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LOCATION:	**CSL :: Grand :: GRANDDEPOS BOOKSTACKS**
TYPE:	Article CC:CCL
JOURNAL TITLE:	Journal of the Fisheries Research Board of Canada
USER JOURNAL TITLE:	Canadian journal of fisheries and aquatic sciences
CSL CATALOG TITLE:	Journal of the Fisheries Research Board of Canada.
ARTICLE TITLE:	Autotrophic production in Carnation Creek, a coastal rainforest stream on Vancouver Island, British Columbia
ARTICLE AUTHOR:	Stockner,
VOLUME:	33
ISSUE:	
MONTH:	
YEAR:	1976
PAGES:	1553-
ISSN:	0015-296X
OCLC #:	
CROSS REFERENCE ID:	404282
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Autotrophic Production in Carnation Creek, a Coastal Rainforest Stream on Vancouver Island, British Columbia

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STOCKNER, J. G., AND K. R. S. SHORTREED. 1976. Autotrophic production in Carnation Creek, a coastal rainforest stream on Vancouver Island, British Columbia. J. Fish. Res. Board Can. 33: 1553–1563.

Attached algal growth in Carnation Creek and its estuary were monitored in 1974 and 1975 as part of the Carnation Creek Experimental Watershed Project. Net production on the estuary was 17.8 μg organic matter (org)·cm^{-2}·day^{-1}, and in Carnation Creek the average was 3.4 μg org·cm^{-2}·day^{-1}. Algal growth in Ritherdon Creek, located in an adjacent logged watershed, was slightly higher (4.6 μg org·cm^{-2}·day^{-1}) than the Carnation Creek average. In a streamside nutrient enrichment experiment, nitrate and phosphate concentrations in one trough were increased to twice the normal Carnation Creek values present in the control. In 35 days the nutrient-enriched trough had a total algal volume 3 times that of the control. It is suggested that extremely low nutrient concentrations (especially phosphate), and secondarily, poor light conditions under the canopy, are responsible for the paucity of algal growth in Carnation Creek. Major loss of algae from the system is caused by periodic freshets which scour the stream bed. Losses by grazing herbivorous insects were considered negligible. Dominant diatoms in Carnation Creek were *Achnanthes minutissima*, *Synedra ulna*, *Hannaea arcus*, *Diatoma hiemale*, and *Eunotia pectinalis*. *Ulothrix* sp., *Draparnaldia* sp., and *Mougeotia* sp. were the dominant filamentous green algae. Net production and algal biomass (chlorophyll *a*) in Carnation Creek are among the lowest ever reported in the literature.

STOCKNER, J. G., AND K. R. S. SHORTREED. 1976. Autotrophic production in Carnation Creek, a coastal rainforest stream on Vancouver Island, British Columbia. J. Fish. Res. Board Can. 33: 1553–1563.

Nous avons suivi de façon continue la croissance d'algues fixées dans le ruisseau Carnation et son estuaire en 1974 et 1975, comme partie du Projet du bassin expérimental du ruisseau Carnation. La production nette dans l'estuaire est de 17.8 μg de matière organique (org)·cm^{-2}·jour^{-1}, et dans le ruisseau Carnation la moyenne est de 3.4 μg org·cm^{-2}·jour^{-1}. La croissance algale dans le ruisseau Ritherdon, situé dans un bassin avoisinant où se fait le flottage de billots, est légèrement plus élevée (4.6 μg org·cm^{-2}·jour^{-1}) que la moyenne du ruisseau Carnation. Dans une expérience d'enrichissement en substances nutritives sur le bord du cours d'eau, nous avons augmenté dans une auge les concentrations de nitrates et de phosphates à un niveau deux fois plus élevé que le niveau normal du ruisseau Carnation présent dans l'auge témoin. Après 35 jours, l'auge enrichie de substances nutritives a un volume total d'algues 3 fois plus grand que celui de l'auge témoin. Nous suggérons que la pauvreté en algues du ruisseau Carnation est due à des concentrations extrêmement basses de substances nutritives (surtout phosphates), et secondairement à de pauvres conditions d'éclairage sous le canapé. Les crues périodiques qui balayent le lit du cours d'eau sont responsables de la majeure partie de la perte d'algues dans le système. Les pertes causées par les insectes herbivores brouteurs sont considérées comme négligeables. Les diatomées dominantes du ruisseau Carnation sont *Achnanthes minutissima*, *Synedra ulna*, *Hannaea arcus*, *Diatoma hiemale* et *Eunotia pectinalis*. *Ulothrix* sp., *Draparnaldia* sp. et *Mougeotia* sp. sont les algues vertes filamenteuses dominantes. La production nette et la biomasse algale (chlorophylle *a*) du ruisseau Carnation sont parmi les plus faibles jamais signalées dans la littérature.

Received January 23, 1976
Accepted March 31, 1976

Reçu le 23 janvier 1976
Accepté le 31 mars 1976

Printed in Canada (J4165)
Imprimé au Canada (J4165)

STUDIES were initiated in March 1974 to assess attached algal growth and production in Carnation Creek Experimental Watershed, Vancouver Island, B.C. The 1974 program was the 5th consecutive yr of intensive prelogging data collection on Carnation Creek, and the last year the watershed remained undisturbed. The overall objectives of the Carnation Creek Project are: a) to develop a better understanding of how undisturbed coastal rainforest–salmonid stream ecosystems work in order; b) to explain and quantity the impacts of timber production activities on stream environments and their capacity to produce salmonid fishes in sufficient detail; and c) to provide continuous input to the further development of integrated resource management guidelines (Narver 1974).

Within the scope of these broad objectives was the assessment of prelogging autotrophic stream production including an appraisal of factors known to influence attached algal growth and distribution in these ecosystems.

Description of Study Area

Carnation Creek flows into Barkley Sound on the west coast of Vancouver Island, B.C. The watershed is in the western hemlock biogeoclimatic subzone with a very high annual rainfall of 2.8–3.6 m (Fig. 1). Stream flow is highly variable, ranging from .025 in summer to 39 $m^3 s^{-1}$ during winter freshet. The stream supports small populations of resident cutthroat trout (*Salmo clarki*) in its upper reaches, and is accessible for only 3 km to anadromous fish, namely chum salmon (*Onchorhynchus keta*), coho salmon (*O. kisutch*), and steelhead trout (*S. gairdneri*). The watershed area is approximately 10 km^2, and contains no lakes.

Methods

The extreme ranges of flow common in Carnation Creek necessitated use of samplers capable of withstanding considerable variation in flow velocity. Concrete blocks 31 × 31 × 18 cm with two threaded steel pins embedded in their upper surfaces were constructed (Fig. 2A). Each block weighed between 45 and 50 kg. Plates of 1-cm thick plexiglass were bolted to the pins, 5–7 cm above the surface of the block. The upper surfaces of the plexiglass plates were roughened with fine steel wool and divided into four 100-cm^2 quadrants (Fig. 2B).

Six samplers were placed in Carnation Creek in a variety of habitats within predefined study areas (Table 1). Two were placed in Ritherdon Creek in an adjacent watershed that was clear-cut logged and burned to the stream edge in 1969. Remaining samplers (two in 1974 and four in 1975) were placed at various tidal heights on the Carnation Creek estuary (Table 1; Fig. 1). At each station the sampler was embedded in gravel to a depth of about

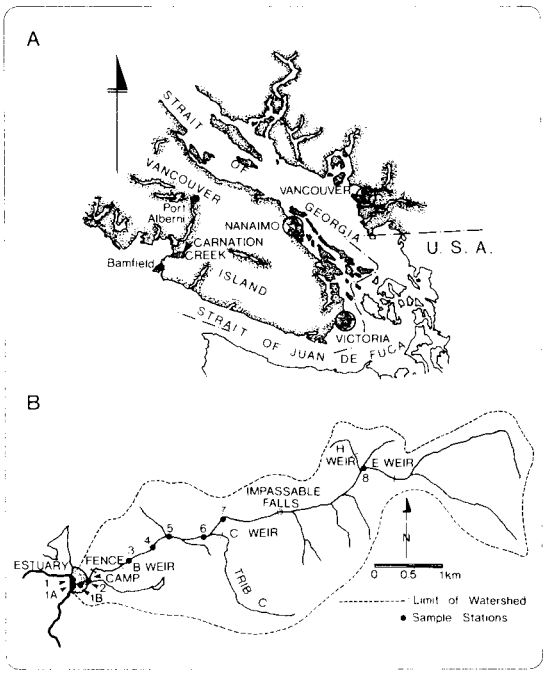

FIG. 1. Southern portion of Vancouver Island showing location of Carnation Creek, and detailed map of Carnation Creek watershed with station locations.

18 cm. The corner of the block was placed perpendicular to the direction of streamflow to reduce resistance and ensure a more even flow over the plexiglass plate.

In 1974 sampling intervals varied from 2 wk at times of high production (good light, low flow), to 4 wk during periods of low production (high flow and/or low light). In 1975 samples were obtained at monthly intervals. It was initially assumed and later verified, that time between sampling periods (3–4 wk) was of sufficient duration to enable a relatively stable population to develop.

Sampling consisted of removing the plexiglass plate from the block, scraping the accumulated growth from each quadrant into a glass jar, and immediately returning the cleaned plexiglass plate to the block. The most efficient scraper was a clean glass microscope slide.

The contents of one jar were filtered onto a 5.5-cm Whatman glass fiber filter. One milliliter of saturated $MgCO_3$ solution was added to prevent acidification prior to analysis. Filters were folded, placed in aluminum weighing dishes, and frozen. Chlorophyll was extracted using methods of Yentsch and Menzel (1963), with minor modifications used when algal growth was exceptionally heavy. Filters were macerated in a tissue grinder with 10 ml of 90% acetone, and the filtrate was analyzed for chlorophyll *a* on a Cary (Model 15) recording

FIG. 2. A,
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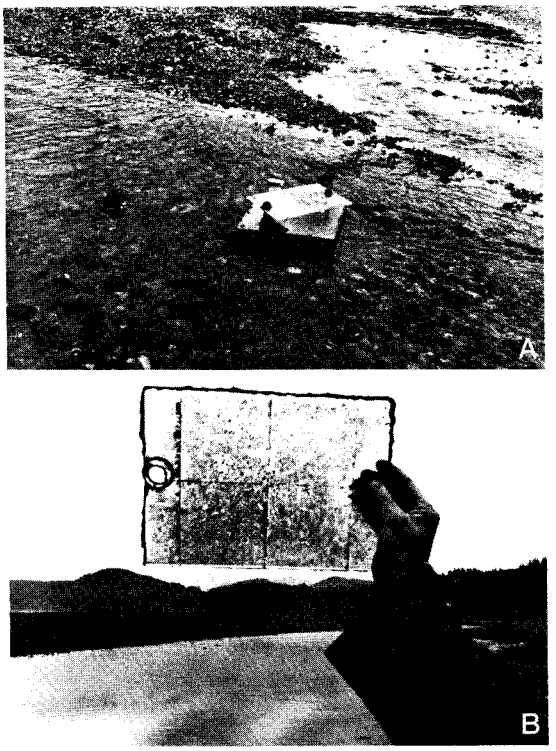

FIG. 2. A, Sampler with plexiglass plate attached; B, Plexiglass plate prior to sampling after 4-wk growth.

spectrophotometer. The equation of Strickland and Parsons (1968) was used to calculate chlorophyll *a*.

The contents of one jar were filtered onto an ashed and weighed 5.5-cm Whatman glass fiber filter. Filters were folded, placed in aluminum weighing dishes, and frozen. Samples were dried at 105 C to constant weight, weighed, ashed at 500 C for 4 h in a muffle furnace, and weighed again. Values are expressed as ash-free dry weight (organic = loss-on-ignition) cm^{-2}.

Net production (accumulation) was estimated by dividing total organic accumulation over a given sampling interval by the number of days in the interval. Values are expressed as micrograms organic matter cm^{-2} day^{-1}. For purposes of comparison with literature values, carbon was estimated as 50% of organic (loss on ignition) weight (Stockner and Armstrong 1971).

Lugol's acetate solution was added to two of the jars. A portion of the algae from one jar was counted using a Zeiss inverted plankton microscope (160 and 470×). This count determined relative abundance of major algal groups and identified nondiatom algae to the genus level.

Permanent quantitative Hyrax mounts of diatoms were made from one 100-cm^2 quadrat. Counts from these slides were converted to number of diatoms·cm^{-2} using methods described by Stockner and Armstrong (1971). The abundance of diatoms relative to other algal groups, calculated from inverted microscope counts, was applied to this value to give total algal cells·cm^{-2}. Algal volumes were determined using values calculated by Nauwerck (1963), and by Evans and Stockner (1972), although some direct volume estimates were made by the authors.

The relative abundance of each diatom species was calculated and used in a "distance" index (MacIntosh 1967), to compare similarities between diatom communities in the stream.

Light to the canopy (overstory) was measured using a Belfort recording pyrheliometer placed on a clear-cut-logged hill beside the Carnation Creek estuary. A second pyrheliometer was placed for 2 wk beside the first (for calibration), and then for 2-wk intervals beside each stream sampler under the forest canopy and in Ritherdon. Using these data, percentage of total available light reaching the samplers was calculated for each sampling interval (Table 1).

Current velocity was measured at only one level of flow (0.23 $m^3 \cdot s^{-1}$) by recording the average time taken for a small stick to travel 1 m. Temperature was recorded on a Lambrecht distance thermograph (Model 256).

Nutrient concentrations, major ions, and stream discharge were monitored throughout the study using methods and instrumentation described by Scrivener (1975).

In August and September 1975 a streamside nutrient enrichment experiment was conducted in Carnation Creek. Creek water from B weir (Fig. 1), was piped into a header-box, split equally into two chambers, and discharged onto two identical troughs 3.5 m long × 15 cm wide, with 5-cm sides). A concentrated solution of $NaNO_3$ and Na_2HPO_4 in an N:P ratio of 11:1 was dripped into one chamber of the header-box to produce concentrations in one trough approximately double mean nitrate and phosphate concentrations in natural Carnation Creek water.

Prior to any nutrient additions, each trough had 4 wk to establish an attached algal community. Sampling consisted of removing all accumulated growth from a known area (usually 100 cm^2) on each trough at weekly intervals. Each sample came from upper undisturbed portions of each trough. Each sample was split into four equal portions which were used for determination of chlorophyll *a*, ash-free dry weight, and algal numbers, volume, and species composition.

Results

Percentage of total available light that actually reached the samplers in Carnation Creek ranged from 5% at Station 8, with heavy canopy and understory, to 47% at Station 3, with moderate canopy openings and little overhanging streamside vegetation (Table 1). Stations 4, 5, 6, and 7 had similar light conditions with reductions by

TABLE 1. Salient information on station locations in Carnation and Ritherdon creeks, 1974 and 1975.

Station no.	Location	Description	Current velocity cm · s^{-1} (at low flow)	% available light
		Estuary		
1	extreme edge of estuarine fan	predominantly marine 10 m from creek channel exposed on a 0.8-m tide	—	100
1A	extreme edge of estuarine fan	predominantly marine in creek channel exposed on a 0.6-m tide	—	100
1B	100 m from edge of fan	brackish	—[a]	100
2	edge of forest canopy	brackish	—[a]	65
		Carnation		
3	630 m	pool	9	47
4	1150 m	run	24	39
5	1480 m	pool	11	37
6	2000 m	riffle	64	42
7	2350 m	run	36	36
8	4500 m	pool	4	5
		Ritherdon		
9		riffle	56	72
10		pool	20	72

[a]Current flow variable, dependent on tide level.

forest canopy of 40, 39, 40, and 36%, respectively. Stations on the estuary received full sunlight, while Station 2, on the edge of the estuary was beneath streamside vegetation and received only 65% of available light. Both stations in clear-cut-logged Ritherdon Creek received 72% of total available light.

Late fall, winter, and early spring discharges in Carnation Creek were extremely variable, with an annual mean of 1.56 m^3·s^{-1} (Fig. 3). Station 1 on the estuary fan was away from any direct current influence, but was subject to considerable wave action. Flow velocity over Stations 1B and 2 was dependent upon tidal height, but never exceeded 35 cm s^{-1}. Velocity of flow over samplers in Carnation ranged from 4 cm s^{-1} at Station 8 to 64 cm s^{-1} at Station 6 (Table 1).

An arbitrary classification of current velocities into pool (0–20 cm s^{-1}), run (21–45 cm s^{-1}), and riffle (46–100 cm s^{-1}) was made. Stations 3, 5, and 8 were located in pools, Station 4 and 7 in runs, and Station 6 in a riffle. Stations 9 and 10 in Ritherdon Creek were in riffle and pool, respectively (Table 1). This classification is probably an accurate representation of conditions during summer low-flows, but not during most winter flows or sudden freshet periods.

Water temperature at B weir (Fig. 1) ranged from lows of 2.0 C in January to highs of 12 C in August in both years (Fig. 3). Diurnal stream temperature variation did not exceed 2.5 C. Temperatures in Ritherdon Creek ranged from winter lows of 2.0 C to summer highs of 18 C. Diurnal variation in Ritherdon was up to 4.0 C in summer.

Water temperatures on the estuary were subject to greater seasonal and diurnal variation because of tidal conditions, variable stream flow, and more open exposure to direct sunlight.

Dominant major ions in Carnation are calcium, sodium, bicarbonate, chloride, silicate, and sulfate, with only trace amounts of iron, manganese, potassium, and magnesium (Scrivener 1975). The extremely low total dissolved solids value in both Carnation and Ritherdon creeks is indicative of the oligotrophic nature of surface water discharges from both watersheds (Table 2).

Nutrient concentrations in both Carnation and Ritherdon creeks are very low, with silicate the most abundant nutrient (Table 2). Almost all of

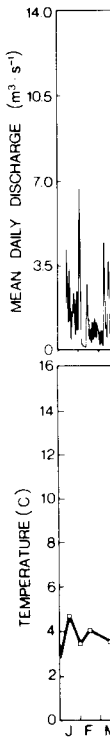

FIG. 3. M
weir, in Ca

TABLE 2. Water chemistry, Carnation and Ritherdon creeks.

	Mean values Carnation July 1971–May 1974[a]	Mean values Carnation from six dates in 1975[b]	Mean values Ritherdon from same six dates in 1975[b]
Major ions ($mg \cdot liter^{-1}$)			
Ca^{2+}	3.0	2.6	4.3
Mg^{2+}	0.5	0.6	0.6
Na^{+}	2.0	2.3	1.9
K^{+}	0.1	0.2	0.4
Cl^{-}	2.4	3.1	3.4
Fe^{3+}	0.04	0.01	0.04
Mn^{2+}	<0.01	<0.01	<0.01
SO_4^{2+}	3.7	3.2	4.7
HCO_3^{-}	8.4	—	—
Nutrients ($\mu g \cdot atoms \cdot liter^{-1}$)			
NO_3^{-}(N)	2.50	3.13	7.89
NH_4^{+}(N)	0.30	0.40	0.40
TP	0.05	0.09	0.11
SiO_2	34.0	24.8	24.2
TDS ($mg \cdot liter^{-1}$)	25.0	27.8	36.3

[a]After Scrivener (1975).
[b]J. C. Scrivener unpublished data.

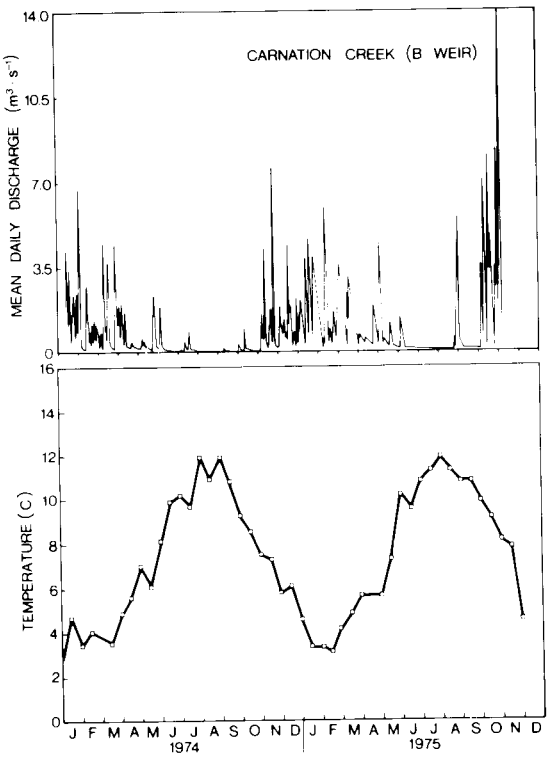

FIG. 3. Mean daily discharge and temperature at B weir, in Carnation Creek, 1974 and 1975.

the total phosphorus measured was dissolved orthophosphate with a mean concentration of 0.05 μg atoms liter^{-1}, ranging from <0.01 to 0.29 μg atoms liter^{-1}. The mean nitrate concentration was 2.5 μg atoms liter^{-1}, with concentrations varying from lows of 0.5 to highs of >6.0 μg atoms liter^{-1}. With the exception of some freshet periods, nitrate and silicate concentrations showed a significant inverse relation with discharge (Scrivener 1975). Ritherdon Creek displayed slightly higher values of most dissolved constituents than Carnation (Table 2).

Mean chlorophyll *a* concentrations for both years in Carnation Creek estuary were nearly an order of magnitude greater than either Carnation or Ritherdon creeks (Table 3). Lowest mean concentrations were at Station 8, under heavy forest canopy, 0.21 $\mu g \cdot cm^{-2}$, and highest at Station 1A on the estuary, 3.99 $\mu g \cdot cm^{-2}$. Mean values for Carnation Creek were slightly lower than Ritherdon Creek values for both years.

Seasonally, greatest concentrations on the estuary and in Carnation occurred during an exceptionally warm, dry fall in 1974, while in Ritherdon Creek concentrations were highest in May and June of 1974 (Fig. 4). In 1975 the estuary showed peak values from February to April, while Carnation and Ritherdon creeks displayed little seasonal variation.

Mean ash-free dry weight value on the estuary

TABLE 3. Mean values of attached algal biomass, net production, and percentage diatoms at 10 stations in study area in 1974 and 1975. Grand means for estuary (Stations 1, 1A, 1B, 2), Carnation Creek (Stations 3–8), and Ritherdon Creek (Stations 9 and 10) listed below station means.

Station	Chlorophyll *a* ($\mu g \cdot cm^{-2}$)	Ash-free dry wt ($\mu g \cdot cm^{-2}$)	Algal cells ($no. \cdot cm^{-2}$)	Diatoms ($no. \cdot cm^{-2}$)	Algal vol ($mm^3 \cdot cm^{-2}$)	% of Diatoms in Total vol	Net production ($\mu g\ org \cdot cm^{-2}\ day^{-1}$)
1	1.73	805	2.23×10^6	1.62×10^6	1.53	92	30.9
1A[a]	3.99	635	1.25×10^6	9.89×10^5	0.88	90	18.8
1B[b]	0.46	344	2.18×10^6	1.16×10^6	0.54	86	10.8
2	1.26	302	3.04×10^6	1.48×10^6	0.96	66	10.7
3	0.19	110	1.28×10^6	2.20×10^5	6.93×10^{-2}	54	4.2
4	0.12	100	8.13×10^5	1.85×10^5	5.45×10^{-2}	70	3.9
5	0.19	144	1.01×10^6	2.79×10^5	6.16×10^{-2}	52	5.5
6	0.12	38	4.55×10^5	7.80×10^4	3.19×10^{-2}	56	1.6
7	0.21	86	9.56×10^5	2.11×10^5	7.53×10^{-2}	52	3.5
8	0.09	43	1.10×10^5	2.41×10^4	6.55×10^{-3}	68	1.6
9	0.19	98	6.55×10^5	3.54×10^5	2.26×10^{-1}	78	4.0
10	0.26	138	7.34×10^5	3.68×10^5	9.83×10^{-2}	69	5.2
				Grand means			
1[b]	1.72	533	2.52×10^6	1.49×10^6	1.18	82	17.8
2	0.16	87	8.02×10^5	1.66×10^5	4.99×10^{-2}	60	3.4
3	0.23	118	6.95×10^5	3.61×10^5	1.62×10^{-1}	74	4.6

[a]1975 only.
[b]1, Carnation Creek estuary; 2, Carnation Creek; 3, Ritherdon Creek.

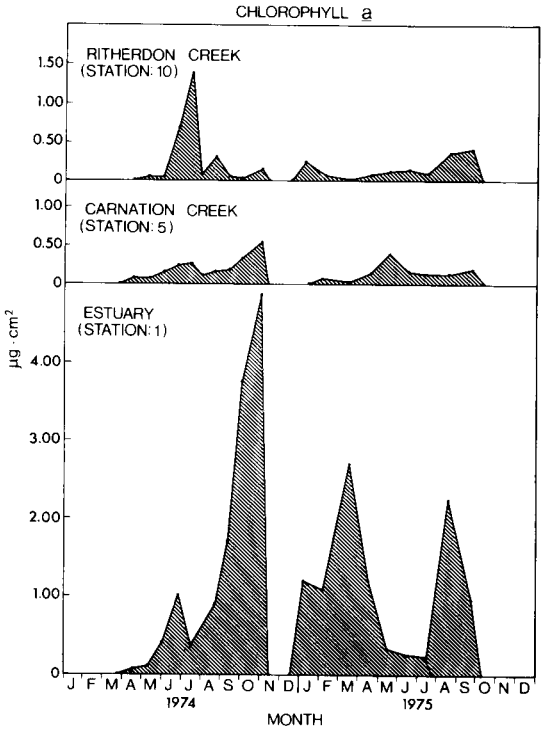

FIG. 4. Seasonal variation in chlorophyll *a* concentration at Stations 1, 5, and 10 in estuary, Carnation Creek, and Ritherdon Creek, respectively.

for both years was 533 $\mu g\ org \cdot cm^{-2}$, which was over 6 times the Carnation Creek values, and 5 times the Ritherdon Creek value (Table 3). Highest values were at Station 1 on the estuary, and lowest at Station 8 under heavy forest canopy (Table 3). Seasonal variation was similar to that discussed for chlorophyll *a* (Fig. 4).

Diatoms were the dominant algal group by volume in all habitats in Carnation and Ritherdon creeks. *Achnanthes minutissima* was the dominant species at all stations except on the estuary, where a more diverse diatom assemblage occurred, with no single species dominant.

The most common diatoms on the estuary were *Cocconeis* spp., *Licmophora* spp., *Nitzschia* spp., *Navicula* spp., and *Synedra tabulata*. Diatoms occurring commonly in Carnation Creek were *Diatoma hiemale*, *Fragilaria* sp., *Eunotia pectinalis*, *E. tenella*, *Gomphonema parvulum*, *S. ulna*, and *Tabellaria flocculosa*. *Synedra ulna* and *D. elongatum* were more abundant in Ritherdon than in Carnation Creek. A complete species list is presented in Table 4.

The most common nondiatom algae were *Microcystis* sp. and an unidentified flagellate in a gelatinous matrix closely resembling *Chromulina* sp. Filamentous chlorophytes such as *Draparnaldia* sp., *Mougeotia* sp., and *Ulothrix* sp. were more prevalent in Ritherdon than Carnation, at times forming a mat covering large areas of creek

TABLE 4. Species list and computed volumes of attached algae in Carnation Creek, Ritherdon Creek, and Carnation Creek estuary (Volume computed for dominants only).

Diatoms	Vol (μ^3)
Carnation and Ritherdon creeks	
Achnanthes lanceolata (Breb). Grun.	50
A. minutissima Kutz	30
Achnanthes sp.	20
Capartogramma crucicula (Grun. ex Cl.) Ross	—
Cocconeis placentula Ehr.	240
Cymbella turgida (Gregory) Cleve.	200
C. ventricosa Kutz	2500
Cybella sp.	500
Diatoma heimale (Roth) Heib.	450
D. elongatum (Lyngb.) Ag	250
Eunotia diodon Ehr.	—
E. lunaris (Ehr.) Grun.	1500
E. pectinalis (Kutz.) Rabh.	700
E. perpusilla Grun.	300
E. sudetica O. Mull.	200
E. tenella (Greve) Cleve	50
Fragilaria sp.	100
Frustulia rhomboides var. saxonica (Rabh.) Det.	3000
F. rhomboides var. capitata (A. Mayer) Patr.	2000
Gomphonema constrictum (Ehr.) V.H.	1000
G. lanceolatum Ehr.	2000
G. parvulum Kutz	300
Hannaea arcus (Ehr.) Patr.	500
Meridion circulare var. constrictum (Ralfs) V.H.	200
Navicula sp.	400
Nitzschia sp. A	800
Nitzschia sp. B	50
Stauroneis phoenicenteron (Nitz.) Ehr.	—
Stauroneis sp.	—
Synedra ulna (Nitz.) Ehr.	3300
Synedra sp.	—
Tabellaria fenestrata (Lyngb.) Kutz.	3000
T. flocculosa (Roth.) Kutz.	1000
Nondiatom algae	
Batrachospermum sp.	—
Draparnaldia sp.	—
Microcystis sp.	20
Mougeotia sp.	200
Oscillatoria sp.	4
Rhizoclonium sp.	—
Spirogyra sp.	—
Ulothrix sp.	170
Zygnema sp.	—
Unidentified colonial flagellate	50
Diatoms	
Carnation Creek Estuary	
Achnanthes brevipes Agardh.	1000
Amphiprora surrirelloides Hendey	—
Amphora sp.	—
Biddulpjia laevis Ehr.	—
Caloneis sp.	—
Cocconeis placentula var. lineata (Ehr.) V.H.	240
Cocconeis sp.	—
Coscinodiscus radiatus Ehr.	—

TABLE 4. (*Concluded*)

Diatoms	Vol (μ^3)
Carnation Creek Estuary	
Diploneis sp.	—
Grammatophora serpentina Ehr.	600
Licmophora gracilis (Ehr.) Grun.	7000
Melosira juergensii Agardh	4000
M. nummuloides Agardh	7000
Navicula inflexa	50
N. clementis	50
Navicula sp.	—
Nitzschia bilobata Wm. Smith	1000
Pleurosigma elongatum Wm. Smith	—
Rhiocosphenia sp.	—
Surirella ovata Kutz	1500
Synedra pulchella Kutz	2000
S. tabulata (Agardh.) Kutz	3000
Nondiatom algae	
Enteromorpha sp.	—
Fucus sp.	—
Pylaiella sp.	—
Ulothrix sp.	170

bed. The rhodophyte *Batrachospermum* sp. was observed at irregular intervals in both Carnation and Ritherdon creeks. *Ulothrix* sp. was common in early spring and late fall, but was rarely observed in summer months. A detailed discussion of algal succession and species composition appears in Stockner and Shortreed (1975).

The greatest volume of algae occurred on the estuary, where the mean for both years was 1.18 $mm^3 \cdot cm^{-2}$. Ritherdon Creek had a slightly higher mean algal volume than Carnation (Table 3).

The percentage of total algal volume contributed by diatoms varies seasonally (Stockner and Shortreed 1975). Diatoms were least important early in the year, increasing steadily to gain dominance at most stations during low-flow periods.

There was nearly an order of magnitude difference in mean algal density for both years between Carnation estuary and Creek stations (Table 3). The mean value for Ritherdon was twice the Carnation Creek value. There was no well-defined period of maximum algal abundance (Stockner and Shortreed 1975).

Greatest growth was noted on the estuary, notably in September 1974, and in March and August 1975 (Table 3; Fig. 4). Algal growth rates in Carnation and Ritherdon creeks were much lower than those seen on the estuary and showed no clear seasonal maxima.

Stations 3, 4, and 5 in Carnation Creek were most similar to one another, with mean values

of D_{ih} for both years ranging from 16 to 22 (Table 5). Stations on the estuary showed a greater similarity to one another than to any other stations in Carnation or Ritherdon creeks. Station 10 in Ritherdon was most similar to Stations 3, 4, and 5 in Carnation Creek (Table 5).

There was a marked difference between algal growth in the control and enriched troughs (Fig. 5). After 35 days there were 3 times as many diatoms, 3 times the total algal volume, and over twice the amount of chlorophyll and organic matter·cm^{-2} on the nutrient-enriched trough than on the control trough. The nitrogen and phosphorus content in the enriched side was always double the Carnation Creek values, and differences in nitrate values between enriched and control troughs showed greater variation than did phosphate (Fig. 5A).

Discussion

If light were the major factor limiting algal growth then removal of the forest canopy would result in an immediate increase in production. This has happened only to a limited extent in Ritherdon Creek, on the adjacent clear-cut-logged watershed, which suggests that factors other than light may be limiting algal growth in these streams. Nonetheless, the importance of light to algal growth in Carnation Creek and estuary is demonstrated by the significant, positive relation between mean chlorophyll *a* (biomass) and percent light reduction by forest canopy at each station for both years (Fig. 6).

Values from Carnation Creek Stations 3–8 are clustered near the ordinate and represent a low light–low chlorophyll condition. Values from the estuary are separated from the other and represent a high light–high chlorophyll, as well as high nutrient situation. When Ritherdon Creek values are plotted (Fig. 6), the relation is no longer significant. This is because it is likely that nutrients, not light, prevent greater growth in Ritherdon, and produce the observed high light–low chlorophyll condition.

Another interesting observation was the relation between available light and contribution of diatoms to total algal volume (Fig. 7). These data suggest that diatoms, as a group, are better adapted to a moderate to high light situation, than to poor, diffuse light conditions under the canopy.

We consider nutrients the major factor regulating attached algal growth in both Carnation and Ritherdon creeks. Nutrient content of both systems is remarkably low; in fact, all dissolved constituents are present at extremely low levels (Table 2). Greatest algal growth occurred on the Carnation Creek estuary, an area which receives,

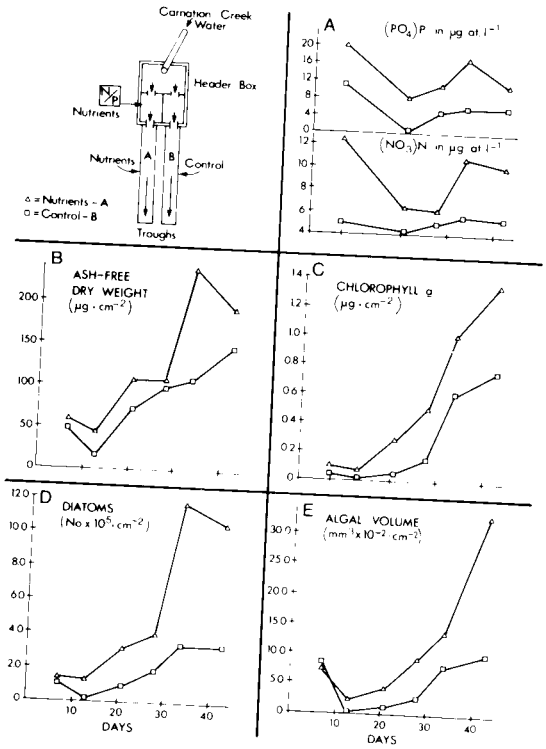

FIG. 5. Nutrient enrichment experiment: diagram of apparatus used and plots of A, nutrient concentrations; B, ash-free dry weight; C, chlorophyll *a*; D, number of diatoms; E, and algal volume; for both experimental and control troughs.

Table 5 set up as an illustration.

Table 5. Matrix of 1974-75 mean distance index[a] (D_{jh}) values for Carnation and Ritherdon creeks.

$$D_{jh} = \sqrt{\sum_{i=1}^{s} \left(X_{ij} - X_{ih}\right)^2}$$

Distance Index

where: D_{jh} = degree of difference between the jth and h^{th} community s_i

X_{ij} = abundance of ith taxonomy in the jth community

s = number of taxa.

STATIONS	1A	1B	2	3	4	5	6	7	8	9	10
1A		49									
1B	63		63								
2	68	62		70							
3	90	96	96		61						
4	92	97	82	63		21					
5	90	94	95	60		16	22				
6	79	80	87	56		62	44	62			
7	87	89	94	60		30	35	33	48		
8	87	88	79	63		52	40	50	52	46	
9	86	65	81	65		73	62	70	72	78	76
10	98	99	100	67		24	25	22	63	31	48	50

[a] MacIntosh (1967).

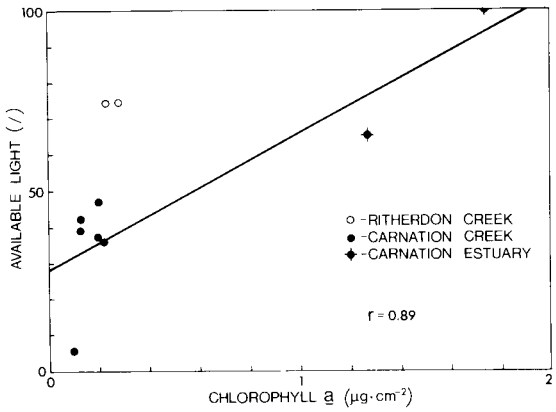

FIG. 6. Linear regression of mean chlorophyll *a* concentration for both 1974 and 1975 and percentage light penetration through the canopy for both years. Ritherdon values not included in regression.

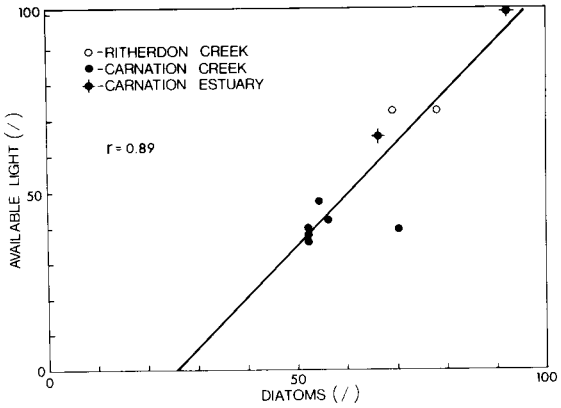

FIG. 7. Linear regression of percentage diatoms of total algal volume and percentage light penetration through the canopy for both years.

in addition to plentiful light, an abundant supply of nutrients from sea water. In Carnation Creek it is likely that phosphate and low light limit growth at all stations, while in Ritherdon phosphate alone limits growth.

The nutrient enrichment experiment demonstrated the response of attached algae to increased nitrate and phosphate concentrations under normal light conditions beneath the forest canopy (Fig. 5). Each nutrient was not tested separately so that relative importance of each cannot be separated at this time. However, because phosphorus is at or near the detection limit throughout much of the year, while nitrate values remain considerably higher, we consider phosphorus concentrations more critical than nitrate in both streams.

There was little diurnal or seasonal variation in water temperature in Carnation and though Ritherdon showed greater variations, annual mean temperatures of both streams were similar. It is unlikely that temperature plays a significant role in limiting production in either stream.

Export of particulate matter in Carnation Creek increases as a linear function of flow, but most of the material is allochthonous (P. Neaves unpublished data). Accumulations of algae on substrates are susceptible to export when flow increases suddenly (freshet). However, Carnation and Ritherdon creeks are so unproductive that in spring and summer visible accumulations of algae are difficult to perceive with the naked eye. Though some losses occur during infrequent freshets in May and June, we suspect that during the growing season (April–October) flows are so low (average 0.23 $m^3 \cdot s^{-1}$) that losses by physical means are negligible.

We made no direct quantitative assessment of grazing rates by streams invertebrates, but did note the direct utilization of attached algae by several species, notably the stonefly *Alloperla severa* and the mayflies *Cinygmula* sp. and *Baetis* sp. From numerous in situ observations and stomach content analysis, grazing losses are apparently not substantial, and account at most for a 5–10% loss of attached algae over a given sampling interval.

If growth in both streams were more rapid and biomass greater, competition for stable substratum could play some role in limiting populations of certain species. However, we feel nutrients and light prevent algal populations from reaching a density where space limitation becomes a problem.

There are few comparable data on Pacific rainforest streams for meaningful comparison of algal communities. Many of the dominants in Carnation or Ritherdon creeks, namely *Achnanthes minutissima*, *Synedra ulna*, and *Diatoma spp.* are also abundant in streams of the Alsea watershed on the Oregon coast (Hansmann 1969). However, there is little similarity in species composition of Carnation and Ritherdon creeks and the flora of artificial streams in Oregon studied by McIntire and Phinney (1965).

Some species displayed rather clear habitat preferences in Carnation and Ritherdon. *Achnanthes minutissima* and *D. heimale* were common in all locations in Carnation under the canopy, except in riffles, where *Hannaea arcus* was dominant. *Diatoma elongatum*, *S. ulna*, and *Tabellaria flocculosa* were more common in Ritherdon than in Carnation suggesting a preference for high

TABLE 6. Comparison of chlorophyll *a* and net production accumulation of attached algal communities, and average nutrient content of water from a variety of habitats.

Community	Chlorophyll *a* (*mg Chlorophyll a* · m^{-2})	Net production (*mgC* · m^{-2} · day^{-1})	Nutrients (*μg atoms* · $liter^{-1}$)	
			$(NO_3)N$	$(PO_4)P$
Carnation Creek	1.6	20	2.5	.05
Ritherdon Creek	2.3	30	5.2	.03
Carnation Estuary	10.7	120	7.0	.70
ALSEA streams, Oregon natural substrate (Hansmann 1969)	60	380–580	13.8	.41
Laboratory Streams, Oregon				
Light adapted	480–2010	1200–3000	4.8	.31
Shade adapted (McIntire and Phinney 1965)	140–1300	800–1900	4.8	.31
Logan River, Utah (McConnell and Sigler 1959)	300–1420	2000–8000	16.1	2.08
Silver Springs, Florida (Odum 1957)	2950	10000	7.4	.20

light conditions. In ultraoligotrophic lakes, diatoms tend to be less numerous than small motile chrysophytes and dinoflagellates (Schindler and Holmgren 1971). In Carnation Creek, although diatoms were common, there was a greater number of algae from other groups, namely chlorophytes and chrysophytes. In Ritherdon Creek and on the Carnation estuary, diatoms were the dominant group throughout the year. In both lenthic and lotic aquatic habitats, poor nutrient conditions tend to reduce the importance of diatoms relative to other algal groups.

The composition of algal communities on the Carnation estuary went from strictly marine species (Station 1) to a community composed of species known to be tolerant to brackish water e.g. *Melosira nummuloides*, *S. tabulata*, and *Surirella ovata* (Pomeroy 1974).

Average values of chlorophyll *a*, net production, and water nutrient content from Carnation Creek and estuary and Ritherdon Creek were among the lowest recorded in the literature (Table 6). In a comparative evaluation of chlorophyll *a* content of attached algae from a variety of habitats by Moss (1968) and Odum et al. (1958), values for Carnation and Ritherdon creeks were lower than attached algal communities growing on arctic sea ice (10–12 $mg \cdot m^{-2}$) (Appolonio 1965, as cited by Moss 1968) Among the highest chlorophyll *a* and production values were from Silver Springs, Florida (Table 6).

Values from the Alsea watershed in western Oregon were considerably higher, likely because of the higher nutrient content of these streams (Table 6). The upper threshold of autotrophic production in flowing waters occurs in tepid springs with abundant nutrients and light, while the lower limit occurs in the nutrient poor conditions typified by Carnation and Ritherdon creeks.

Other evidence of the oligotrophic nature of Carnation Creek can be seen in fisheries and stream benthos data. Juvenile coho salmon normally spend a year in the native stream prior to seaward migration, but in Carnation Creek about 50% require 2 yr to reach sufficient size to migrate (Narver and Anderson 1974). The stoneflies *Alloperla* sp. and *Capnia* sp. have a 1-yr life cycle in most British Columbia streams, but in Carnation Creek have a 2-yr cycle (J. C. Scrivener unpublished data). These observations substantiate our conclusions on autotrophic production and collectively provide sufficient evidence to indicate that these ecosystems are among the least productive ever studied at temperate latitudes.

Acknowledgments

We acknowledge the continuing support of these studies by the Carnation Creek Cordinating Committee and the Pacific Biological Station, Nanaimo. Many persons have given generously of their time in aspects of this work. Messrs B. Andersen, R. Leahy, I. Walters, and P. Neaves have assisted in field operations. Mr C. Scrivener has assisted in coordination of the program and with Drs D. W. Narver and M. Waldichuk, has assisted in critical review of this manuscript.

EVANS, D., AND J. G. STOCKNER. 1972. Attached algae on artificial and natural substrates in Lake Winnipeg, Manitoba. J. Fish. Res. Board Can. 29: 31–44.

HANSMANN, E. W. 1969. The effects of logging on periphyton communities of coastal streams. Ph.D. Thesis. Oregon State Univ., Corvallis, Oreg. 120 p.

MACINTOSH, R. P. 1967. An index of diversity and the relation of certain concepts to diversity. Ecology 48: 392–404.

MCCONNELL, W. J., AND W. F. SIGLER. 1959. Chlorophyll and productivity in a mountain river. Limnol. Oceanogr. 4: 335–351.

MCINTIRE, C. D., AND H. K. PHINNEY. 1965. Laboratory studies of periphyton production and community metabolism in lotic environments. Ecol. Monogr. 35: 237–258.

MOSS, B. 1968. The chlorophyll *a* content of some benthic algal communities. Arch. Hydrobiol. 65: 51–62.

NARVER, D. W. 1974. Carnation Creek experimental watershed project. Fish. Res. Board Can. Annu. Rep. 23 p.

NARVER, D. W., AND B. C. ANDERSEN. 1974. Fish populations of Carnation Creek and other Barkley Sound streams — data record and progress report. Fish. Res. Board Can. MS Rep. 1351: 115 p.

NAUWERCK, A. 1963. Die Beziehungen zwischen Zooplankton und Phytoplankton im See Erken. Symb. Bot. Ups. 17: 163 p.

ODUM, H. T. 1957. Trophic structure and productivity of Silver Springs, Florida. Ecol. Monogr. 27: 55–112.

ODUM, H. T., W. MCCONNELL, AND W. ABBOTT. 1958. The chlorophyll *a* of communities. Inst. Mar. Sci. 5: 66–96.

POMEROY, W. M. 1974. Distribution and primary production of benthic algae on the Squamish River Delta, British Columbia. M.Sc. Thesis. Univ. Manitoba, Winnipeg, Man. 191 p.

SCHINDLER, D. W., AND S. K. HOLMGREN. 1971. Primary production and phytoplankton in the Experimental Lakes area, northwest Ontario, and other low-carbonate waters, and a liquid scintillation method for determining ^{14}C activity in photosynthesis. J. Fish. Res. Board Can. 28: 189–201.

SCRIVENER, J. C. 1975. Water, water chemistry, and nutrient budgets for Carnation Creek Watershed, July 1971 to May 1974. Fish. Res. Board Can. Tech. Rep. 564: 121 p.

STOCKNER, J. G., AND F. A. J. ARMSTRONG. 1971. Periphyton of the experimental Lakes area, northwestern Ontario. J. Fish. Res. Board Can. 28: 215–229.

STOCKNER, J. G., AND K. R. S. SHORTREED. 1975. Attached algal growth in Carnation Creek: a coastal rain forest stream on Vancouver Island, British Columbia. Fish. Res. Board Can. Tech. Rep. 558: 56 p.

STRICKLAND, J. D. H., AND T. R. PARSONS. 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Board Can. 167: 310 p.

YENTSCH, C. S., AND D. W. MENZEL. 1963. A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence. Deep Sea Res. Oceanogr. Abstr. 10: 221–231.