AFDW) and inorganic (ash) : concentrations ($mg \cdot l^{-1}$) and per cent ash of the seston (%).

	AFDW		Ash		Per cent ash		Number of samples
	X̄	SE	X̄	SE	X̄	SE	
d streams							
	5.58	0.13	19.05	0.83	72.9	1.12	39
	3.62	0.13	9.37	0.86	71.0	1.16	36
	2.63	0.14	5.02	0.86	64.5	1.16	36
	2.85	0.18	6.75	1.15	68.1	1.55	21
	1.53	0.14	2.54	0.86	60.4	1.16	36
	1.14	0.14	0.97	0.86	43.7	1.16	36
	1.24	0.14	0.99	0.86	48.3	1.20	36[2]
:nce streams							
	3.01	0.14	6.67	0.86	66.8	1.16	36
	1.76	0.14	2.36	0.86	56.6	1.16	36
	2.37	0.13	3.32	0.83	57.0	1.12	39
	1.22	0.14	1.05	0.86	44.8	1.16	36
	2.17	0.14	2.45	0.86	51.9	1.16	36

ıns and standard errors are based on least square means to correct for unbalanced design.
C22 N = 36 for AFDW and N = 34 for ash and per cent ash.

Discussion

ased on samples from C14, our results support the conclusion that there is no rela- ;hip between stream power and organic seston concentration and transport during storm periods (Sedell et al. 1978; Naiman & Sedell 1979). Samples taken along the :h of C14 indicate that most organic seston is generated within the stream, and we ĸ that organic seston transport during non-storm periods is related to biological phe- .ena. It appears that organic seston production is highest in spring (Figs. 1, 2) when ·conditioned benthic particulate organic matter is abundant and increasing tempera- ; result in elevated biological activity. Organic seston production probably decreases ugh summer and fall as the supply of conditioned material is depleted, and produc- remains low through winter when decreased temperature reduces biological activ- Similarly, Erman & Chouteau (1979) concluded that most organic seston carried by ıms draining fens was of biological origin, and Malmqvist et al. (1978) suggested that eased summer seston concentrations in Swedish streams might be attributed to high ogical activity. Suberkropp et al. (1975) clearly demonstrated that leaf breakdown, thus production of seston from leaf litter, is highly temperature dependent.

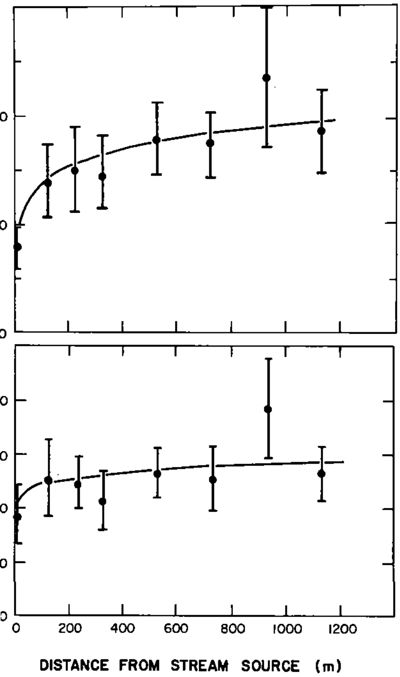
Wallace et al. (1982) recently reported results of an experimental study which was done at Coweeta and which supports the conclusion that non-storm organic seston iologically generated within the stream. They found that eliminating stream insects ı insecticide resulted in a significant decrease in organic seston concentration. In addi- ι, a computer simulation based on data from Coweeta streams demonstrated that :roinvertebrate egestion could account for about 45 % of the annual non-storm anic seston transport in a second order stream, and during summer, 83 % of the anic seston transport could be attributed to macroinvertebrate egestion (Webster

1983). The model predicted that macroinvertebrate egestion could account for nearly all non-storm transport of organic seston in first order streams. WALLACE et al. (1982) found a seasonal pattern of seston concentrations similar to Fig. 1 which they attributed seasonal differences in the time between major storms. The effect of seasonal temperature on biological activity is perhaps a better explanation that is also consistent with our results.

Our seston samples from disturbed and reference catchments (Table 2) suggest that seston concentrations and per cent ash remain elevated for 10—20 years following disturbance (C6 and C7). During this time there may be some channel erosion even during non-storm periods. This may be especially true for C6 where all slash was burned following logging. There is now an almost complete absence of debris dams in that stream, and consequently the stream apparently has little ability to retain particulate material. BILBY (1981) observed a similar large transport of seston when he removed debris dams from a stream in New Hamsphire. For catchments other than C6 and C7, time since disturbance explained little of the variation in seston concentrations or per cent ash. However, the various disturbances may have affected the streams differently, so time since disturbance may not be a very useful variable in this case.

The conclusion that non-storm organic seston is biologically generated within undisturbed streams has interesting implications. Since the proportion of organic and inorganic seston is relatively constant during the year for any stream (e.g., Figs. 1, 3, 4 for C14), it appears that the two types of material must originate from the same source. Since primary production is not an important source of organic matter in these streams (WEBSTER et al. 1983), the source of seston is primarily allochthonous leaf material. Biological processing of leaf material results in the production of small particles and, as these particles are leached and organic material is metabolized, the per cent ash increases. The more efficiently particulate organic material is processed within the stream, the higher the per cent ash of the seston leaving the stream during non-storm periods.

We found that total, organic, and inorganic seston concentrations, and per cent ash all decreased significantly with increasing mean elevation of the catchment ($\alpha = .05$, Fig. 5). Elevation may affect seston through a variety of mechanisms. Average channel gradient is generally higher in higher elevation streams; however, differences in catchment morphology make average channel gradient a rather useless parameter. Undisturbed, higher elevation streams have more woody debris, but disturbed streams even at higher elevation have less woody debris (WEBSTER & GOLLADAY unpubl. data). Because vegetation changes with elevation, the quantity and quality of allochthonous stream inputs also change with altitude. We speculate that the effect of altitude on temperature may be the most important factor. At higher elevations, lower stream temperature reduces biological processing resulting in reduced seston concentrations and lower per cent ash of the seston. At lower elevations, where stream temperature is generally higher, biological processing is more efficient. Logging can have a similar effect by opening the canopy and allowing sunlight to reach the stream, thus increasing stream temperatures (e.g., SWIFT & MESSER 1971; WEBSTER & WAIDE 1982). WALLACE et al. (1982) found few significant relationships between seston and elevation; however, their samples were taken from a single stream as it increased in size from first to fourth order rather than from similar small streams draining catchments at different elevations. Their lower elevation samples were a mixture of material generated over the whole elevation range and are not directly comparable with our results.



·. Relationships between organic)W) and inorganic (ash) particle concen- ›ns and distance from the source of C14. point is the mean of 21 to 36 samples, :rror bars are 95% confidence intervals. ›les were taken at approximately :hly intervals over one year. All samples taken during non-storm periods. Corre- ı coefficients (r values) for the regression (with log transformation of both varia- were 0.95 and 0.70, respectively with 8 in each case.

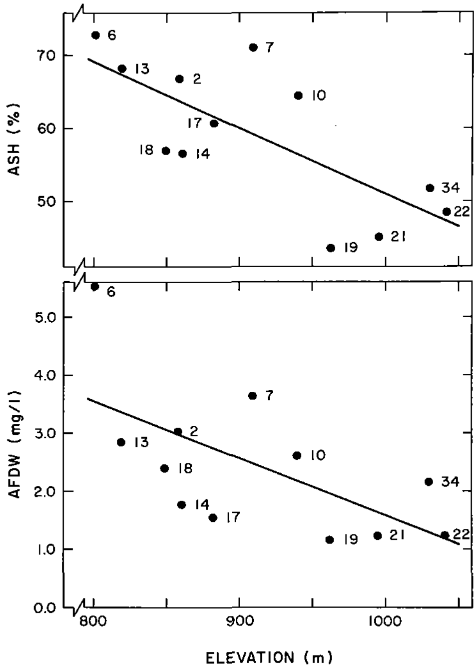


Fig. 5. Relationships of per cent ash of seston and organic (AFDW) particle concentrations with mid-catchment elevation of the various study streams. Each point is the least-square mean of 21 to 39 samples taken from each stream at approximately monthly intervals over one year. All samples were taken during non-storm periods. Correlation coefficients (r values) for the regression lines were −0.74 and −0.62, respectively with N = 12 in each case. Numbers beside each point refer to the catchment number.

'he decreased biological processing efficiency of higher altitude streams may appear ıuse increased ecosystem efficiency (sensu Fisher & Likens 1973) of streams. How- , as Wallace et al. (1982) and Webster (1983) discussed, when ecosystem effi- :y is determined from non-storm information, biological activity reduces stream ystem efficiency because it increases transport loss. If, however, unprocessed ma- l accumulating in the stream is physically entrained and lost as transport during ns, long-term ecosystem efficiency is reduced. Biological activity may promote long- ı stream efficiency by producing continuous downstream transport of seston rather highly episodic transport.

'he efficiency of organic material processing in streams can be expressed in terms of ılling (Webster & Patten 1979). The spiralling length of organic carbon depends on factors, biological turnover and physical transport (Newbold et al. 1982; Minshall . 1983). Where biological turnover is higher, as would result from higher temperatures, spirals are tighter and even though more material is being moved downstream during non-storm conditions, the stream is more efficient. Where temperatures are lower, biological processing is slower, and material accumulates in the stream, ultimately to be physically transported from the system. Thus on the long term, higher elevation streams at Coweeta are ecologically less efficient than similar sized, lower elevation streams. This elevation factor overrides long term effects due to catchment disturbance.

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References

Bagnold, R. A., 1966: An approach to the sediment transport problem of general physics. — U. S. Geol. Survey Professional Paper No. 422-1, Washington, D. C., U. S. A.

Benke, A. C. & Wallace, J. B., 1980: Trophic basis of production among net-spinning caddisflies in a southern Appalachian stream. — *Ecology* **61:** 108—118.

Bilby, R. E., 1981: Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. — *Ecology* **62:** 1234—1243.

Bilby, R. E. & Likens, G. E., 1979: Effect of hydrologic fluctuations on the transport of fine particulate organic carbon in a small stream. — *Limnol. Oceanogr.* **24:** 69—75.

Erman, D. C. & Chouteau, W. C., 1979: Fine particulate organic carbon output from fens and its effect on benthic macroinvertebrates. — *Oikos* **32:** 409—415.

Fisher, S. G. & Likens, G. E., 1973: Energy flow in Bear Brook, New Hamsphire: An integrative approach to stream ecosystem metabolism. — *Ecol. Monogr.* **43:** 421—439.

Gurtz, M. E., Webster, J. R. & Wallace, J. B., 1980: Seston dynamics in southern Appalachian streams: Effects of clearcutting. — *Can. J. Fish. Aq. Sci.* **37:** 624—631.

Malmqvist, B., Nilsson, L. M. & Svensson, B. S., 1978: Dynamics of detritus in a small stream in southern Sweden and its influence on the distribution of the bottom animal community. — *Oikos* **31:** 3—16.

Minshall, G. W., Petersen, R. C., Cummins, K. W., Bott, T. L., Sedell, J. R., Cushing, C. E. & Vannote, R. L., 1983: Interbiome comparison of stream ecosystem dynamics. — *Ecol. Monogr.* **53:** 1—25.

Naiman, R. J. & Sedell, J. R., 1979: Characterization of particulate organic matter transported by some Cascade Mountain streams. — *J. Fish. Res. Bd. Can.* **36:** 17—31.

Newbold, J. D., Mulholland, P. J., Elwood, J. W. & O'Neill, R. V., 1982: Organic carbon spiralling in stream ecosystems. — *Oikos* **38:** 266—272.

Sedell, J. R., Naiman, R. J., Cummins, K. W., Minshall, G. W. & Vannote, R. L., 1978: Transport of particulate organic material in streams as a function of physical processes. — *Verh. Internat. Verein. Limnol.* **20:** 1366—1375.

Short, R. A. & Maslin, P. E., 1977: Processing of leaf litter by a stream detritivore: effect on nutrient availability to collectors. — *Ecology* **58:** 935—938.

Suberkropp, K., Klug, M. J. & Cummins, K. W., 1975: Community processing of leaf litter in a woodland stream. — *Verh. Internat. Verein. Limnol.* **19:** 1653—1658.

Swift, L. W., Jr. & Messer, J. B., 1971: Forest cuttings raise temperatures of small streams in the southern Appalachians. — *J. Soil Wat. Conserv.* **26:** 111—116.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R. & Cushing, C. E., 1980: The river continuum concept. — *Can. J. Fish. Aq. Sci.* **37:** 130—137.

Wallace, J. B., Ross, D. H. & Meyer, J. L., 1982: Seston and dissolved organic carbon dynamics in a southern Appalachian stream. — *Ecology* **63:** 824—838.

LLACE, J. B., WEBSTER, J. R. & CUFFNEY, T. F., 1982: Stream detritus dynamics: regulation by invertebrate consumers. — *Oecologia* (Berlin) **53:** 197—200.

BSTER, J. R., 1983: The role of benthic macroinvertebrates in detritus dynamics of streams: a computer simulation. — *Ecol. Monogr.* **53:** 383—404.

BSTER, J. R., GURTZ, M. E., HAINS, J. J., MEYER, J. L., SWANK, W. T., WAIDE, J. B. & WALLACE, J. B., 1983: Stability of stream ecosystems. — In: BARNES, J. R. & MINSHALL, G. W. (eds.), *Stream Ecology Application and Testing of General Ecological Therory:* 355—395. Plenum, New York.

BSTER, J. R. & PATTEN, B. C., 1979: Effects of watershed perturbation on stream potassium and calcium dynamics. — *Ecol. Monogr.* **49:** 51—72.

BSTER, J. R. & WAIDE, J. B., 1982: Effects of forest clearcutting on leaf breakdown in a southern Appalachian stream. — *Freshwat. Biol.* **12:** 331—344.

hors' address:

Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, U. S. A.

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