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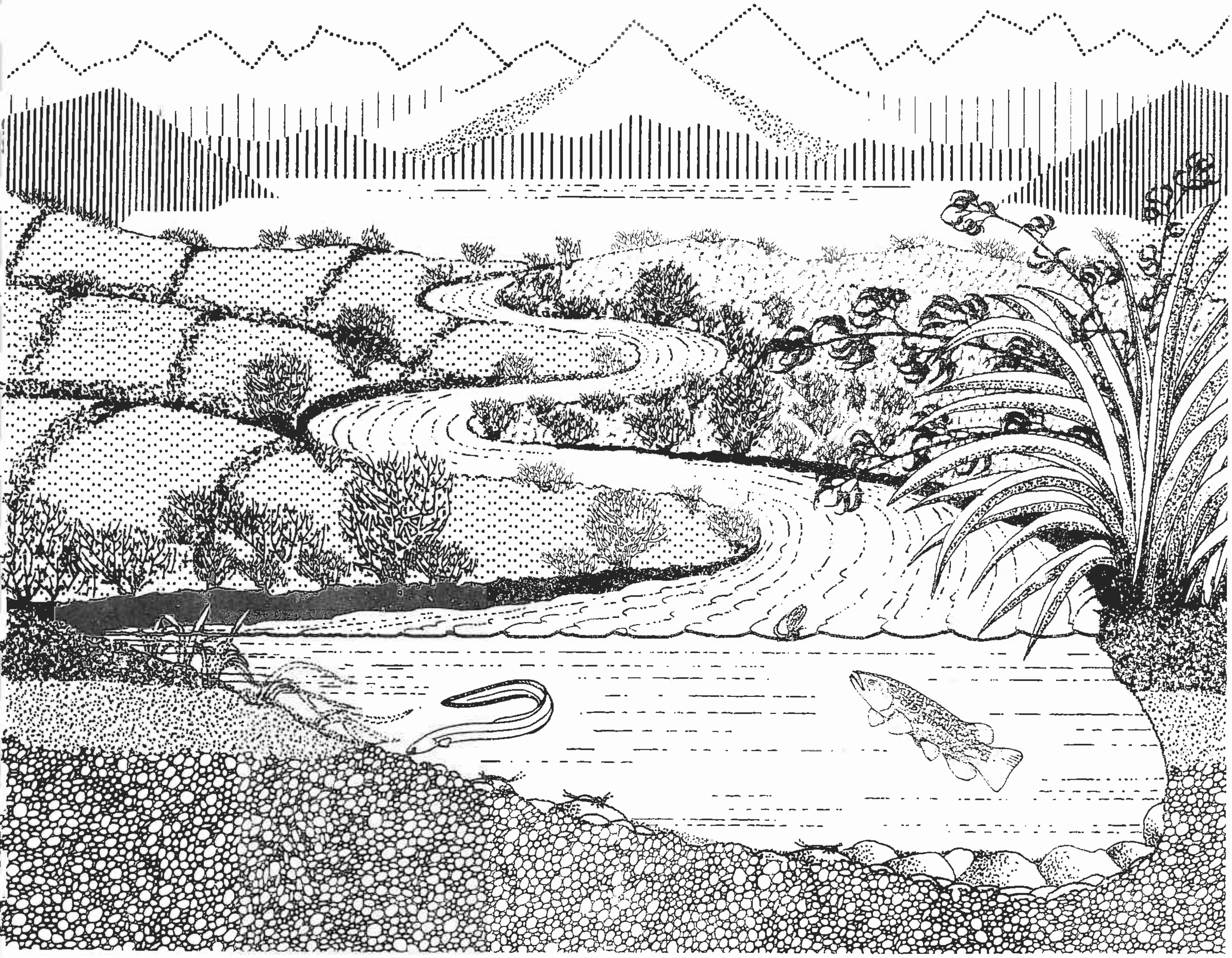
Effect of silver carp on blue-green algal blooms in Lake Orakai

Fisheries Environmental Report No.68



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Effect of silver carp on blue-green algal blooms in Lake Orakai

by

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N.Z. Ministry of Agriculture and Fisheries
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SUMMARY

This report describes the results of investigations, carried out between 1978 and 1982, on the effect of silver carp on blue-green algal blooms in Lake Orakai.

Lake Orakai (area 4 ha) is one of the most eutrophic lakes in New Zealand with a daily algal production of about 100 kg/ha. The algae in the blooms were predominantly blue-green (cyanobacteria, for example, *Microcystis* sp.).

Surface water temperatures in the lake fluctuated seasonally and ranged from 8°C to 28°C. The lake was generally stratified from October to April, with the thermocline between 1.5 m and 2.0 m.

Strong wind and heavy rain, or combinations of both, caused sudden mixing accompanied by a loss of temperature gradients and very low dissolved oxygen levels. From personal observations, these events were often followed by an upsurge in productivity and bloom intensity.

Lake Orakai was divided into two unequal areas of 0.5 ha and 3.5 ha by a PVC barrier, the design of which prevented interchanges of water and fish between the two areas.

In September and October 1978 the 0.5 ha area was stocked with 1500 silver carp (3000 fish per hectare), which had an estimated biomass of 1916 kg by April 1979. This resulted in improved water clarity by January 1979. Secchi disk transparency, pH, and dissolved oxygen results for February-March, when compared to the control, confirmed the silver carp had achieved measurable improvement in water quality.

In June 1979 the trial and control areas were reversed and further releases of fish were made in September 1979 and March 1981, to give a

stocking density of 1571 fish per hectare. Estimated biomass by May 1983 was 2554 kg/ha. Similar results to those of 1979 were achieved in March 1982, though the differences between trial and control areas were not as distinct.

The silver carp were unable to contain the fluctuations in bloom intensity, and, as a result, cycling from clear to bloom conditions and back to clear in 3 to 4 weeks occurred in the trial area.

At temperatures below 16°C the fish cease to grow. Growth was fastest during summer and early autumn when water temperatures and algal densities were at their greatest.

From the results of the investigations it was concluded that there was an improvement in the lake appearance and water clarity with control by silver carp of the blue-green algal blooms and surface scums.

A potential use of silver carp is the control of blue-green algae in small lakes and ponds used for stock watering. *Microcystis* sp. can be responsible for ill health and death in stock. The improvement in water quality in stock watering ponds could be of significant economic value to the farming community.

1. INTRODUCTION

Blooms of blue-green algae (cyanobacteria) are not a product of modern civilisation, but have occurred since biblical times. An event which can be interpreted as an algal bloom occurs in Exodus 7: 20-21. In Britain there is a lake in which algal blooms have appeared intermittently for more than 800 years (Flint 1966). With the enrichment of inland waters that has occurred throughout the world in recent times, blue-green blooms have become a significant problem. In New Zealand, with its agricultural background, they are a major problem in many lakes and farm ponds. Blue-green algal blooms often produce foul odours and poor aesthetic values, and at times they can be highly toxic to farm stock. (Flint 1966, Prescott 1969, Scott, Barlow, and Hauman 1981, Paerl and Ustach 1982, McBarron and May 1966). Dense growths of blue-green algae and the development of a thermocline are common in eutrophic lakes.

The anoxic conditions which develop in the hypolimnion of such lakes restrict the bottom area available to fish for feeding, and force fish into the warmer surface water. In highly eutrophic conditions fish such as salmonids may not be able to survive because of high temperature in the epilimnion. Periodic mixing of stratified lakes can result in extremely low dissolved oxygen levels throughout the water column, and can cause fish kills.

The use of plankton feeding fish to control algal blooms was suggested by Prowse (1969). He indicated that in fresh water, silver carp (*Hypophthalmicthys molotrix* (Val.)) (Fig. 1) was probably the most suitable species. Silver carp were used successfully to control blooms in Singapore (Buck 1977). Despite this, little work has been done on the effectiveness of the fish in controlling algal blooms (Henderson 1983). The silver carp is a native of some large rivers in China, the Amur being the most notable, and it is extensively used in fish farming. It was introduced into Japan in 1878 (Inaba and Nomura 1956) and since 1950 it has been introduced into many parts of the world. Large numbers are now farmed in Russia, India, Israel, and Hungary.

The silver carp is a filter feeding herbivore which is equipped with a unique gill structure (Jirasek, Hampl, and Airotek 1981/82), which enables it to filter out large quantities of phytoplankton with particle sizes ranging from 8 µm to 100 µm (Cremer and Smitherman 1980). It can consume 10-16% of its body weight daily (Barthelmes and Jahnichen 1978). Silver carp cease to feed below 10°C and are most active at temperatures over 20°C. They are not known to spawn in lakes and ponds (Henderson 1977), but require specific conditions for spawning and these occur only in rivers carrying large volumes of water and with flow rates sufficient to suspend the ova and fry for 3-5 days, at temperatures of 22-24°C. Thus the possibility of their breeding in the wild in New Zealand is remote. Even if they should spawn, the lack of suitable food in New Zealand rivers would prevent their survival there. The possibility of them migrating between catchments by way of the sea is also unlikely, because they have a very low tolerance to salt water: Chervinski (1977) found that they did not survive more than 48 hours in 30% sea water.

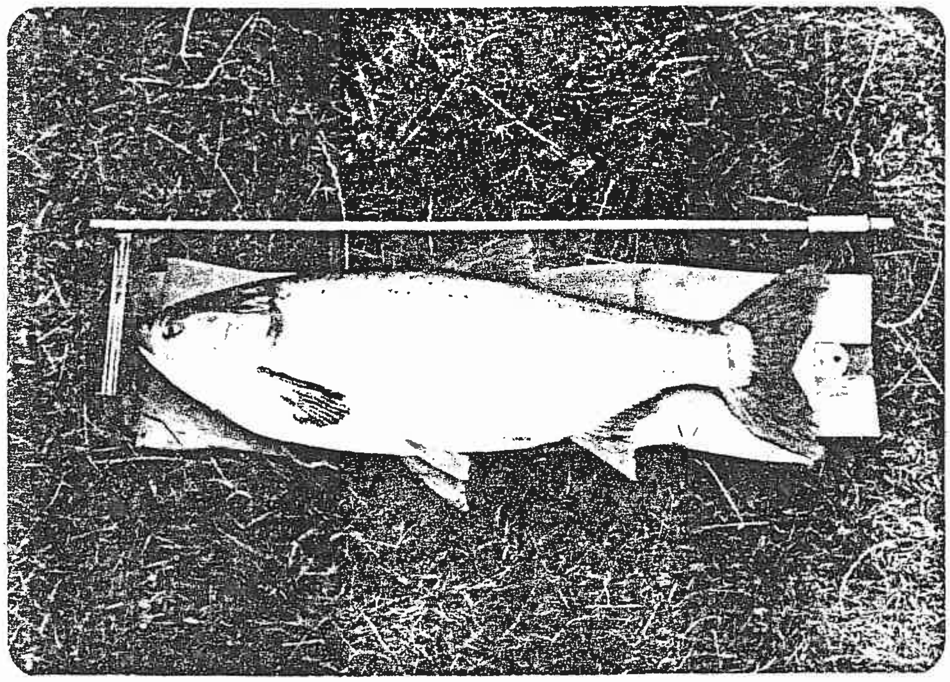

FIGURE 1. Silver carp (*Hypophthalmicthys molotrix* (Val.)) used for control of phytoplankton blooms.

During a visit to New Zealand in 1967, Dr Prowse suggested that the fish could be used to control problem algal blooms in Lake Tutira (Fig. 2), where poor water quality was causing problems with the management of the rainbow trout fishery. There are three lakes at Tutira, all with the same problem.

The lakes are in an area of tertiary siltstone and mudstone, and were probably formed when a valley drainage system became blocked by the partial collapse of a ridge to the east. This view is supported by the presence of landslide materials reported by Ferguson and Rafter (1959). They suggest that the blockage occurred at the same time as the slip which formed Lake Waikaremoana, where carbon dating of drowned beech trees has indicated that this lake was formed about 2230 years ago.

Lake Orakai (area 4 ha) was chosen for the silver carp trials because it was the smallest of the three lakes and because the configuration of the lake enabled it to be divided into a trial and a control area. The object of the trial was to assess the ability of the silver carp to control algal blooms.

The catchment of Lake Orakai (13.91 ha) is rolling to steep and predominantly pasture land with scattered kanuka (*Leptospermum ericoides*) scrub (Fig. 3). The lake has two basins (about 6 m deep) and shelves evenly to the shoreline (Fig. 2). There are no permanent streams entering the lake, and the outlet at the lake's western end functions only during wet weather when the lake level rises. Survey information has confirmed that the lake area has remained static for the last 50 years (Department of Lands and Survey, Napier pers. comm.).

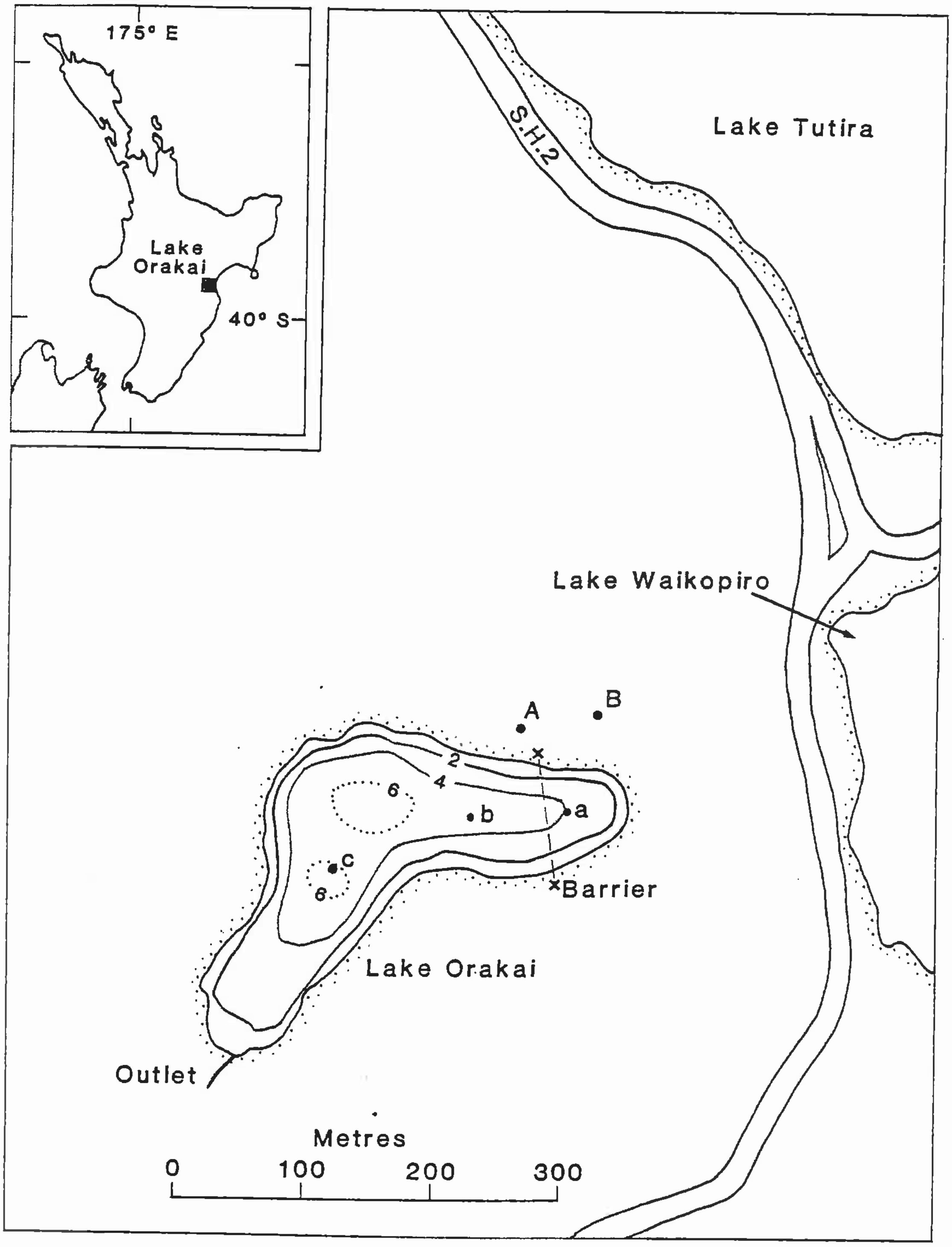

FIGURE 2. Location and bathymetry of Lake Orakai on the east coast of the North Island, New Zealand. (Colour photographs in Figs. 5, 6, 7, and 8 were taken from positions A and B: a, b, and c are data logger stations.

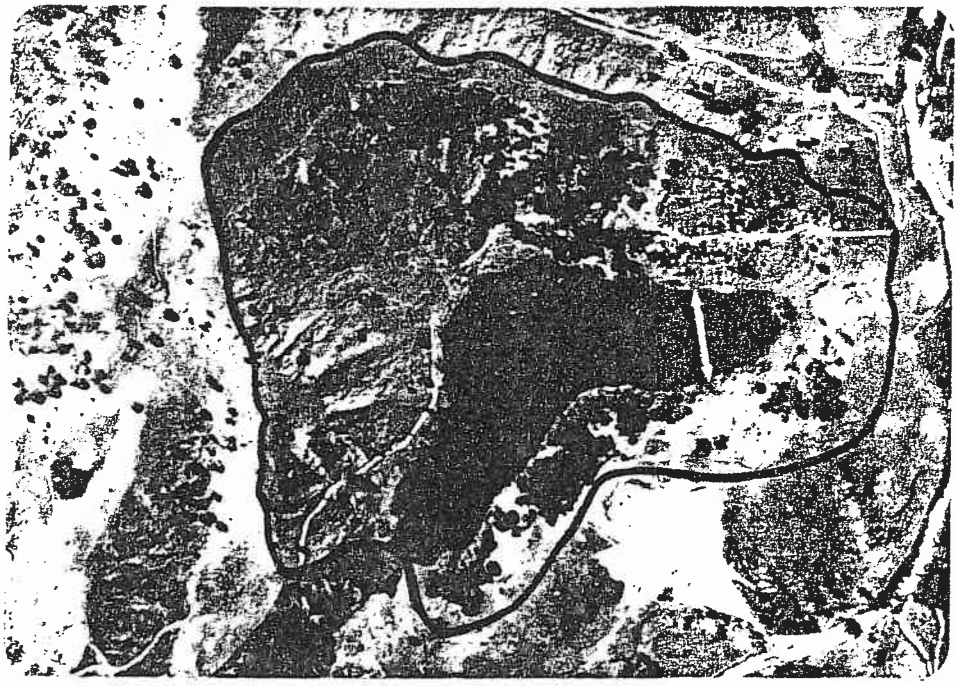

FIGURE 3. Aerial view of lake Orakai showing its catchment boundary (heavy black line) and the position of the PVC barrier (white line).

The area immediately surrounding the lake was established as a wildlife refuge by the late Mr Guthrie-Smith, who formerly owned the property. The lake supports small populations of black teal (*Aythya novaeseelandiae*), dabchick (*Podiceps rufopectus*), pukeko (*Porphyrio melanotus*), black swan (*Cygnus atratus*), mallard (*Anas platyrhynchos*), grey duck (*Anas superciliosa*) and paradise duck (*Tadorna variegata*); it has visiting populations of shags (*Phalacrocorax* spp.). It also has indigenous populations of short-finned eels (*Anguilla australis*) and common bullies (*Gobiomorphus cotidianus*). A brown trout (*Salmo trutta*) fishery was maintained by stocking until 1967 (T.B. Munro pers. comm.), but no records are available about the quality of the fishery.

The lake is now highly eutrophic (Burnet and Wallace 1973) and the lake bottom is covered with a layer of black organic sludge. Although no information is available to indicate when the deterioration started, it was probably in the early 1950s (Tutira Technical Committee 1976) when there was an upsurge in the aerial application of phosphate.

In response to the suggestion by Dr Prowse, the Hawke's Bay Acclimatisation Society obtained permission to import a trial shipment of silver carp from Malacca. Thirty-five juvenile fish were imported in 1969 and held in quarantine. All these fish survived. A further shipment of 1000 juveniles was imported in 1970, but only 94 fish survived. Samples of the survivors examined by Dr P.M. Hine of Fisheries Research Division (FRD) at intervals up to October 1973 were free of parasites and disease. No further imports were permitted, and so field experiments could not begin until sufficient fish were bred from the fish already in New Zealand.

In December 1973, 25 silver carp were transferred to a floating cage at Lake Orakai to accelerate growth rate by the provision of a source of natural food. The fish did not mature sexually until they were 4 years old, when they were induced to spawn by hormone injections. Sufficient fingerlings were produced by January 1977 to allow field trials to begin in September 1978. Further spawnings were necessary in 1979 and 1980.

2. METHODS

In February 1978 the lake was divided into two unequal areas of 0.5 ha and 3.5 ha by a vertical barrier of nylon reinforced PVC sheeting. The barrier position is shown in Figure 2 and can be seen in the top right-hand arm of the lake in Figure 3. The barrier (Fig. 4) was designed to prevent the interchange of water and fish between the two areas of lake. A permanent fish screen had been erected across the lake's outlet in April 1971.

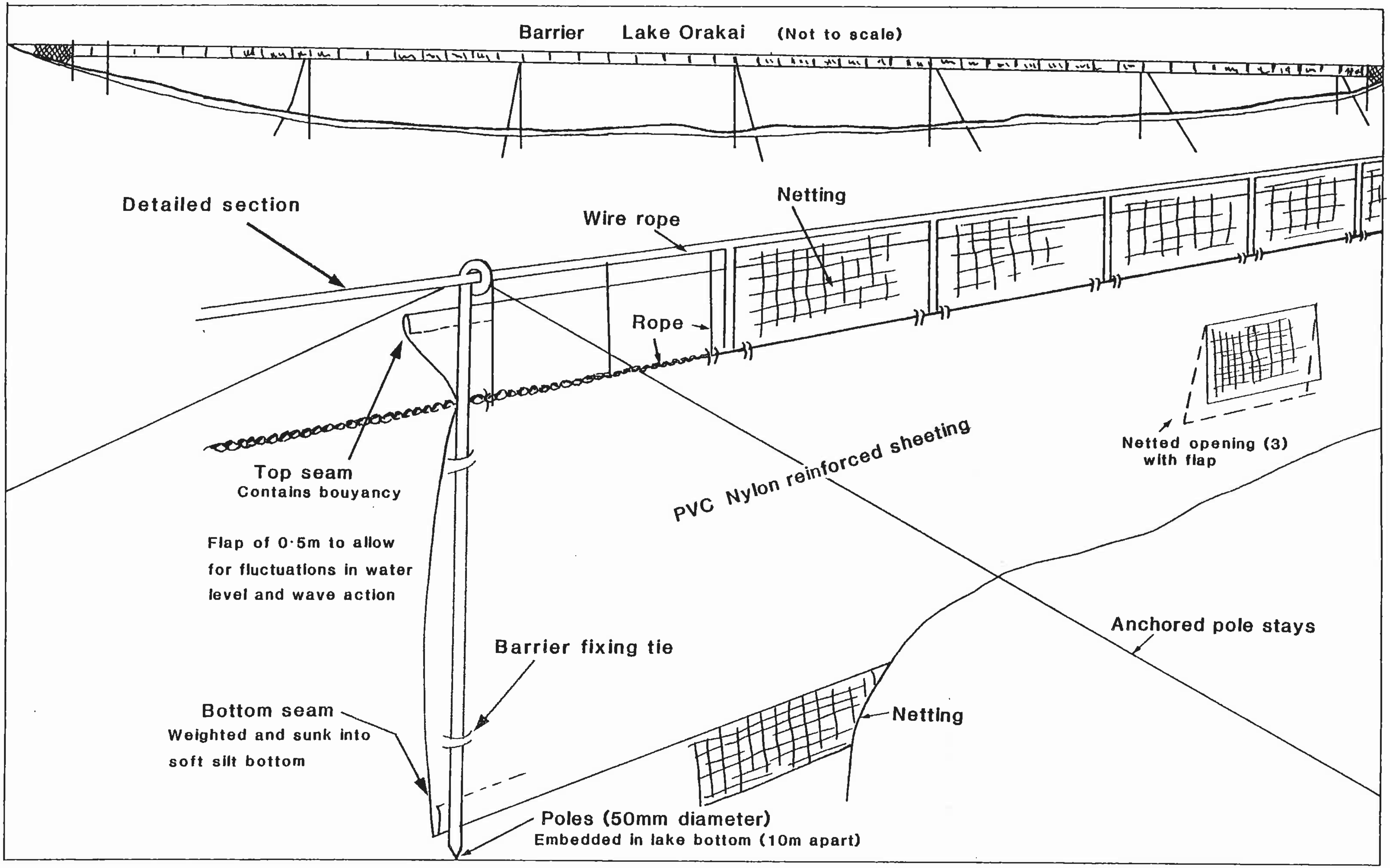

FIGURE 4. Construction of barrier used in Lake Orakai.

Fifteen hundred silver carp were released into the 0.5 ha trial area of the lake in September and November 1978 to give a population density of 3000 fish per hectare. The choice of this density was based on the work of Januszko (1974), who observed a decrease in algal biomass at this stocking density, though he suggested that the decrease may have been influenced by other factors. In June 1979 the control and trial areas were reversed. The barrier was lifted, the fish were driven into the 3.5 ha area and the barrier was reset. The fish remained in the 3.5 ha section until the conclusion of the trial in June 1982. The reason for reversing the trial and control areas in 1979 was to demonstrate that the improvement in the trial area was not caused by the barrier altering the morphology of the lake or the characteristics of the algal bloom, but was caused by the fish. Further releases of fish were made in September 1979 and March 1981 to build up the stocking density. The size and age of fish at release are shown in Table 1.

TABLE 1: Age, size at release, and numbers of silver carp per hectare in Lake Orakai

Date	Number released	Initial Biomass (kg)	Size range (mm)	Age (months)	Area (ha)	Population density (per hectare)
Sep, Nov 1978	1500	54	45-210	21	0.5	3000
Sep 1979	2000	2.5	35.50	9	3.5	1000
Mar 1981	2000	2.6	35-65	4	3.5	1571

Growth rates and biomass of the fish were estimated from fish caught in floating traps and trammel nets and were checked against periodic measurements of fish held in cages.

Silver carp were analysed for total nitrogen and phosphorus content of the carcass. Microscopic examination of gut contents and faecal matter was used to assess ingestion of algae and zooplankton. Monthly field sampling was done to measure dissolved oxygen and temperature at depth intervals of 0.5 m, and pH was measured at the water surface. A 200-mm diameter Secchi disk with black and white segments was used to define water clarity, which was used as a measure of the amount of algal material in the upper lake water (White 1976, Stewart 1976). Results for dissolved oxygen and temperatures at four depths for 1978 to 1982, and for pH, Secchi disk transparencies, dissolved oxygen and temperatures from 1979 to 1981 are given in Appendix I. Colour photographs were taken as a visual record of differences in both areas. Water samples were collected for laboratory analysis of total nitrogen and phosphorus, and for algal and zooplankton identification.

In October 1979 a data logger (Burnet 1982) was installed with sensors on each side of the barrier. Parameters measured were air temperature, water temperature, dissolved oxygen, light intensity, and wind velocity (Burnet 1983). Rainfall records were from the New Zealand Meteorological Service, Station D96281 at Tutira. A summary of the data logger results from 1979 to 1984 is given in Appendix II. To determine the long term effect of the silver carp on the lake, monitoring of these parameters by data logger is continuing.

The relationship between surface water temperature and fish growth was assessed by holding fish in a floating mesh cage (3 x 3 x 2 m). Thirteen marked, caged fish were weighed and measured at 2-monthly intervals, and surface water temperatures were recorded from 1973 to 1976 before the barrier was erected.

3. RESULTS

3.1 Water clarity changes and fish growth

Colour photographs were taken from the northern shore looking south across the lake from points A and B (see Fig. 2). Figure 5, taken from point A on 29 December 1978, shows that the fish had produced little effect on the water clarity in the trial area (to the left of the barrier) 2 months after the November 1978 release. However, 24 days later, on 22 January 1979, water in the trial area was noticeably clearer than in the control area (Fig. 6).

The distinct improvement in water clarity was followed by an expansion of the macrophyte beds compared with their extent before the start of the experiment. A photograph taken from point B on 22 January 1979 (Fig. 7) shows the development of a dense bed of *Elodea canadensis* around the margin of the trial area. No such increase in macrophytes occurred in the 3.5 ha trial area in 1981-82.

After the transfer of the fish to the 3.5 ha area in June 1979, similar trends occurred in the water clarity of the trial and control areas, though the differences in clarity between the areas were less distinct. However, by 29 March 1982 there was an obvious effect on the appearance of the trial area. This is shown in Figure 8 which was taken from point A (see Fig. 2).

Secchi disk transparencies also reflected the improved clarity in the trial area in 1978-79 and 1981-82 (Fig. 9). The improved water clarity was attributed to the reduction of the algal bloom by the silver carp, and the changes confirmed the ability of the fish to control blooms.

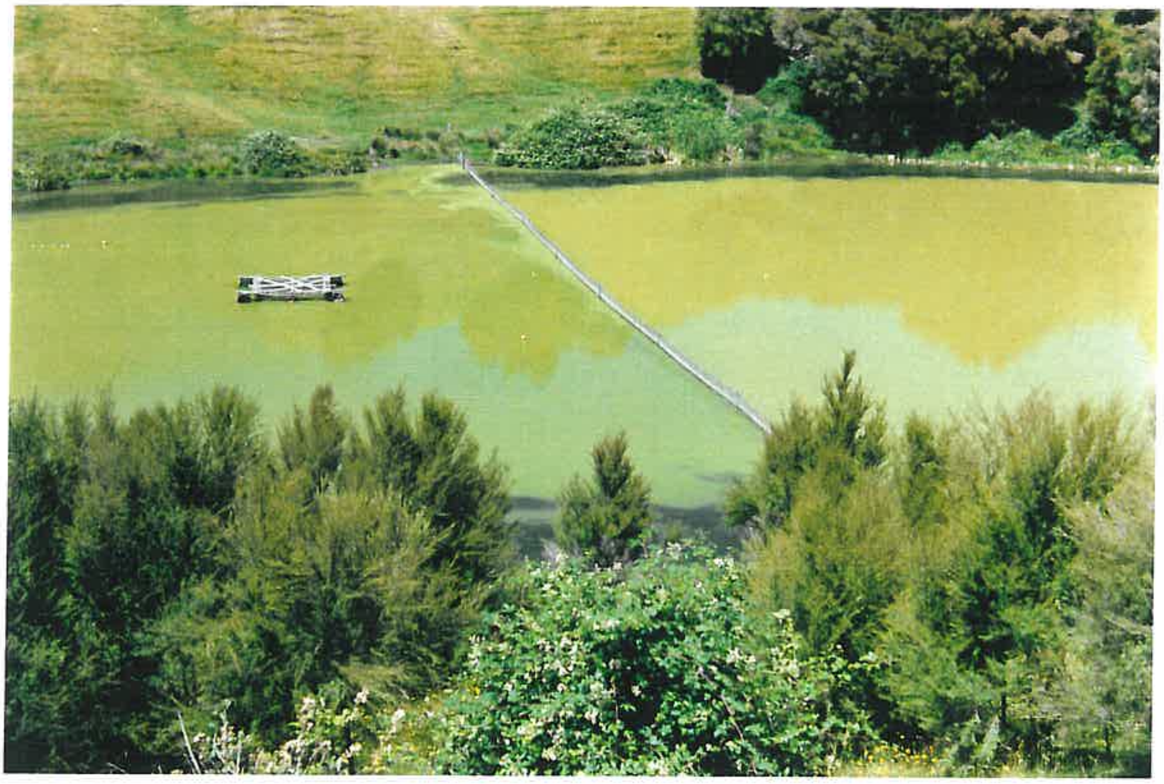

FIGURE 5. Lake Orakai on 29 December 1978, 2 months after the release of silver carp in November 1978 (trial area is to the left of the barrier).

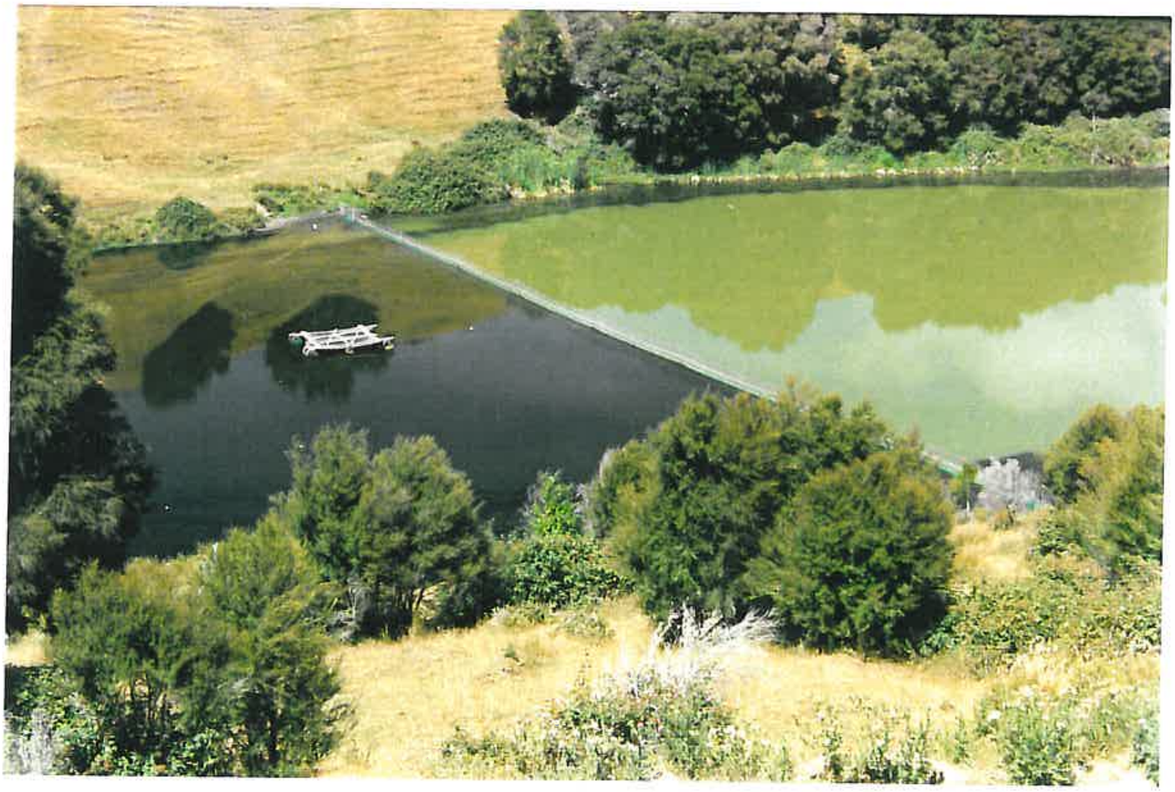

FIGURE 6. Lake Orakai on 22 January 1979, 3 months after the release of silver carp in November 1978 (trial area is to the left of the barrier).

FIGURE 7. Development of *Elodea canadensis* bed in Lake Orakai on 22 January 1979. This followed a distinct improvement in water clarity caused by silver carp.

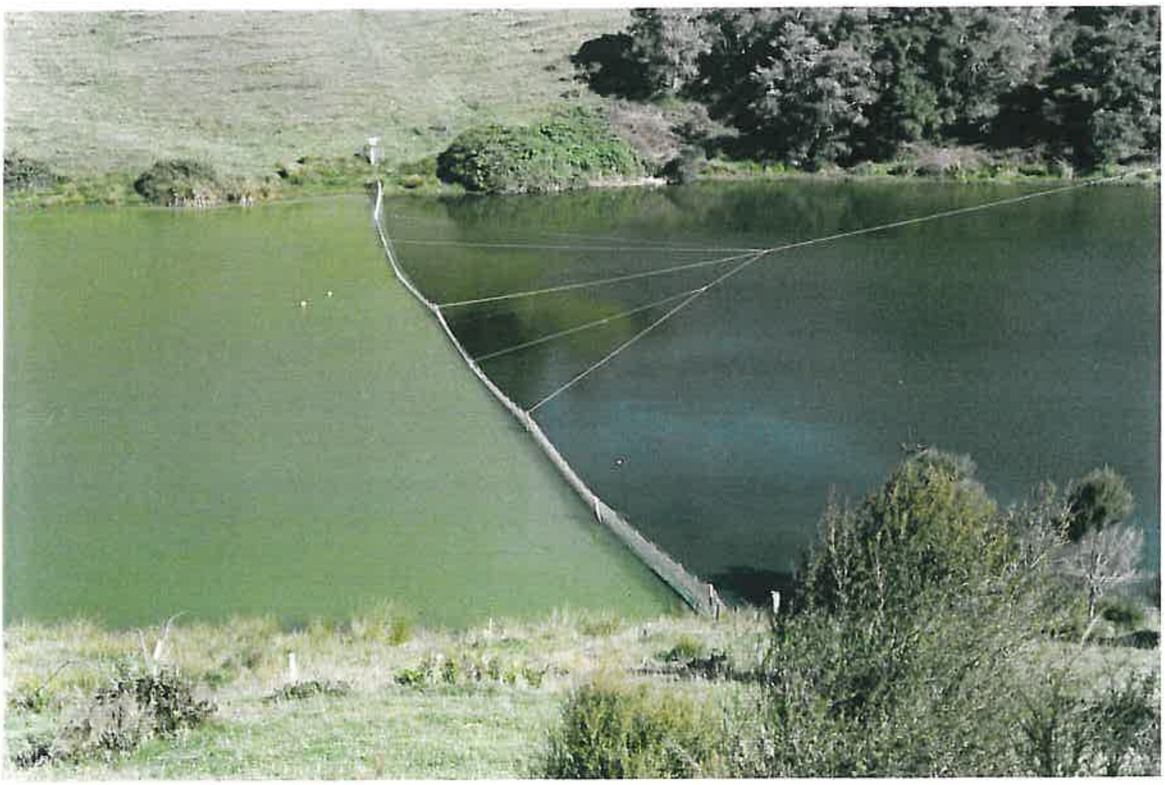

FIGURE 8. Lake Orakai on 29 March 1982, 34 months after the silver carp were transferred to the 3.5 ha area (trial area is to the right of the barrier).

The time lag in achieving control in the larger area can be explained by the time taken to build up a biomass of fish per hectare equivalent to that in the smaller area in 1979 (Fig. 10). Seasonal and climatic fluctuations also influenced the ability of the fish to control blooms.

Growth of the fish held in a cage from 1973 to 1975 (Fig. 11) was closely related to surface water temperatures. In autumn and winter when water temperatures dropped below 16°C, the growth of the caged fish was static, with a slight decline in weight. When temperatures increased in spring, fish growth recommenced. Growth was fastest during summer and early autumn when water temperatures and algal densities were at their greatest (see Figs. 9 and 11).

Water clarity measured by Secchi disk from 1978 to 1982 showed fluctuations over time. However, it was evident that while the fish were in the 0.5 ha area (1978-79) summer and early autumn water clarity improved compared with that in the control area (see Fig. 9a). At other times of the year clarity differences between the areas were less marked and the trial area was not consistently clearer.

After the trial and control areas were reversed the water clarity showed smaller differences between areas during the summer and early autumn (1979-81, see Fig. 24, Appendix I). However, by the summer of 1981-82, when the estimated fish biomass had increased eight-fold (see Fig. 10) there was a marked difference in the water clarities of the two areas, similar to the difference in the summer of 1978-79 (see Fig. 9).

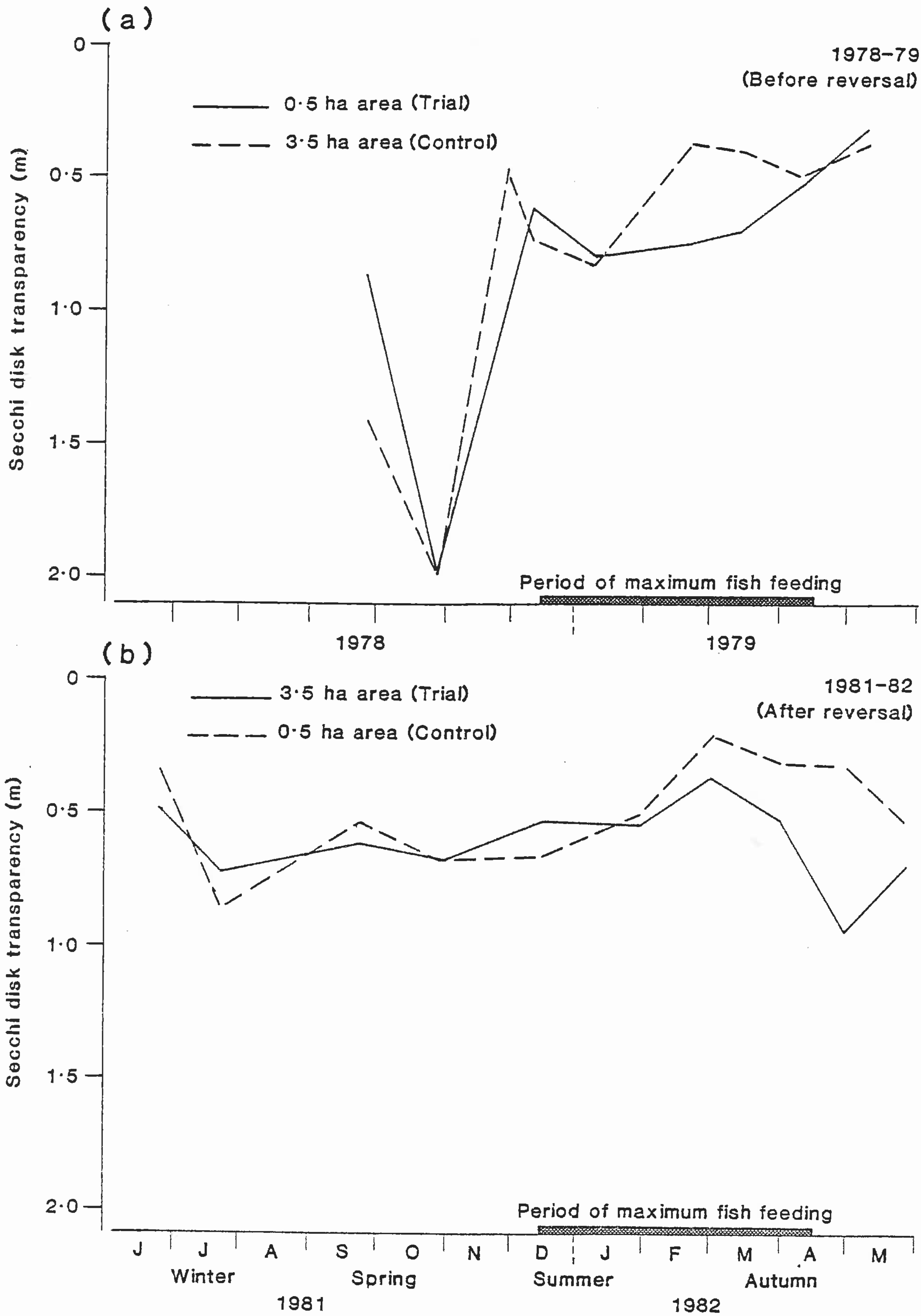

FIGURE 9. Secchi disk transparencies in the silver carp trial and control areas, Lake Orakai: (a) 1978-1979 (before reversal of areas), (b) 1981-82 (after reversal of areas).

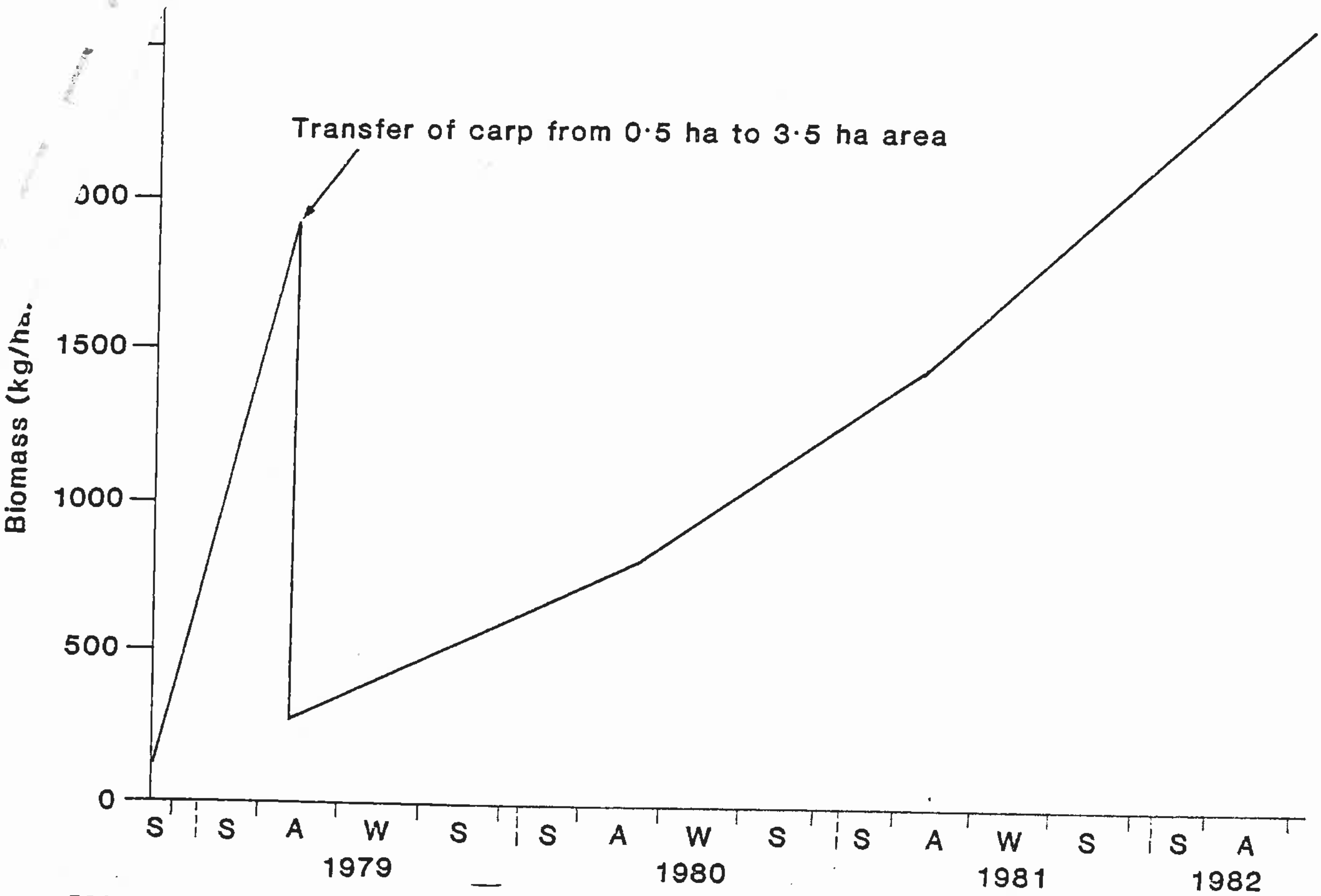

FIGURE 10. Biomass (kg) of silver carp per hectare, Lake Orakai 1978-82.

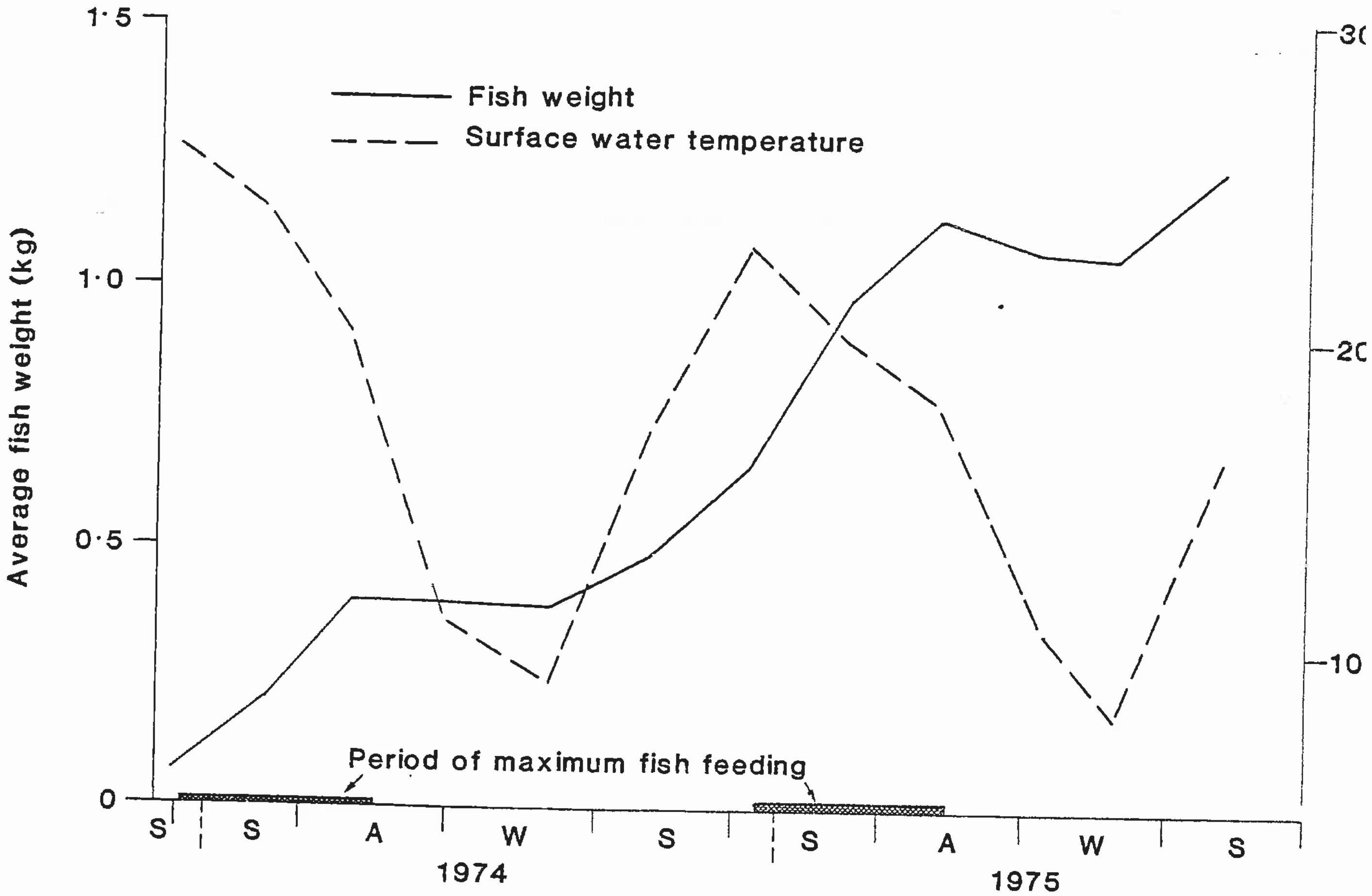

FIGURE 11. Average weight (kg) of 13 marked fish grown in a cage in Lake Orakai, and surface water temperatures, 1973-75.

3.2 Surface dissolved oxygen and pH

Dissolved oxygen and pH measured at the surface in the 0.5 ha and 3.5 ha trial areas fluctuated in a similar pattern over time (Figs. 12 and 13). Paerl and Ustach (1982) showed that there was a close relationship between dissolved oxygen and high pH in dense algal blooms. The results in Lake Orakai showed a similar relationship. In the summer periods (January-March 1978-79 and 1981-82) dissolved oxygen and pH were lower in the trial area than in the control (Figs. 12 and 13) and at the same time Secchi disk transparencies showed increased water clarity in the trial area (see Fig. 9). Similar results were seen for a short period in spring. The differences in the two areas in the 1978-79 summer and early autumn trial (3000 fish per hectare) were more pronounced than in the 1981-82 summer and early autumn trial (1571 fish per hectare).

3.3 Surface temperatures

Surface temperature showed seasonal fluctuations ranging from 8°C to 28°C annually (Fig. 14). Temperatures from 1978 to 1981 showed fluctuating differences between the control and trial areas, except that the 3.5 ha trial area in 1981-82 (Fig. 14) and 1979-80 (see Fig. 25, Appendix I) was slightly, but consistently, cooler than the control area.

3.4 Data logger and rainfall

The lake was generally stratified from October to April each year and the thermocline, as determined by monthly sampling, was consistently between 1.5 and 2.0 m from the surface (dissolved oxygen and temperature results in Appendix I and temperatures in Appendix II).

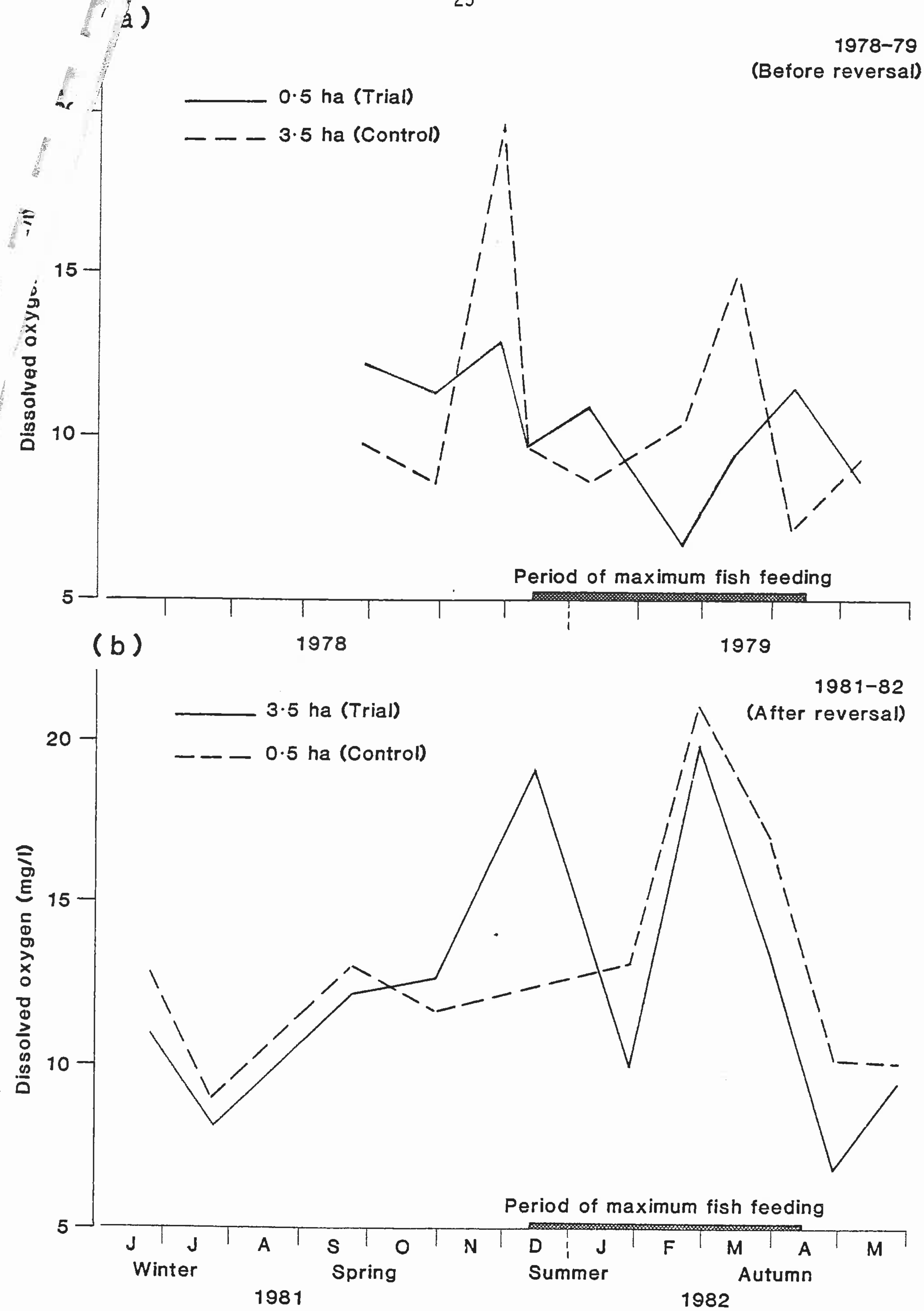

FIGURE 12. Dissolved oxygen in surface water in the silver carp trial and control areas: (a) 1978-79 (before reversal of areas), (b) 1981-82 (after reversal of areas).

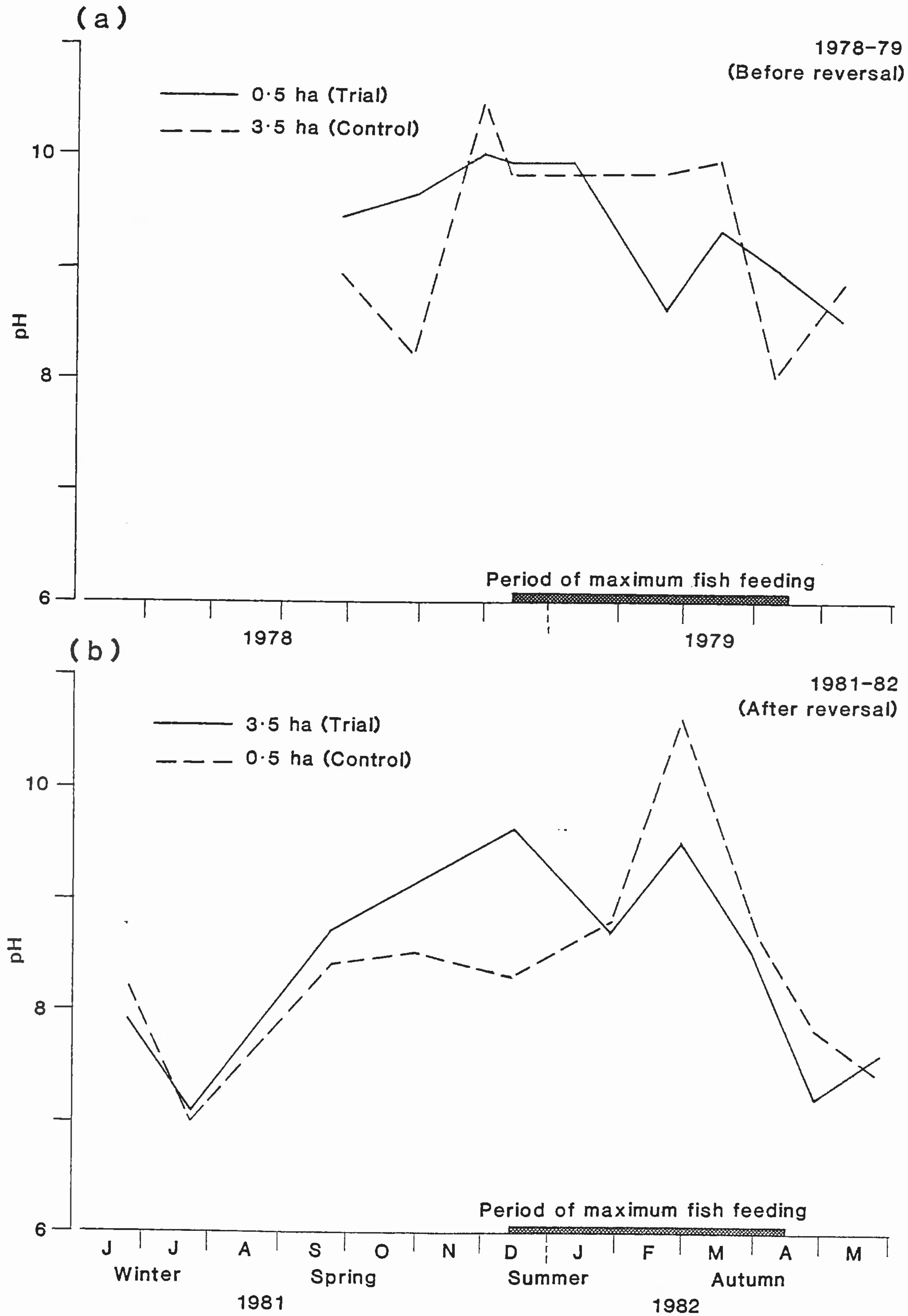

FIGURE 13. Surface water pH in the silver carp trial and control areas: (a) 1978-79 (before reversal of areas), (b) 1981-82 (after reversal of areas).

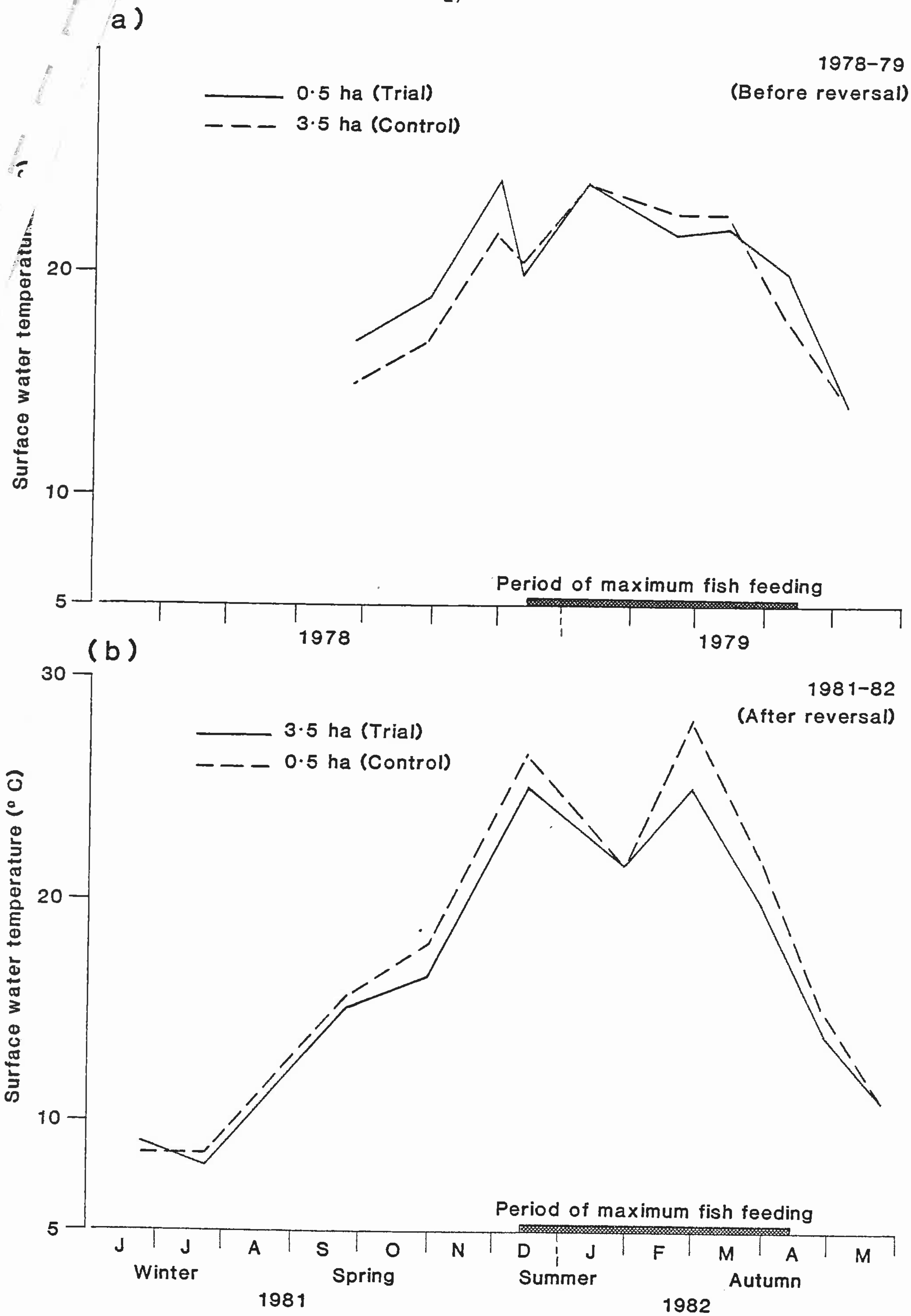

FIGURE 14. Surface water temperatures in the silver carp trial and control areas: (a) 1978-79 (before reversal of areas), (b) 1981-82 (after reversal of areas).

Conditions that maintained stratification can be seen in a typical section of data logger records taken over 30 days in the 3.5 ha trial area during early summer (December) 1980 (Fig. 15).

Temperatures measured at 0.25 metres showed diurnal fluctuations corresponding to light intensity, and the gradient in temperatures from different depths generally reflected stratification.

When strong wind, heavy rain, or a combination of both, occurred they caused sudden mixing. This was indicated by loss of the temperature gradient (Fig. 15, days 9-11). A sudden drop in dissolved oxygen at 0.25 m also occurred, and dissolved oxygen at 3.6 m showed an increase when mixing was complete, this condition was of short duration.

3.5 Volume ratios

The drop in dissolved oxygen caused by mixing is partly attributable to the volume of the lake in each area above and below the thermocline. The ratio of the volume above 2 m compared with that below 2 m was 1.7:1 in the 0.5 ha area and 1.02:1 in the 3.5 ha area. Because of this, mixing of the anoxic hypolimnion reduced the overall dissolved oxygen in the larger area to a greater extent than in the smaller area. (Unpublished data logger results).

3.6 Feeding relationships

Throughout the trial period, fish were observed to forage actively in shoals in areas with dense algal scums and blooms, generally within 30 cm of the surface. This is consistent with the observation of Barthelmes and Jahnichen (1978).

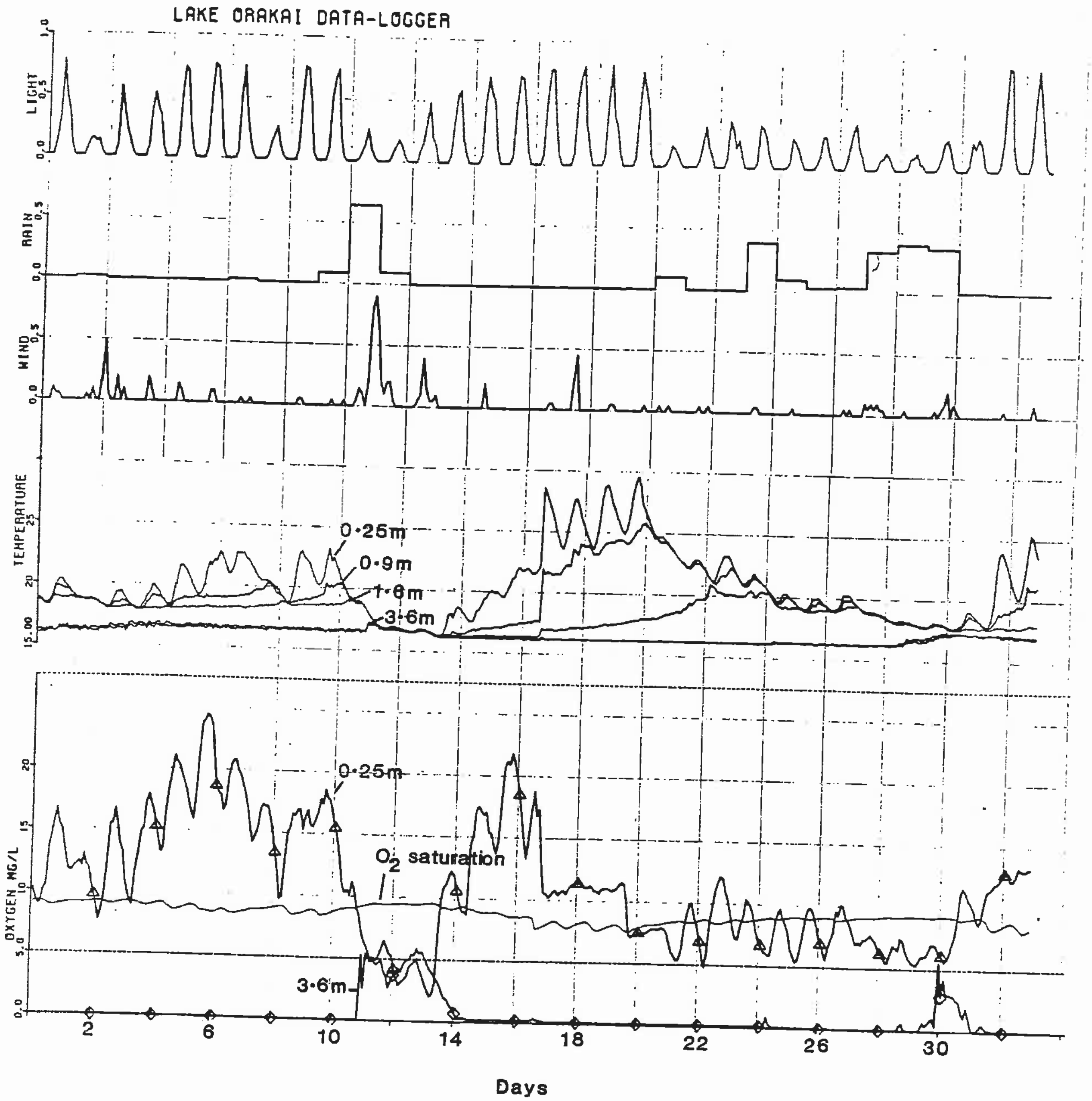

FIGURE 15. Typical section of data logger record for 30 days in early summer (December) 1980 in the 3.5 ha trial area with silver carp. (These data were from a data logger temporarily installed at station c (see Fig. 2) between 15 December 1980 and 21 May 1981. The sensors for this data logger were at slightly different depths than were those for the data logger results in Appendix II. Rainfall results are from N.Z. Meteorological Station D96281.)

The gut contents and faecal samples examined from fish of various sizes showed the same dominant algal genera as were in the lake water samples. *Microcystis* sp. was consistently found in all gut contents (n = 30) and faecal samples (n = 93) of feeding fish, and was always predominant. Rotifers (*Keratella* sp. and *Brachnionus* sp.) and Crustaceans (*Bosmina* sp. and *Boeckella* sp.) were found in 87% of the gut contents and faecal samples analysed.

The maximum size of animal species found in the samples was 500 µm, except for four individuals of *Boeckella* sp., which were about 1000 µm. Different sized fish were not found to feed selectively.

During periods when increased cell buoyancy (Paerl and Ustach 1982) lead to surface scums of *Microcystis* sp., significant amounts of silver carp faecal matter were found floating at the surface. The faecal matter was covered with a mucous coating and eventually sank.

3.7 Total phosphorus and nitrogen levels in water and fish

The total phosphorus and total nitrogen levels in the wet weight of silver carp (n = 6) averaged 0.64% and 2.62% respectively and were similar to the results of Bull and MacKay (1976) for four other species of fish.

Column samples of lake water showed total phosphorus to vary from 135 mg/m^3 to a high of 420 mg/m^3 and total nitrogen from 1360 mg/m^3 to 2855 mg/m^3.

4. DISCUSSION

Despite considerable international research, the complexity of factors associated with development and behaviour of algal blooms is not fully understood.

Burnet and Wallace (1973), in studies of 15 New Zealand lakes, found that Lake Orakai was one of the most eutrophic. In another study, Burnet (1983) found the lake had one of the highest levels of algal production he had measured; the daily algal production was about 100 g/m^2 or 100 kg/ha. Chemical analyses for the major nutrients gave no indications that they were limiting algal production. R.H.S. McColl (pers. comm.) estimated that the input of biologically available phosphorus from the catchment was about 575 mg/m^3/yr or 80 kgs for the lake. Nutrients can also be recycled from lake sediments and play an important part in the production cycle. Fillos and Swanson (1975) showed that anaerobic conditions resulted in a dramatic increase in the release rates of nutrients from sediments.

Climatic conditions which cause sudden mixing and re-stratification (Fig. 15, days 10 and 20) were frequent and recurring events in the lake and from personal observations were often followed by an upsurge in productivity and bloom intensity.

Silver carp were unable to cope with these events immediately, but would do so eventually with the result that the trial areas have cycled from clear to bloom conditions and back to clear in 3-4 weeks.

The relationship between temperature and fish growth rate (see Fig. 11), which is assumed to be directly related to the amount of food consumed, explains the minimal effect of the fish on bloom conditions in late spring (November) to early summer for both trials. During this period algal densities (as indicated by Secchi disk transparency) were high (see Fig. 9), while surface water temperatures were fluctuating (see Fig. 14). Water temperatures were still rising to the optimum level for sustained maximum feeding by the fish (about 20°C) and hence maximum algal control. When surface temperatures were below 18°C control of the algăl populations present was minimal.

Barthelmes and Jahnichen (1978) estimated that silver carp consumed between 10-16% of the body weight per day at temperatures above 18°C, and Omarov (1970) gave a consumption of 17.25% body weight per day without specifying temperature.

Assuming that silver carp consume 10% of their body weight per day, (the lowest figure quoted by Barthelmes and Jahnichen (1978)) then 1000 kg of fish should consume the estimated daily production of algae per hectare for late spring, summer, and early autumn (100 kg/ha) (Burnet 1983). However, the result illustrated in Figure 8 was not achieved until the estimated biomass of carp in the 3.5 ha area was 2000 kg/ha (see Fig. 10).

Secchi disk transparency, pH, and lower dissolved oxygen results for February-March 1979 and 1982 (see Figs. 9, 12 and 13) confirmed that the silver carp had achieved measurable improvements in the trial areas, when compared with the control areas. A suitable hypothesis to explain the cooler surface temperature in the 3.5 ha trial area in 1981/82 (see Fig. 14) could be that less heat was absorbed at the surface because the algal bloom had been reduced. This could also explain the cooler surface temperature in the 0.5 ha (trial) area from January to March 1979 (see Fig. 14).

The stocking biomasses which reduced the severity of blue-green algal blooms (*Microcystis* sp.) during the summer and autumn in the two experiments were similar; an estimated biomass of 1916 kg/ha (3000 silver carp per hectare) for the 0.5 ha area in April 1979, and 2554 kg/ha (1571 silver carp per hectare) in May 1982, assuming zero mortality for both experiments. The photographs (see Figs. 6, 7 and 8) illustrate the effect of the silver carp on the algal blooms more clearly than the monthly sampling results.

Control of the blue-green blooms can reduce the risk of fish kills caused by deoxygenation following mixing. An example of this occurred in Lake Orakai in 1979. Before the installation of the barrier in February 1978 several silver carp escaped from their cage during experiments; these fish were in the control area when the barrier was installed. Heavy rain and strong winds were recorded on 30-31 March 1979, and it was assumed total mixing of the lake water occurred. When the Lake was inspected (on 9 April) 26 dead silver carp were found around the shoreline of the control area. No dead fish were found in the trial area (which included caged fish). Silver carp can survive dissolved oxygen levels of 1 mg/ℓ (Zhong Lin *et al.* 1980). No dead native species of fish were found, but mortalities may have occurred and not been detected. No New Zealand information is available on the tolerance in the wild, of eels or the common bully to very low dissolved oxygen levels. No fish mortalities have occurred in the large (3.5 ha) area since it has been the trial area, though conditions similar to those that caused the fish kill (above) have occurred there several times.

Silver carp ingest zooplankton when feeding, but most rotifers and many arthropods appeared undamaged after passing through the fishes gut.

Spartaru (1977) found that such organisms survived and continued to multiply 2 months after passing through the intestine. Barthelmes and Jahnichen (1978), who supported this observation, commented that the gill structure of silver carp may be responsible for the low ingestion of zooplankton and noted that some algae and certain zooplankton can pass through the carp alive. Cremer and Smitherman (1980) found silver carp gut contents were almost entirely phytoplankton with a particle size less than 100 μm; zooplankton were rarely present. They also found that the gut contents of bighead carp from the same ponds contained a mean of 23.6% of zooplankton.

Control of blooms may affect the unstable equilibrium between aquatic macrophytes and algal growth (see Fig. 7). *Elodea canadensis* was not visible before the trial in the 0.5 ha area, or after the reversal of the trial and control areas. However, no increase in macrophyte growth was observed in the 3.5 ha area after the reduction of algal bloom by silver carp.

One potential disadvantage of the silver carp is the production at times of large quantities of floating faecal material which can be aesthetically displeasing, but which may be more acceptable than an uncontrolled bloom and its associated smell and fish kills. The amount of floating faecal matter appears to be related to the formation of algal scums, which according to Reynolds and Walsby (1975) (cited by Paerl and Ustach (1982)) is a form of aging and precedes the massive death of the algae. It may be possible to reduce the amount of floating faecal matter by increasing the stocking rate of silver carp. This would increase the amount of algae consumed, hence the level of control of the blue-green algae, and also reduce the number of aging cells.

Nutrient stripping by the harvest of silver carp may be possible in lakes similar to Orakai. Given the levels of total phosphorus found in wet weights of silver carp, the increase in biomass for 1978-79 (see Fig. 9) would account for 57.9% of the total phosphorus entering the 0.5 ha area per year. Because of their proportionately greater weight gain, the harvest of larger fish would result in the removal of a greater proportion of the total phosphorus input. To obtain data on this would require further work and would be a long term investigation.

A further potential use of the fish is the control of algae (such as *Microcystis* sp., which can be responsible for ill-health and death of stock) in small lakes and ponds used for stock drinking water. In New Zealand there are many ponds where blue-green blooms are a problem, but mortalities and ill-health from the consumption of water containing toxic amounts of blue-green algae may have gone undetected and unsuspected. The use of silver carp to improve drinking water quality for stock, could be of significant economic value to the farming community. Flint (1966) cited *Microcystis* as the cause of lamb deaths in Hawke's Bay, and M.C. Price (pers. comm.) identified a similar cause for the death of 10 cattle in 1977. G. Shirley (pers. comm.) suspected a blue-green bloom as the cause of 9 cattle deaths near Oamaru in 1981. Prescott (1969), Scott *et al.* (1981), Paerl and Ustach (1982), and McBarron and May (1966) have made similar observations in other parts of the world.

5. CONCLUSION

From the results of this investigation it can be concluded there was an improvement in the lake appearance and water clarity with control by silver carp of blue-green algal blooms and surface scums.

ACKNOWLEDGMENTS

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APPENDIX I. Dissolved oxygen and temperatures at depths of 1 m, 1.5 m, 2.0 m, and 2.5 m for trial and control areas, Lake Orakai, 1978-82, and dissolved oxygen, water temperature and pH at the surface, and Secchi disk transparencies in both areas, 1979-81.

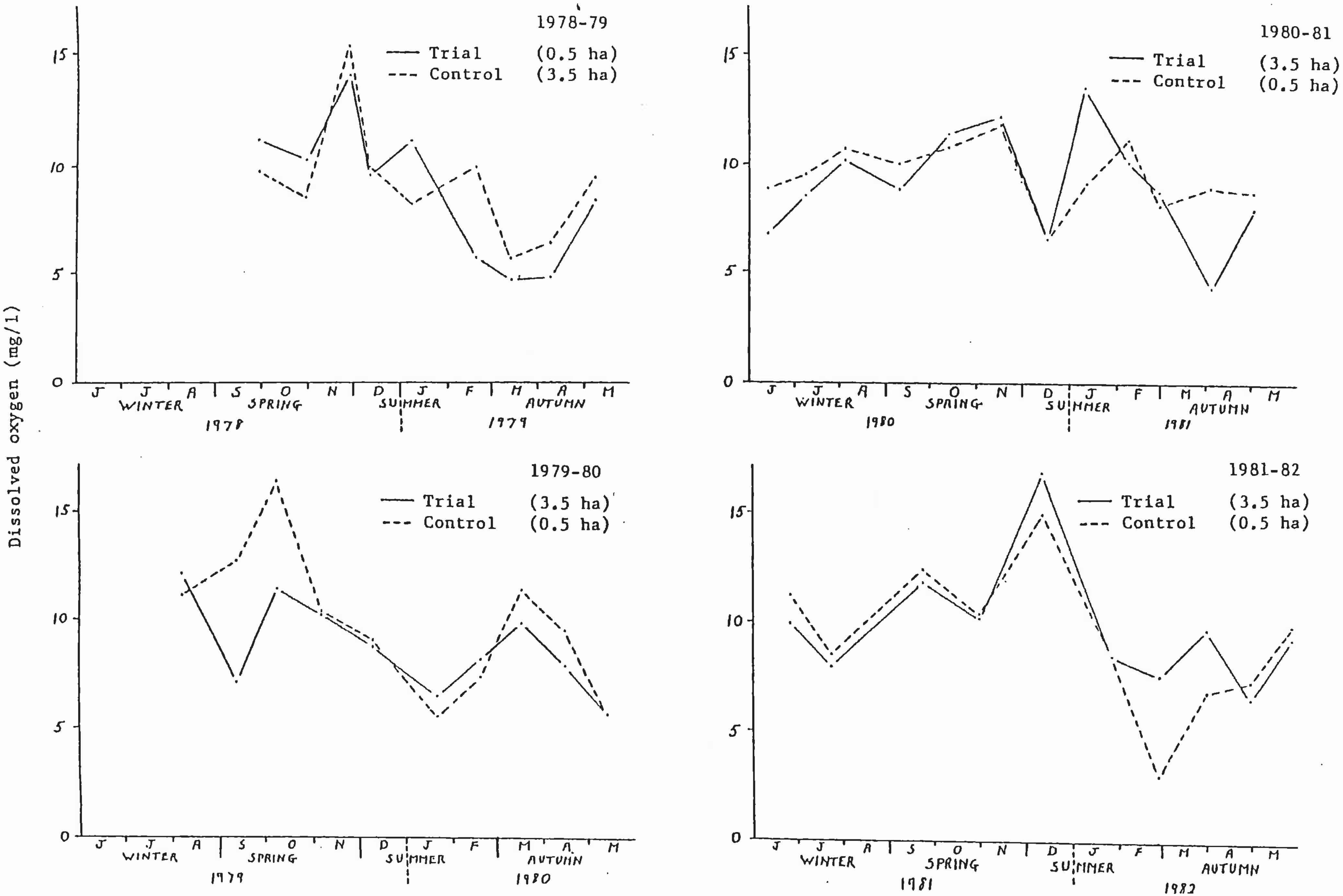


FIGURE 16. Dissolved oxygen at 1 m. trial and control areas. 1978-82.

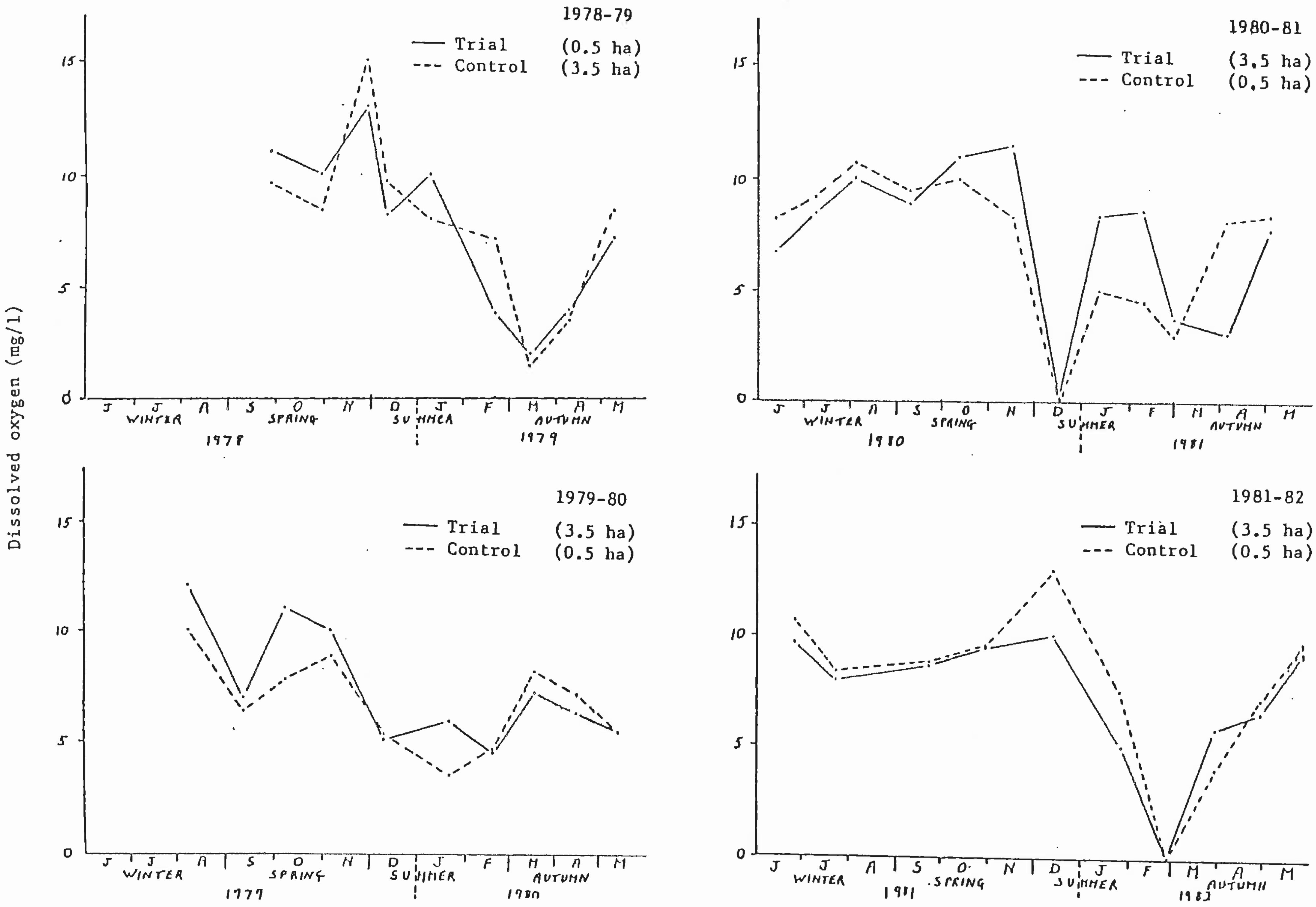


FIGURE 17. Dissolved oxygen at 1.5 m, trial and control areas, 1978-82.

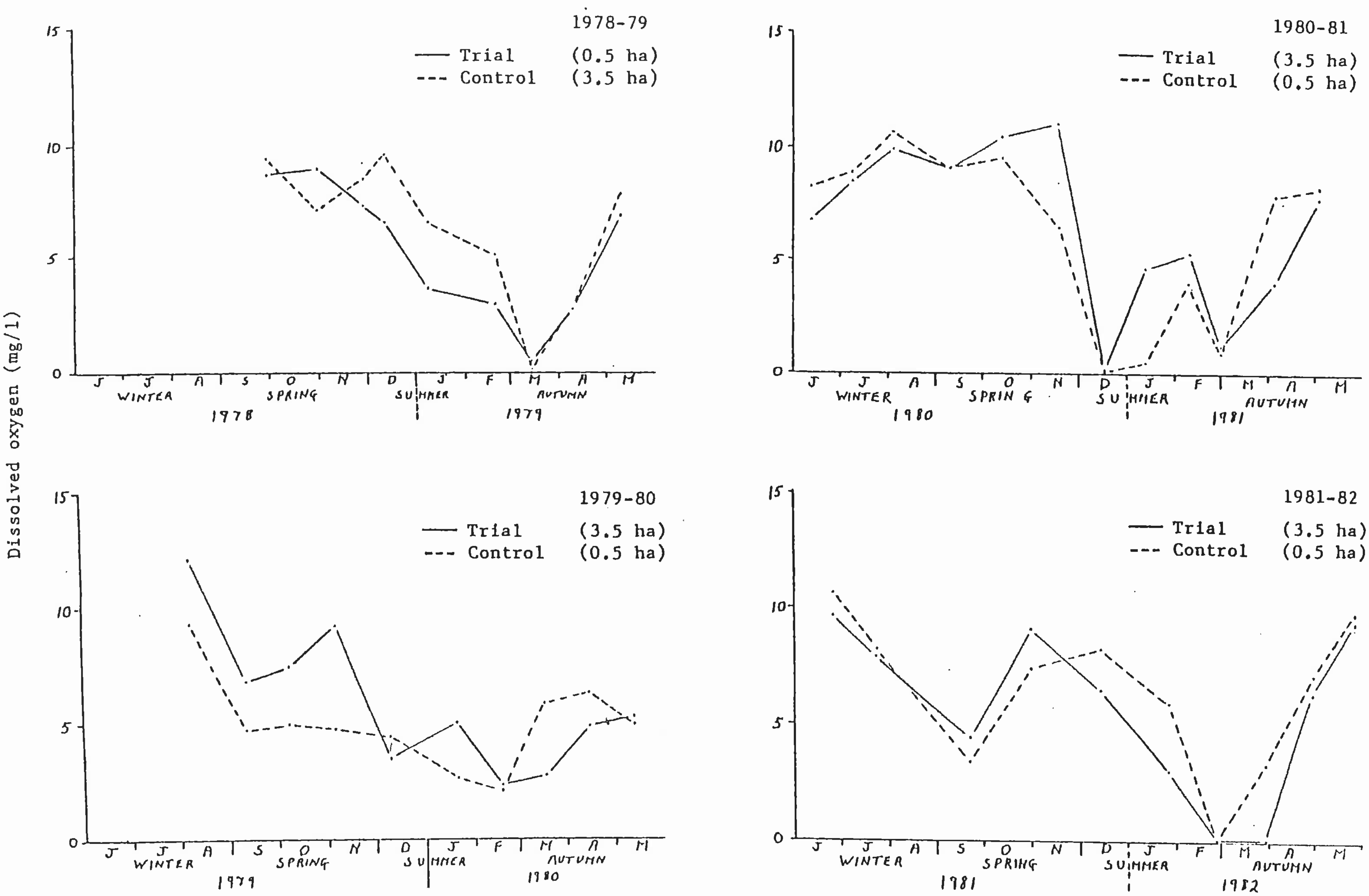


FIGURE 18. Dissolved oxygen at 2 m. trial and control areas, 1978-82.

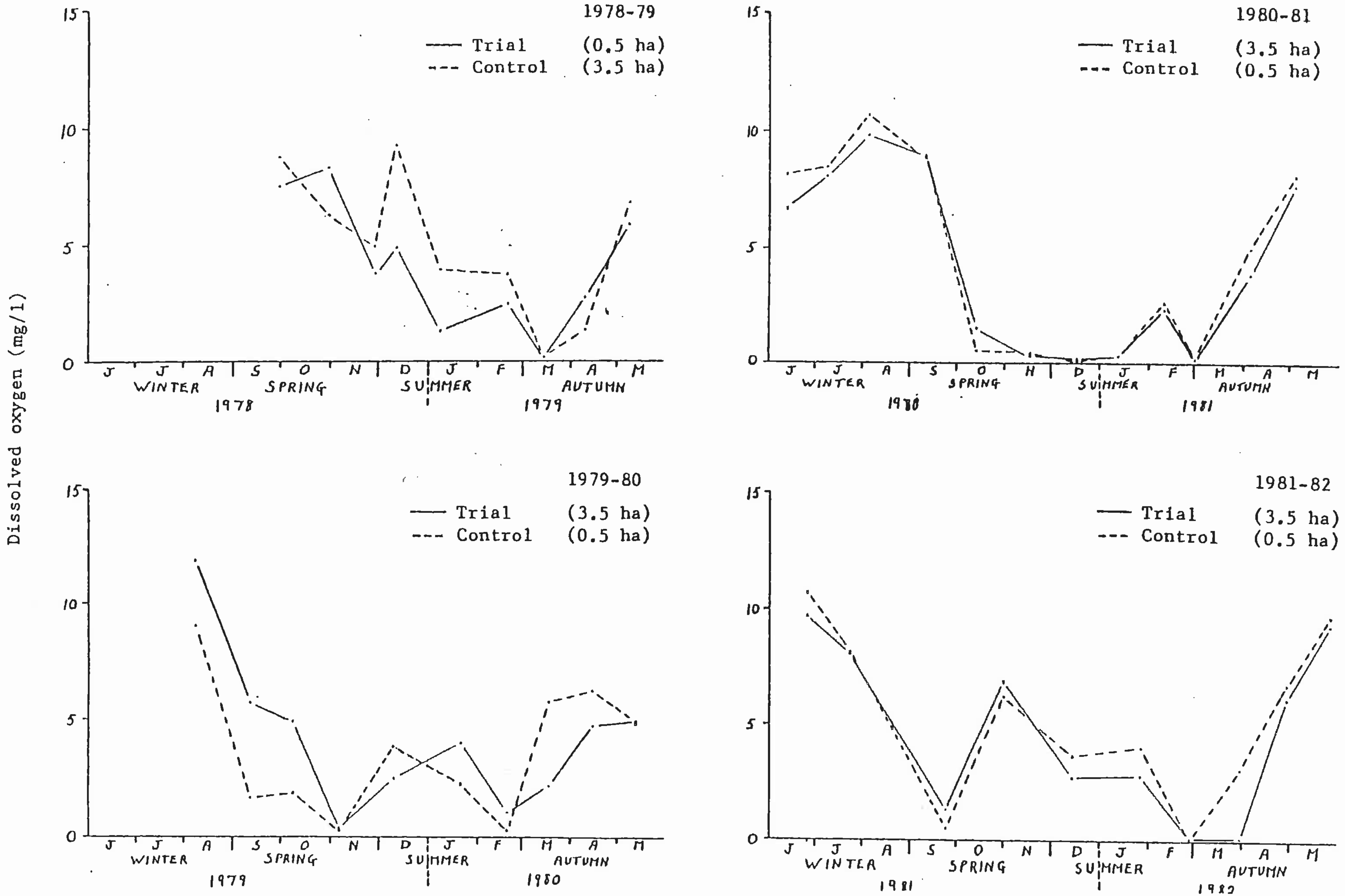
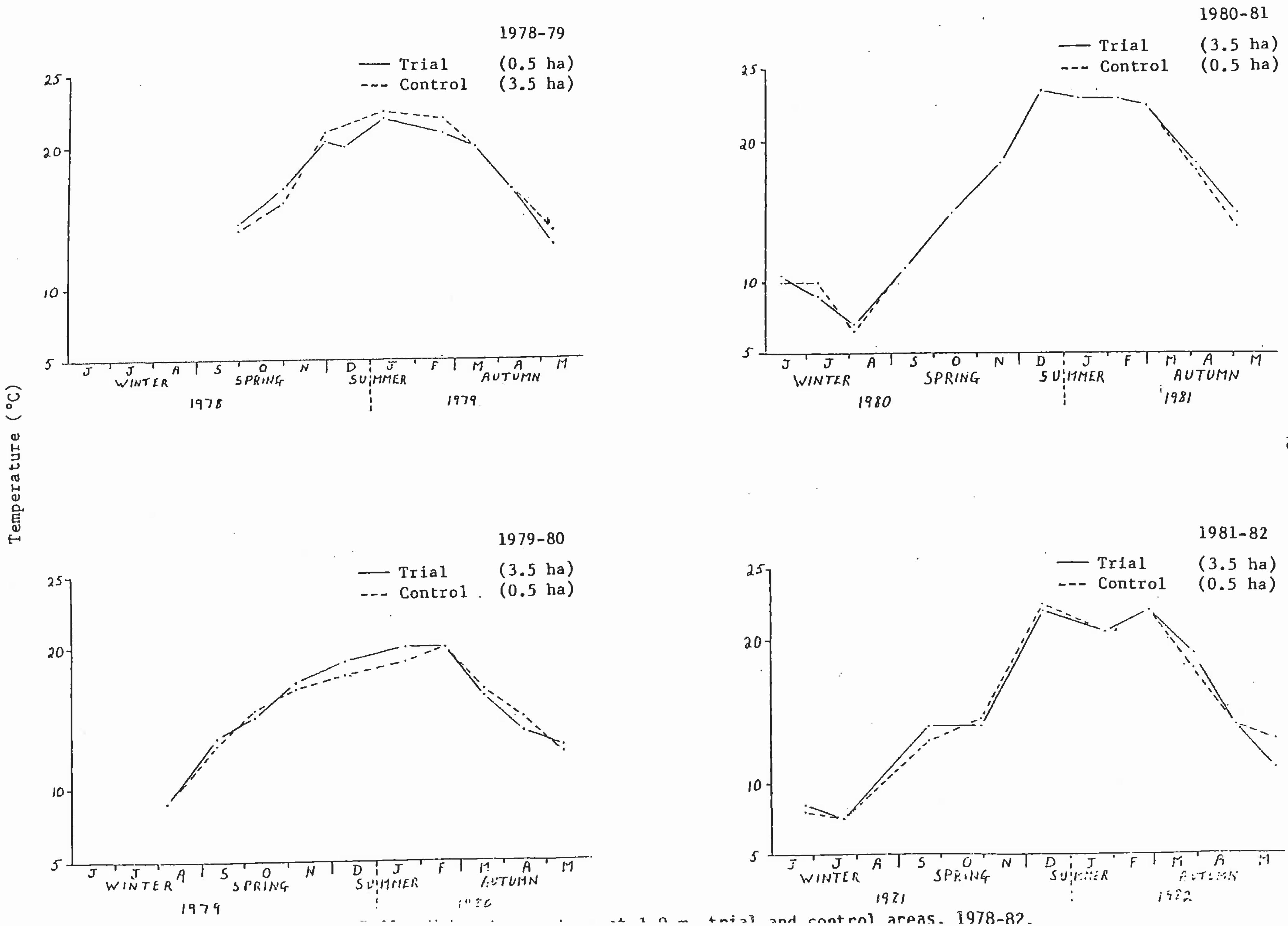


FIGURE 19. Dissolved oxygen at 2.5 m, trial and control areas, 1978-82.



trial and control areas, 1978-82.

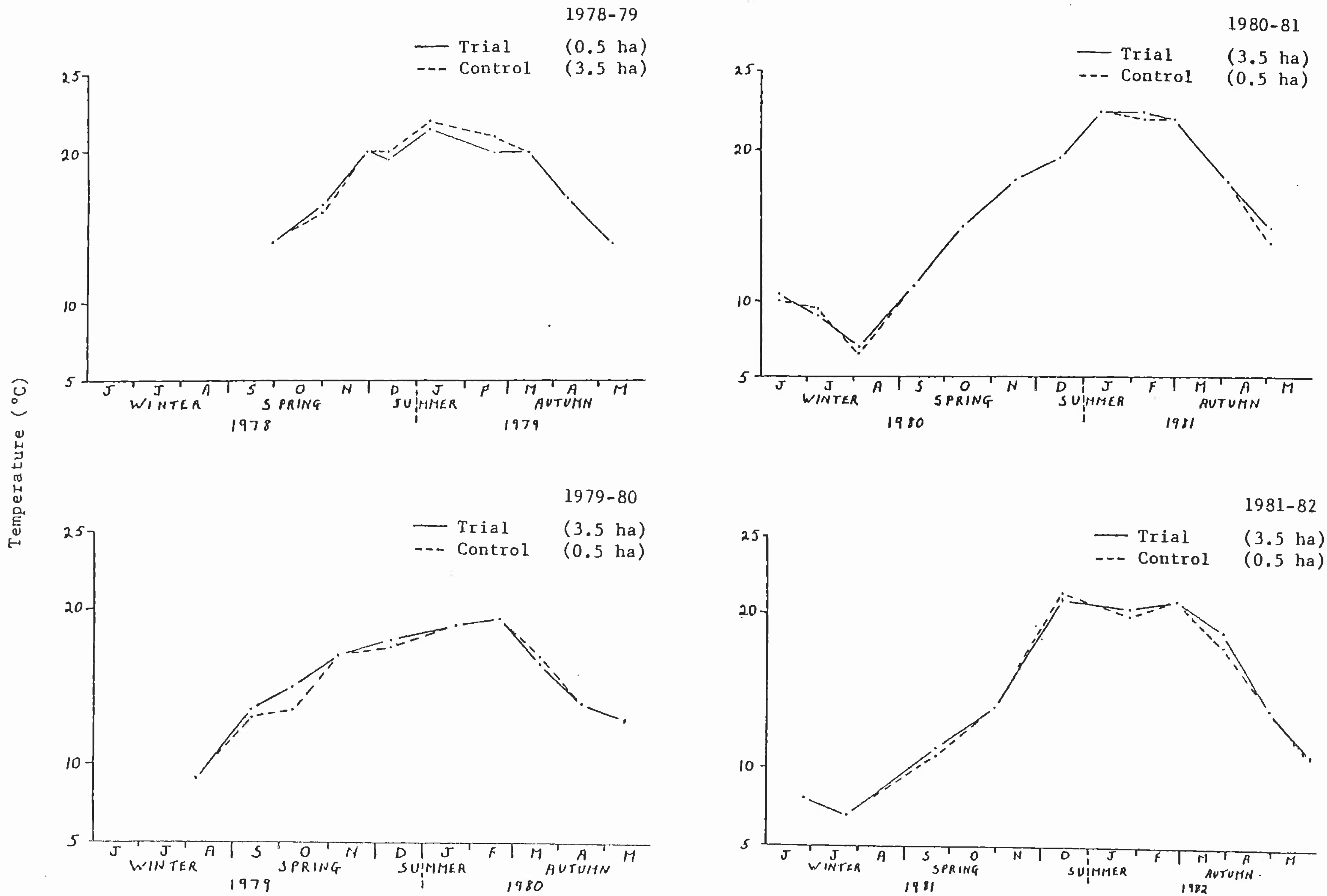
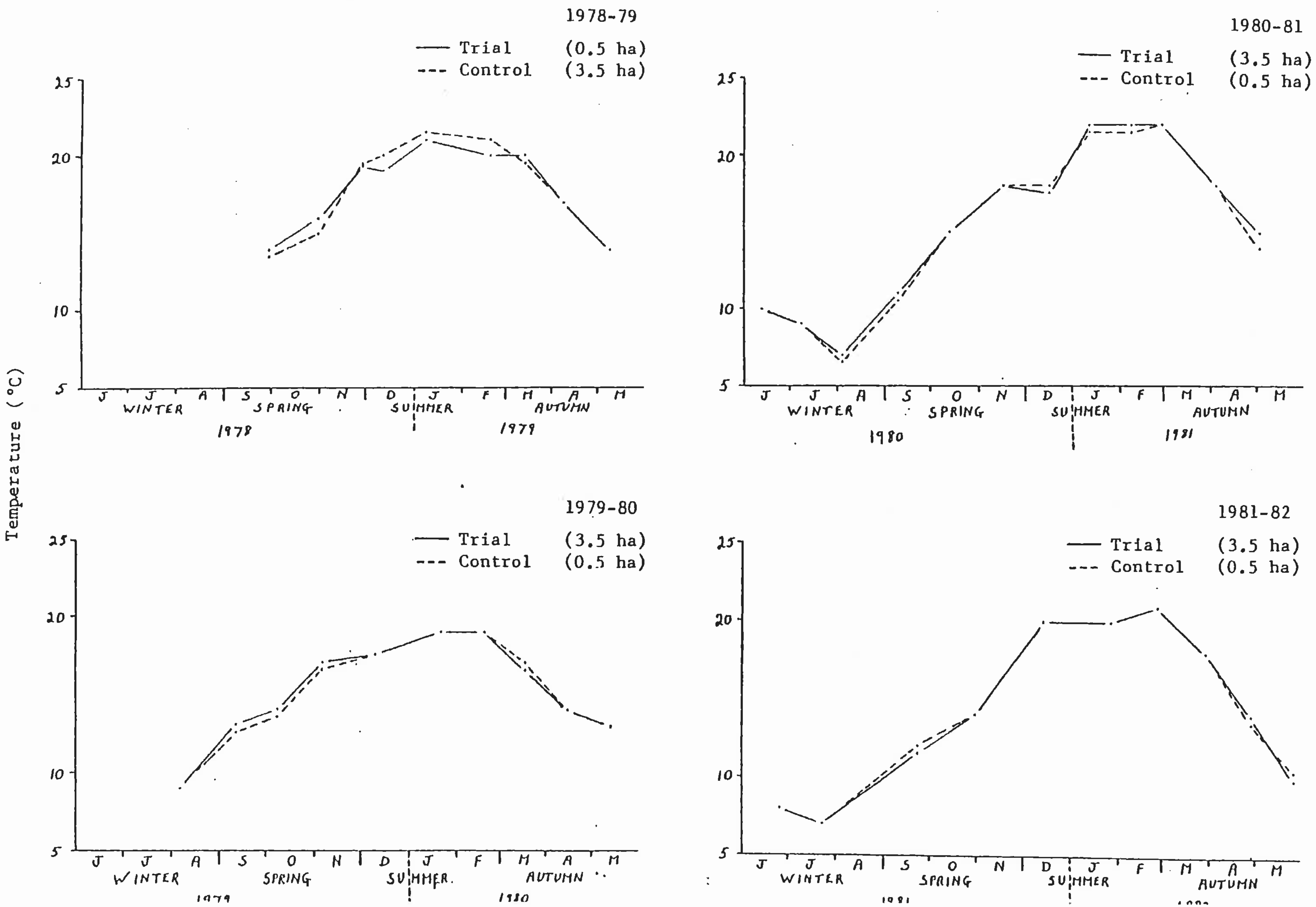


FIGURE 21. Water temperature at 1.5 m, trial and control areas, 1978-82.


Temperature (°C)
1978-79
— Trial (0.5 ha)
--- Control (3.5 ha)
1980-81
— Trial (3.5 ha)
--- Control (0.5 ha)
1979-80
— Trial (3.5 ha)
--- Control (0.5 ha)
1981-82
— Trial (3.5 ha)
--- Control (0.5 ha)
25
20
10
5
J J A S O N D J F M A M
WINTER SPRING SUMMER AUTUMN
1978 1979
1980 1981

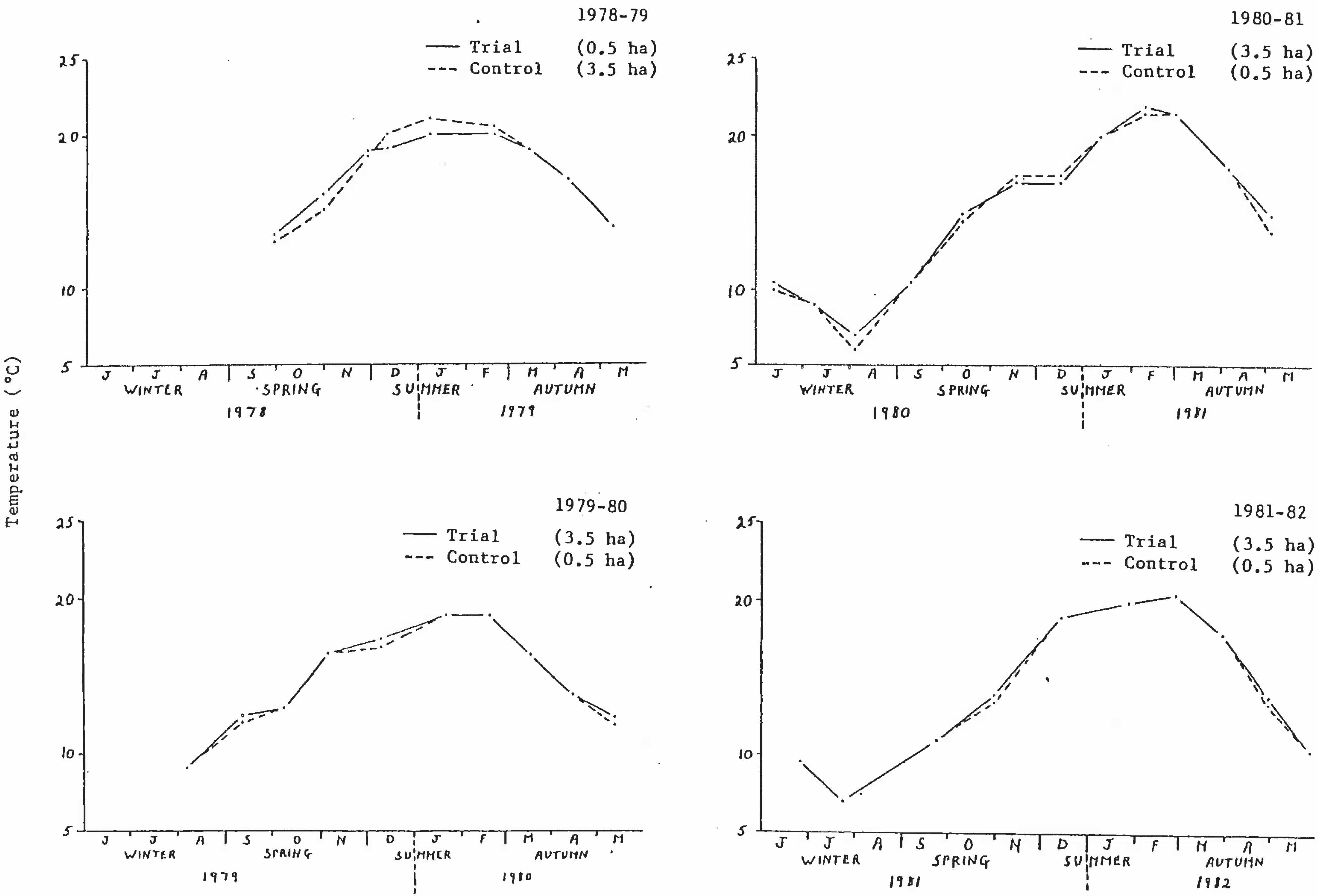


FIGURE 23. Water temperature at 2.5 m, trial and control areas, 1978-82.

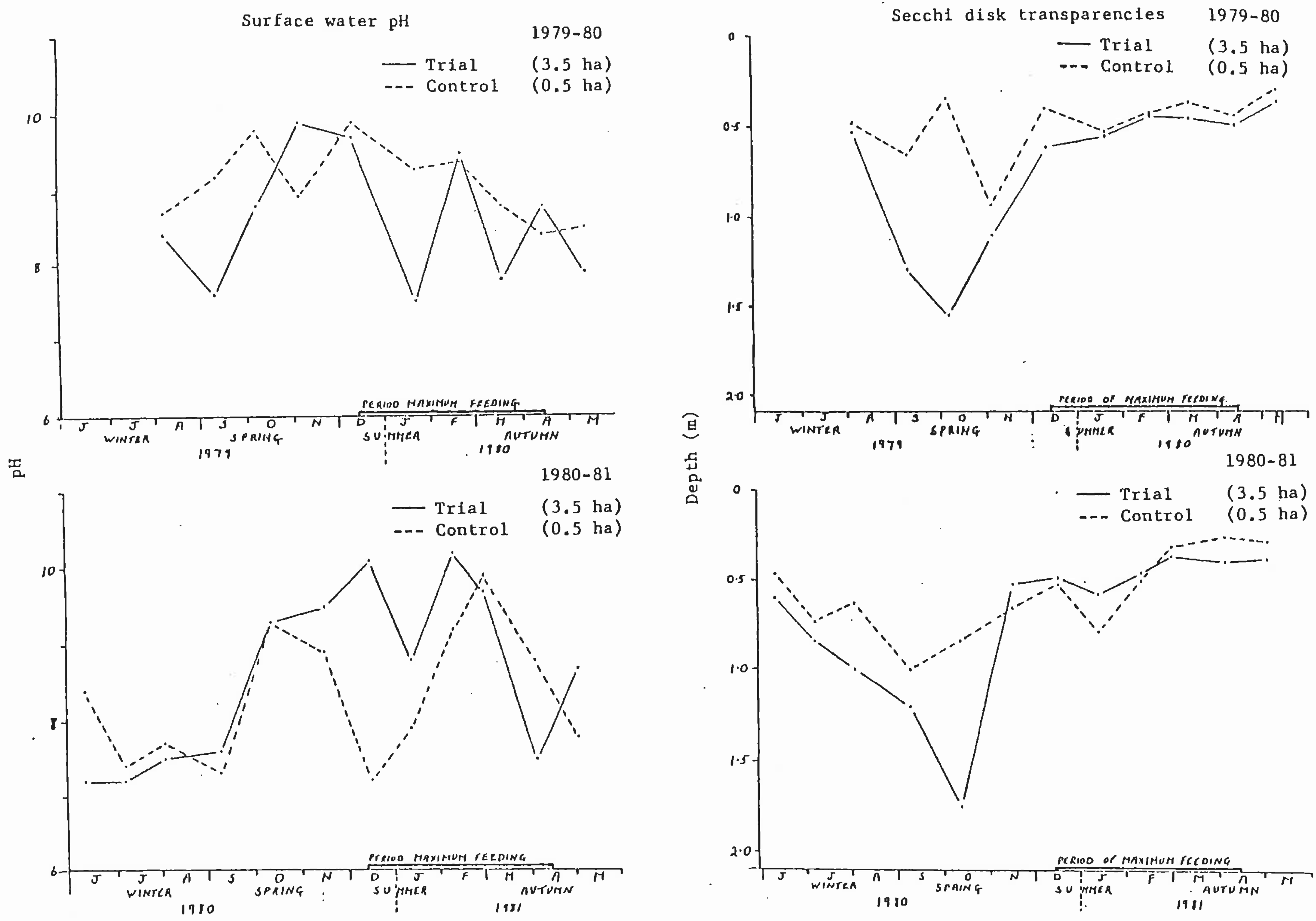


FIGURE 24 Surface water pH and Secchi disk transparencies, trial and control areas, 1979-80, 1980-81

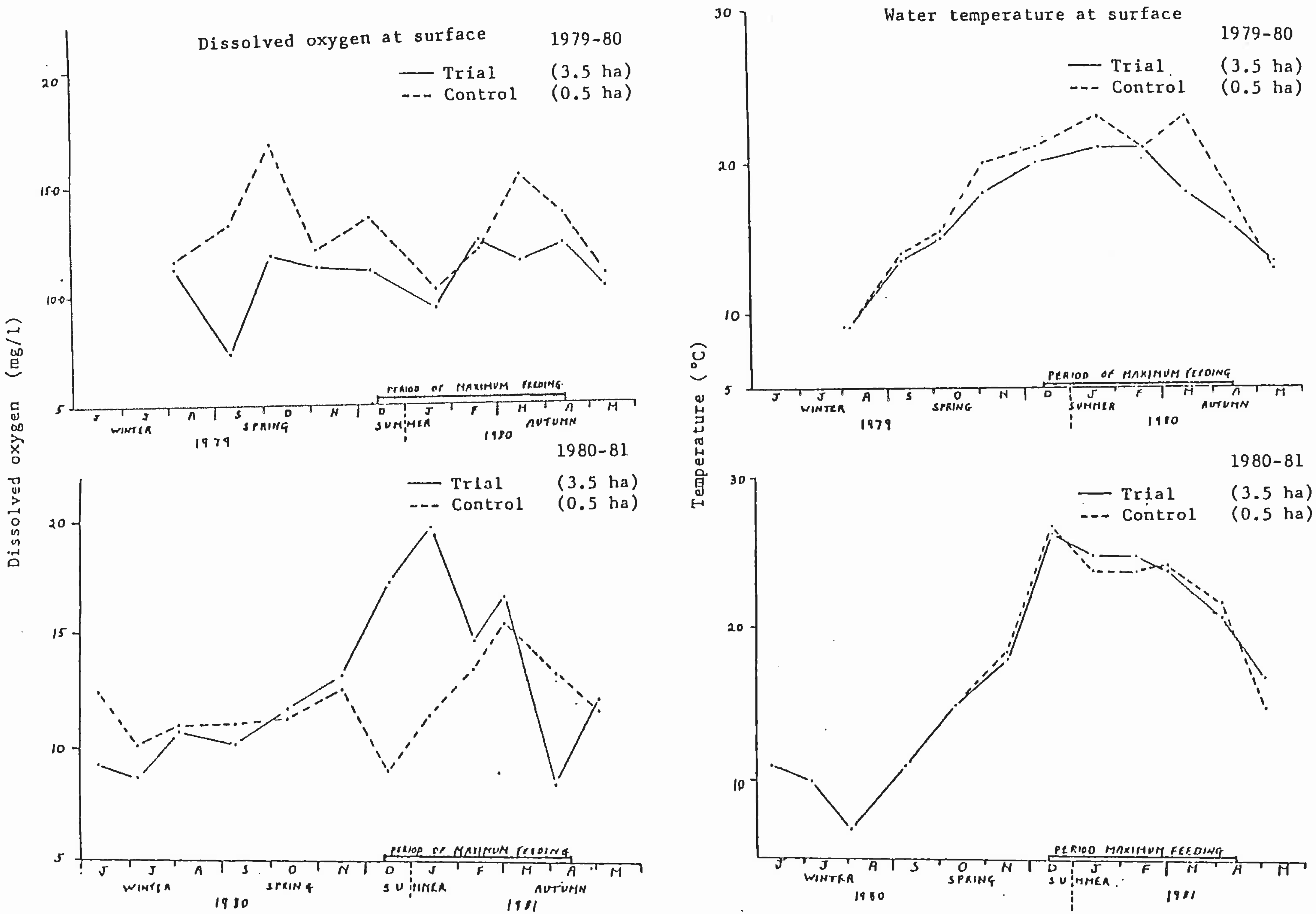


FIGURE 25. Dissolved oxygen and surface water temperature, trial and control areas, 1979-80, 1980-81.

APPENDIX II. A summary of data-logging results, Lake Orakai, 1979-84.

By A.M.R. Burnet and A.D. Carruthers.

A cassette data logger, installed in Lake Orakai in October 1979 records 14 parameters 50 times a day. The sensors measure water temperatures, oxygen levels, and light absorption in the water. These parameters were selected as being likely to show the limnological changes resulting from silver carp feeding on algae in the lake. Sensors were located at station a in the control area of the lake (0.5 ha), and at station b in the trial area (3.5 ha). Both sets of sensors are similar, but surface water temperatures are recorded only at Station a (see Fig. 2). (A second recorder was located at station c in the deeper area at the eastern end of the lake during the summer and autumn of 1980-81. Oxygen levels were measured at four depths - 0.25 m, 0.9 m, 1.6 m, and 3.6 m, and data from this logger were used for Fig. 15.)

The first 3 years of data starts after the silver carp were first moved to the larger trial area, and were consequently at a comparatively low density (see Fig. 9, p.22). In July 1982 the barrier separating the two areas was partially lifted: thus there was interchange of water and fish between the two areas, and a reduction in the fish population density.

The sensors at each location are set at the same depths from the surface, but the total water depth is greater at station b.

The data recorded were: 1. surface light level, 2. wind velocity, 3. air temperature, 4. water temperatures at the surface, 1 m, 2 m, and 4 m, 5. Oxygen levels at 1 m, 6. underwater light at 3 m.

Standard Yellow Springs Instruments Company sensors were used for temperature and oxygen, and special units were constructed for the light and wind measurements. The light sensors were calibrated to measure the vertical extinction coefficient, that is, the turbidity of the water. The relation between extinction coefficients and chlorophyll A levels, established from measurements made at Lake Orakai and three other North Island lakes (Rotorua, Rotoiti, and Parkinsons Lake), was:

$$\text{Chl A (mg/m}^3\text{)} = (\text{Extinction} * 51.14) - 18.52 \quad (N=100,\ R=0.95))$$

Intensive data collection over several years has demonstrated the importance and frequency of short term limnological changes which could be missed altogether by the usual sampling routine, or discarded as aberrant measurements. The details from the data logger records for part of the summer of 1980 (Fig. 15, p. 29) show the normal diurnal temperature and oxygen cycles in this small, highly eutrophic lake. The plot includes diurnal oxygen fluctuations of up to 10 mg/ℓ and also illustrates a complete breakup of the thermocline and mixing of the water column associated with heavy rainfall and wind, with the consequent changes in temperature and oxygen levels.

The 5 years of recording is a large data base of over 1.5 million records, and its size alone makes analysis difficult. In addition, there are distinct seasonal patterns which differ from year to year, and comparisons between years has the computing difficulties associated with evaluating complex patterns and measuring the differences. The present analysis is further complicated by several breaks in the continuity of the records owing to equipment failures. The missing data prevent simple comparisons between the years, but all the summer observations are complete, and averages for each summer (December, January, February) have been extracted and listed in Table 2.

TABLE 2: Averages of daily means of environmental parameters, summers 1979-84.

Summer (Dec,Jan,Feb)	Wind (*)	Rainfall (total mm for period)	Air temp (°C)	Water temperature (°C) a Surface	a 1 m	b 1 m	Oxygen a 1 m mg/ℓ	b 1 m mg/ℓ
1979-80	-	304.1	18.6	22.8	20.4	20.7	10.6	12.0
1980-81	6	629.4	-	23.3	21.2	21.8	9.8	11.6
1981-82	23	179.0	18.6	23.4	21.3	22.2	10.7	11.2
1982-83	48	55.8	17.2	21.5	20.2	20.7	10.8	10.2
1983-84	43	328.0	16.9	21.2	20.1	20.5	9.4	7.6

* Not calibrated units.

The graphs and discussion in this summary, except for Fig. 15, (p.29), are of daily means, that is, are averages of 50 readings. The source data base is stored by the Fisheries Research Division, Ministry of Agriculture and Fisheries, Wellington.

Water temperatures.

A well defined thermocline forms close to the surface in the spring, and breaks up in the autumn. The thermocline was strongest during the first 3 summers (1979-80, 1980-81, 1981-82) (Fig. 26), but in all years there is at least one complete mixing, and a number of partial mixings associated with rainfall and/or wind.

In the last two periods (1982-3 and 1983-4 (Fig. 27) the thermocline formed earlier and had a lower temperature differential. The graphs also indicate a greater degree of mixing than in previous years. It is clear that the maximum summer surface water temperatures are lower than in previous years, and so is the average summer temperature of the epilimnion (see Table 2).

Preliminary calculations from the temperature records indicate that the total energy absorbed by the lake is similar for all years, which suggests that there has been a greater movement of energy into the deeper layers in the last 2 years. It is probable that the temperature changes were due in part to the reduction of surface algal scums, by the silver carp, (see Fig. 8, p.21) but there are other factors that must be considered. The air temperatures were lower in the last 2 years and there was more wind; consequently there was a greater cooling effect. In this complex situation, it is unwise to draw conclusions about causes of the temperature change over the short observation period, but whatever the reasons for the decrease in epilimnion temperatures, the difference was sufficient to reduce the feeding activity of the silver carp over the last 2 summers.

Light extinction coefficient.

In three of the years (1979-80, 1980-81, and 1982-83) (Fig. 28) there was a similar pattern of a spring minimum followed by a gradual increase to an autumn maximum. Of the other years, 1981-82 had a fairly uniform low level throughout, and 1983-84 was also fairly uniform; but at a higher level.

When the control and experimental results were compared (Fig. 29) there was an appreciably higher turbidity in the control area - mainly in the autumn, and especially in 1981-82. After the barrier was lifted (1982-83 and 1983-84) the two stations were similar with a small bias towards station a, which is the shallower location. Thus the differences between results from the trial and control areas are in part due to the physical differences between the two areas, but the results for the three years 1979-82 indicate that the silver carp had a measurable effect on the clarity of the water.

There is some evidence over the whole five years of a long term trend towards improved clarity in the larger experimental areas.

Oxygen levels.

Periods of low oxygen (below 5 mg/ℓ) have adverse direct and indirect effects on the survival of fish. Low oxygen levels over short intervals of a few days or less are significant, and so the continuous records from a data logger are ideal for detecting and measuring the frequency and severity of oxygen minima, as illustrated in Fig. 15 (p.29).

The diurnal pattern of fluctuations, and high oxygen concentrations - frequently over twice the saturation level, indicate that the amount of oxygen in the water is mainly a function of the relation between the quantity produced by photosynthesis and that absorbed by biological respiration. Thus, the oxygen levels are related to algal production rates: this is a complex relationship which requires further study.

There is a general pattern to the oxygen levels. The greatest variation is in spring and summer, when peaks of 270% saturation and minima less than 3 mg/ℓ occur. The size of the fluctuations gradually decreases, and in autumn oxygen concentrations approach and fall below saturation; they usually return to saturation levels during the winter.

The years 1980-81, 1981-82, and 1982-83 (Fig. 30) have a similar seasonal pattern, with some decrease in the amplitude of the fluctuations each year. A pattern is not so clear for 1979-80, where the fluctuations were greater and lasted longer. In the 1983-4 years the amplitude was considerably lower than in previous years, and the autumn levels were much lower than in previous years. The oxygen measurements also indicated contamination of the probe, by biological decomposition products at station b.

There were appreciable differences between the control and trial areas in the three years 1979-82 (Fig. 31). Higher oxygen levels occurred more frequently in the trial areas, mainly in the spring and summer, when the silver carp were actively feeding. This is the likely response of the algal population to changed cropping with the addition of silver carp, specially as it introduces another trophic level to the system.

After the barrier was lifted the oxygen differences between the two areas were small, especially in 1982-83, but were greater in 1983-84 when the oxygen levels were very low, and there were periods of zero readings in the trial area (b).

Conclusions.

This brief overview deals with the summarised versions of the data logging results from Lake Orakai during part of the silver carp trials, and presents preliminary analyses and conclusions. There are other possible approaches to analysing the data, and there are further analyses to do, when time and facilities are available. Continuation of data collection will result in a better appreciation of the influences of the varying weather patterns, and it will confirm whether or not the changes that have been observed are due to the silver carp.

Although neither the comparison between control and trial areas of the 3 years data from the data logger, nor the five years of data from the trial area are conclusive, it is clear that the silver carp have been asociated with significant changes in the algal population of the lake. This is seen mainly in a reduction in the magnitude of the fluctuations in oxygen levels in the trial area over the five years of records.

However, there has been considerable variation from year to year in both the short term and annual weather patterns, and these have had appreciable effects on the complex limnology of this shallow, highly eutrophic lake. Thus it is difficult and unwise to arrive a firm conclusions on the basis of these few annual cycles.

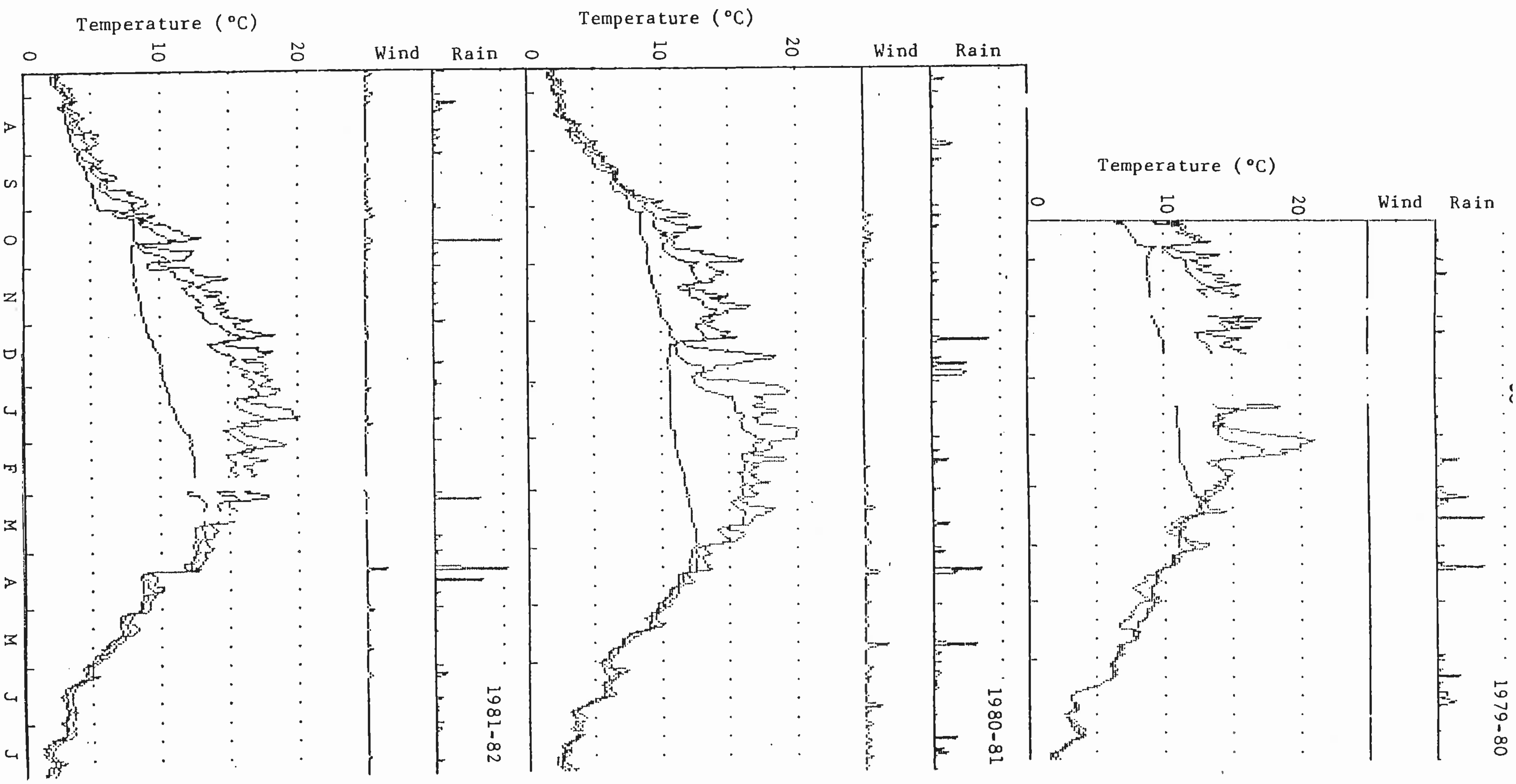


FIGURE 26. Daily rainfall, daily means of wind, and daily water temperatures at 1 m, 2 m, and 4 m below the surface, station b, 1979-80, 1980-81, 1981-82.

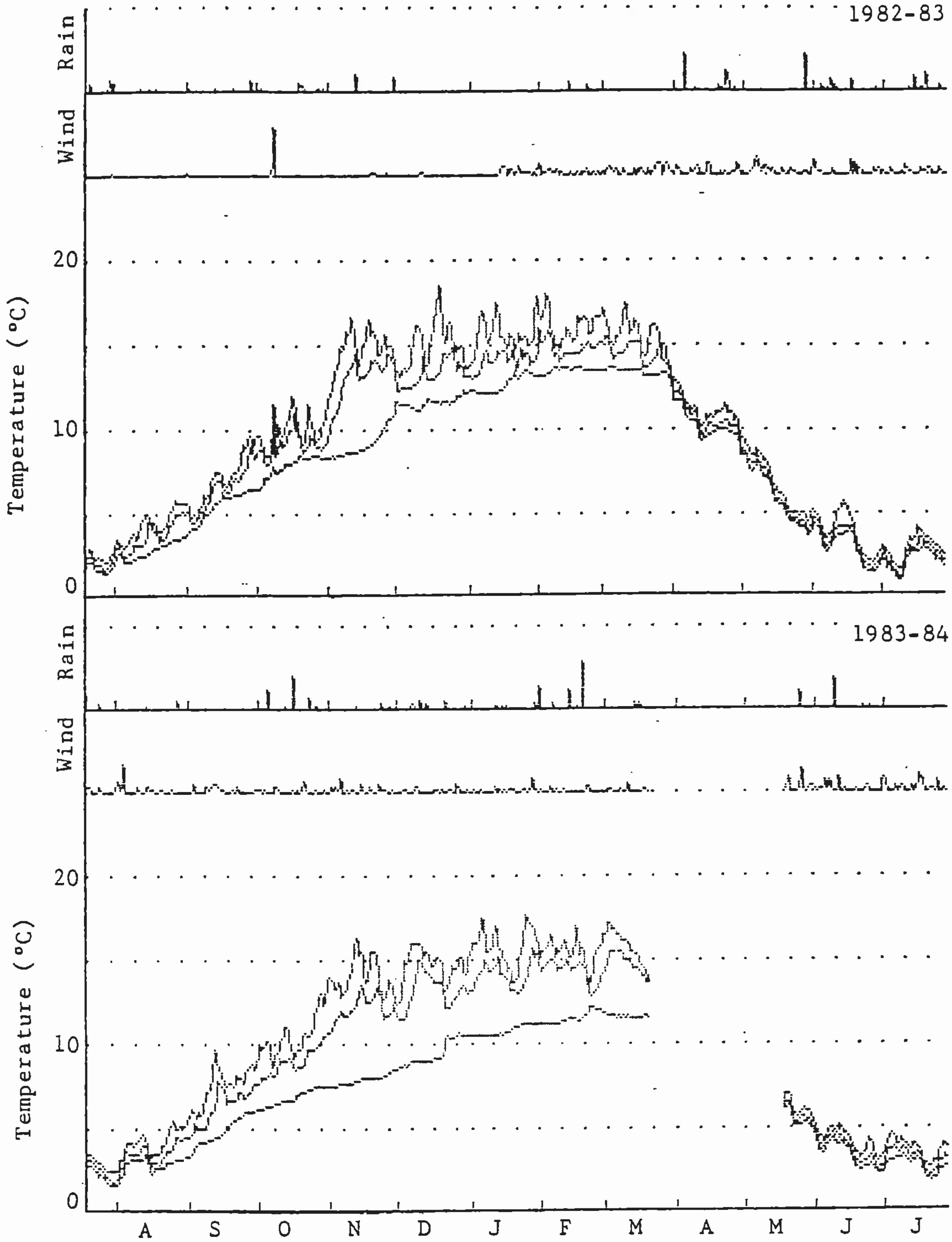


FIGURE 27. Daily rainfall, daily means of wind, and daily water temperatures at 1 m, 2 m, and 4 m below the surface, station b, 1982-83, 1983-84.

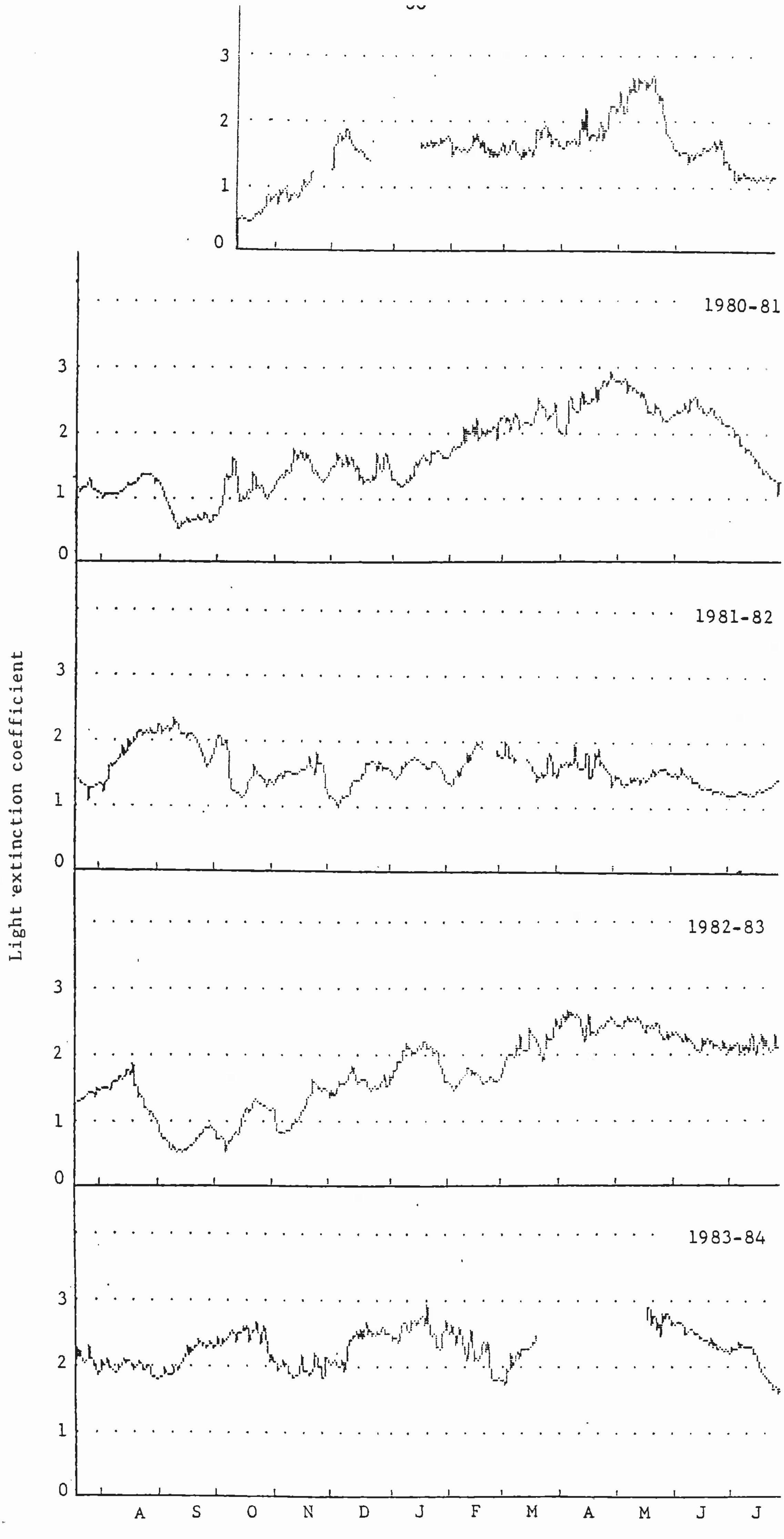


FIGURE 28. Daily light extinction coefficients for station b, 1979-84.

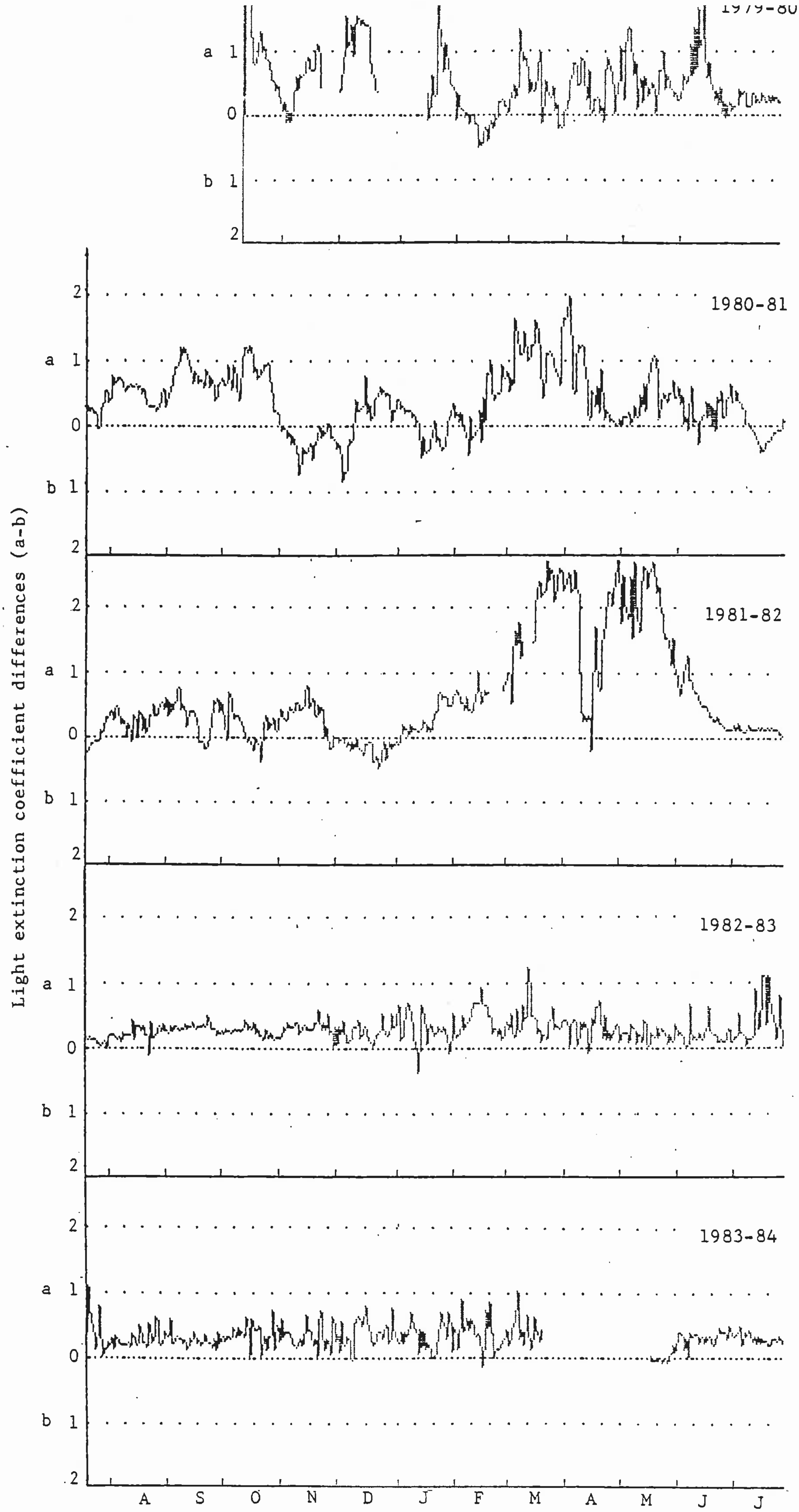


FIGURE 29. Light extinction coefficient differences between the trial and control areas (Ext a - Ext b).

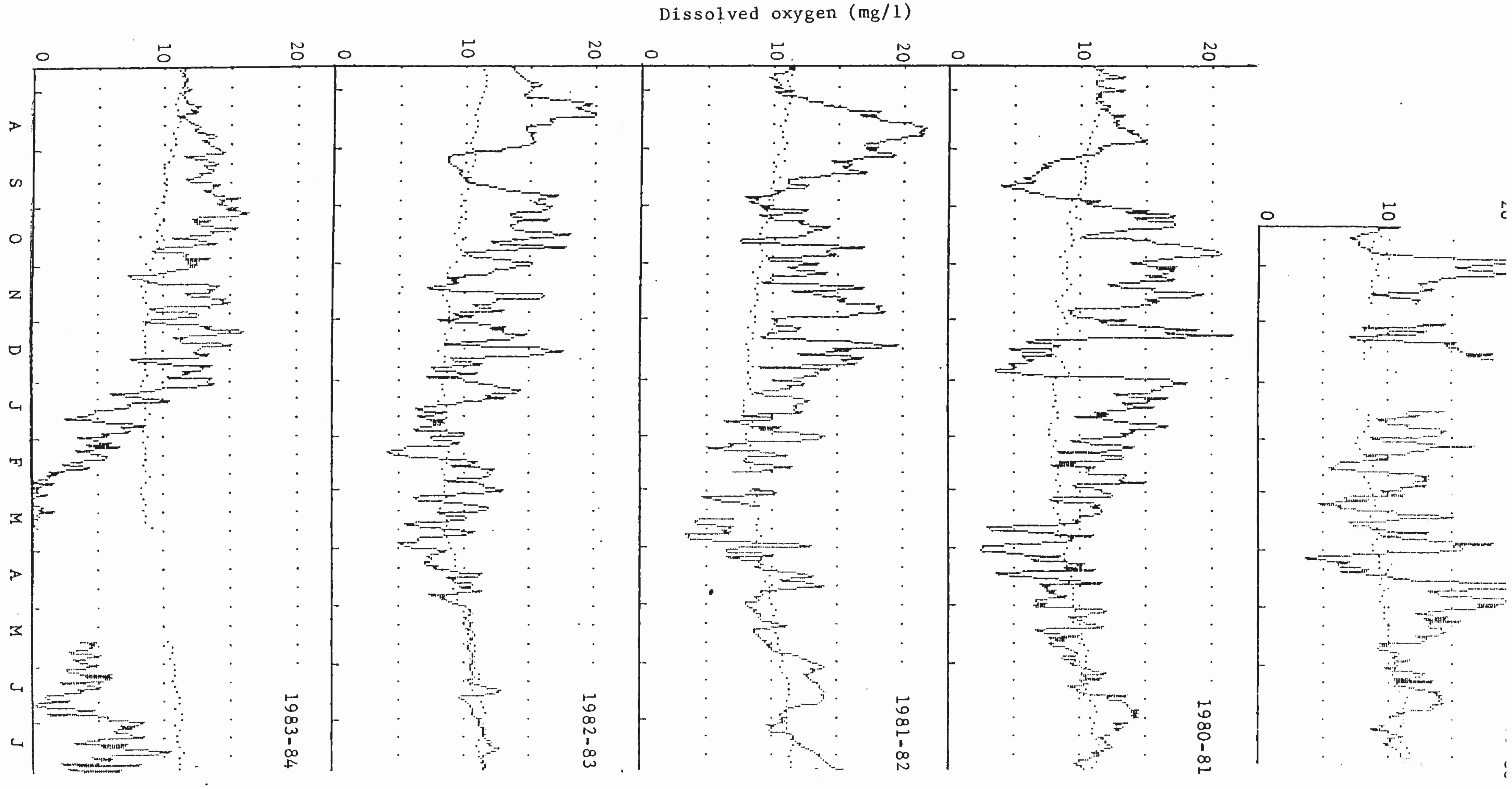


FIGURE 30. Daily oxygen means for station b, measured 1 m below the surface, and saturation level (dotted line) calculated from the surface water temperature, 1979-84.

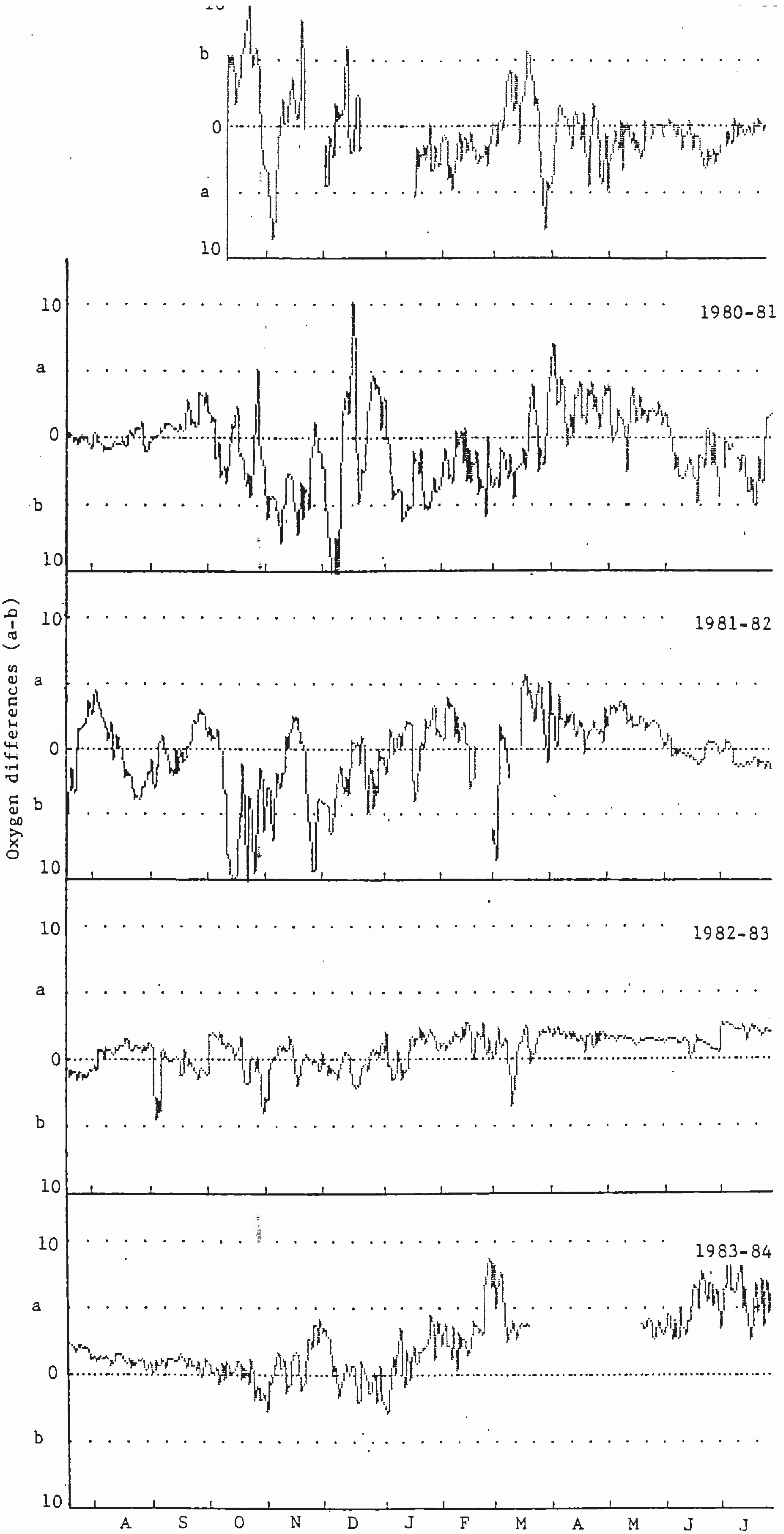


FIGURE 31. Oxygen differences between the trial and control areas (Oxy a - Oxy b).

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