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NORRIS RESERVOIR FERTILIZER STUDY

II. EFFECTS OF THERMAL STRATIFICATION AND NUTRIENT AVAILABILITY ON THE PRODUCTIVITY OF RESERVOIR PHYTOPLANKTON

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ABSTRACT

Phytoplankton productivity was determined biweekly in six coves of Norris Reservoir, during April to October 1967, to study the relation between phytoplankton productivity and certain physical and chemical factors. Fertilizer was distributed to four of the six coves between biweekly sampling dates. Productivity declined durng May and June and remained low in all coves until September. This decline was directly related to the onset of thermal stratification and reduction of the phosphorus content to less than detectable levels in the epilimnion. Nitrogen gradually declined, but levels did not fall below about 0.2 mg/1. An outburst in productivity occurred in September after phosphorus in the epilimnion had increased. Productivity was greater in fertilized than control coves, but the differences were not statistically significant.

INTRODUCTION

During 1967 the Fish and Wildlife Branch of TVA fertilized coves in Norris Reservoir to determine if stimulation of the food-chain base with nutrients would enhance fish production in partially enclosed areas of large bodies of water. The effect of experimentally altering the nutrient content on phytoplankton productivity in deep reservoirs is of particular interest in water quality management. An understanding of the level of nutrients, together with other important physical and chemical factors that affect phytoplankton production, will be valuable in controlling the process of eutrophication and associated problems in large reservoirs. Therefore, this program gave the Water Quality Branch an excellent opportunity to study the effect of artificial enrichment on nutrient distribution and productivity in a large, unproductive reservoir.

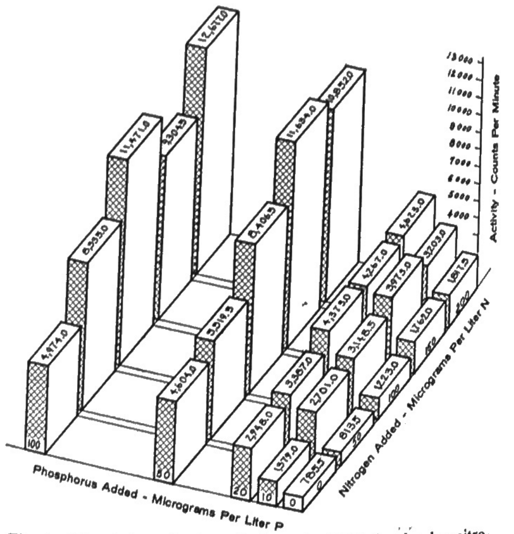

Fig. 1 Stimulation of phytoplankton in BOD bottles by nitrogen and phosphorus during a 96-hour test period in Norris Reservoir.

A preliminary bioassay was conducted in August 1966 to determine the concentration of nitrogen and phosphorus that limited productivity in Norris Reservoir. This study showed that at the 95% confidence level additions of 50 μg/1 of P and 100 μg/1 of N significantly increased phytoplankton productivity in bottles incubated in the reservoir (Fig. 1). Higher levels of artificial enrichment did not cause a further significant increase. It was of interest to determine if the nutrient concentration that was optimum in the bottles was also optimum, in the natural environment. Factors such as nutrient loss from the epilimnion, movement and exchange of water, and variability in the seasonal growth cycles of phytoplankton were not operative in the bottle bioassay and would probably modify the effect of the nutrients added to the open coves.

This study summarizes the effect of fertilization on nutrient content and distribution and on productivity in cove environments of Norris Reservoir. The study has demonstrated the overriding influence of thermal stratification on nutrient distribution, particularly phosphorus, and the resulting response of the phytoplankton to nutrient.

METHODS AND MATERIALS

ENVIRONMENTAL MONITORING

Design of the experiment, fertilizer quantities, and application methods are present in Part I of this study (Wood and Sheddan, 1971). Phytoplankton cell counts, primary productivity, chlorophyll concentration, nutrient concentration, pH, total alkalinity, water transparency, and temperature were monitored on a continuous biweekly schedule throughout the study. Each monitoring period was scheduled one week after the fertilizer was applied. Sampling started on April 13 and 14 and the schedule was uninterrupted until it was terminated on October 23 and 24.

Phytoplankton analysis. Water samples were collected in the epilimnion throughout the study period and preserved with Lugol's solution. Organisms were identified to genera and cell concentrations determined with an inverted microscope.

Carbon-14 technique. The C^{14} technique was used for measuring primary productivity of the phytoplankton population. Water samples for C^{14} productivity determinations were collected in a PVC Van Dorn sampler from various depths depending upon the depth of the photic zone. This method was first used by Steemann-Nielsen (1952) and the procedures were similar to those by Strickland (1960). From each sample approximately 250 ml of water was added to each of two or three BOD bottles, usually two light and one dark. Dark bottles were included with each experiment (but not always every depth) to determine the nonphotosynthetic uptake of C^{14}. Approximately two microcuries of Na $^{14}CO_3$ were added to each bottle. Each bottle was attached to a line and incubated at the collection depth for about three hours. After incubation 1 ml of 10% formalin was added to the bottles and they were placed in a light proof box for transport to the laboratory.

Each sample was filtered, within two hours, through a 0.45 micron Millipore filter to retain the phytoplankton cells. The filter was glued to a planchet of 5-cm diameter, and placed in a desiccator. Later they were counted in a thin-window, low background, gasflow proportional counter. Activity of standard solutions and machine efficiency was determined by Dr. C. R. Goldman, Professor of Zoology, University of California, Davis, with his total combustion method. Productivity during the incubated period was extrapolated to the total per day based on a ratio of total incident light to light during the incubation period.

Chlorophyll "a" technique. Plant pigment content is used as a measure of phytoplankton standing stock. Water samples were collected for chlorophyll determinations from depths corresponding to those sampled for C^{14} productivity. Phytoplankton cells were filtered from the water onto a 1.2 μ pore size Millipore filter. Chlorophyll was extracted by 90% acetone for a period of at least 24 hours. Absorption was determined on a model DBG spectrophotometer and chlorophyll "a" was calculated according to an equation by Richards and Thompson (1952), as modified by Parsons and Strickland (1963).

Water chemistry. During the regularly scheduled C^{14} productivity and chlorophyll measurements, samples for total phosphate (PO_4-P) and total nitrogen (NH_3-N, NO_3-N, NO_2-N, and organic nitrogen) were also collected at various depths. The depths sampled most frequently were one, five, and ten meters. These samples were collected in the Van Dorn sampler, transferred to acid-cleaned glass liter bottles, and preserved with 2 ml of $HgCl_2$. NO_3-N and NO_2-N were determined by the N (1-Naphthyl)-ethylenediamine dihydrochloride method by Kamphake, Hannah, and Cohen (1967). NH_3-N and organic nitrogen were determined by Kjeldahl distillation and nesslerization according to *Standard Methods for the Examination of Water and Wastewater* (1965). Total phosphate was determined by an automated ammonium molybdate stannous chloride colorimetric procedure also described in *Standard Methods* (1965).

Total inorganic carbon, essential for calculations of photosynthetic rates using C^{14}, was determined with a table from Bachmann (1962) using measured total alkalinity and pH values.

Physical measurements. Solar radiation data were obtained from the Atmospheric Turbulence and Diffusion Laboratory at Oak Ridge, Tennessee. These data were supplied in langleys (gm cal/cm^2) for each day that C^{14} studies were conducted.

Secchi disk disappearance was recorded during each sampling period to determine the photic zone depth and for comparison of light available in the different coves. Rainfall and reservoir elevation data were obtained from the TVA *Daily River Bulletin.*

Special monitoring. Certain situations arose during the study to warrant special monitoring techniques. Late in the study, compiled nutrient and productivity data showed evidence that once distributed, the fertilizer seemed to disappear from the photic zone of the coves before the phytoplankton could utilize it. On Sepember 18, 1967, samples for phosphorus and nitrogen determinations were collected immediately before fertilization and at intervals of 30 minutes, and 1, 6, 24, and 48 hours after the fertilizer had been added to the coves. Samples were collected at depths of 1, 5, 10, 15, and 20 meters. Methods of collection and determination of nutrients are the same as those described in the section on "Water Chemistry."

RESULTS

Changes in Concentrations of Nitrogen and Phosphorus

Nutrient concentrations in the epilimnion of the test coves did not increase as predicted (Fig. 2). In Fig. 2A the seasonal variations in nitrogen concentration seemed to follow a similar pattern in all coves of Cove Creek except that on May 23 and August 1, when unusually high values (1.03 and 0.79 mg/1) were observed in

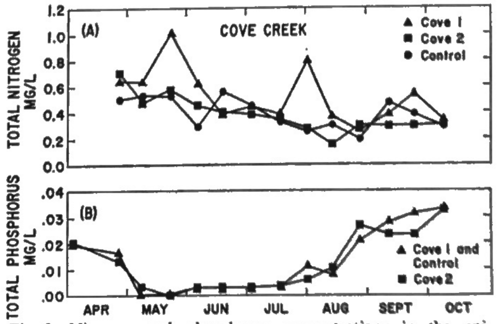

Fig. 2 Nitrogen and phosphorus concentrations in the epilimnion of the three coves studied in Cove Creek.

Cove 1 and on August 14, when a comparatively low value (0.16 mg/1) was observed in Cove 2. On two occasions (June 19 and September 12) the Control Cove had higher nitrogen values than Cove 1 or Cove 2.

Fig. 2B shows the total phosphorus concentrations in the three coves of Cove Creek throughout the summer. Control Cove and Cove 1 are so similar in phosphorus concentrations that a single line on the chart denotes results from both coves. Phosphorus content in Cove 2 also follows a pattern similar to that of the other two coves. The greatest difference in phosphorus concentration between the coves was observed on September 25. Cove 2 had 0.023 mg P/1 as compared to 0.031 mg P/1 for Cove 1 and the Control Cove.

Nitrogen results for Big Creek during fertilization show a similar pattern for all coves from May through September (Fig. 3A).

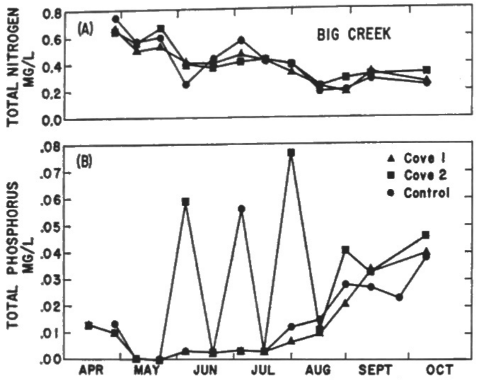

Fig. 3 Nitrogen and phosphorus concentrations in the epilimnion of the three coves studied in Big Creek.

Measurements of phosphorus concentration in the various coves in Big Creek were erratic, as shown in Fig. 3B. Phosphorus was not detected in any cove on May 9, which followed the first week of fertilization. A compartively high concentration of phosphorus (0.056 mg/1) was reported in the Control Cove on July 4. Similar high concentrations, 0.059, 0.077, 0.041, and 0.046 mg P/1, were recorded in Cove 2 on June 5, July 31, August 29, and October 9, respectively. Cove 1 shows no unusually high values of phosphorus concentrations as compared to the other coves of Big Creek.

Special samples for phosphorus and nitrogen were collected on September 18 in Cove 1, and Cove Creek, and results are displayed in Fig. 4.

Thirty minutes after the fertilizer was applied samples collected from one-meter depth showed that the total nitrogen content was 0.46 mg/1 more than that in prefertilization samples (Fig. 4A). NH_3-N had risen from 0.0 mg/1 to 0.36 mg/1 and the total phosphorus concentration was up from 0.033 mg/1 to 0.081 mg/1. Results from samples at 5- and 10-meter depths indicated no significant change. The change in the phosphorus concentration at 15 meters is probably due to a large amount of sediment in the sample. Samples collected from one-meter depth, one hour after fertilization, show that the phosphorus is back to prefertilization concentrations. NH_3-N has almost left the one-meter depth, as a concentration of 0.04 mg/1 shows. The major portion of the fertilizer was at the five-meter depth after one hour. All results after six hours indicate that most of the added fertilizer was between the 5- and 15-meter depths. Fig. 4 shows that a large percentage of this amount is near the bottom at 15 meters.

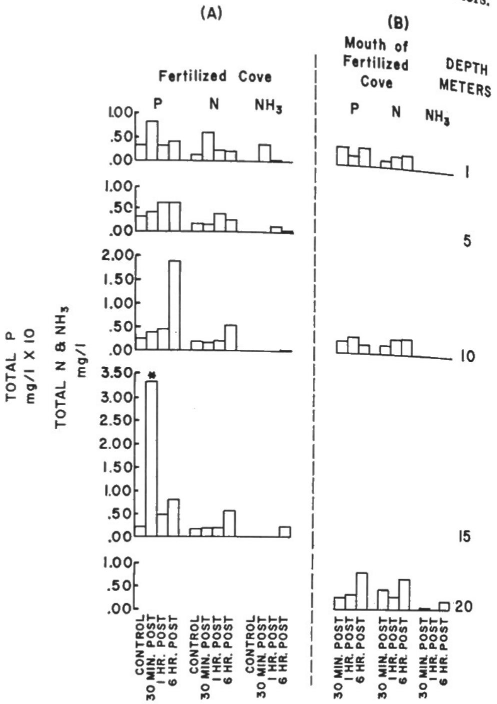

Fig. 4 Dispersion of nutrients immediately after fertilization. (*Sediment in sample possible cause for high P value.)

Special samples were also taken at the mouth of the cove on September 18 outside of the fertilized area. Results in Fig. 4B show that 3 minutes after fertilization NH_3-N was detected at 20 meters, but phosphorus concentrations did not change appreciably with depth. One hour after fertilization, concentrations of nitrogen and phosphorus were uniform from 1 to 20 meters. Samples after six hours showed that a large part of the fertilizer had moved to a depth of 20 meters at the mouth of the cove, as indicated by phosphorus and NH_3-N concentrations.

Analyses of sediment samples taken on October 24 after the fertilization program was completed are shown in Table 1. A pattern of nutrient content in the sediment related to fertilization is not apparent. Cove 2 in Cove Creek had notably higher values of extractible P and organic P than the other two coves. Cove 1, which was the deepest cove, had a lower content of extractible P than Control, but a higher content of organic P. Sediment from Cove 2 in Big Creek had a considerably higher content of total nitrogen, extractible phosphorus,

and organic phosphorus. Cove 2 is the shallowest studied in Big Creek. Cove 1, the heaviest fertilized cove, had the smallest amount of extractible and organic phosphorus in the sediment.

TABLE I. Nitrogen and phosphorus in sediment samples from all study coves on October 24, 1967

	Total N %	Extractible P mg/kg	Organic P mg/kg
Cove 1, Cove Creek	0.08	183	68
Cove 2, Cove Creek	0.08	330	107
Control, Cove Creek	0.07	230	0
Cove 1, Big Creek	0.09	170	20
Cove 2, Big Creek	0.13	225	64
Control, Big Creek	0.09	183	34

PHYSICAL AND ENVIRONMENTAL CONDITIONS

Fig. 5 provides a summary of data on physical variables that probably affect productivity. These include rainfall, elevation, isolation transparency (Secchi disk), mean temperature, and temperature distribution with depth.

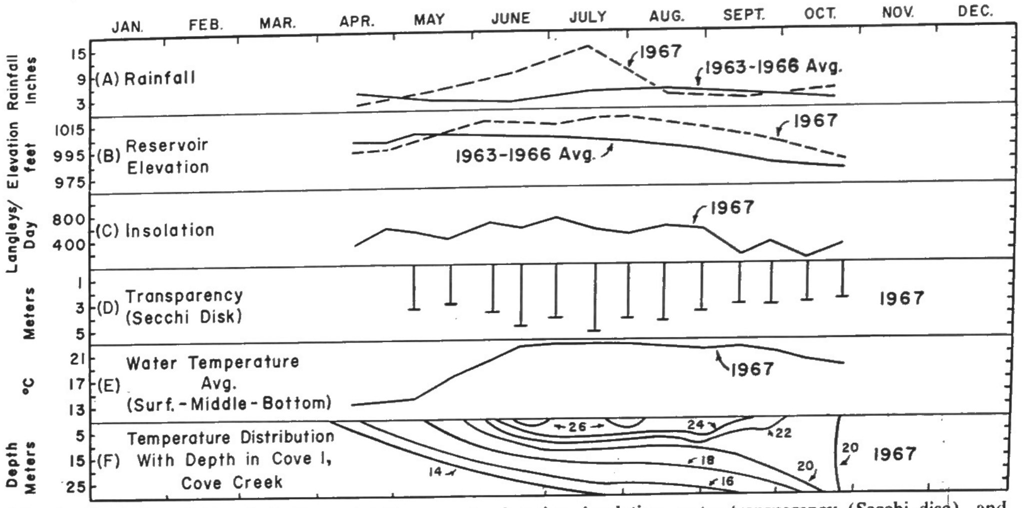

Fig. 5 Physical variables, including rainfall, reservoir elevation, insolation, water transparency (Secchi disc), and temperature distribution in Norris Reservoir and some of its coves during April to October 1967.

As shown in Fig. 5A, rainfall in 1967 was much greater than rainfall during the period 1963 through 1966. As a result of the increased rainfall, the elevation ranged from 5 to 20 feet higher in 1967 during the period June through October than during this period in 1963-1966. Throughout July and August the elevation was approximately 15 feet higher than in 1963-1966 (Fig. 5B).

Fig. 5C shows the insolation for sampling days during the study. Cloudy, partly cloudy, and sunny days caused considerable daily variation in the amount of light energy available. From April 13 to October 25 the insolation ranged from 142 to 667 langleys/day. The lowest insolation values were in October and the highest in June and July.

The penetration of light into Norris Reservoir was measured by a Secchi disk (Fig. 5D). Transparency follows a similar pattern in all coves. The average Secchi disk reading from April through October was 3.70 meters in all coves except Cove 1 in Big Creek, which was 3.60 meters. The Secchi disk was always visible at two meters and, as shown in Fig. 5D, it was visible at five meters during the middle of July.

The average of water temperature readings at surface, middle, and bottom depths followed a smooth seasonal curve throughout the study period. There was no significant difference in temperature between Cove and Big Creeks, so a single line represents these values in Fig. 5E.

Fig. 5F shows the vertical temperature with time for Cove 1, in Cove Creek, which is the deepest cove studied. The distributions for the other coves are similar to that in Cove 1. A reasonably strong thermocline persisted in the vicinity of 6 to 10 meters in depth from June to September 12.

PHYTOPLANKTON CONCENTRATIONS

Diatoms were the most abundant phytoplankton throughout all seasons of the study period. *Nitzschia* was present in the epilimnion during each month. During late April *Fragilaria* was the dominant alga with cell concentrations ranging from 1000 to 2000 cells/ml. In late May concentrations of *Dinobryon* exceeded 1000 cells/ml. From early June to August the phytoplankton count was low and total cell concentrations were usually below 300 cells/ml. During late August and especially early September, a bloom of *Nitzschia* occurred in all coves with concentrations exceeding 3000 cells/ml;

Nitzschia accounted for over 65% of the total cell concentration of 4600 cells/ml during the second week of September. Green and blue-green algae were relatively scarce from April through October. Highest concentrations of green algae occurred during September and October and consisted mainly of *Chlorella, Scenedesmus,* and several desmid species. *Oscillatoria* and *Merismopedia* composed almost the entire blue-green algae species with *Oscillatoria* having the highest counts of 82 cells/ml in October. The April-through-October cycle of phytoplankton in Norris Reservoir included 28 general of diatoms, green algae, and blue-green algae.

PRIMARY PRODUCTIVITY

Primary productivity showed a similar but marked seasonal variation in all three coves in Cove Creek (Fig. 6A). Productivity declined during June and remained low until September. During this period (June-August) the mean productivity was 275 mg C/M²/day (mean of the three coves) in Cove Creek. Highest productivity values occurred in September. An outburst of productivity occurred on September 12 with a mean of 3525 mg C/M²/day. Mean productivity in the Cove Creek coves declined to 260 mg C/M²/day in October.

Results of productivity in Big Creek are shown in Fig. 6B. Here again the seasonal variation was greater than the variation among coves. Productivity per square meter of reservoir surface was least during June, July, and August (mean of 290 mg C/M²/day) in Big Creek. Productivity was not measured in Cove 1 on July 31. Comparatively high productivity values were recorded in April (mean of 881 mg C/M²/day on April 14 and 28, 1967) and September (mean of 2102 mg C/M²/day on September 11 and 1343 mg C/M²/day on September 25). Mean productivity in Big Creek during the last two sampling periods in October had declined to 386 mg C/M²/day.

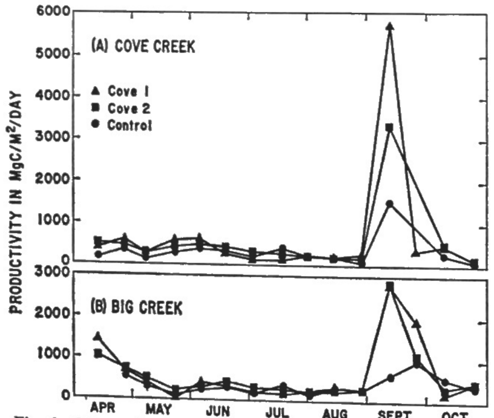

Fig. 6 C^{14} productivity per unit surface area in all coves studied in Cove Creek and Big Creek during April to October 1967.

The percentage increases and decreases in productivity between control and test coves are shown in Fig. 7. The two horizontal lines (shaded area) in each plot represent the average percentage of increased production in the test coves as compared to the control coves before fertilization. The vertical lines represent the percentage increase or decrease in productivity of the test coves as compared to the control coves on the date sampled. When the vertical lines cross the upper horizontal line the percentage increase in productivity of the test cove over the control cove on that date exceeds the percentage increase of test over control prior to fertilization. For example, in Fig. 7A the two horizontal lines show that Cove 1, Cove Creek, averaged 82% more production prior to fertilization (April 13 and 27) than the Control Cove. During fertilization, the percentage increase in productivity of Cove 1 over the Control Cove exceeded 82% on only three dates, which were before and after the period of strongest stratification. The productivity in Cove 1 was actually less than in the Control Cove for about 10 consecutive weeks during June, July, and August.

Cove 2 of Cove Creek showed 78% greater productivity than the Control Cove before addition of fertilizer. The pattern of productivity in Cove 2, Cove Creek, was similar to that in Cove 1 except that there were fewer instances when productivity was less than that in the Control Cove and the differences during June through August are not as evident.

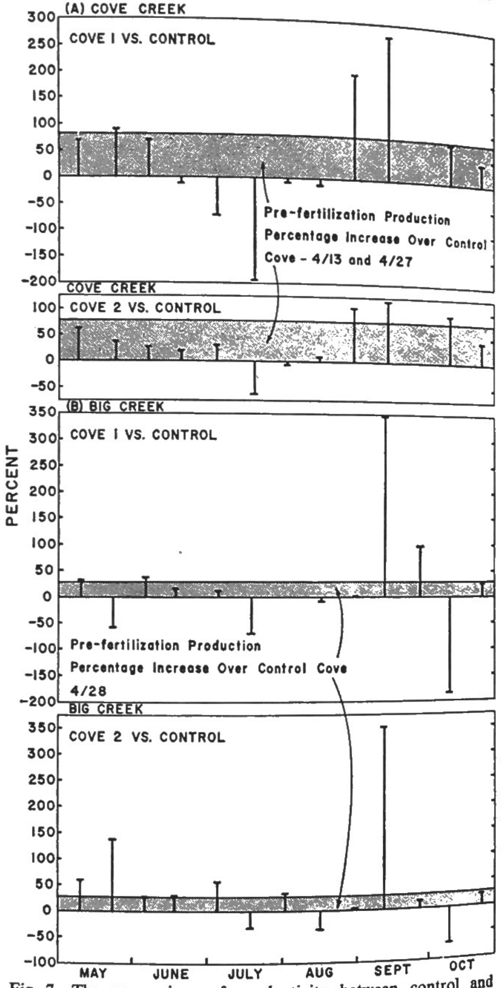

Fig. 7 The comparison of productivity between control and test coves before and during fertilization.

The prefertilization increase in productivity of Cove 1 over the Control Cove in Big Creek was 29% on April 28 (Fig 7B). The pattern of productivity in this cove was very similar to that of the Cove Creek coves, except productivity was less in Cove 1 than in Control Cove on two occasions which do not correspond to the period of strong stratification. These occasions were May 22 and October 9.

Cove 2, Big Creek, had 28% more productivity than the Control Cove before fertilizer addition. The percentage increase in productivty of Cove 2 as compared to Control Cove exceeded 28% on six occasions after fertilizer was added to Cove 2. Productivity in Cove 2 was less than that in Control Cove on three occasions. These three occasions were not restricted to midsummer, but rather they occurred during July, August, and October. In most cases when productivity in the test coves exceeded the prefertilization percentage increase between test and control cove, it occurred before or after the summer stratification. Cove 2, Big Creek, was an exception. This cove is shallower, narrower, and longer. The bottom area that is shallower than the thermocline is about twice that of the other coves. Therefore, nutrient recirculation between bottom and surface water during the period of summer stratification was probably greatest in this cove.

Although there is some indication that productivity increased slightly on several occasions as a result of fertilization, as indicated in Fig. 7, the differences in mean productivity between control and test coves for the whole study period are not significant, as shown by an analysis of variance in Table 4. The F-values, in comparing productivity among all coves (Cove Creek and Big Creek, Table 2A), or among coves in each creek separately (Cove Creek, Table 2B, and Big Creek, Table 2C), are not significant at the 95% confidence level.

TABLE II. Analysis of Variance Comparing Cove and Seasonal Productivity Differences of the Following:
(A) Six Coves in Cove Creek and Big Creek,
(B) Three Coves of Cove Creek, and
(C) Three Coves of Big Creek

All Coves - Cove Creek and Big Creek

	Source of Variation	SS	df	ms	F value		
(A)	Coves	1437056	5	287411	1.14	F95=2.35	F99=3.29
	Time (Season)	36312990	14	2593785	10.27**	F95=1.80	F99=2.30
	Error	17681970	70	252599			
	Total	55432020	89				
				Cove Creek			
(B)	Coves	931969	2	465984	1.58	F95=3.34	F99=5.45
	Time (season)	29611010	14	2115072	7.18**	F95=2.06	F99=2.80
	Error	8243696	28	294417			
	Total	38786670	44				
				Big Creek			
(C)	Coves	491486	2	245743	1.94	F95=3.34	F99=5.45
	Time (Season)	12491850	14	892275	7.03**	F95=2.06	F99=2.80
	Error	3552444	28	126873			
	Total	16535780	44				

** Highly significant

A comparison of productivity with time shows that the differences in values among the various sampling dates from April through October are highly significant (99% level) in both creeks.

Chlorophyll "a". Chlorophyll content does not follow a similar pattern with C^{14} production in the coves of Norris Reservoir. This is a clear example of a productivity measurement showing a more sensitive response to physical and chemical conditions than a standing crop measurement.

Chlorophyll content (total amount in photic zone) increased gradually throughout the study period after reaching a low in May (Fig. 8). Chlorophyll "a" content ranged from a low of 9.0 mg/M² in Cove 2 on May 8 to a high of 45.0 mg/M² in Cove 1 on October 24. In Big Creek the maximum amount of chlorophyll "a" (52 mg/M²) was found in Cove 2 on October 24 while the minimum (8.0 mg/M²) was found in Cove 1 on May 23.

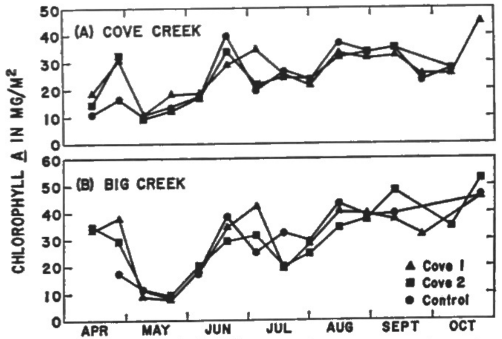

Fig. 8 Total chlorophyll "a" content in a square meter water column throughout the photic zone in the coves studied.

DISCUSSION

This study shows that the primary productivity of Norris Reservoir is governed by the interaction of several physical factors that control the distribution of nutrients seasonally. These controlling factors originate directly or indirectly from solar radiation. Increased radiation warms the water and leads to formation of a thermocline which serves as an effective barrier to mixing. Surface water temperature is increased further which strengthens the density gradient and the barrier to mixing. Although increased radiation leads to more available light for phytoplankton growth, the thermocline restricts vertical movement of nutrients to the lighted zones and thereby eventually limits productivity. These factors must be considered in order to determine the causes for the amount of distribution of productivity.

Fertilization of the aquatic environment has been most often attempted in farmponds and lakes, rather than reservoirs. Each one of these environments has species and seasonal cycles that in many respects are unique. Because of this it is always difficult to predict effects in one environment based on results from another. When evaluating fertilization results from the literature, certain factors must be considered, such as depth, portion of surface, surface shallower than thermocline, and water detention time.

The problem associated with fertilizing the coves in Norris Reservoir is keeping the added nutrients in the epilimnion. The added nutrients were completely gone from the epilimnion six hours after fertilization. The brief contact time of nutrients with phytoplankton in the photic zone of Norris Reservoir was probably not adequate to significantly increase productivity.

The rapid disappearance of large amounts of added phosphorus in aquatic environments is not uncommon. Heper (1958) has reviewed the fertilization programs of fishponds in Israel which were started in 1946. These ponds received approximately 0.7-1.0 ton of superphosphate per hectare each year. This amount of water soluble phosphorus should theoretically raise the phosphorus concentrations in the Israel fishponds to about 0.5 mg/l. Shortly after fertilization (24-48 hours), only 1 to 5 per cent of this fertilizer remained. Most of this phosphorus added was found to be precipitated as $Ca_3(PO_4)_2$. Nisbet (1951) and Zeller (1952), as reported by Hepher (1958), also show a similar decline in phosphorus concentrations after fertilization in fishponds. Hooper and Ball (1964) likewise attributed the loss of phosphorus added to a marl lake in Michigan to precipitation with calcium. They cite Barrett's (1953) results of adding phosphorus to unstratified lakes in Michigan, which ranged in alkalinity from 138 to 192 mg/l. That author stressed the impracticality of fertilizing stratified, alkaline bodies of water because phosphorus sank to the hypolimnion and became adsorbed to the bottom sediments. However, he held out some hope for fertilizing unstratified bodies of water lower in alkalinity (nearer to 120 mg/l). The alkalinity in the Norris coves ranged from about 70 to 90 mg/l during the study. Nelson and Edmondson (1955) observed phosphate and nitrate to fall to an undetectable level in a few days after fertilization, in a fertilization study of 120-acre Bare Lake in Alaska. The phytoplankton population increased many fold and the density of the lake water changed. However, this lake was unstratified. Hayes (1952) used radioactive phosphorus (P^{32}) in tracing the fate of added nutrients. This work shows that an addition of radiophosphorus that increased the phosphorus content only 0.25 percent disappeared from the lake rapidly at first but reached an equilibrium after a month. This suggests that there is a continuous exchange of phosphorus going on between the water and solids of the lake. In all of the above cases, added phosphorus disappeared from the water in amounts larger than that taken up by the phytoplankton.

Although these previous farmpond and lake fertilization results are from different type environments they still provide useful information with which to interpret results of reservoir fertilization. Since most investigators who traced the fate of phosphate fertilizers in fishponds and lakes similarly found a rapid loss of the material, disappearance of phosphorus from Norris Reservoir would probably be equally as fast since it is a much less stable environment. In fact, the added fertilizer should seemingly disappear even faster in reservoirs than in farmponds or lakes, especially unstratified lakes.

The summer decline in productivity in Norris Reservoir was related to the onset of thermal stratification and reduction of phosphorus to less than the detectable levels in the epilimnion. Total nitrogen also showed a continual reduction in the epilimnion during June, July, and August,, but not as abrupt as phosphorus. The outburst in productivity that occurred in all coves during September immediatelly followed about a 6- to 8-meter lowering of the thermocline. The phosphorus content also increased to approximately 0.04 to 0.05 mg P/1 in the epilimnion of most coves during late August and September. Following this productivity outburst in September, NO_3-N content reached a summer low of about 0.01 mg N/1 in most coves. This was a considerable reduction in NO_3-N from maximum concentrations of about 0.35 mg N/1, which occurred in the spring. Thermal stratification from June through August reduced productivity in spite of the addition of nutrients. Goldman (1962) also demonstrated in the stratified waters of Castle Lake, California, that the thermocline is an effective barrier to mixing and prevented reentry of nutrients lost from the lighted zone.

The total seasonal productivity in Big Creek is greater than that of Cove Creek, especially if the week of September 12 is omitted. This greater productivity in Big Creek may be related to a greater water detention time. The coves in Big Creek have a morphology and location that probably result in less exchange with the open creek than is the case in Cove Creek. The mean cove depth is greater in Cove Creek than Big Creek and as the thermocline of Cove Creek (especially Cove 1) lowers in early September, the change in productivity is more abrupt than the change in Big Creek. The sudden outburst in productivity indicates that the trapped nutrients below the thermocline in the deeper hypolimnion (e.g., Cove 1, Cove Creek), are unused until an overturn ocurs. The productivity increase in Big Creek during September is more gradual than the increase in Cove Creek and the higher level is maintained until September 25. The more gradual increase and greater total productivity in Big Creek coves, compared to coves in Cove Creek, are probably due to their shallower depth and generally weaker thermoclines. The thermocline of Cove 2, Big Creek, did not fully develop until two weeks after the development of thermoclines in the other five coves.

The relationship between physical characteristics, nutrient distribution, and productivity was of particular interest in Cove 2, Big Creek. In this cove the bottom area in contact with the epilimnion is more than twice that of the other coves, except the control on Cove

Creek. For Cove 2, Big Creek, the contact of this greater bottom area with the mixed epilimnion may account for the high concentrations of phosphorus observed in the epilmnion during the startified period. Only one other cove, Big Creek control, showed a high phosphorus value in the surface waters. In addition to this, the difference in productivity between test cove and control exceeded the prefertilization difference in only Cove 2, Big Creek, during the stratified period. The occurrence of these three conditions in the same cove suggests that recirculation of nutrients by greater contact of the mixed epilimnion with the bottom actually increased productivity. Bryozoan colonies were very abundant in this cove, whereas they were relatively scarce in other coves. The fact that these organisms feed on suspended organic particulate matter supports the contention that greater nutrient recycling and productivity occurred in this cove even though a gross analysis of mean productivity among the coves showed no significant difference.

Some authors have presented concentrations of nutrients (P and N) that when present in the euphotic zone will increase the productivity of a plankton community to nuisance proportions. Sawyer (1952) analyzed data from 17 lakes in Wisconsin and concluded that concentrations in excess of 0.01 mg/l inorganic phosphorus and 0.30 mg/l inorganic nitrogen at the time of the spring turnover could be expected to produce nuisance algal blooms. Hepher (1958) indicates that 0.50 mg P/1 for a short period of time (24-48 hours) will increase algal production. The bioassay study of Norris Reservoir water showed that levels of 0.10 mg N/1 and 0.05 mg P/1 will significantly increase phytoplankton productivity. Although these values may be useful in interpreting results in a particular environment, they cannot be extracted from the literature and used as rigid guidelines in predicting maximum phytoplankton production. Not only do different type environments have varying physical characteristics that control the availability of the nutrients, but different phytoplankton species in the same environment show seasonal periodicities in productivity. Fournier (1952) states that each distinctive period within the annual phytoplankton cycle represents a different temporal stage of phytoplankton in the same community. Therefore, the nutrient requirements of phytoplankton would vary during each temporal stage of development. Also according to Einsele (1941), phosphorus can be stored in phytoplankton cells for several months and after certain concentrations are reached in the cells no further uptake is required. This picture is more complicated as phytoplankton cells sink and are replaced by different cells. All of these ecological factors suggest that it is difficult to establish absolute nutrient values for maximum phytoplankton production.

The results in Norris are a case in point. Nitrogen and phosphorus added to coves at concentrations, which in bottle experiments in August 1966 stimulated phytoplankton productivity, did not significantly increase productivity in the natural environment. This difference in results is probably related to the effect of the thermocline in limiting nutrient availability in the open environment. This is further supported because as the hypolimnion was removed, the thermocline was lowered, more bottom area was brought in contact with the mixed epilimnion, and the phosphorus content in the epilimnion increased. At values greater than 0.03 mg P/1, an outburst in phytoplankton productivity occurred. In environments such as ponds where the bottom is continually in contact with the mixing zone, recycling of nutrients is not prevented and total productivity from a given addition of nutrients will almost surely be greater than in a deep lake.

Hasler (1947) has shown that a constant seepage of sewage to a lake, which probably keeps nutrients in continuous contact with phytoplankton in the epilimnion, promotes eutrophication. In deep lakes, such as Norris, continual addition of nutrients would probably be most effective in stimulating phytoplankton productivity rather than adding it in slugs. This procedure, which incidentally would more closely represent waste effluent releases, would result in greater availability of the nutrients in the epilimnion and also in a greater probability of their being available during a susceptible stage in the phytoplankton growth cycle.

The methods of applying fertilizer that were used in this study need to be changed for future studies in similar environments. This method allowed less than six hours fertilizer-phytoplankton contact time in the epilimnion. This undoubtedly affected the expected results of the study and accounts for the insignificant increases in productivity.

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