STUDY OF PLANKTON IN RELATION TO CAGE AND POND CULTURE OF TROUT IN SCOTLAND

by

TRIDEEP DEY

A Thesis Submitted for the Degree of
Doctor of Philosophy

Institute of Aquaculture
University of Stirling

July 1984

DECLARATION

I declare that this thesis has been composed by myself and that it embodies the results of my own research. It has neither been accepted nor is being submitted for any other degree. Where appropriate I have acknowledged the nature and extent of work carried out in collaboration with others and included in the thesis.

TRIDEEP DEY

TO MY PARENTS

ABSTRACT

An investigation of phytoplankton and zooplankton, together with physico-chemical parameters of water quality and periphyton, was undertaken from November 1980 to December 1981 at a large cage fish farm for rainbow trout in Loch Fad, Isle of Bute, and from February to December 1981 in earth ponds used for culturing brown trout at Howietoun Farm, Central Scotland.

Thermal stratification in Loch Fad was not observed. In Loch Fad pH was lower at the cage site than at a control station at the other end of the Loch, while at Howietoun, pH decreased as the water passed through the ponds. These effects were ascribed to the respiratory effects of the fish and the decomposition of fish wastes and metabolites. Inorganic nutrient concentrations were higher at the cage site than at the control station in Loch Fad, while at Howietoun they also increased from the inlet water to the outlet of the farm. This increase in nutrient concentrations was related to increased phytoplankton density at the cage site at Loch Fad and in the outlet water of Howietoun Farm.

A bloom of *Microcystis aeruginosa* was observed in Loch Fad where it formed 92% to 99% of the total phytoplankton and reached densities of 5×10^8 cells/l. At Howietoun, Cyanophyceae were also dominant from April to November, the most dominant species being *Oscillatoria agardhi*.

The zooplankton population at both Loch Fad and Howietoun displayed

maxima during summer when the phytoplankton population was also maximum. Cladocera and Copepoda in Loch Fad were lower in number at the cage site than at the control, which might be due to predation by cage and wild fishes. In Howietoun all groups of zooplankton increased as the water passed through the farm. Common zooplankton species in Loch Fad were Bosmina longirostris, Daphnia longispina, Cyclops abyssorum and Diaptomus gracilis; while in Howietoun Farm common species were Bosmina longirostris, Cyclops vicinus and Diaptomus laciniatus.

Periphyton collected by using submerged wooden blocks was more dense at the cage site than at the control in Loch Fad. It was also more dense at the outlet than at the inlet at Howietoun. In Loch Fad, Bacillariophyceae dominated the periphyton in contrast to the observed dominance in the phytoplankton of Microcystis aeruginosa, which was absent in the periphyton. At Howietoun Cyanophyceae, especially Oscillatoria agardhi were dominant from April to October.

ACKNOWLEDGEMENTS

I am deeply indebted to Dr H. P. Stirling for constant encouragement, keen interest in this work and for his guidance and constructive criticism throughout the tenure of my work. My grateful thanks are due to Professor R. J. Roberts, Director, Institute of Aquaculture, for his support and for providing all the possible facilities. I particularly wish to thank Dr M. Beveridge for his invaluable help during the period of study, and all the Institute staff members for their support, especially Dr J. Muir.

I wish to thank Dr D. Robertson for permission to work at Howietoun Fish Farm. Mr T. Rae of Rothesay Sea Foods Ltd., kindly allowed me to work at Loch Fad.

I gratefully acknowledge the cooperation and assistance of Laura Cumming, Sheila McEwan, Sue Horne, Ian MacRae and my friends.

Special thanks are also due to Mrs Irene Lindsay for the considerable time and effort she spent typing this thesis.

CONTENTS

		Page
	Abstract	i
	Acknowledgements	iii
	List of figures	iv
	List of tables	xv
1.	Introduction	1
2.	Meteorology	10
3.	Site description	13
	3.1 Loch Fad	13
	3.2 Howietoun Fish Farm	15
4.	Materials and methods	19
5.	Results	24
	5.1 Loch Fad	24
	5.1.1 Water temperature	24
	5.1.2 Transparency	24
	5.1.3 pH	27
	5.1.4 Dissolved oxygen	27
	5.1.5 Inorganic nitrogen	31
	5.1.6 Total ammonia	31

Page

5.1.7 Nitrite	31
5.1.8 Nitrate	31
5.1.9 Orthophosphate	35
5.1.10 Silicate	35
5.1.11 Total suspended solids	37
5.1.12 Chlorophyll-a	37
5.1.13 Phytoplankton	37
5.1.13.1 Seasonal trend of phytoplankton	44
(A) Chlorophyceae	44
(B) Bacillariophyceae	52
(C) Dinophyceae	52
(D) Cyanophyceae	59
5.1.13.2 Relative abundance of phytoplankton	59
(A) Chlorophyceae	59
(B) Bacillariophyceae	63
(C) Dinophyceae	63
(D) Cyanophyceae	63
5.1.13.3 Summary of species succession of phytoplankton	65
5.1.14 Zooplankton	65
5.1.14.1 Seasonal trend of zooplankton	67
(A) Cladocera	67
(B) Copepoda	67
(C) Rotifera	73
5.1.14.2 Relative abundance of zooplankton	73
(A) Cladocera	73

Page

(B) Copepoda 78

(C) Rotifera 78

5.1.15 Periphyton 78

5.1.15.1 Seasonal trends of periphyton 80

(A) Chlorophyceae 80

(B) Bacillariophyceae 85

(C) Cyanophyceae 85

(D) Fungi 92

5.1.15.2 Relative abundance of periphyton 92

(A) Chlorophyceae 92

(B) Bacillariophyceae 92

(C) Cyanophyceae 95

5.1.15.3 Summary of species succession of periphyton 95

5.1.16 Diurnal studies 95

5.2 Howietoun Fish Farm 101

5.2.1 Water temperature 101

5.2.2 p^H 101

5.2.3 Dissolved oxygen 101

5.2.4 Inorganic nitrogen 108

5.2.5 Nitrite 108

5.2.6 Ammonia 108

5.2.7 Nitrate 108

5.2.8 Orthophosphate 110

5.2.9 Silicate 110

		Page
5.2.10	Total suspended solids	110
5.2.11	Chlorophyll-a	113
5.2.12	Phytoplankton	113
	5.2.12.1 Seasonal trend of phytoplankton	113
	(A) Chlorophyceae	113
	(B) Bacillariophyceae	121
	(C) Rhodophyceae	121
	(D) Cyanophyceae	128
	5.2.12.2 Relative abundance of phytoplankton	128
	(A) Chlorophyceae	128
	(B) Bacillariophyceae	128
	(C) Rhodophyceae	133
	(D) Cyanophyceae	133
	5.2.12.3 Species succession of phytoplankton	133
5.2.13	Zooplankton	133
	5.2.13.1 Seasonal trend of zooplankton	135
	(A) Cladocera	135
	(B) Copepoda	135
	(C) Rotifera	140
	5.2.13.2 Relative abundance of zooplankton	140
	(A) Cladocera	140
	(B) Copepoda	140
	(C) Rotifera	144

Page

5.2.14 Periphyton 144

5.2.14.1 Seasonal trend of periphyton

(A) Chlorophyceae 144

(B) Bacillariophyceae 150

(C) Rhodophyceae 150

(D) Cyanophyceae 154

5.2.14.2 Relative abundance of periphyton 155

(A) Chlorophyceae 155

(B) Bacillariophyceae 155

(C) Cyanophyceae 155

5.2.14.3 Summary of species succession of periphyton 158

5.2.15 Diurnal studies 158

6. Discussion 162

7. Summary and conclusion 198

8. References 202

LIST OF FIGURES

Fig. No.		Page
1.	Seasonal changes in mean monthly rainfall and mean maximum and minimum air temperature at Rothesay (Island of Bute) during 1981	11
2.	Seasonal changes in mean monthly rainfall and mean maximum and minimum air temperature at Stirling during 1981	12
3.	Bathymetric map of Loch Fad	14
4.	Location of sampling stations and fish farm in Loch Fad	16
5.	Plan of Howietoun Fish Farm, showing main earth ponds and the main flowroutes and location of sampling stations	17
6.	Seasonal changes in Water temperature and Transparency in Loch Fad at control and cage sites during 1980-81	25
7.	Seasonal changes in Dissolved oxygen and pH in Loch Fad at control and cage sites during 1980-81	29
8.	Seasonal changes in Inorganic nitrogen in Loch Fad at control and cage sites during 1980-81	32
9.	Seasonal changes in Ammonia in Loch Fad at control and cage sites during 1980-81	33
10.	Seasonal changes in Nitrite and Nitrate in Loch Fad at control and cage sites during 1980-81	34
11.	Seasonal changes in Orthophosphate and Silicate in Loch Fad at control and cage sites during 1980-81	36

LIST OF FIGURES cont'd.

Fig. No.		Page
12.	Seasonal changes in Total suspended solids in Loch Fad at control and cage sites during 1980-81	38
13.	Seasonal changes in Chlorophyll-a in Loch Fad at control and cage sites during 1980-81	39
14.	Seasonal changes in abundance of Total phytoplankton in Loch Fad at control and cage sites during 1980-81	40
15.	Seasonal changes in abundance of Chlorophyceae in Loch Fad at control and cage sites during 1980-81	45
16.	Seasonal changes in abundance of *Ankistrodesmus falcatus*, *Botryococcus braunii* in Loch Fad at control and cage sites during 1980-81	46
17.	Seasonal changes in abundance of *Closterium Kutzingii* and *Eudorina elegans* in Loch Fad at control and cage sites during 1980-81	47
18.	Seasonal changes in abundance of *Gleocystis gigas*, *Oocystis elliptica*, *Pandorina morum* in Loch Fad at control and cage sites during 1980-81	48
19.	Seasonal changes in abundance of *Pediastrum boryanum*, *Pediastrum duplex*, and *Scenedesmus abundans* in Loch Fad at control and cage sites during 1980-81	49
20.	Seasonal changes in abundance of *Scenedesmus quadricauda* and *Sphaerocystis schroeteri* in Loch Fad at control and cage sites during 1980-81	50
21.	Seasonal changes in abundance of *Spirogyra gracilis* and *Staurodesmus cuspidatus* in Loch Fad at control and cage sites during 1980-81	51

LIST OF FIGURES cont'd.

Fig. No.		Page
22.	Seasonal changes in abundance of Bacillariophyceae in Loch Fad at control and cage sites during 1980-81	53
23.	Seasonal changes in abundance of *Amphora ovalis*, *Asterionella formosa*, and *Cyclotella comta* in Loch Fad at control and cage sites during 1980-81	54
24.	Seasonal changes in abundance of *Cymbella ventricosa*, *Gomphonema constrictum* and *Melosira italica-subarctica* in Loch Fad at control and cage sites during 1980-81	55
25.	Seasonal changes in abundance of *Meridion circulare*, *Navicula viridis*, *Nitzschia linearis* in Loch Fad at control and cage sites during 1980-81	56
26.	Seasonal changes in abundance of *Stephanodiscus astraea*, *Synedra ulna*, and *Tabellaria fenestrata* in Loch Fad at control and cage sites during 1980-81	57
27.	Seasonal changes in abundance of Dinophyceae, *Ceratium hirundinella*, *Peridinium willei*, in Loch Fad at control and cage sites during 1980-81	58
28.	Seasonal changes in abundance of Cyanophyceae in Loch Fad at control and cage sites during 1980-81	60
29.	Seasonal changes in abundance of *Anabaena flos-aquae*, *Coelosphaerium naegelianum*, and *Microcystis aeruginosa* in Loch Fad at control and cage sites during 1980-81	61
30.	Seasonal changes in abundance of *Oscillatoria agardhi* and *Oscillatoria limosa* in Loch Fad at control and cage sites during 1980-81	62

LIST OF FIGURES cont'd.

Fig. No.		Page
31.	Relative abundance of phytoplankton in Loch Fad at control and cage sites during 1980-81	64
32.	Seasonal changes in abundance of Total zooplankton in Loch Fad at control and cage sites during 1980-81	66
33.	Seasonal changes in abundance of Cladocera in Loch Fad at control and cage sites during 1980-81	70
34.	Seasonal changes in abundance of *Bosmina longirostris*, *Chydorus sphaericus*, and *Daphnia longispina* in Loch Fad at control and cage sites during 1980-81	71
35.	Seasonal changes in abundance of Copepods in Loch Fad at control and cage sites during 1980-81	72
36.	Seasonal changes in abundance of *Cyclops abyssorum*, and *Diaptomus gracilis* in Loch Fad at control and cage sites during 1980-81	74
37.	Seasonal changes in abundance of Rotifera in Loch Fad at control and cage sites during 1980-81	75
38.	Seasonal changes in abundance of *Ascomorpha ovalis*, *Conochilus hippocrepis*, *Filinia terminalis*, *Kellicottia longispina*, *Keratella cochlearis*, and *Trichocerca capucina* in Loch Fad at control and cage sites during 1980-81	76
39.	Relative abundance of zooplankton in Loch Fad at control and cage sites during 1980-81	77

LIST OF FIGURES cont'd.

Fig. No.		Page
40.	Seasonal changes in abundance of Total periphyton in Loch Fad at control and cage sites during 1980-81	79
41.	Seasonal changes in abundance of Total Chlorophyceae, *Ankistrodesmus falcatus* and *Closterium Kutzingii* on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	83
42.	Seasonal changes in abundance of *Pediastrum boryanum*, *Pediastrum duplex*, *Scenedesmus abundans*, *Scenedesmus quadricauda*, and *Spirogyra gracilis* on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	84
43.	Seasonal changes in abundance of Bacillariophyceae on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	86
44.	Seasonal changes in abundance of *Amphora ovalis*, *Asterionella formosa*, *Cyclotella comta*, and *Cymbella ventricosa* on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	87
45.	Seasonal changes in abundance of *Gomphonema constrictum*, *Melosira italica-subarctica*, *Meridion circulare* on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	88
46.	Seasonal changes in abundance of *Navicula viridis*, *Nitzschia linearis*, *Stephanodiscus astraea*, *Synedra ulna*, *Tabellaria fenestrata* on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	89

LIST OF FIGURES cont'd.

Fig. No.		Page
47.	Seasonal changes in abundance of Cyanophyceae on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	90
48.	Seasonal changes in abundance of Anabaena flos-aquae, Oscillatoria agardhi, Oscillatoria limosa, on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	91
49.	Seasonal changes in abundance of Fungi on wooden substrates suspended at surface, 4m, 9m depths in Loch Fad at control and cage sites during 1981	93
50.	Relative abundance of periphyton in Loch Fad at control and cage sites during 1981	94
51.	Diurnal changes in Water temperature, Dissolved oxygen, Ammonia, Nitrite and Nitrate in Loch Fad at cage site during 2nd-3rd April 1981	96
52.	Diurnal changes in Orthophosphate, Silicate, Peridinium willei, Bosmina longirostris, Chydorus sphaericus in Loch Fad at cage site during 2nd-3rd April 1981	97
53.	Diurnal changes in Daphnia longispina, Cyclops abyssorum, Diaptomus gracilis, and Ascomorpha ovalis in Loch Fad at cage site during 2nd-3rd April 1981	98
54.	Diurnal changes in Conochilus hippocrepis, Filinia terminalis, Kellicottia longispina, Keratella cochlearis, Trichocerca capucina in Loch Fad at cage site during 2nd-3rd April 1981	99
55.	Seasonal changes in Water temperature and p^H in Howietoun Fish Farm at six stations during 1981	102

LIST OF FIGURES cont'd.

Fig. No. | Page

56. Seasonal changes in dissolved oxygen and inorganic nitrogen in Howietoun Farm at six stations during 1981 — 107

57. Seasonal changes in ammonia, nitrite, nitrate in Howietoun Farm at six stations during 1981 — 109

58. Seasonal change in orthophosphate and silicate in Howietoun Farm at six stations during 1981 — 111

59. Seasonal changes in total suspended solids and chlorophyll-a in Howietoun Farm at six stations during 1981 — 112

60. Seasonal changes in abundance of total phytoplankton and Chlorophyceae in Howietoun Farm at six stations during 1981 — 114

61. Seasonal changes in abundance of *Ankistrodesmus falcatus* and *Ankistrodesmus* sp. in Howietoun Farm at six stations during 1981 — 117

62. Seasonal changes in abundance of *Botryococcus braunii* and *Closterium parvulum* in Howietoun Farm at six stations during 1981 — 118

63. Seasonal changes in abundance of *Oedogonium* sp., *Pandorina morum*, and *Scenedesmus quadricauda* in Howietoun Farm at six stations during 1981 — 119

64. Seasonal changes in abundance of *Scenedesmus obliquus* and *Spirogyra varians* in Howietoun Farm at six stations during 1981 — 120

65. Seasonal changes in abundance of Bacillariophyceae and *Amphora ovalis* in Howietoun Farm at six stations during 1981 — 122

LIST OF FIGURES cont'd.

Fig. No.		Page
66.	Seasonal changes in abundance of _Asterionella formosa_, _Cyclotella meneghiniana_, and _Diatoma elongatum_ in Howietoun Farm at six stations during 1981	123
67.	Seasonal changes in abundance of _Diatoma vulgare_, _Gomphonema constrictum_, and _Gomphonema geminatum_ in Howietoun Farm at six stations during 1981	124
68.	Seasonal changes in abundance of _Melosira italica-subarctica_, _Meridion circulare_, and _Navicula cryptocephala_ in Howietoun Farm at six stations during 1981	125
69.	Seasonal changes in abundance of _Navicula viridis_, _Nitzschia linearis_, and _Stephanodiscus hantzschii_ in Howietoun Farm at six stations during 1981	126
70.	Seasonal changes in abundance of _Synedra ulna_, _Tabellaria flucculosa_, and _Tabellaria fenestrata_ in Howietoun Farm at six stations during 1981	127
71.	Seasonal changes in abundance of Rhodophyceae, _Chantransia pygmaea_, and _Lemanea mammillosa_, in Howietoun Farm at six stations during 1981	129
72.	Seasonal changes in abundance of Cyanophyceae and _Anabaena flos-aquae_ in Howietoun Farm at six stations during 1981	130
73.	Seasonal changes in abundance of _Coelosphaerium Kuetzingianum_ and _Oscillatoria agardhi_ in Howietoun Farm at six stations during 1981	131
74.	Relative abundance of phytoplankton in Howietoun Farm at stations 1 and 6 during 1981	132

LIST OF FIGURES cont'd.

Fig. No.		Page
75.	Seasonal changes in abundance of total zooplankton in Howietoun Farm at six stations during 1981	134
76.	Seasonal changes in abundance of Cladocera in Howietoun Farm at six stations during 1981	137
77.	Seasonal changes in abundance of *Alonopsis elongata*, *Bosmina longirostris*, *Chydorus ovalis* in Howietoun Farm at six stations during 1981	138
78.	Seasonal changes in abundance of Copepoda and *Cyclops vicinus* in Howietoun Farm at six stations during 1981	139
79.	Seasonal changes in abundance of *Diaptomus laciniatus* and Rotifers in Howietoun Farm at six stations during 1981	141
80.	Seasonal changes in abundance of *Ascomorpha ecaudis*, *Brachionus angularis*, *Filinia terminalis*, and *Keratella valga* in Howietoun Farm at six stations during 1981	142
81.	Relative abundance of zooplankton in Howietoun Farm at stations 1 and 6 during 1981	143
82.	Seasonal changes in abundance of total periphyton in Howietoun Farm at stations 1, 3 and 5 during 1981	145
83.	Seasonal changes in abundance of Chlorophyceae, *Ankistrodesmus falcatus*, *Ankistrodesmus* sp., on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981	148

LIST OF FIGURES cont'd.

Fig. No.		Page
84.	Seasonal changes in abundance of Oedogonium sp., Scenedesmus obliquus, Scenedesmus quadricauda, and Spirogyra varians on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981	149
85.	Seasonal changes in abundance of Bacillariophyceae Amphora ovalis, Asterionella formosa, and Cyclotella meneghiniana on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981	151
86.	Seasonal changes in abundance of Diatoma elongatum, Diatoma vulgare, Gomphonema constrictum, Gomphonema geminatum, Meridion circulare, Melosira italica-subarctica, on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981	152
87.	Seasonal changes in abundance of Navicula cryptocephala, Navicula viridis, Nitzschia linearis, Stephanodiscus hantzschii, Synedra ulna, on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981	153
88.	Seasonal changes in abundance of Tabellaria fenestrata, Tabellaria flucculosa, and Lemanea mammillosa, on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981	154
89.	Seasonal changes in abundance of Cyanophyceae, Anabaena flos-aquae, Oscillatoria agardhi on wooden substrates in Howietoun Farm at stations 1, 3, and 5 during 1981	156

LIST OF FIGURES cont'd.

Fig. No.		Page
90.	Relative abundance of periphyton on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981	157
91.	Diurnal changes in Water temperature, p^H, dissolved oxygen, ammonia, nitrite, nitrate, in Howietoun Farm at stations 4 and 5 during 5th - 6th April 1981	159
92.	Diurnal changes in orthophosphate, silicate, *Bosmina longirostris*, *Brachionus angularis*, *Keratella valga*, *Ascomorpha ecaudis*, in Howietoun Farm at stations 4 and 5 during 5th - 6th April 1981	160

LIST OF TABLES Page

1. Results of the t-test for paired comparison of physico-chemical parameters at each depth between control and cage sites in Loch Fad over 14 months 26

2. Correlation coefficient between phytoplankton and other parameters in Loch Fad during 1980-81 28

3. Percent saturation of dissolved oxygen at both control and cage site in Loch Fad (1980-81) 30

4. Species of phytoplankton recorded in Loch Fad during 1980-81 41

5. Results of the t-test for paired comparison of chl.-a and phytoplankton at each depth between control and cage site in Loch Fad over 14 months 43

6. Results of t-test for paired comparison of zooplankton at each depth between control and cage site over 14 months 68

7. Species of zooplankton recorded in Loch Fad during 1980-81 69

8. Results of the t-test for paired comparison of periphyton at each depth between control and cage site in Loch Fad over 12 months 81

9. Periphytic algae recorded in Loch Fad during 1980-81 82

10. Percent saturation of dissolved oxygen at all six stations during 1981 at Howietoun Farm 103

11. Correlation coefficient between the parameters at each station at Howietoun Fish Farm 104

12. Results of analysis of variance (2-way without replication) of different parameters between stations at Howietoun Farm (Critical values of $F_s = 3.2$ for df = 5, 100 at P = 0.01, and $F_s = 5.85$ for df = 2, 20 at P = 0.01) 105

LIST OF TABLES cont'd. Page

13. Species of phytoplankton recorded in Howietoun Fish Farm during 1981 115

14. Species of zooplankton recorded in Howietoun Fish Farm during 1981 136

15. Species of periphytic algae recorded in Howietoun Fish Farm during 1981 146

16. Suggested trophic states related to transparency compiled from the literature 164

17. Suggested trophic states based on Chlorophyll-a (mg/m^3) compiled from the literature 176

1. INTRODUCTION

There has been a marked increase in the production of commercial fish in freshwater cages in the United Kingdom in recent years, and there are now at least 16 cage rainbow trout farms in Scotland alone. Coche (1976) defines cage culture as the "raising of a group of fish from the juvenile stage to the commercial size in a volume of water on all sides, including the bottom, while permitting the free circulation of water through the cage". Expansion in this sector of the aquaculture industry is likely to continue, providing the economic climate is suitable. Coche (1976, 1977), in his reviews of cage culture, has summarised some of the advantages and drawbacks of cage culture. Some of the possible advantages of cage culture are: the use of otherwise unmanageable open water bodies, the possibility of combining several types of culture within one water body, easy observation of fish, easier handling, easy control of competitors and predators, lower capital outlay and operating costs, and it allows for easier and complete harvesting of fish, whilst facilitating the manipulation of the harvest to match market requirements. The main limitations of cage culture are: it is difficult to manage when the water surface is rough, the risk of cage damage in adverse weather conditions, the need for adequate water renewal in the cages for elimination of metabolites, fouling of cages, dependence on artificial food and food losses through the cage walls, interference from local fish and bird populations, and, most important of all, adverse changes in the nutrient status and quality of water bodies used in cage culture are likely to occur as a result of the accumulation of wastes from cage farms (Kilambi _et al_, 1976; Korycka and Zadanowski, 1980; Penezak _et al_, 1982).

Rothesay Seafoods Ltd., established a cage fish farm in Loch Fad (Rothesay, Isle of Bute) in late 1976. Loch Fad is a medium size freshwater loch, approximately 2.5 km long and 0.3 km wide, with a total surface area of 0.71 km^2 and a maximum depth of 12m. It is situated about 2 km to the south of Rothesay on the Isle of Bute which is located in the Firth of Clyde on the West Coast of Scotland. The fish farm cages, which produce approximately 200 tonnes of fish per annum (mainly of rainbow trout, _Salmo gairdnerii_) are situated at the northern end of the loch. Cages were used for both portion size production of fish and for on-growing of large fish. Stocking density was approximately $15kg/m^3$ Both dry pellet food (Edward Baker Ltd.) and frozen blocks of trash fish were used to feed the cultured fish. Very little scientific data are available on the physico-chemical and biological parameters before the cage-fish farm was established. Since 1980, however, a number of research projects on the environmental impact of fish cage culture in Loch Fad have been undertaken. Beveridge (1981) in a preliminary survey found twenty times the concentration of bacteria under the cages compared to the south (control) basin. His benthic study of Loch Fad showed that there were distinct differences between cage and control sites in the numbers and types of benthic invertebrates present. In particular the numbers of tubificid worms (very tolerant of high levels of organic wastes) were exceptionally high (approximately 20 times higher than expected for a loch of this type) which indicates the large amounts of wastes falling onto the mud below the cages. He also noted the smaller and less persistent plankton blooms at the control site compared with the vicinity of the cages, and this he suggested could be the result of higher nutrient release around the cages. North (1983) noted the absence of an oxidized microzone in the sediment under the cages which resulted in the release of inorganic phosphorus by the mechanism suggested by Mortimer (1941a, 1941b). In laboratory simulation experiments North (1983) found that the high degree of organic loading to which the sediment under the cages is subjected, and the consequent high rates of mineralisation, are reflected in the release of phosphorus, even under oxygenated conditions. He suggested a possible cause was the binding of all ferric ion to only some of the available phosphorus.

The effects of cage culture in Loch Fad on perch (*Perca fluviatilis*), pike (*Esox lucius*), roach (*Rutilus rutilus*) and rainbow trout (*Salmo gairdneri*) were assessed by Forbes (1981). His investigation revealed that perch in the Northern basin containing the cages grew faster in their first year after the fish farm was formed. Perch in the Southern basin showed no such difference and it appeared that the fish farm had not affected their growth. Roach also appeared to have grown faster after the establishment of the fish farm but there was no observable difference between Northern and Southern populations of roach. This difference in growth rates between perch and roach in the north and south basin was ascribed to the more sedentary nature of perch. Forbes (1981) also noted the higher density of perch, pike and feral rainbow trout around the cages compared with the southern end of the Loch. The reason, he proposed, was the greater availability of food around the cages (higher number of plankton and the uneaten fish food). Phillips (1983) also noted that large rainbow trout (300mm) occupied and remained confined to the area close to the cages. Dietary studies of these large fish showed that they were using the cages as feeding stations.

Pollock (1981) reported on the higher level of parasitic infection in fishes sampled from a stationadjacent to the cages. The higher density of intermediate hosts present in this area is suggested as a possible explanation.

In addition to cage culture in freshwater lochs, earthen ponds are a traditional and important system for trout culture. Pond culture of Salmonids in Scotland is a common practice. An excellent and very early example of a pond culture farm in Scotland is Howietoun Fish Farm, Bannockburn. Howietoun Farm was founded in 1871 by Sir James Maitland, and took 10 years to complete. This included a hatchery from which brown trout (Salmo trutta) eggs were produced for stocking throughout the world, including New Zealand in 1893. In 1966 the farm changed hands and gradually became run down. It was purchased by the University of Stirling in 1979. Renovation work has since been carried out and Howietoun Farm is now run as a commercial enterprise. The design and planning of the earth ponds are a masterpiece, and with little modification they are still in working condition. Rainbow trout (Salmo gairdneri), brown trout

(*Salmo trutta*) and salmon (*Salmo salar*) smolts are being reared in earth ponds using dry compounded fish food pellets (Edward Baker Ltd.). Apart from some irregular measurements of physico-chemical parameters (pH, dissolved oxygen, ammonia) very little research has been undertaken on the ponds. The prime cause of poor water quality and discharged pollutants are unconsumed fish feed and fish faeces and metabolic wastes. Gibson (1981) attempted to compare the Ewos low pollution feed, with another commercially available trout feed (Edward Baker's 'Omega' range of Trout Foods, Bathgate), in order to assess the effects of two diets on growth performance and the resultant water quality in earth ponds. He noticed no marked difference in the food conversion ratios of the two diets used, and in B.O.D. between the two dietary treatments. He reported relatively higher nutrient concentrations in the ponds fed with the high density Baker diet, compared to the ponds fed the low pollution Ewos diet. As the overflows of effluent water between the ponds could not be adequately controlled, it was not possible to make an accurate comparison of the effect of the two diets on water quality.

A brief study of physico-chemical parameters in Loch Fad was reported by Beveridge (1981) and seasonal changes in these were noted. Beveridge (1981) also reported the existence of plankton blooms but no detailed identifications and investigation of the seasonal changes were made. The freshwater lochs of Scotland have been the subject of a variety of research projects for well over a hundred years. Before the bathymetric survey of Murray and Pullar (1910) a number of individual papers appeared (Christison, 1871; Buchan, 1872; Watson, 1903; Wedderburn, 1907), most of them dealing with aspects of physical limnology. Later papers dealing with physico-chemical parameters in Scottish lochs have been published by Holden and Caines(1974), Smith (1974), Bindloss (1976), Tippet (1978), Bailey-Watts and Duncan (1981) and Smith _et al_ (1981).

Early works on the identification and ecology of phytoplankton in Scottish waters are those by West and West (1903, 1905) and Bachmann (1907). Recently, several papers have been published dealing with the species composition, seasonal changes and ecology of phytoplankton in Scottish lochs. Some of the notable papers include Bailey-Watts (1974, 1976, 1978), Boney (1978), Tippet (1978), Maulood _et al_ (1978), Maulood and Boney (1980, 1981a, 1981b), and Maitland _et al_ (1981). Maitland (1981) edited the book "The Ecology of Scotland's Largest Lochs: Lomond, Awe, Ness, Morar and Shiel", which covered mainly the research on land use, physical limnology, chemistry, phytoplankton, macrozooplankton, littoral invertebrates and fish. All these five lochs fall into the temperate oligotrophic type, but in the biological classification of trophic status, there are indications that Loch Lomond (in particular the south basin) is mesotrophic rather than oligotrophic. In the nutrient range of the five lochs concerned, Loch Lomond lies at the richer end of the spectrum. The species composition, seasonal cycles and ecology of zooplankton in Scottish lochs have been reported by Chapman (1965, 1969, 1972), Walker (1970), Goldspink and Scott (1971) and Johnson and Walker (1974).

It was not until 1963 that regular observations were carried out and chemical studies were initiated following the appearance of extensive algal 'blooms' in Loch Leven (Holden and Caines,1974), a shallow eutrophic loch. The regular and continuous observations started as a part of the International Biological programme (I.B.P.) The aim of the I.B.P. project was to assess production at various trophic levels, to define the flow of energy in the food chains, and to relate these to the fish and wild fowl populations.

As part of a programme of investigations into the factors affecting the biological productivity of Scottish freshwater lochs, and of the means of increasing this productivity, several experiments involving the addition of various types of mineral fertilizers have been carried out (Brooks, 1956; Brooks and Holden, 1957; Holden, 1959). Brooks (1956) and Holden (1959) noticed an increase in the abundance of phytoplankton in enrichment experiments of Sutherland lochs with fertilizers. They reported that Nygaard's compound phytoplankton quotient also increased so that oligotrophic lochs, at least for a period, turned distinctly eutrophic. Brooks and Holden (1957) also noticed the significant increase in phytoplankton after 2 weeks of fertlizer application and this increase was maintained for 18 months, and periphyton abundance also increased. They reported the loss of phosphorus after the enrichment was due to water dilution, assimilation by macrophytes, phytoplankton, periphyton, bacteria and fungi, and by adsorption by bottom deposits.

Very little is known about the environmental impact of fish culture (cage and pond culture) in Scotland. The aquaculture of Salmonids has undergone intensive development in recent years. There is no danger to the environment if this aquaculture occurs in an enclosed artificial situation, but often natural habitats (lakes, rivers, estuaries) with high oxygen content and low pollution levels are used. The resulting addition of bioelements (C, P, N) to water can intensify the process of eutrophication (Colby _et al_ 1972, Kajak, 1979). The environmental impact of cage culture has only been reported fragmentarily and to a small extent (Kairesalo, 1979; Enell, 1981; Skogheim and Bergheim, 1981; Holm _et al_, 1982). Skogheim _et al_ (1982) reported on a Norwegian acid lake with a cage-fish farm and found that the levels of N-compounds, primary production and chlorophyll-a were nearly doubled compared with a nearby lake. No information on lake water quality prior to the establishment of the farm was available. Penczak _et al_ (1982), in Poland, have reported that the cage aquaculture of rainbow trout (_Salmo gairdneri_) enriched the mesotrophic Glebokie Lake with carbon, phosphorus and nitrogen.

Water pollution due to fish farming activities results in the increase in concentrations of organic matter, suspended solids and nutrients when water passes through the fish tanks and ponds (Bergheim _et al_ (1982). The concentration of organic components in the effluent from fish farms are closely associated with feeding (Markmann, 1977; Solberg and Bregnballe, 1977) and cleaning operations (Liao, 1970) due to the accumulation of food particles (Bergheim _et al_ 1982). The increased concentrations of total N when water passes through a fish farm are generally caused by the contribution of organic N and ammonia and the levels of these components vary diurnally (Solberg and Bregnballe, 1977). Ammonia is mainly an excretion product (Brett and Groves, 1979) and maintains a more stable concentration level than the periodic feed-induced organic-N components (Markmann, 1978). Bergheim _et al_ (1982) and Markmann (1977) did not notice any increase in NO_3 to the outlet water in Norwegian and Danish investigations, respectively. Hinshaw (1973) referred to significantly increased concentrations of NO_3 and NO_2 at some trout hatcheries.

The prime objective of the present research was to study the effect of cage culture and pond culture of fish on the ecology of phytoplankton and zooplankton. This included investigating the species composition, relative abundance and seasonal changes of plankton together with physico-chemical water quality parameters (viz. temperature, p^H, dissolved oxygen, ammonia, nitrite, nitrate, orthophosphate, silicate and suspended solids) in the vicinity of the fish cages and at a control station at the Southern end of Loch Fad; and at Howietoun Farm as the water passes through a series of farm ponds. Another aim of the present investigation was to record the seasonal changes and relative abundance of periphyton and make observations on the diurnal changes in physico-chemical parameters and plankton behaviour in Loch Fad and Howietoun Farm.

2. METEOROLOGY

1981 was a year of extremes, particularly of low temperature during December throughout the length and breadth of the British Isles. To study the monthly mean maximum and minimum air temperature and total monthly rainfall in Rothesay and Stirling, the data from two climatological stations viz. Rothesay (Isle of Bute) and Parkhead (Stirling), have been referred to, and are presented in Figures 1 and 2. Both the climatological stations are within 5 km from the sampling stations.

2.1	Rothesay :	Height above sea level	: 43 metres
		Latitude	: 55° 50' N
		Longitude	: 5° 3' W

Both mean maximum air temperature and mean minimum air temperature rose from February reaching highest during August and then dropped to minimum during December. Rainfall varied quite a lot, being lowest during April and highest during September.

2.2	Parkhead :	Height above sea level	: 35 metres
		Latitude	: 56° 7' N
		Longitude	: 3° 57' W

Mean maximum air temperature and mean minimum air temperature followed the same trend as in Rothesay, maximum during August and minimum during December. The maximum rainfall was during September and October.

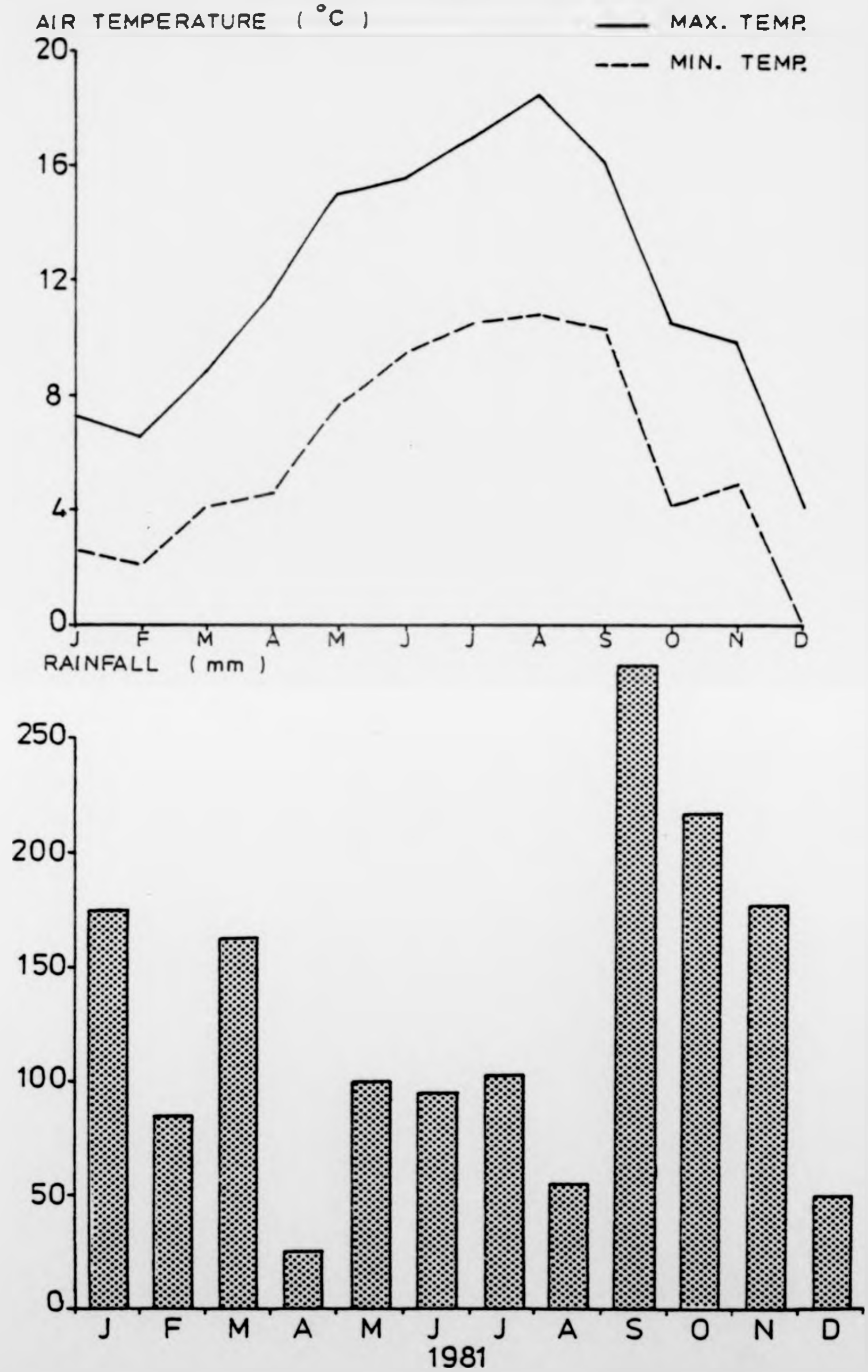

Fig. 1: Seasonal changes in mean monthly rainfall and mean maximum and minimum air temperature at Rothesay (Island of Bute) during 1981

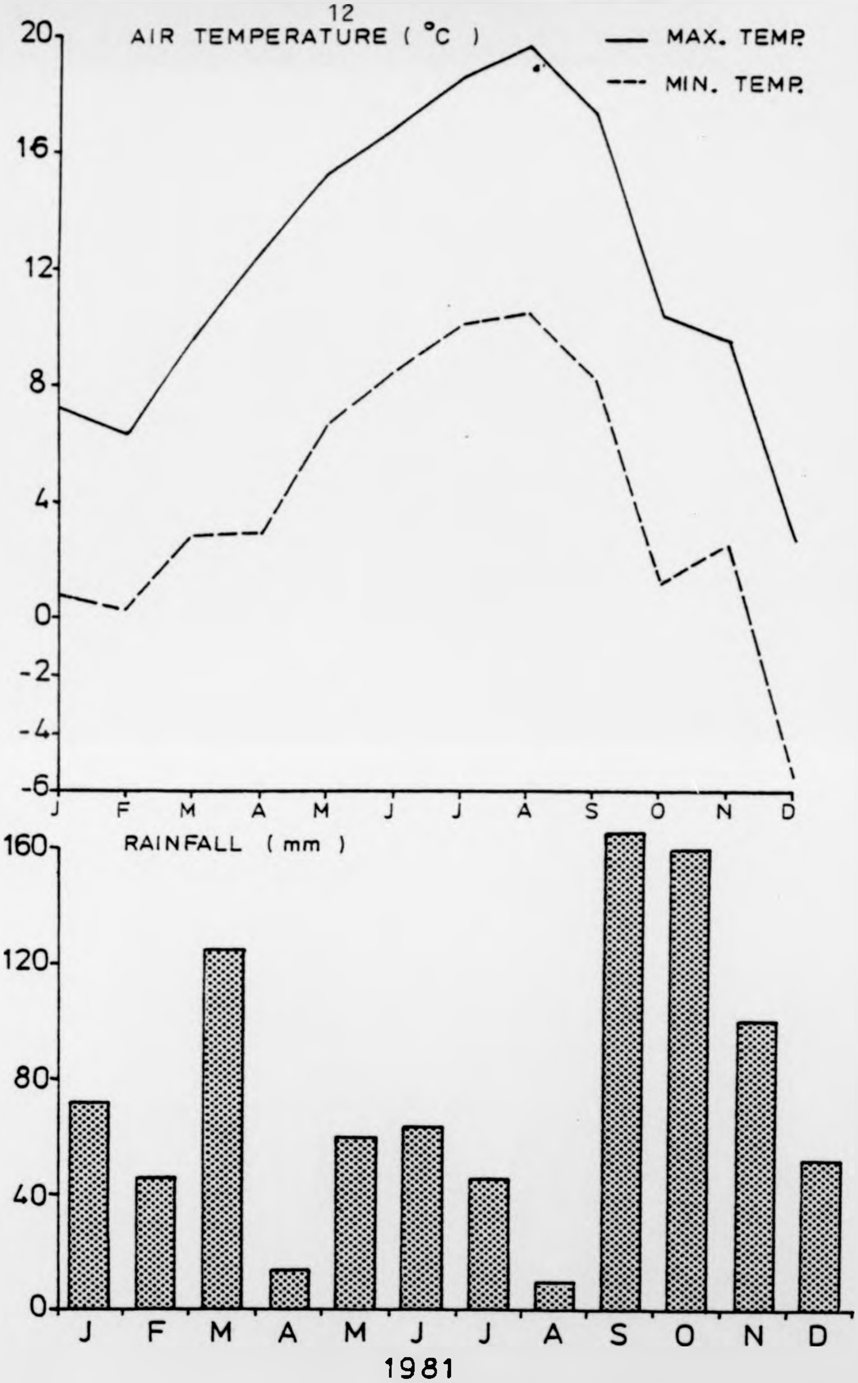

Fig.2: Seasonal changes in mean monthly rainfall and mean maximum and minimum air temperature at Stirling during 1981

3. SITE DESCRIPTION

3.1 Loch Fad

The loch, which is situated approximately 2 km west of Rothesay, is actually a reservoir which was constructed to supply the town's linen mills in the 18th century. It lies 12m above sea level on a N.W.-S.E. line, immediately south of, and parallel to, the Highland Boundary Fault which bisects the island. North of the loch, the land is dominated by metamorphic schists and quartz rocks, while to the south the predominant rocks are sedimentary sandstones. The loch is surrounded by gently sloping hills on the east and west sides, the slopes of the latter being largely covered by deciduous trees. Small plantations of both coniferous and deciduous woodland lie along the eastern shore. The southern end of the loch is surrounded by arable and pasture land.

The loch is approximately 2.5 km long by 0.3 km wide, and the total surface area is 0.71 km^2, with a maximum depth of 12m (fig.3). There are one major and five minor inflows, with an outflow through a non-operational sluice into the Kirk Dam at the north end.

The fish farm is situated at the north end of the loch in about 11m of water. Since it started in 1977, production has risen steadily to over 200 tons in 1981-82. During the study period about 75 Kames-type cages were in use (see Dalton 1976, for description of design). Each cage is $120m^3$ (6 x 5 x 4m) in volume, and stocking density was approximately 15 kg m^{-3}. The cages were moored together in 6 rafts of approximately 12 cages each, and each raft was anchored

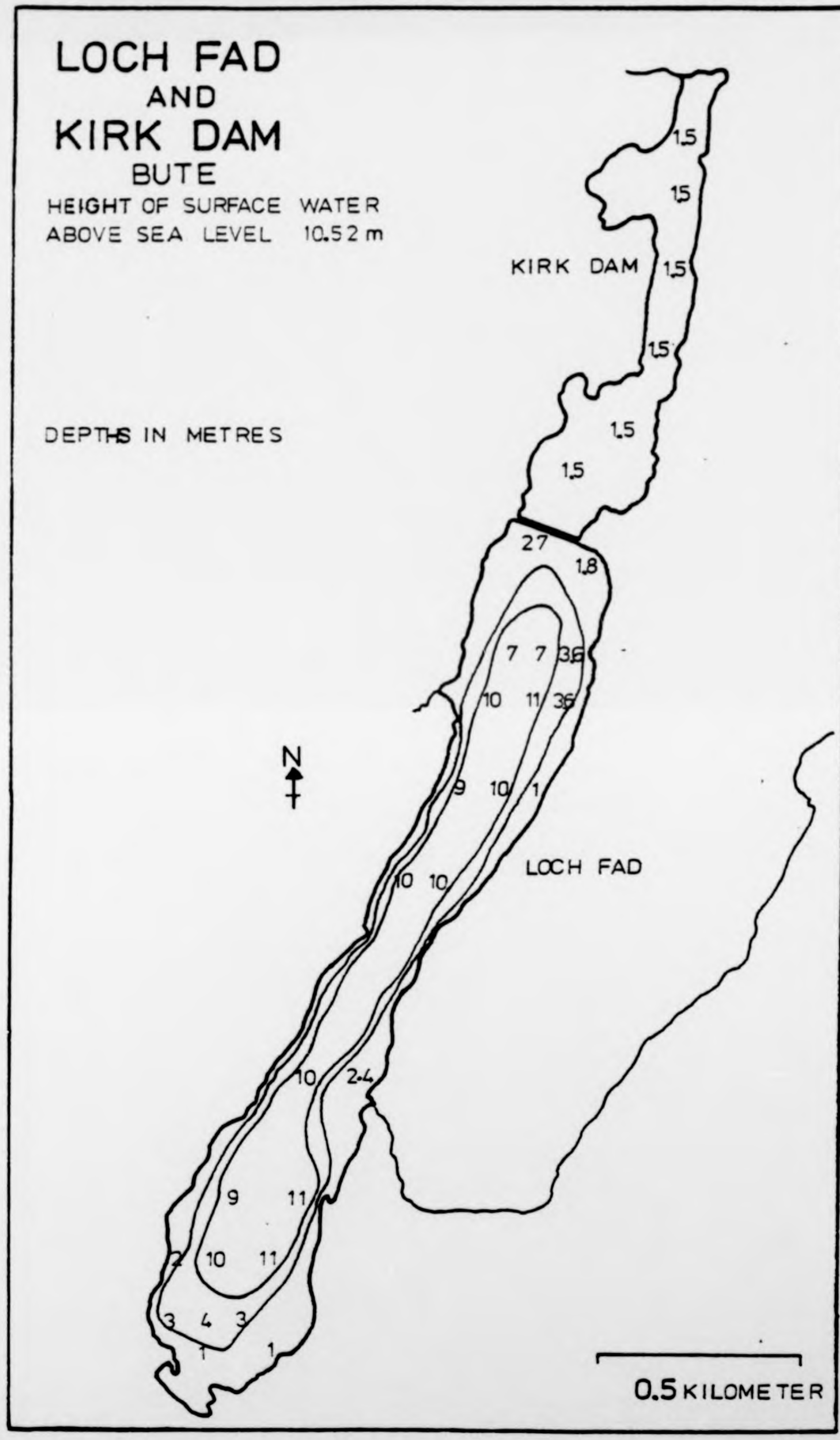

Fig.3: Bathymetric map of Loch Fad

at a single point and was thus free to rotate about that single point.

The loch supported an abundant phytoplankton flora of Cyanophyceae Chlorophyceae, and Bacillariophyceae, and supported a bloom of Microcystis aeruginosa during the spring and summer months. The zooplankton population consisted of crustaceans (cladocera and copepoda) and rotiferans. The macrobethic fauna mainly comprised oligochaetes, chironomids and gastropods. The fish fauna of the loch was dominated by coarse species such as pike (Esox lucius L.), roach (Rutilus rutilus L.), but also had a large population of feral rainbow trout (Salmo gairdneri L.) which had escaped from the cages.

One of the six rafts was chosen as the study area (raft No.1). The total length of the raft is some 33m. Including the anchor chain, the potential area covered by this raft is a circle of radius 41m. Using an echo-sounder, a control site was chosen at the southern end of the loch in a similar depth of water (fig. 4).

3.2 Howietoun Fish Farm

The historic fish farm at Howietoun in Stirlingshire was built between 1871 and 1885 by James Maitland (Bartt) of Sauchieburn to conduct experiments on fish rearing, utilizing the excellent water supply of the local burns and spring. It was bought by the University of Stirling in 1979 to supplement its facilities as a centre for aqua-culture research and training.

The farm consists of 10.12 hectares of land, 4.05 hectares of which

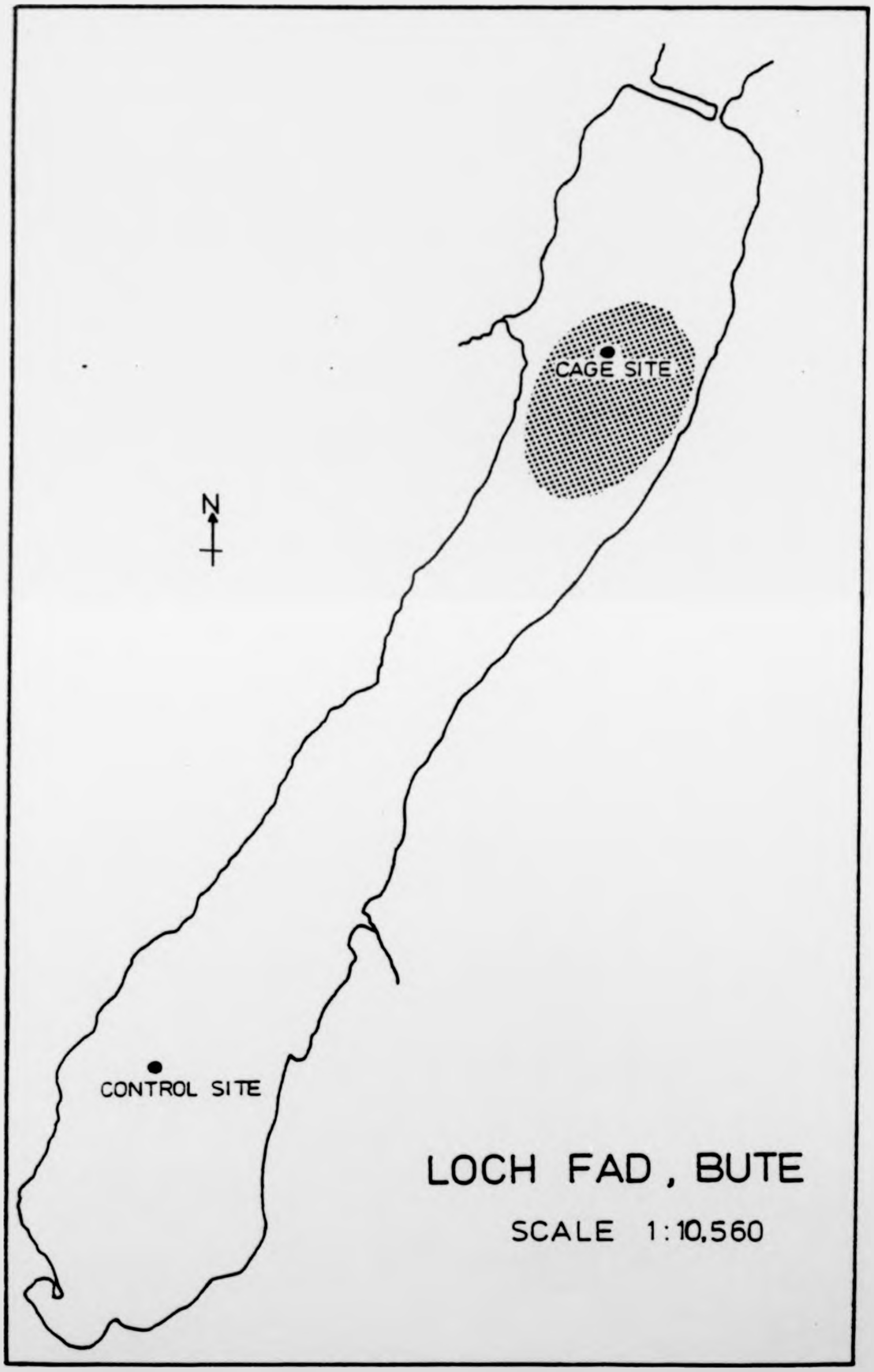

Fig.4: Location of sampling stations and fish farm in Loch Fad

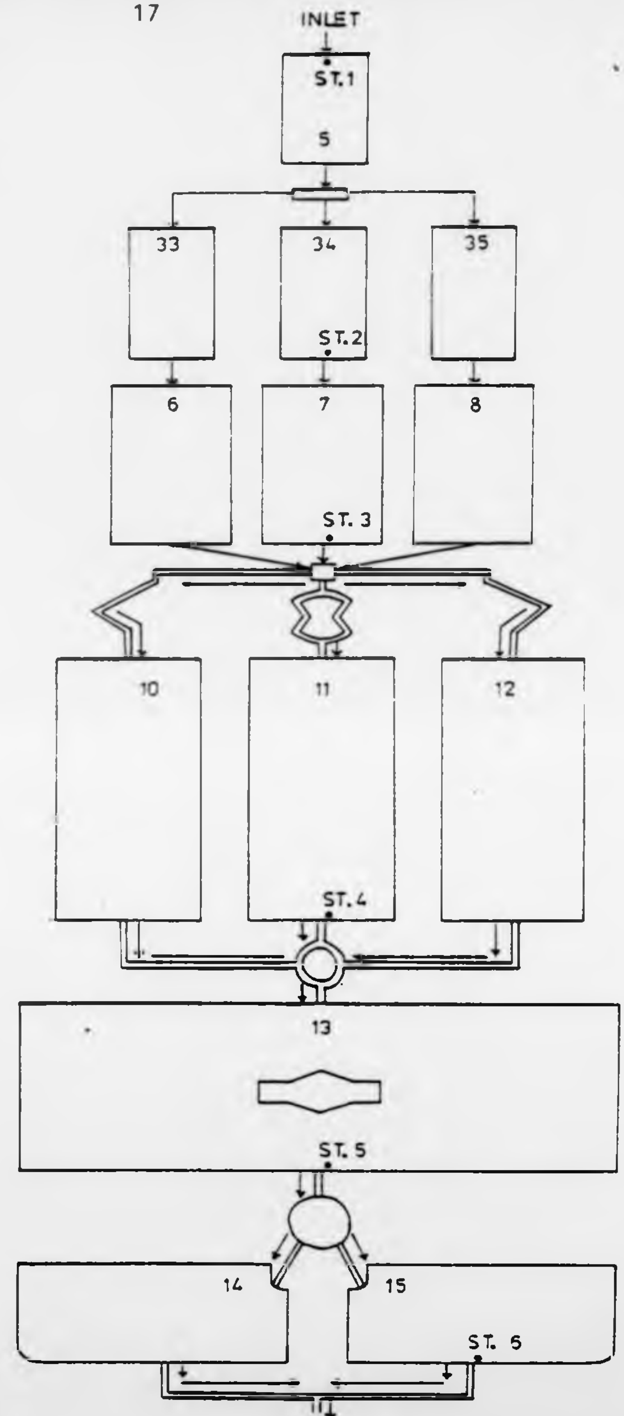

Fig.5: Plan of Howietoun Fish Farm, showing main earth ponds and the main flow routes and location of sampling stations

are ponds with a holding capacity of 40 tonnes of fish. The earth ponds at the fishery part of the farm are a masterpiece of planning and design, and it is a credit to the standard of workmanship that all the ponds are still in use today with only minor modification. As a concession to the obvious advantages of modern plastics, the original wooden hatching boxes have been replaced with glass fibre troughs and plastic trays which can be cleaned and disinfected more easily. In addition to the old hatchery and earth ponds there is now a modern part of the farm designed for the on-growing of brown trout, salmon and rainbow trout in fibreglass tanks.

There are about 40 earth ponds in total, all of varying depth and sizes and all carefully laid out to allow each pond to be serviced by gravity-flow water. The total drop in elevation from the top ponds to the bottom ponds (a distance of 341m) is 6.39m.

There are three sources of water, a stream, a spring, and a guaranteed 1 million gallons per day from a reservoir. The average daily intake of water is 2 million gallons per day, producing 20 tonnes of fish per year. However, it would seem that water availability is limiting as the farm cannot run at full capacity. The main earth ponds, and the main flow routes through the farm are shown in Figure 5.

The sampling stations are shown in fig.5. The ponds 13, 14 and 15 had submerged vegetation along the shore line. Ponds 13, 14 and 15 also supported *Lemna sp.*, which was especially abundant in ponds 14 and 15 compared with pond 13.

4. MATERIALS AND METHODS

At Loch Fad - the investigations were carried out for a period of 14 months from November 1980 to December 1981. Two stations were fixed for taking all the samples, one at the cage site and the other at the south end of the loch, over 1.61 km from the cages. The water samples from the surface were taken with a plastic bucket, while samples from the depth of 4m and 9m were collected with a Van Dorn water sampler. For seasonal studies, the samples were collected at about mid-day at intervals of one month; and for the diurnal study in the month of April 1981, the samples were collected at three hourly intervals, over a period of 27 hours, from the surface, 4m, and 9m depths.

At Howietoun Fish Farm - the samples for the present study were collected for a period of 11 months, from February to December 1981. Six stations were fixed for collecting the samples and their locations are shown in Figure 5. Water samples were collected at about mid-day from the surface with a plastic bucket at fortnightly intervals for the seasonal study, and at three hourly intervals over a period of 27 hours in the month of April for the diurnal study.

Water samples collected at both Loch Fad and Howietoun Fish Farm were analysed for various abiotic and biotic parameters. The abiotic parameters were temperature, transparency, hydrogen-ion concentration, dissolved oxygen, ammonia, nitrite, nitrate, soluble reactive phosphate, silicate, chlorophyll-a, and total solids. The biotic components examined were phytoplankton and zooplankton. In addition to these, attached periphytic algae were also studied on artificial surfaces, as described below.

Water temperature: Water temperature was measured with a mercury-in-glass thermometer.

Transparency: The transparency was measured by a standard Secchi disc of 40cm diameter, painted with black and white quadrants.

Hydrogen-ion concentration: Hydrogen-ion concentration (p^H) was measured using a battery operated portable pH meter (Orion Research, model 201, digital read out). The instrument was calibrated at frequent intervals using standard buffer solutions of p^H 4 and 7.

Dissolved oxygen: Samples for dissolved oxygen were taken in 125 ml glass-stoppered reagent bottles, and dissolved oxygen was estimated according to the modified Winkler's method described in Strickland and Parsons (1972). The oxygen percentage saturation was calculated by Rawson's nomogram (Welch, 1948; Hutchinson, 1957; Strickland and Parsons, 1972).

Nutrients: Water samples for the estimation of ammonia, nitrite, nitrate, soluble reactive phosphate, and silicate, were collected in 500 ml narrow mouth, screw-capped polythene bottles, and were immediately processed (within 4 hours after collection) after taking them to the laboratory.

Total ammonia was measured using Harwood and Kuhn's (1970) phenol-hypochlorite method described in Golterman et al (1978). To measure nitrite in the water samples the sulphanilamide plus N- (1 - naphthyl) ethylenediamine method was used (Golterman _et al_ 1978). Nitrate was quantitatively reduced to nitrite by a cadmium-copper couple in alkaline buffered solution (p^H 8) as described in Golterman _et al_ (1978). Nitrite was then determined as above, and the concentration of nitrate obtained by the difference.

The soluble reactive phosphate was measured using molybdate-antimony and ascorbic acid reducing agent after Olsen (1967) as described in Golterman _et al_ (1978). Silicate was determined colorimetrically using molybdate and reducing agent according to Golterman _et al_ (1978).

Total suspended solids: Total suspended solids were determined by filtering 500 ml of sample water through pre-weighed filter paper (Whatman's GF/C) and dried at 105°C.

Chlorophyll-a: For chlorophyll-a analysis, a 500 ml water sample was collected in a narrow-mouth polythene bottle to which a few drops of 1% $MgCO_3$ solution had been added to prevent the conversion of chlorophyll into phaeophytin during the sample storage time (maximum storage time was 4 hours). On return to the laboratory the water was then filtered through sartorius membrane filter paper (pore size 0.45 micron) under vacuum pressure. The filter paper was dissolved in 90% acetone and placed in complete darkness in a refrigerator for 24 hours to facilitate complete pigment extraction. After 24 hours, the pigment solution was centrifuged at 5000 rpm for 20 minutes. The absorbance was measured in a spectrophotometer at wavelengths of 665 and 750 nm and the concentration of chlorophyll-a was calculated by the following equation.

$$X = 11.9(E_{665} - E_{750}) \quad \text{(Talling \& Driver 1963)}$$

where X = concentration of chlorophyll-a equivalent in the solvent ($\mu g\ ml^{-1}$)

E_{665} and E_{750} = absorbances at 665 and 750 nm, respectively

Phytoplankton: For the collection of phytoplankton, water samples were collected in 500 ml wide-mouth, screw capped polythene bottles. The phytoplanktons contained therein were fixed with acid Lugol's iodine immediately after collection. Algae in the iodised samples were allowed to sediment by stages until a 100-fold concentration had been achieved. From these concentrates, cells of all types were enumerated in a Sedgwick-Rafter counting disc. Algae were identified with reference to West and West (1903, 1905), Komarek and Ettl (1958), Bourrelly (1966, 1968, 1970), West and Fritsch (1927), Lund (1971). The results were expressed in cells per litre. The percentages of various species in the total phytoplankton were also calculated.

Zooplankton: For the quantitative and qualitative estimation of zooplankton, 50 litres of water sample collected by Van Dorn bottle from 4m and 9m layers, while from the surface layer a plastic bucket was used. The zooplankton was concentrated by filtering through fine mesh phytoplankton net to ensure the collection of all zooplankton including the small ones. The sample so obtained was immediately preserved in 4% formalin. Zooplankton numbers were counted under a compound microscope using a plankton counting chamber, and the results were expressed in number per litre. The identification was according to Edmondson (1965), Scourfield and Harding (1966), Harding and Smith (1974), and Pontin (1978).

Periphyton: To study periphyton at Loch Fad, artificial substrates were used both at the cage and control site. The artificial substrates consisted of small (4 x 4 cm) blocks of wood with an unpolished smooth surface which were fixed to a horizontal wooden bar. Four such horizontal bars were fixed at depths of surface, 4m and 9m along a nylon rope, which was weighted at the lower end and suspended from a plastic float at the surface, at both cage site and control site. At Howietoun Fish Farm, the horizontal bars were fixed by the bank of the ponds so that the wooden blocks were just below the surface of the water at stations 1, 3 and 5. On each sampling occasion at both Loch Fad and Howietoun Fish Farm two wooden blocks were removed from each horizontal bar and immediately placed in specimen tubes containing 10% formalin. In the laboratory, periphyton from the surface area of each block was carefully scraped off and the surface was washed with 100 ml of tap water. Samples were removed for identification and counting after shaking to evenly disperse the organisms. Each cell of a multicellular organism was given a count of one and the results are expressed as the mean number of cells per square centimetre of substrate surface.

5. RESULTS

5.1 Loch Fad

5.1.1 Water Temperature: The seasonal changes in the water temperature are shown in fig. 6. Thermal stratification in Loch Fad was not observed throughout the period of observation. The maximum temperature differences between the surface and 9m depth was 0.6°c at the control site while it was 0.5°c at the cage site. The difference of water temperature between the two sites at all depths was not significant when analysed statistically by using the t-test for paired comparisons (Table 1). The surface temperature at both the control and cage sites went on decreasing until January when a minimum of 4.5°c was reached, after which it increased steadily reaching its highest peak of 17°c during July and August. Temperature then decreased steadily until the end of the study during December when it was 4.5°c.

5.1.2 Transparency: Loch water was clearest during the winter months, Secchi disc readings at both the control and cage sites being highest during the month of January. These then decreased gradually to a minimum during August before increasing until the end of the study. The Secchi disc reading showed a wide range of fluctuation and varied between 2.5m and 1.0m at the control site, while it was between 2.2m and 0.6m at the cage site (fig.6). Thus the Secchi disc readings at the cage site were significantly lower than those at the control site (Table 1).

Transparency was inversely correlated with the total phytoplankton population (the correlation coefficient being -.93 at the control

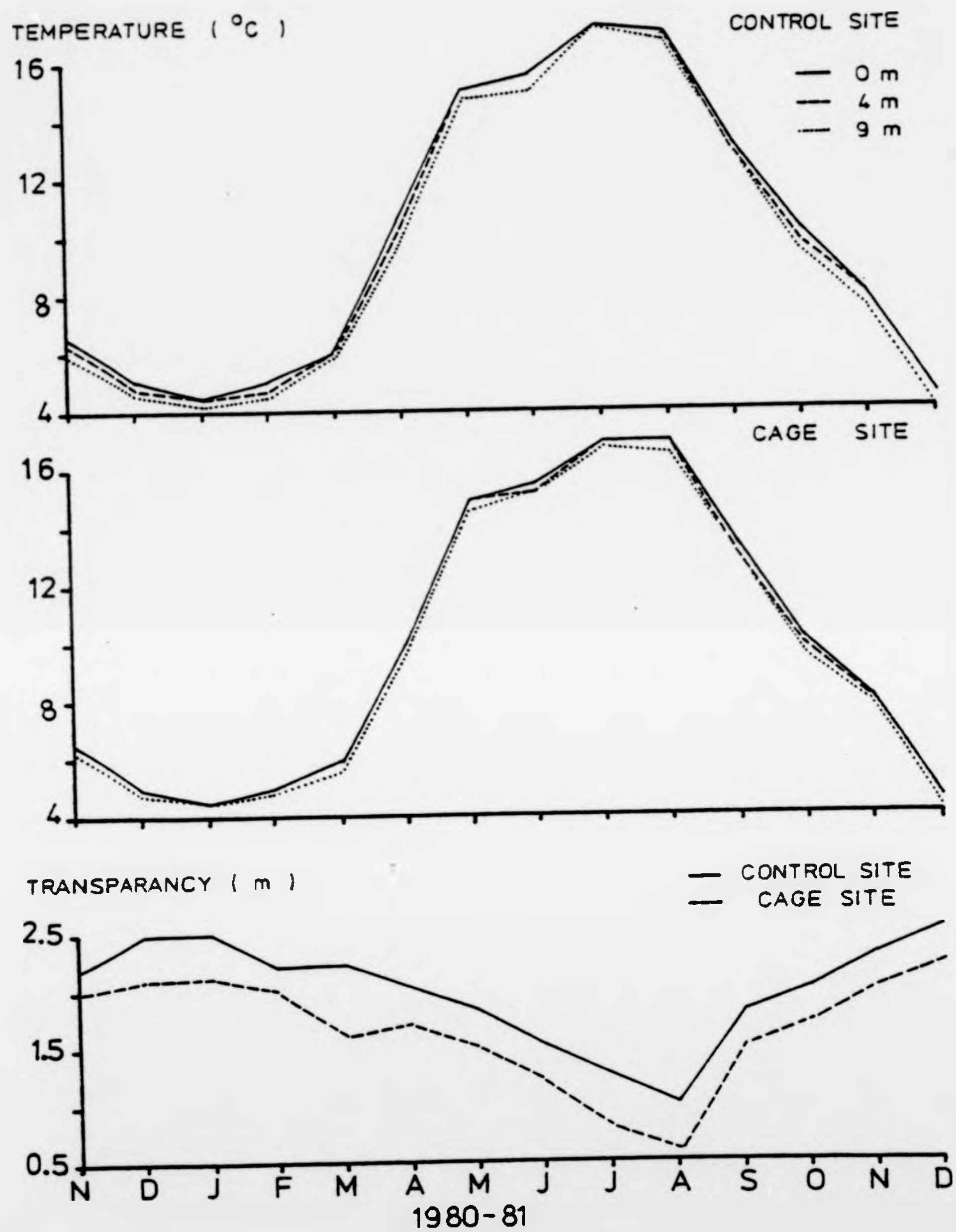

Fig.6: Seasonal changes in Water temperature and Transparency in Loch Fad at control and cage sites during 1981

Table 1: Results of the t-test for paired comparison of physico-chemical parameters at each depth between control and cage sites in Loch Fad over 14 months.

Parameters	Depths	Average recorded at control site	Average recorded at cage site	ts value
Temperature (°c)	Surface 4m 9m	9.86 9.74 9.50	9.82 9.75 9.52	0.919 0.151 0.698
Transparency (m)	-	2.04	1.88	5.078***
p^H	Surface 4m 9m	6.86 6.83 6.76	6.82 6.81 6.69	1.601 .898 2.16*
Dissolved Oxygen (mg/l)	Surface 4m 9m	9.98 9.75 9.50	9.83 9.67 9.30	1.368 .943 4.630**
Inorganic Nitrogen (mg/l)	Surface 4m 9m	6.31 5.60 7.08	6.92 7.33 8.41	2.160* 2.600* 4.630**
Total Ammonia (mg/l)	Surface 4m 9m	.358 .387 .425	.453 .476 .510	5.361*** 8.216*** 6.415***
Nitrite (mg/l)	Surface 4m 9m	.03 .03 .04	.04 .04 .05	1.678 1.812 2.053
Nitrate (mg/l)	Surface 4m 9m	5.92 6.18 6.62	6.43 6.81 7.86	3.105** 2.193* 5.112***
Orthophosphate (mg/l)	Surface 4m 9m	.045 .046 .048	.05 .055 .058	4.187*** 7.790*** 5.515***
Silicate (mg/l)	Surface 4m 9m	3.58 3.74 3.89	3.60 3.73 3.87	.705 .189 .440
Total Suspended Solids (mg/l)	Surface 4m 9m	6.00 5.61 6.25	8.29 9.21 9.32	6.313*** 9.814*** 9.058***

where * $P < .05$ ** $P < .01$ *** $P < .001$

site and -.96 at the cage site, both highly significant at $p<.001$). The transparency was also inversely correlated with total suspended solids, the correlation at both the control and cage sites being highly significant (Table 2).

5.1.3 Hydrogen-ion concentration: The seasonal fluctuations in p^H are presented in fig. 7. The p^H of the loch water was on the alkaline side throughout the period of study, except at 9m where a minimum of p^H 6.8 was recorded at both the control and cage sites. The highest p^H was during July and August at both sites. p^H was always lower at the cage site at all depths, the difference being not significant at surface and 4m depths, but at 9m it was statistically significant (Table 1).

The positive correlation between p^H and total phytoplankton was highly significant at both the sites (Table 2).

5.1.4. Dissolved oxygen: Dissolved oxygen showed seasonal fluctuations with a minimum in May and September and a summer increase in concentration at all depths at both sites as shown in fig.7. Its concentration was always lower at 9m depth, especially at the cage site. The dissolved oxygen was lower at all depths at the cage site than at the control, but the difference was significant only at 9m (Table 1).

Table 3 gives the percentage saturation of dissolved oxygen at surface, 4m, and 9m depths at both the control and cage sites. At both sites and at all depths saturation reached close to 100% or

Table 2: Correlation coefficient between Phytoplankton and other parameters in Loch Fad during 1980-81

Parameters	At control site	At cage site
Total phytoplankton and transparency	-.93***	-.96***
Total phytoplankton and pH	+.86***	+.82***
Total phytoplankton and inorganic nitrogen	-.80***	-.78***
Total phytoplankton and nitrate	-.80***	-.78***
Total phytoplankton and phosphate	-.89***	-.89***
Total phytoplankton and total solids	+.92***	+.92***
Total phytoplankton and silicate	-.49	-.51
Total phytoplankton and chlorophyll-a	+.98***	+.99***
Total phytoplankton and total zooplankton	+.78***	+.79***
Total phytoplankton and total periphyton	+.66*	+.78***
Total Bacillariophyceae and silicate	-.84***	-.78***

where * $P < .05$, *** $P < .001$

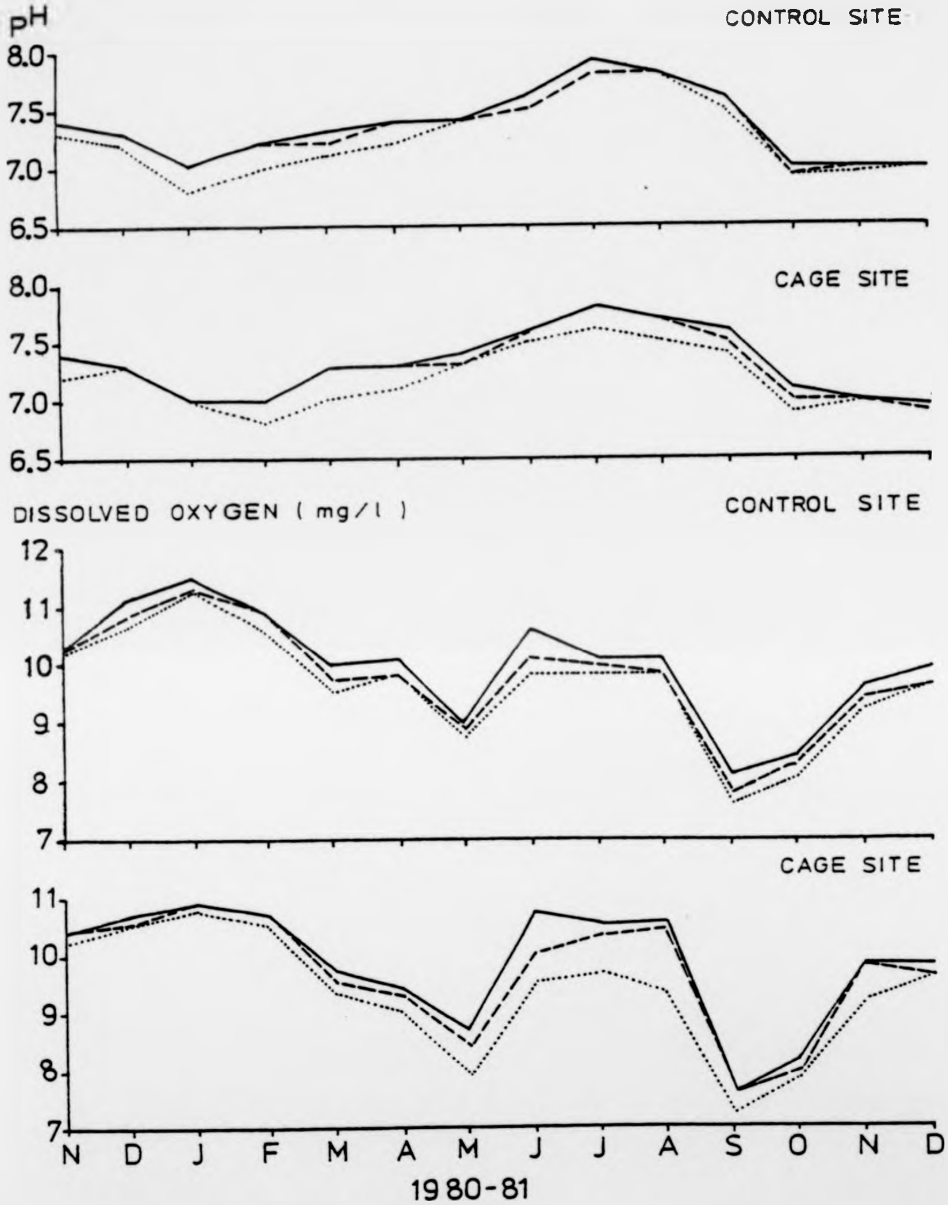

Fig.7: Seasonal changes in Dissolved oxygen and pH in Loch Fad at control and cage sites during 1980-81

(—— surface, ––– 4m, ... 9m)

Table 3: Showing percent saturation of dissolved oxygen at both control and cage sites in Loch Fad during 1980-81

	Control Site			Cage Site		
	Surface	4m	9m	Surface	4m	9m
Nov.	87	85	84	87	87	85
Dec.	90	87	85	86	84	84
Jan.	92	90	87	87	87	85
Feb.	87	85	82	86	86	83
Mar.	82	80	77	80	78	76
Apl.	92	90	87	85	84	82
May	92	90	87	87	86	80
June	110	105	100	110	102	98
July	107	105	105	112	110	102
Aug.	107	104	103	112	110	98
Sep.	80	77	75	75	74	70
Oct.	77	75	72	74	72	70
Nov.	84	82	78	85	85	80
Dec.	78	76	75	78	78	75

above during June to August and was minimum at 70-77% during October.

5.1.5 Inorganic Nitrogen: Inorganic nitrogen reached a maximum during March and then decreased to a minimum during August at both sites at all depths, as shown in fig 8. Its concentration was significantly higher at the cage site at all depths throughout the study period (Table 1).

Inorganic nitrogen was inversely correlated with the phytoplankton population, the correlation coefficient being highly significant at both sites (Table 2).

5.1.6 Total Ammonia: The highest concentration was during January and decreased steadily to a minimum during June to August, before rising again until the end of the study at both the sites. Fig. 9 also shows that ammonia concentration increased with depth throughout the year at both sites. The amount of ammonia was always higher at the cage site than at the control, the difference in concentration at all depths being highly significant (Table 1).

5.1.7 Nitrite: As shown in fig. 10, the concetration of nitrite-nitrogen remained below .05 mg/l at all depths at both sites except during September-October when it rose above 0.1 mg/l. The nitrite concentration was higher at all depths at the cage site than at control, but the difference was not significant (Table 1).

5.1.8 Nitrate: Nitrate-nitrogen was found to be the dominating nutrient over phosphate and silicate throughout the investigation period. Seasonal fluctuations were the same at control and cage

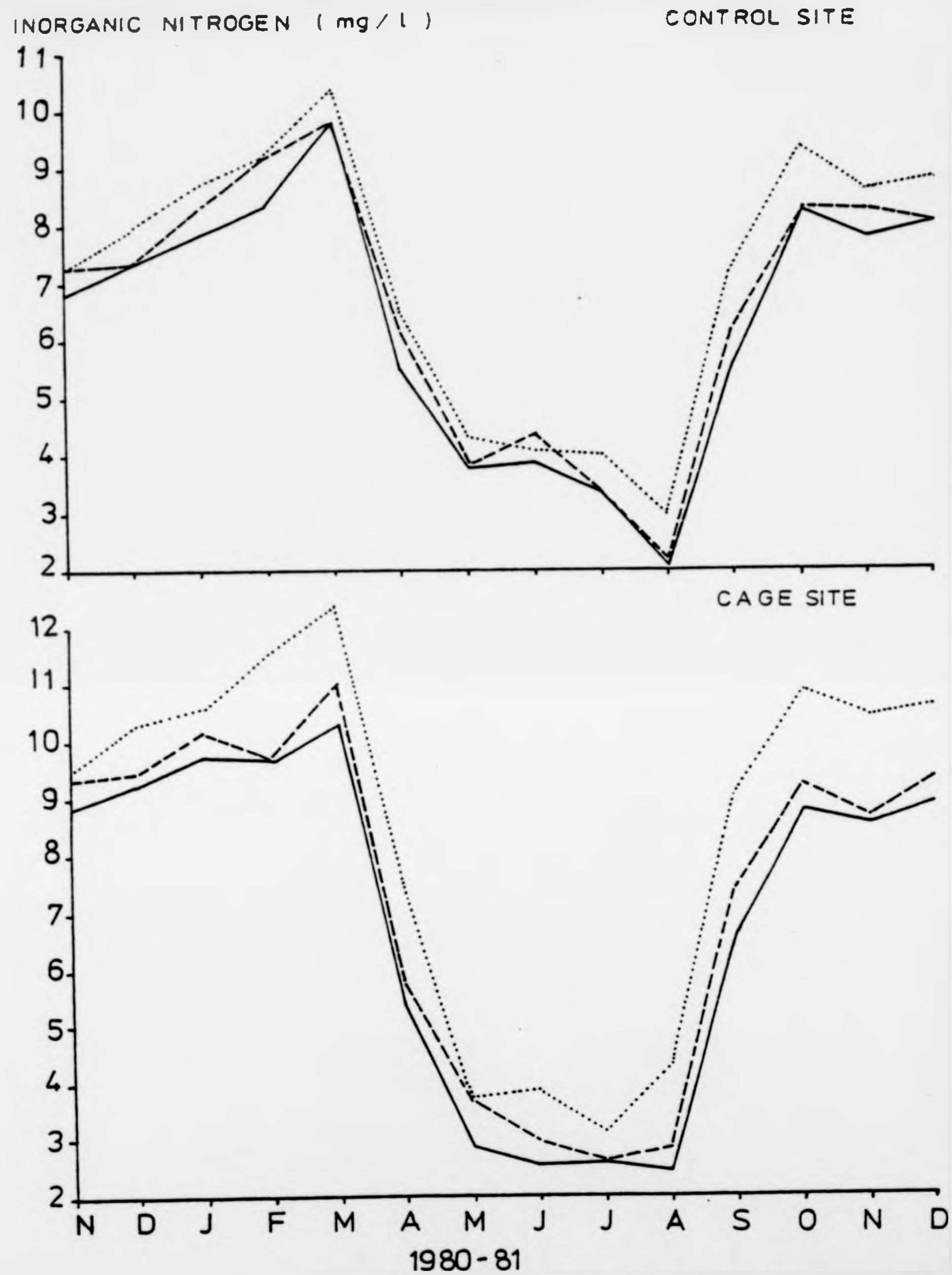

Fig.8: Seasonal changes in Inorganic nitrogen in Loch Fad at control and cage sites during 1980-81

(—— surface, – – – 4m, ... 9m)

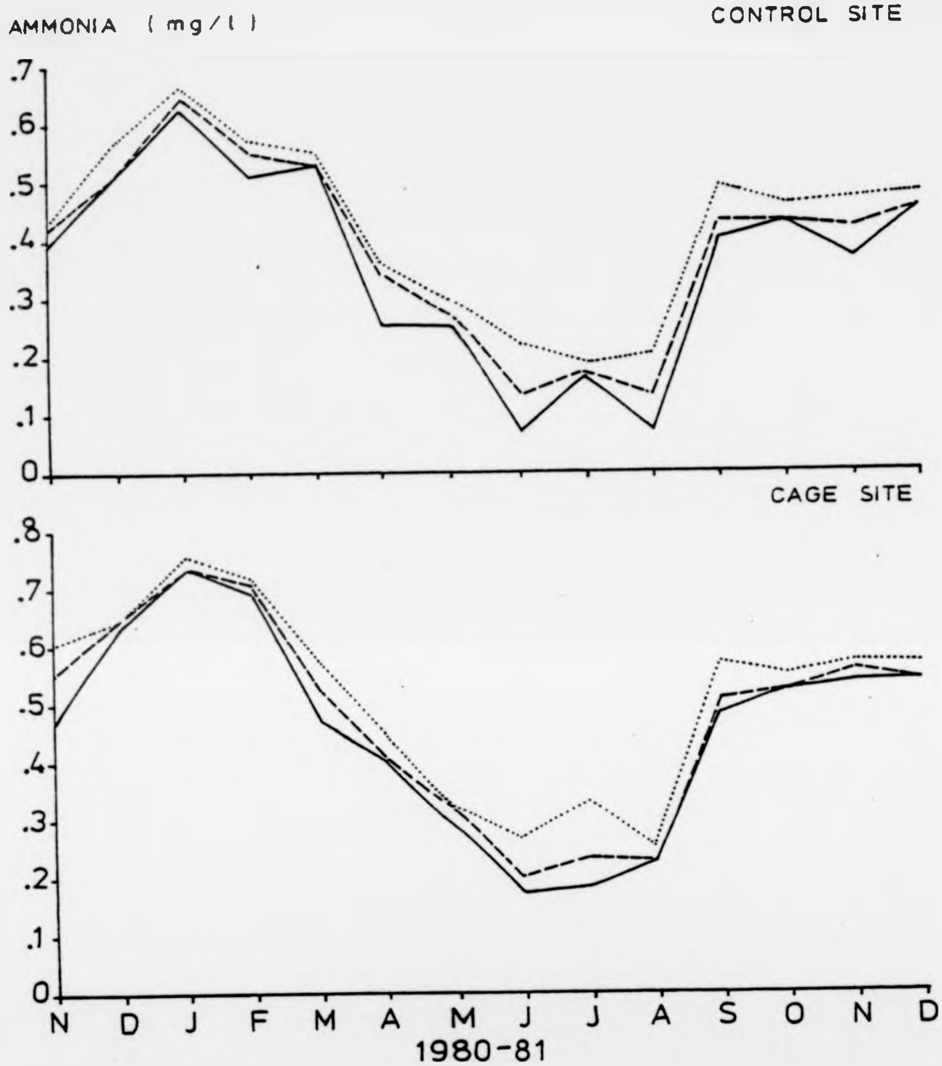

Fig.9: Seasonal changes in Ammonia in Loch Fad at control and cage sites during 1980-81

(—— surface, - - - 4m, ... 9m)

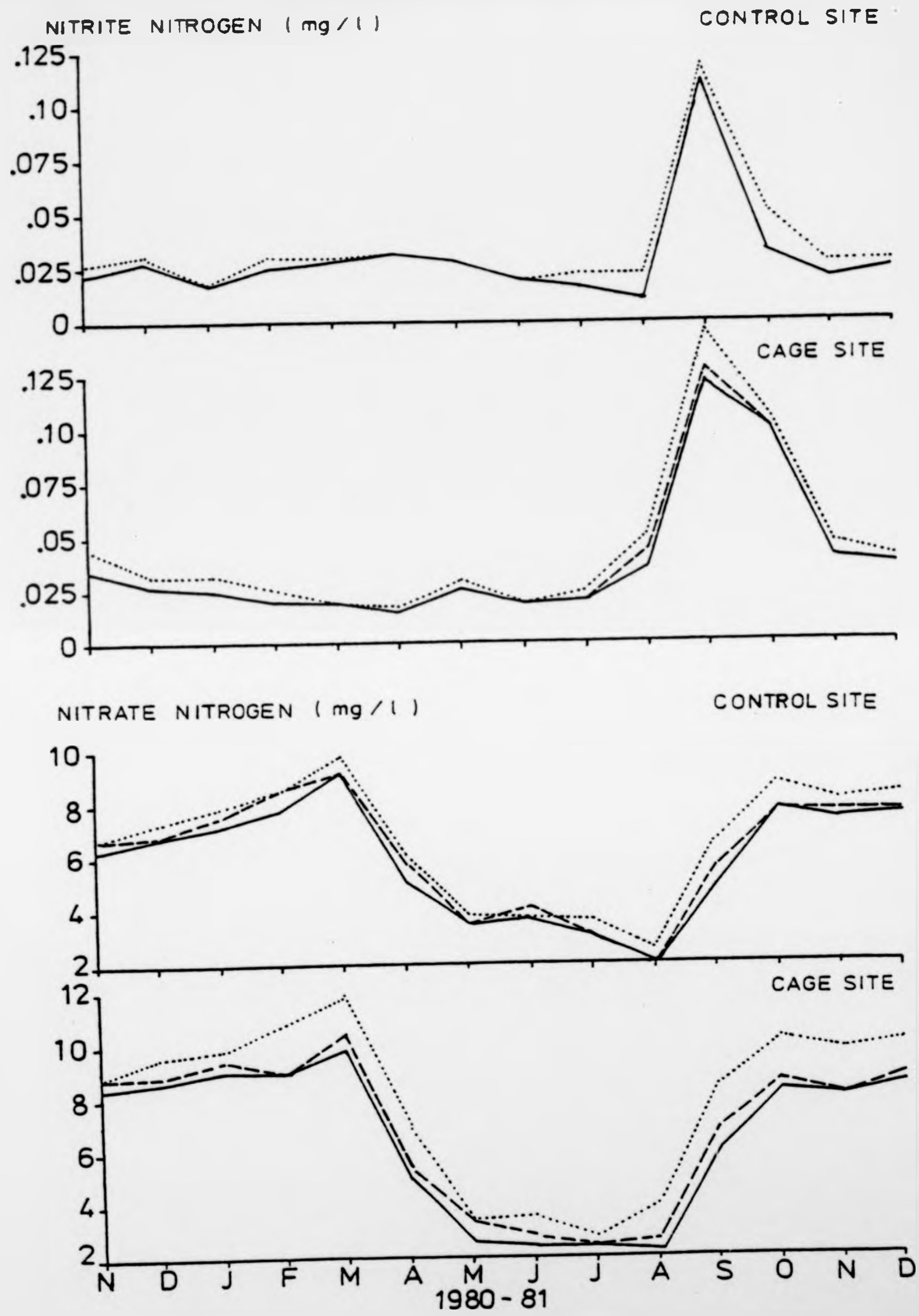

Fig.10: Seasonal changes in Nitrite and Nitrate in Loch Fad at control and cage sites during 1980-81

(—— surface, – – – 4m, ... 9m)

sites with a marked minimum during May-August, but even then the concentrations exceeded 2.0 mg/l. Fig. 10 shows that nitrate concentration increased with depth at both control and cage sites and the mean concentration at each depth was significantly higher at the cage site (Table 1).

As found with total inorganic-nitrogen, the inverse correlation between nitrate concentration and phytoplankton population was highly significant at both the sites (Table 2).

5.1.9 <u>Phosphate</u>: Fig. 11 shows that the seasonal fluctuation of soluble reactive phosphate was the same at both sites with a peak in February-March and a minimum in July-August, a pattern which closely parallels the fluctuation in nitrate-nitrogen. The soluble reactive phosphate concentration always remained below 0.09 mg/l being higher at all depths at the cage site throughout the year. Table 1 shows that this difference was significant.

Phosphate was inversely correlated with total phytoplankton population, the correlation being significant at both sites (Table 2).

5.1.10 <u>Silicate</u>: Fig. 11 shows similar seasonal fluctuations of silicate concentration at both the control and cage sites with a peak in January and the minimum in May-August. The concentration increased with depth at both the sites. The differences in silicate concentrations between control and cage sites were not significant (Table 1).

The inverse correlation between silicate concentration and total

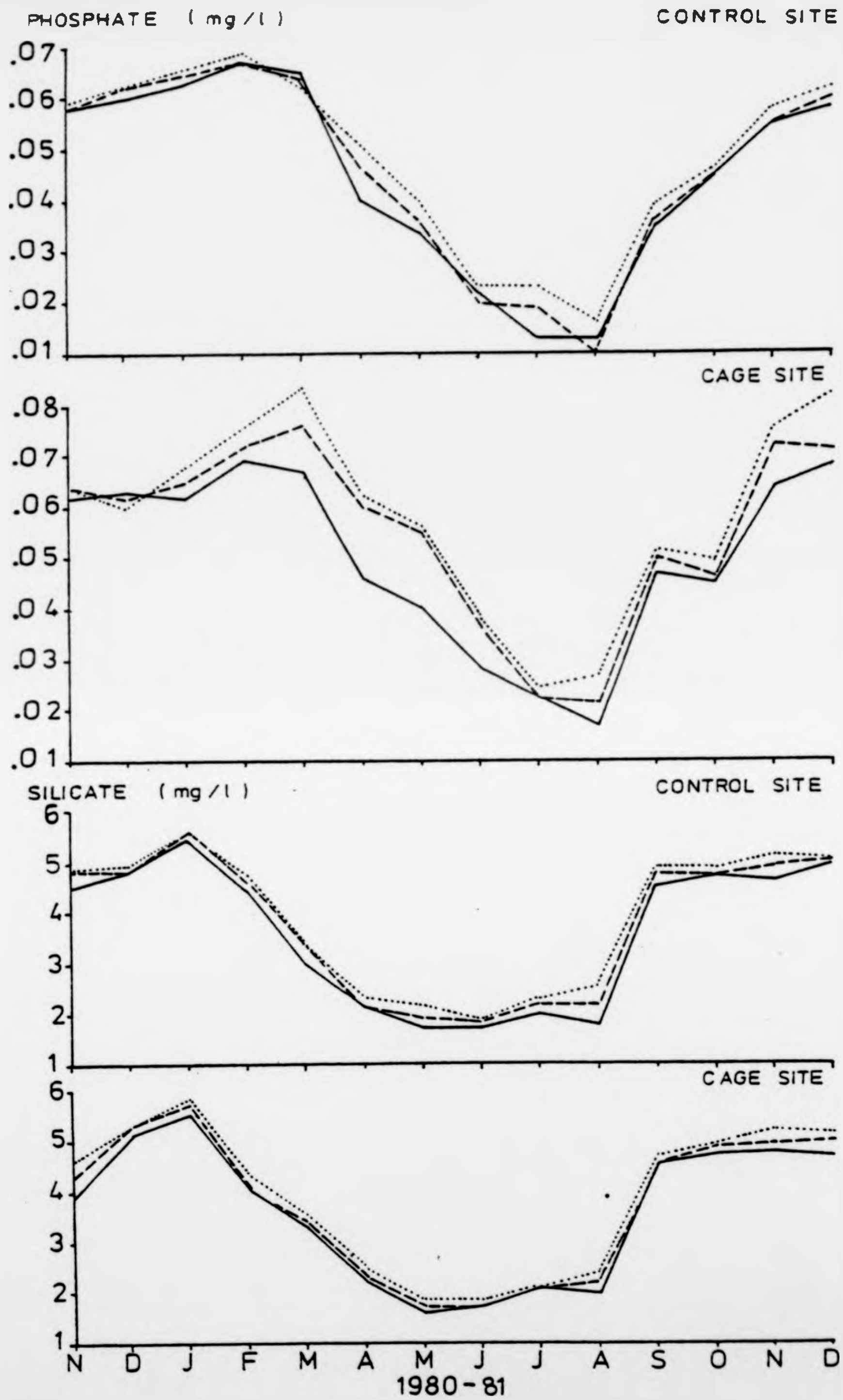

Fig.11: Seasonal changes in Orthophosphate and Silicate in Loch Fad at control and cage sites during 1980-81

(— surface, --- 4m, ... 9m)

Bacillariophycean population was highly significant (Table 2).

5.1.11 Total suspended solids: Fig. 12 shows that the seasonal fluctuation was the same at both sites with a peak in August. Total suspended solids were always higher at the cage site than at control at all depths, the difference being highly significant (Table 1).

A highly significant positive correlation was found between total solids and total phytoplankton population (Table 2).

5.1.12 Chlorophyll-a: Fig. 13 shows that at both the sites there was little fluctuation of chlorophyll-a during November to February, after which it increased to a marked peak during August. The chlorophyll-a concentration decreased with depth at both the sites. Though the chlorophyll-a concentrations were higher at all depths at the cage site than at control, the difference was statistically significant only at the surface (Table 5).

As might be expected, chlorophyll-a concentration was very highly correlated positively with the total phytoplankton population (Table 2).

5.1.13 Phytoplankton: The total phytoplankton population at both the sites showed similar seasonal fluctuations, being low during winter and reaching a maximum during August at the surface (fig. 14). Total phytoplankton cell numbers were significantly higher at the cage site at all depths compared with the control site, but only at the surface was the difference statistically significant (Table 5).

The species of phytoplankton recorded during the period of study are

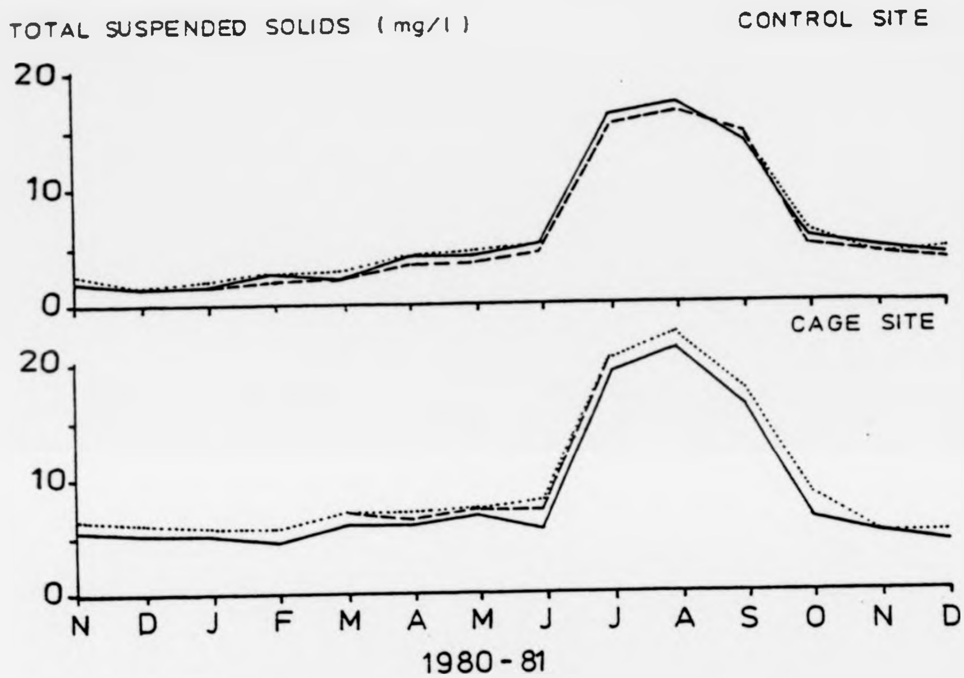

Fig.12: Seasonal changes in Total suspended solids in Loch Fad at control and cage sites during 1980-81

(— surface, --- 4m, ... 9m)

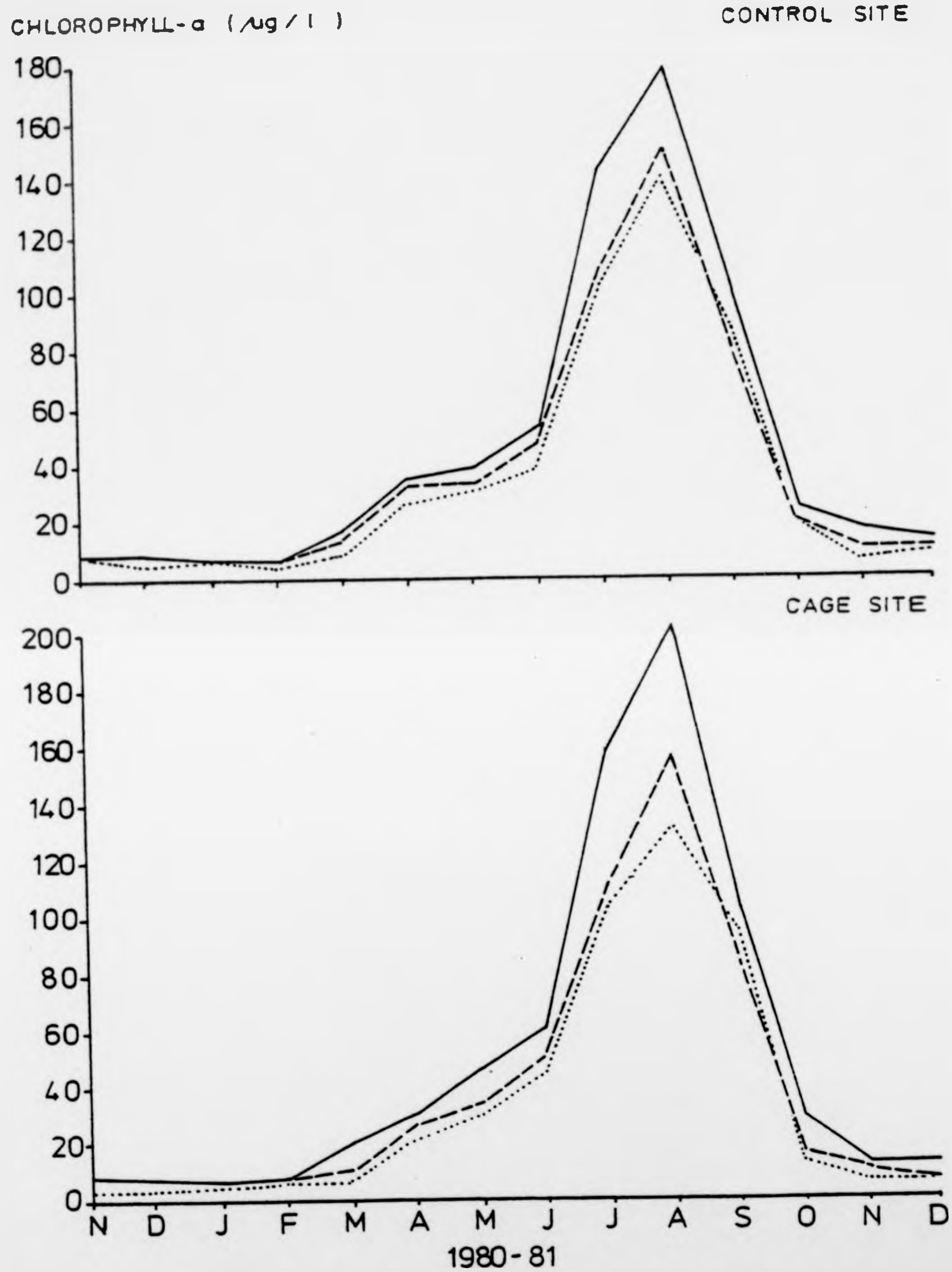

Fig.13: Seasonal changes in Chlorophyll-a in Loch Fad at control and cage sites during 1980-81

(—— surface, ––– 4m, ... 9m)

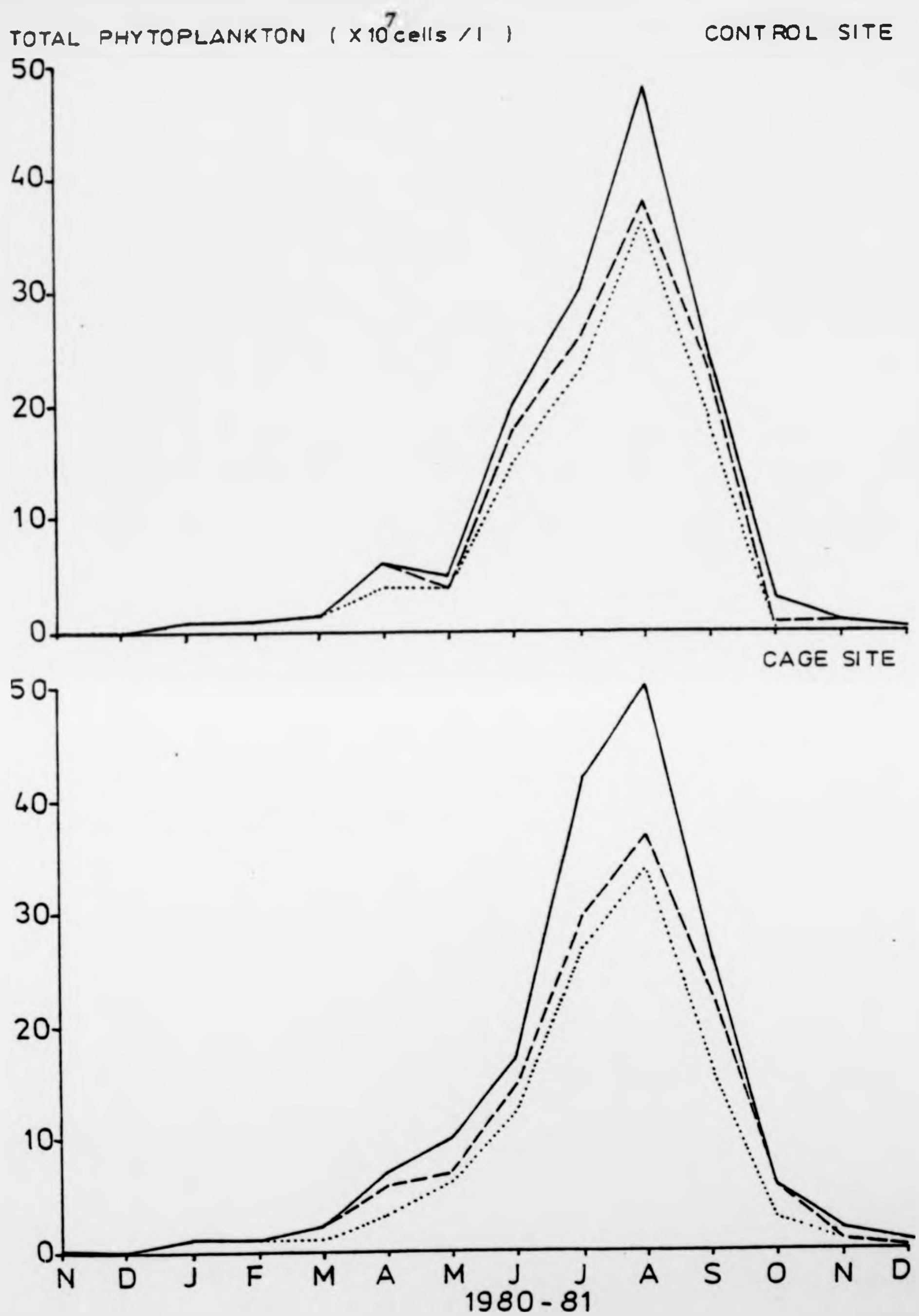

Fig.14: Seasonal changes in abundance of Total phytoplankton in Loch Fad at control and cage sites during 1980-81

(—— surface, ––– 4m, ... 9m)

Table 4: Species of Phytoplankton recorded in Loch Fad during 1980-81

CHLOROPHYCEAE

Ankistrodesmus falcatus (Corde) Ralfs

Botryococcus braunii Kutz

Closterium Kutzingii Breb.

Eudorina elegans Ehrenb.

Gleocystis gigas (Kutz) Legarh.

Oocystis elliptica West

Pandorina morum (Mull.) Bory

Pediastrum boryanum (Turp.) Menegh.

Pediastrum duplex Meyen

Scenedesmus abundans (Kirchn.) Chod.

Scenedesmus quadricauda (Turp.) Breb.

Sphaerocystis schroeteri Chod.

Spirogyra gracilis (Hass.) Kutz.

Staurodesmus cuspidatus (Breb.) Teiling

BACILLARIOPHYCEAE

Amphora ovalis Kutz

Asterionella formosa Hass.

Cyclotella comta (Ehr.) Kutz

Cymbella ventricosa Agardh

Gomphonema constrictum Ehrenb.

Melosira italica- (Ehrenb.) Kutz Subarctica Mull

Meridion circulare (Greville) Agardh

Navicula viridis Kutz

Table 4 cont'd.

BACILLARIOPHYCEAE cont'd.

Nitzschia linearis (Ag.) W.Sm.

Stephanodiscus astraea (Ehr.) Grunow.

Synedra ulna (Nitzsch.) Ehrenb.

Tabellaria fenestrata (Lyngb.) Kutz.

DINOPHYCEAE

Ceratium hirundinella (O.F.M.) Schrank.

Peridinium willei Huntf. - Kass.

CYANOPHYCEAE

Anabaena flos-aquae (Lyngb.) Breb.

Coelosphaerium naegelianum Unger

Microcystis aeruginosa Kutz

Oscillatoria agardhi Gomond

Oscillatoria limosa Ag.

Table 5: Results of the t-test for paired comparison of Chlorophyll-a and phytoplankton at each depth between control and cage site in Loch Fad over 14 months.

	Depths	Average recorded at control site	Average recorded at cage site	ts value
Chlorophyll-a (mg/l	Surface	45.71	49.86	2.160*
	4m	37.71	38.07	0.370
	9m	34.71	34.83	0.830
Total phytoplankton (log_{10} no./ml)	Surface	5.007	5.075	2.277*
	4m	4.941	4.970	1.119
	9m	4.876	4.878	0.083
Chlorophyceae (log_{10} no./ml)	Surface	2.627	2.710	6.097***
	4m	2.560	2.670	4.648***
	9m	2.332	2.472	2.526*
Bacillariophyceae (log_{10} no./ml)	Surface	2.710	2.731	1.244
	4m	2.620	2.629	0.867
	9m	2.326	2.385	0.918
Dinophyceae (log_{10} no./ml)	Surface	0.892	0.898	0.858
	4m	0.665	0.665	-
	9m	0.511	0.512	0.048
Cyanophyceae (log_{10} no./ml)	Surface	5.003	5.071	2.257*
	4m	4.937	4.966	1.733
	9m	4.873	4.875	0.66

where * $P < .05$, ** $P < .01$, *** $P < .001$

listed in Table 4. The group Cyanophyceae was numerically the most abundant, the other groups being Chlorophyceae, Xanthophyceae, Bacillariophyceae, and Dinophyceae.

5.1.13.1 Seasonal trend of phytoplankton:

(A) Chlorophyceae: Fig. 15 shows that the group Chlorophyceae started increasing in number from February, reaching a maximum in July at both sites. Its abundance decreased with depth at both sites. Table 5 shows that cell numbers were significantly higher at the cage site at all depths compared with the control site.

The group Chlorophyceae comprised 14 species as shown in Table 4. Their seasonal fluctuation and vertical distribution are shown in figs. 16 to 21. Cell numbers of all the chlorophyceans were higher at the surface than at lower depths. Only *Pediastrum boryanum*, *Pediastrum duplex*, and *Staurodesmus cuspidatus* were present throughout the year. The population of these species started to increase from March, reaching their highest peak in July in the case of *P. duplex* and *S. cuspidatus*, while *P. boryanum* was at its maximum during August. From the month of March, *Botryococcus braunii*, *Eudorina elegans*, *Pandorina morum*, *Scenedesmus quadricauda*, and *Sphaerocystis schroeteri* started appearing in the phytoplankton samples and their population reached the highest peak during June-July. *Ankistrodesmus falcatus*, *Closterium Kutzingii*, *Gleocystis gigas*, and *Spirogyra gracilis* showed up from April in Loch Fad. *C. Kutzingii* and *G. gigas* had the highest peak during June while *A. falcatus* and *S. gracilis* had the highest peak during July. By May, *Scenedesmus abundans* and *Oocystis elliptica* were present, their population reaching their maxima by July and August respectively.

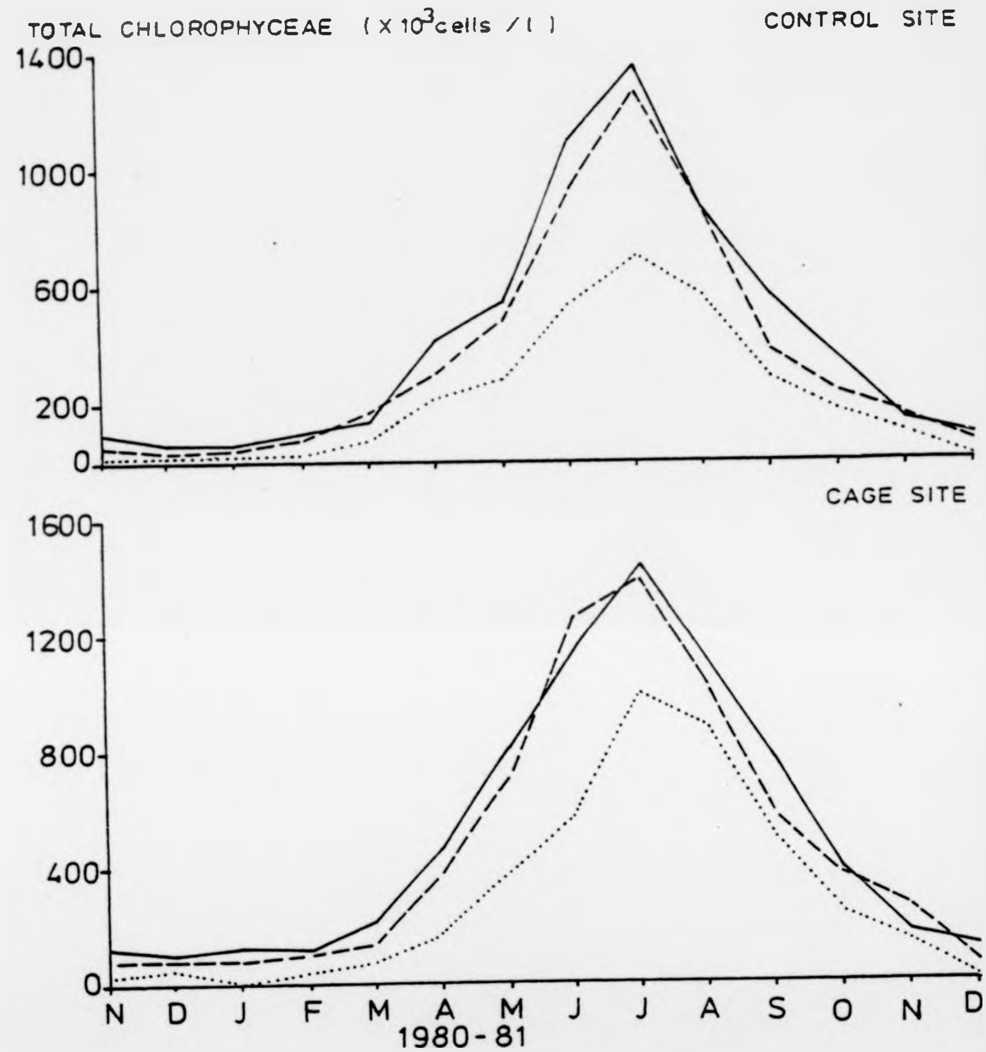

Fig.15: Seasonal changes in abundance of Chlorophyceae in Loch Fad at control and cage sites during 1980-81

(—— surface, ---- 4m, ... 9m)

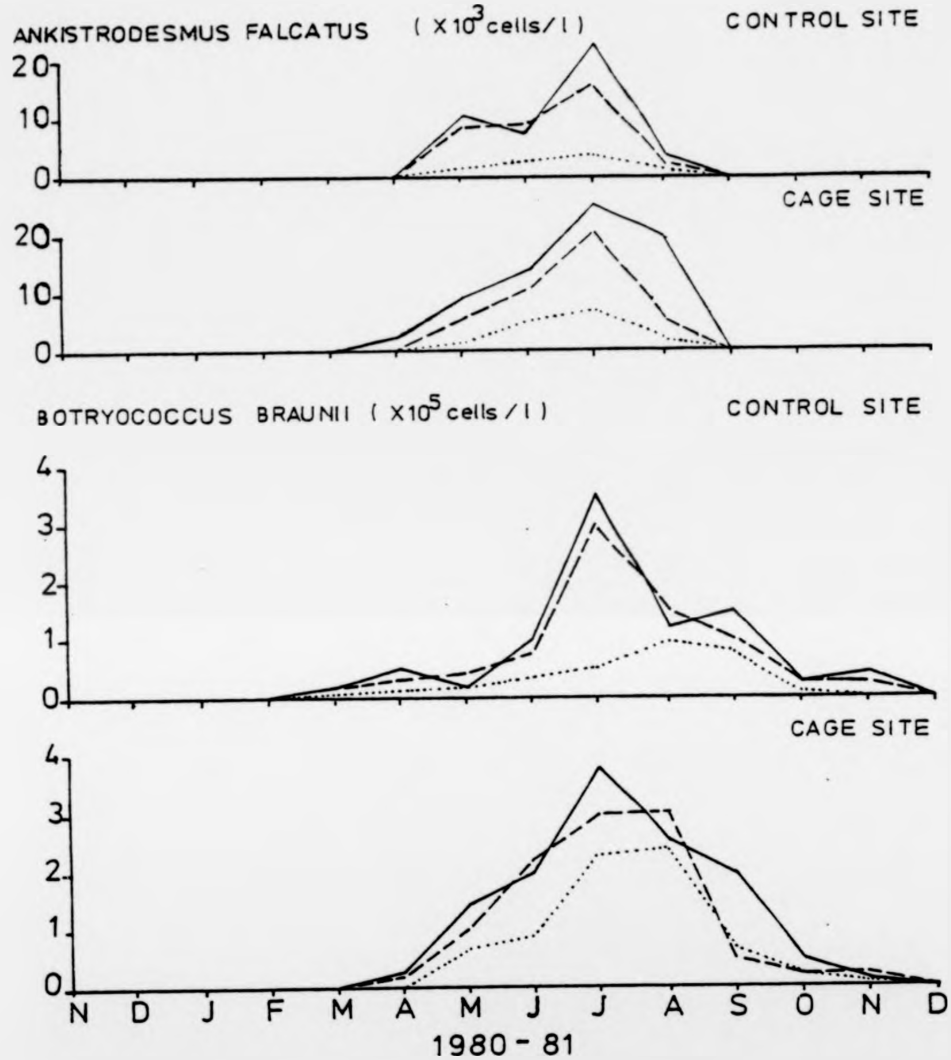

Fig.16: Seasonal changes in abundance of Ankistrodesmus falcatus, Botryococcus braunii, in Loch Fad at control and cage sites during 1980-81

(—— surface, --- 4m, ... 9m)

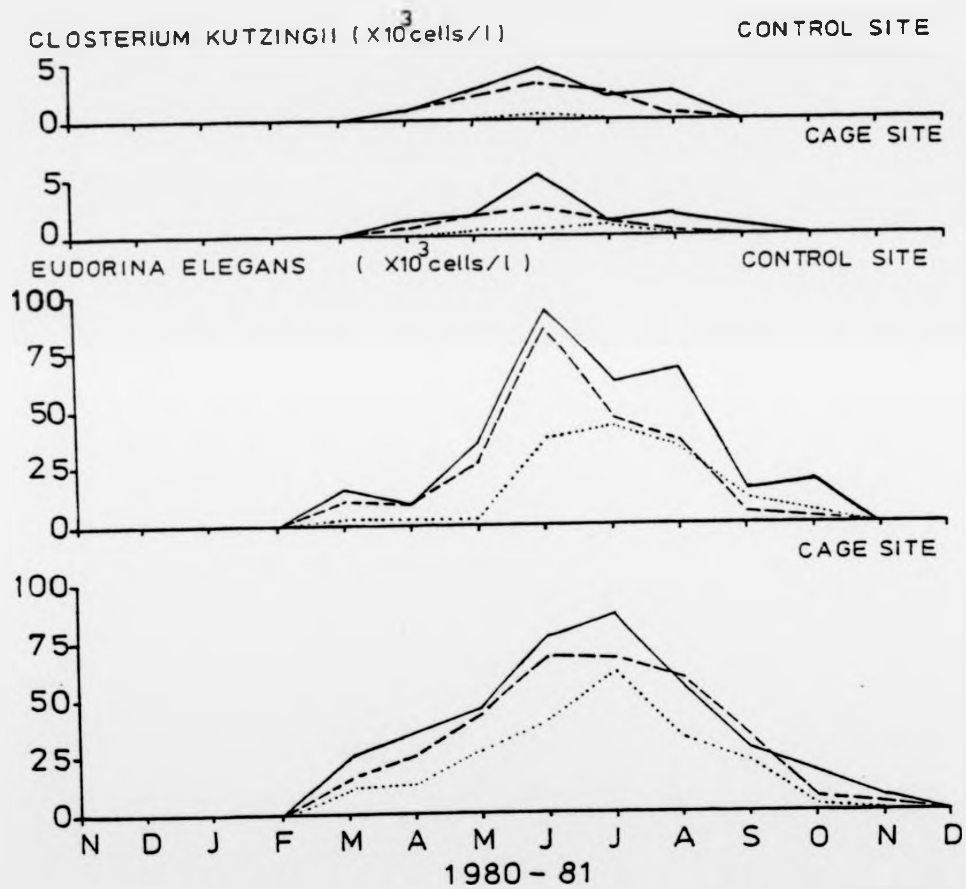

Fig.17: Seasonal changes in abundance of Closterium Kutzingii and Eudorina elegans in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

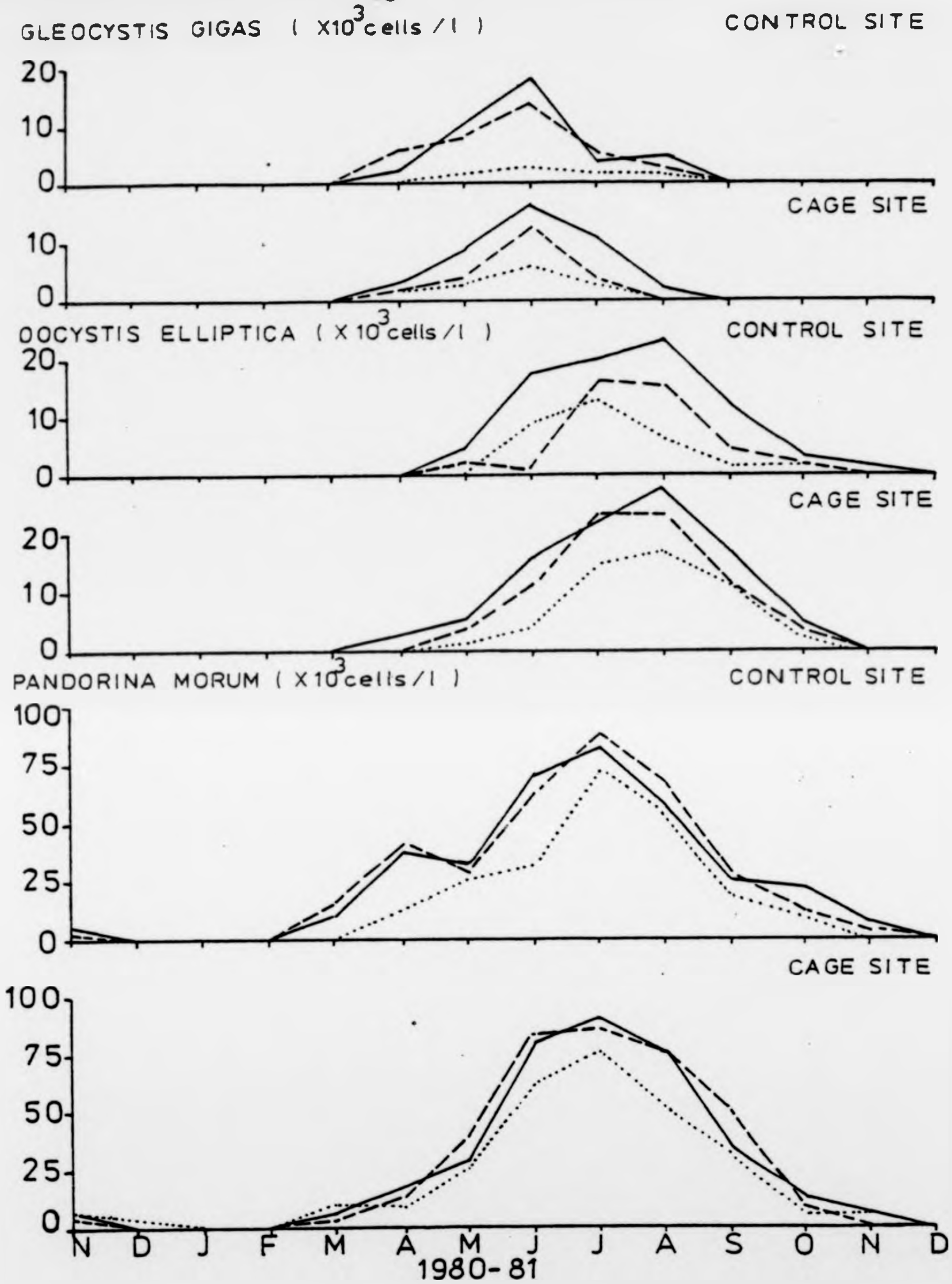

Fig.18: Seasonal changes in abundance of Gleocystis gigas, Oocystis elliptica, Pandorina morum, in Loch Fad at control and cage sites during 1980-81

(—— surface, - - - 4m, ... 9m)

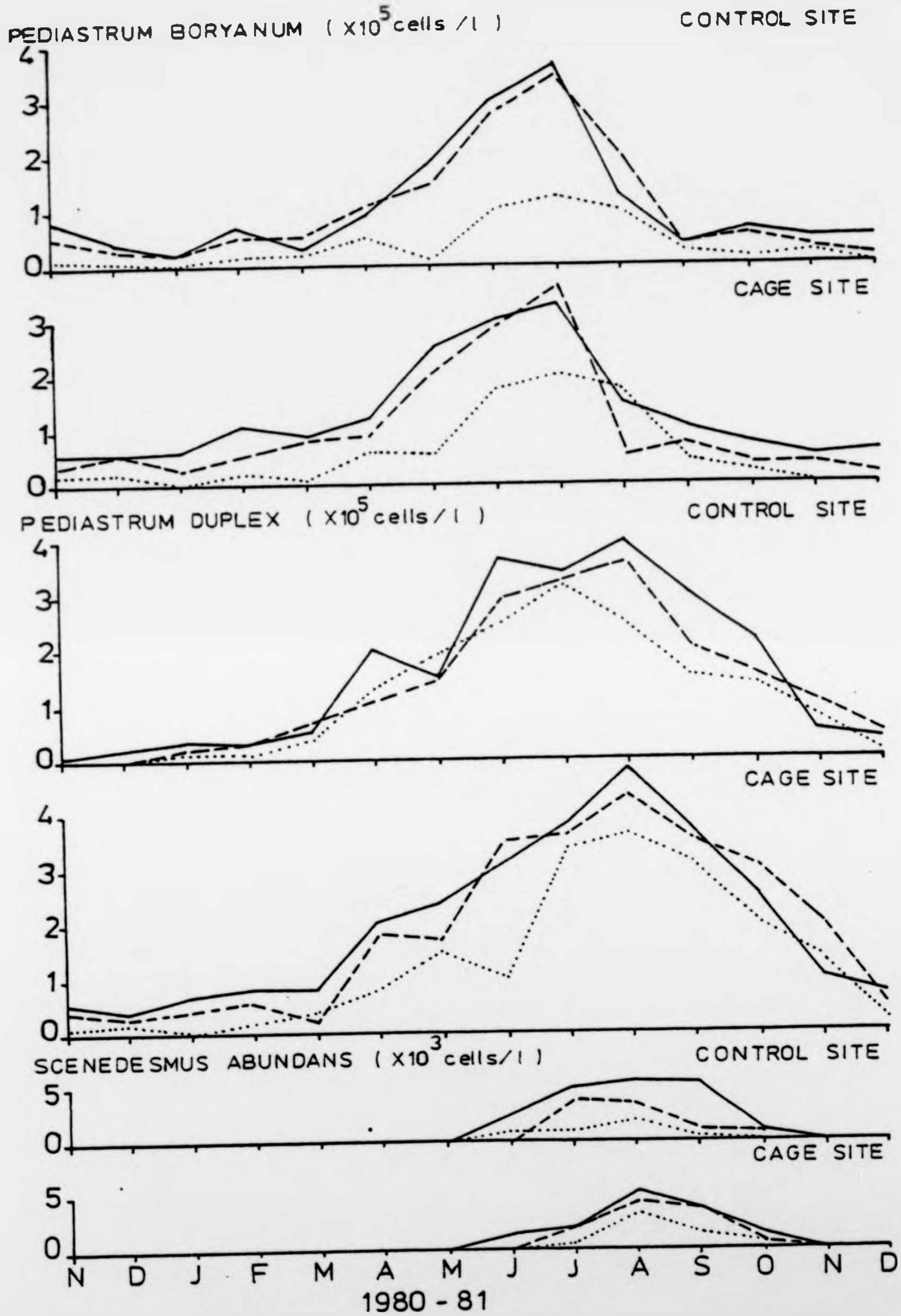

Fig.19: Seasonal changes in abundance of Pediastrum boryanum, Pediastrum duplex, and Scenedesmus abundans in Loch Fad at control and cage sites during 1980-81

(—— surface, - - - 4m, ... 9m)

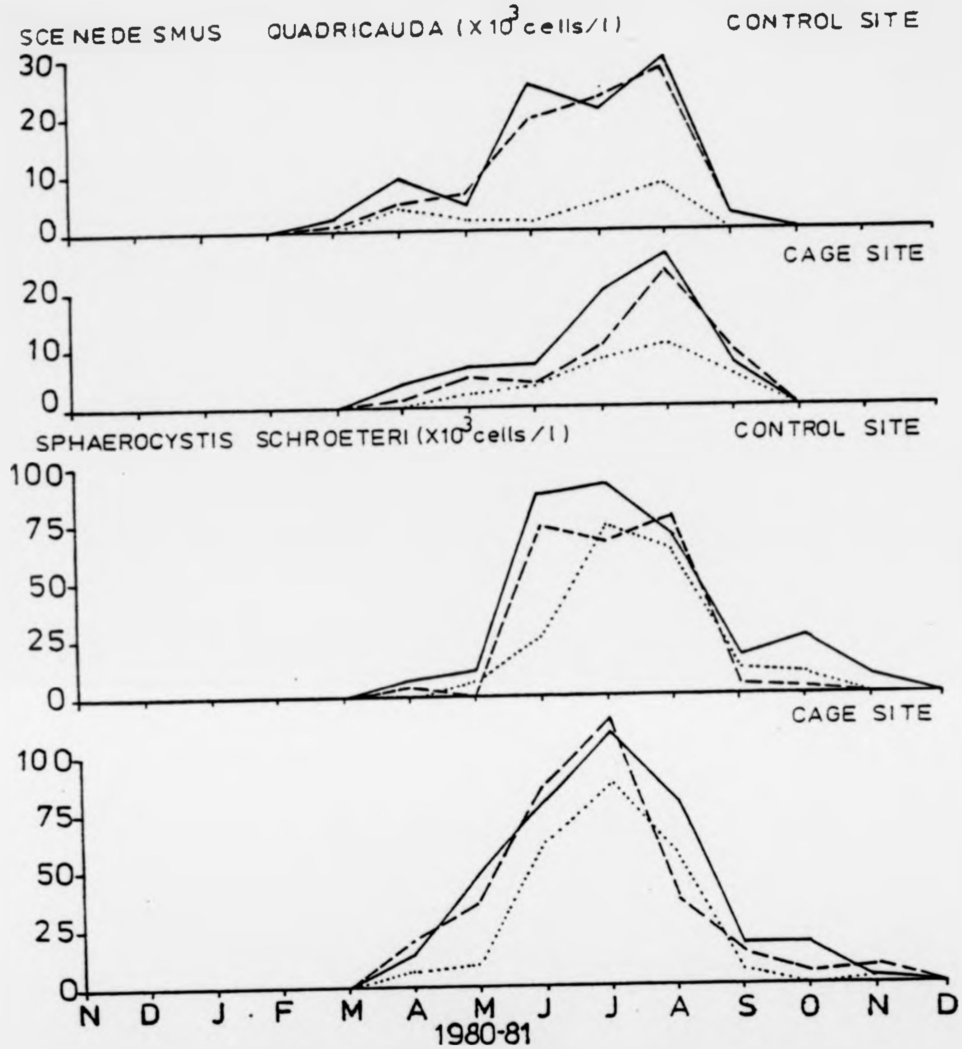

Fig.20: Seasonal changes in abundance of Scenedesmus quadricauda, and Sphaerocystis schroeteri in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

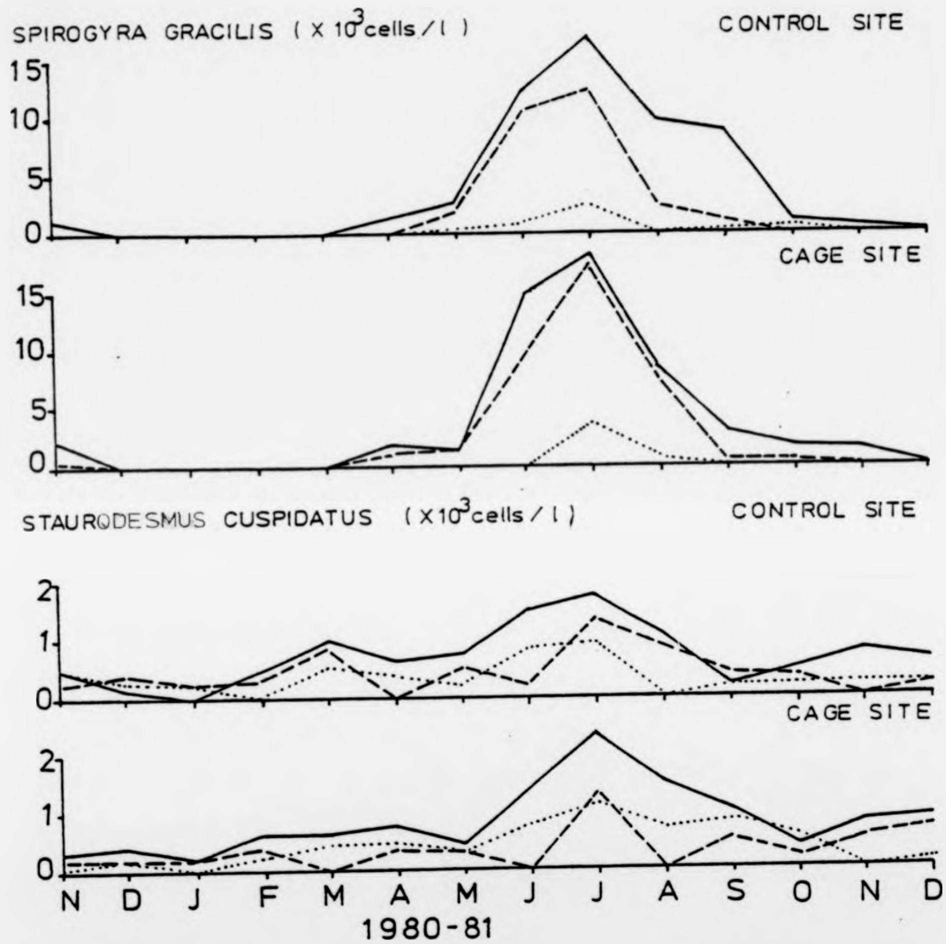

Fig.21: Seasonal changes in abundance of Spirogyra gracilis and Staurodesmus cuspidatus in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

(B) Bacillariophyceae: The seasonal variation of the group Bacillariophyceae and its vertical distribution in Loch Fad are shown in fig. 22. The Bacillariophycean population showed two marked peaks, a smaller one during April and the highest one during August at both sites at all depths. Abundance was mostly higher at all depths at the cage site compared with the control, but the difference was not statistically significant (Table 5).

The seasonal changes of Bacillariophyceans are shown in fig. 23 to fig. 26. Of the twelve species present in Loch Fad, only *Asterionella formosa*, *Cyclotella comta*, *Melosira italica-subarctica*, *Navicula viridis*, and *Stephanodiscus astraea* were present throughout the year. The population of *A. formosa* and *M. italica-subarctica* had two peaks, one during April and the other during August. *C. comta* attained a maximum during November-December, while *S. astraea*'s maximum was during September. *N. viridis* was at a maximum during July at both sites at all depths. *Gomphonema constrictum* was absent only during January and February and had a maximum during August. *Meridion circulare* and *Tabellaria fenestrata* were present from January and were at a maximum by April. *Synedra ulna* was present from February to July with the highest number during May. *Nitzschia linearis* was also at a maximum during May and was present from March to July. Both *Amphora ovalis* and *Cymbella ventricosa* showed their peaks during August.

(C) Dinophyceae: The group Dinophyceae was present from March till October. Seasonal fluctuations and vertical distribution are presented in fig. 27. The total population attained its highest peak during July. The difference in numbers of Dinophyceans

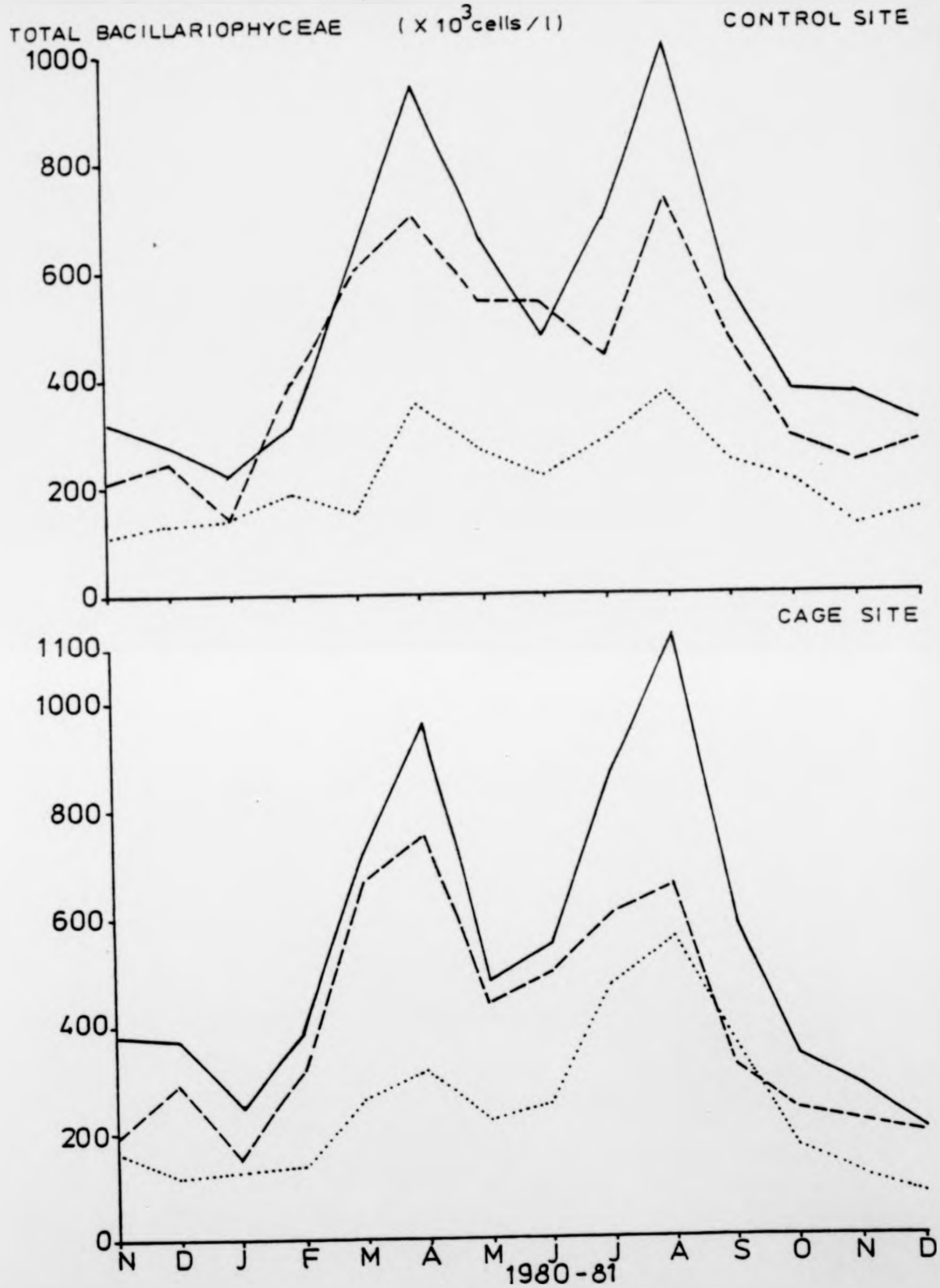

Fig.22: Seasonal changes in abundance of Bacillariophyceae in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

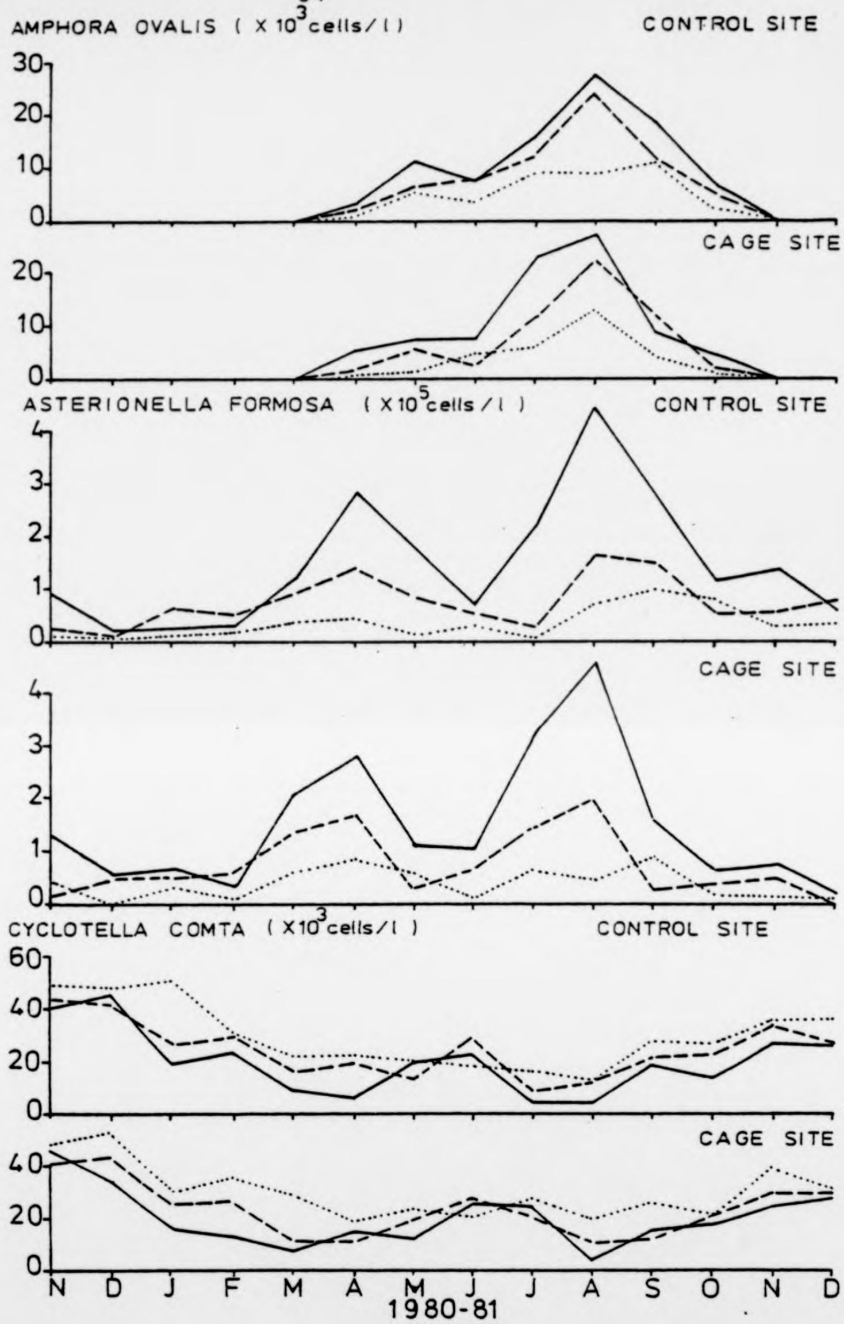

Fig.23: Seasonal changes in abundance of Amphora ovalis, Asterionella formosa, and Cyclotella comta, in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

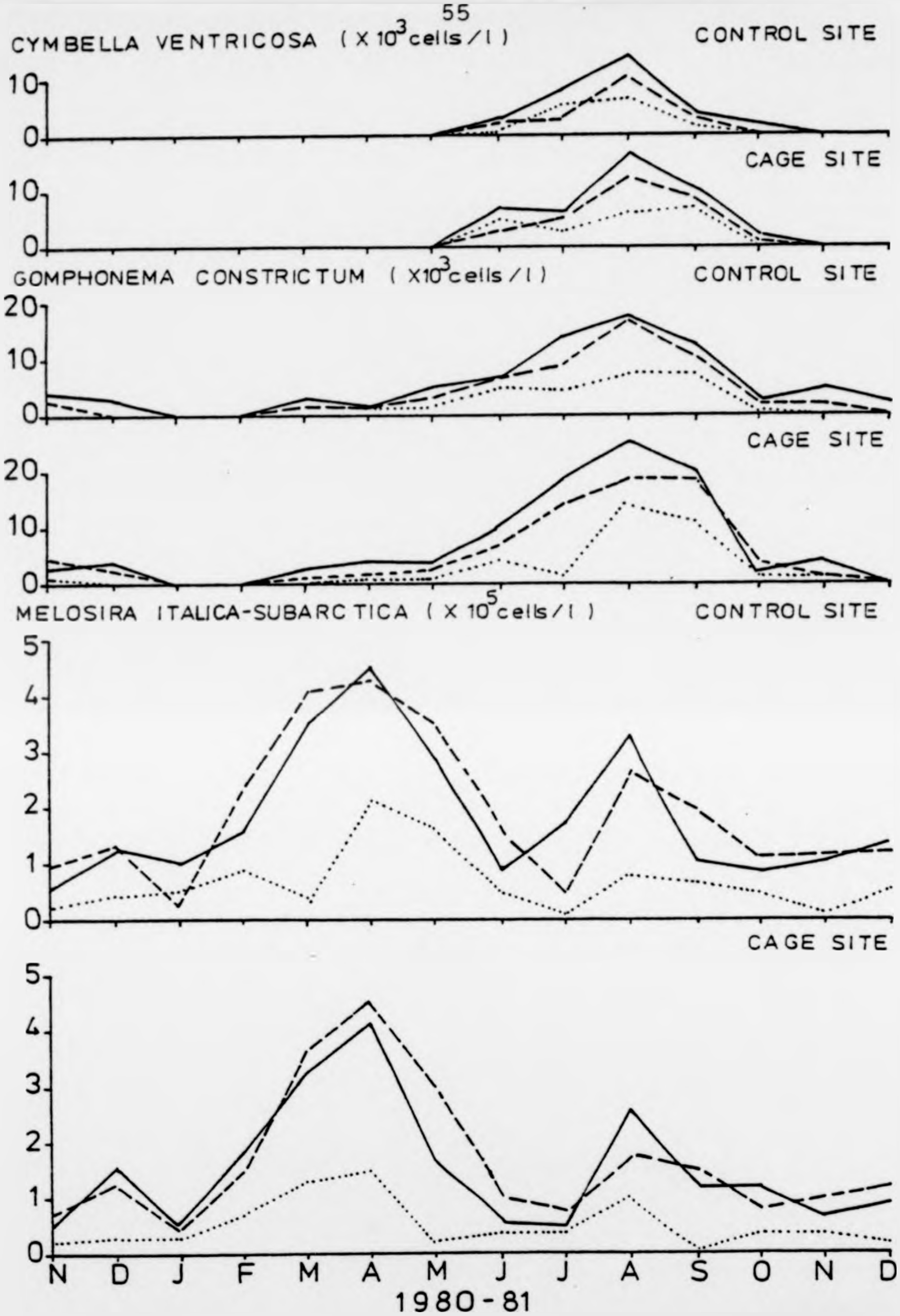

Fig.24: Seasonal changes in abundance of Cymbella ventricosa, Gomphonema constrictum, and Melosira italica-subarctica in Loch Fad at control and cage sites during 1980-81

(—— surface, - - - 4m, ... 9m)

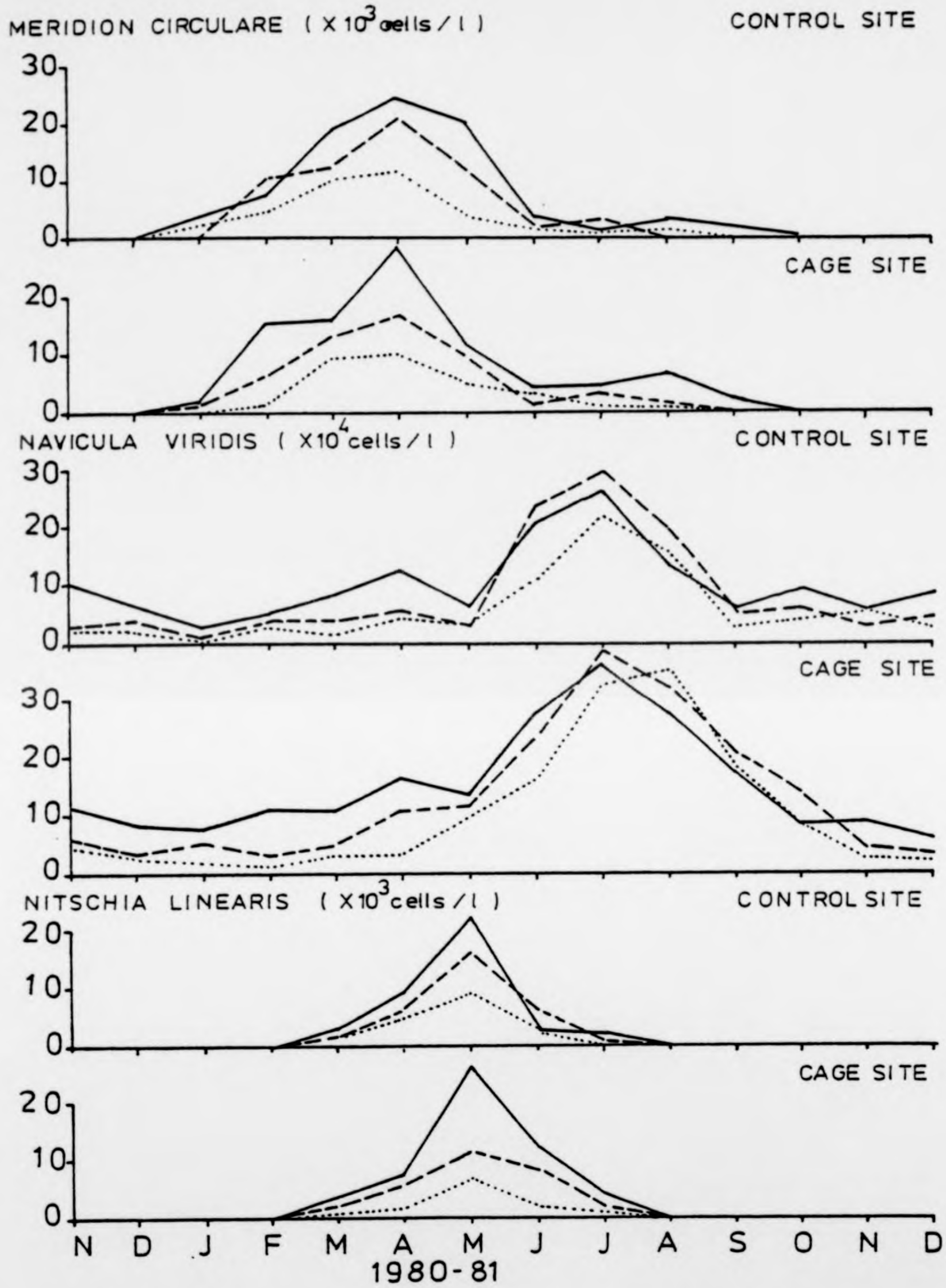

Fig.25: Seasonal changes in abundance of Meridion circulare, Navicula viridis, Nitzschia linearis in Loch Fad at control and cage sites during 1980-81

(—— surface, – – – 4m, ... 9m)

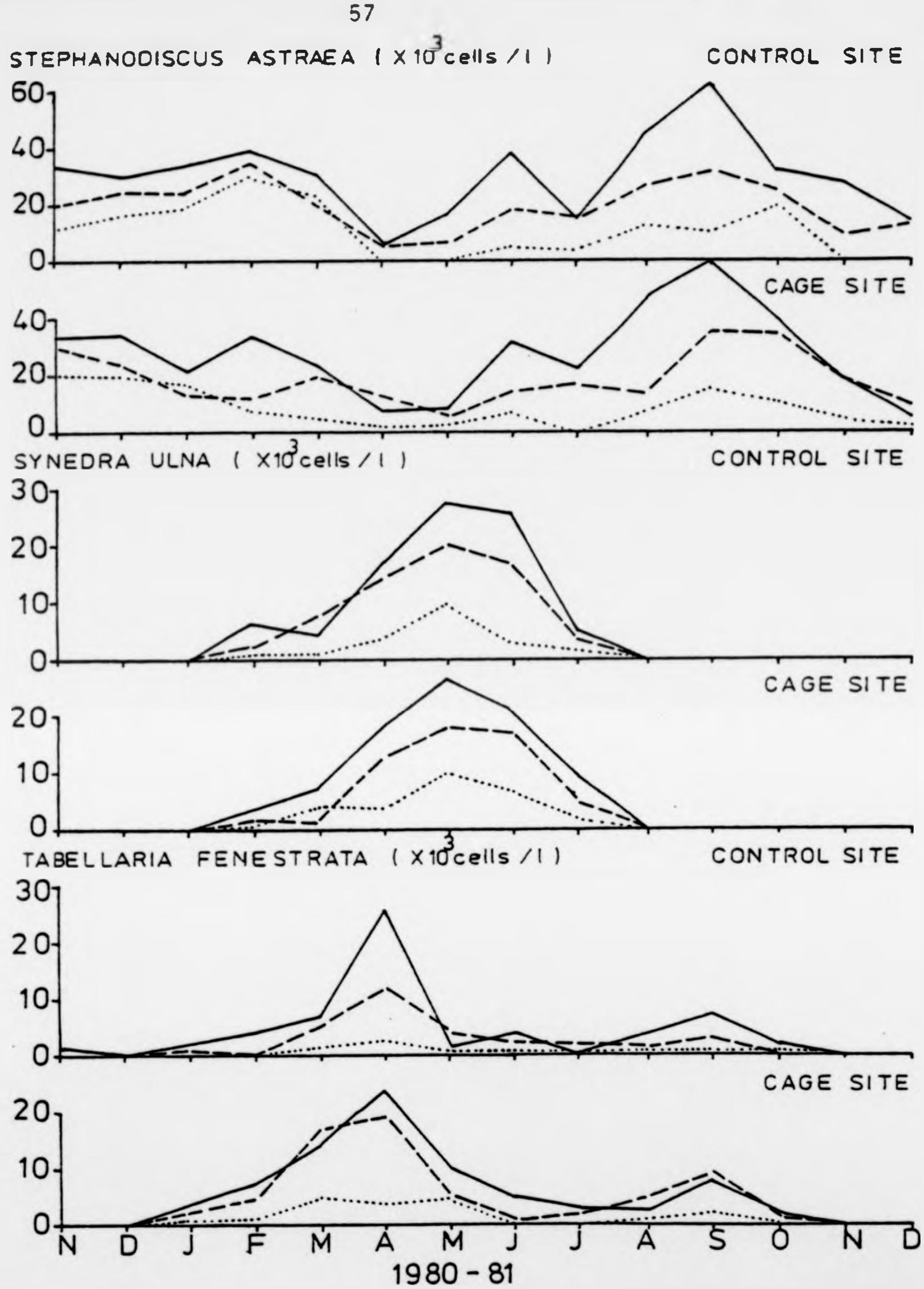

Fig.26: Seasonal changes in abundance of *Stephanodiscus astraea*, *Synedra ulna*, and *Tabellaria fenestrata* in Loch Fad at control and cage sites during 1980-81

(—— surface, ——— 4m, ... 9m)

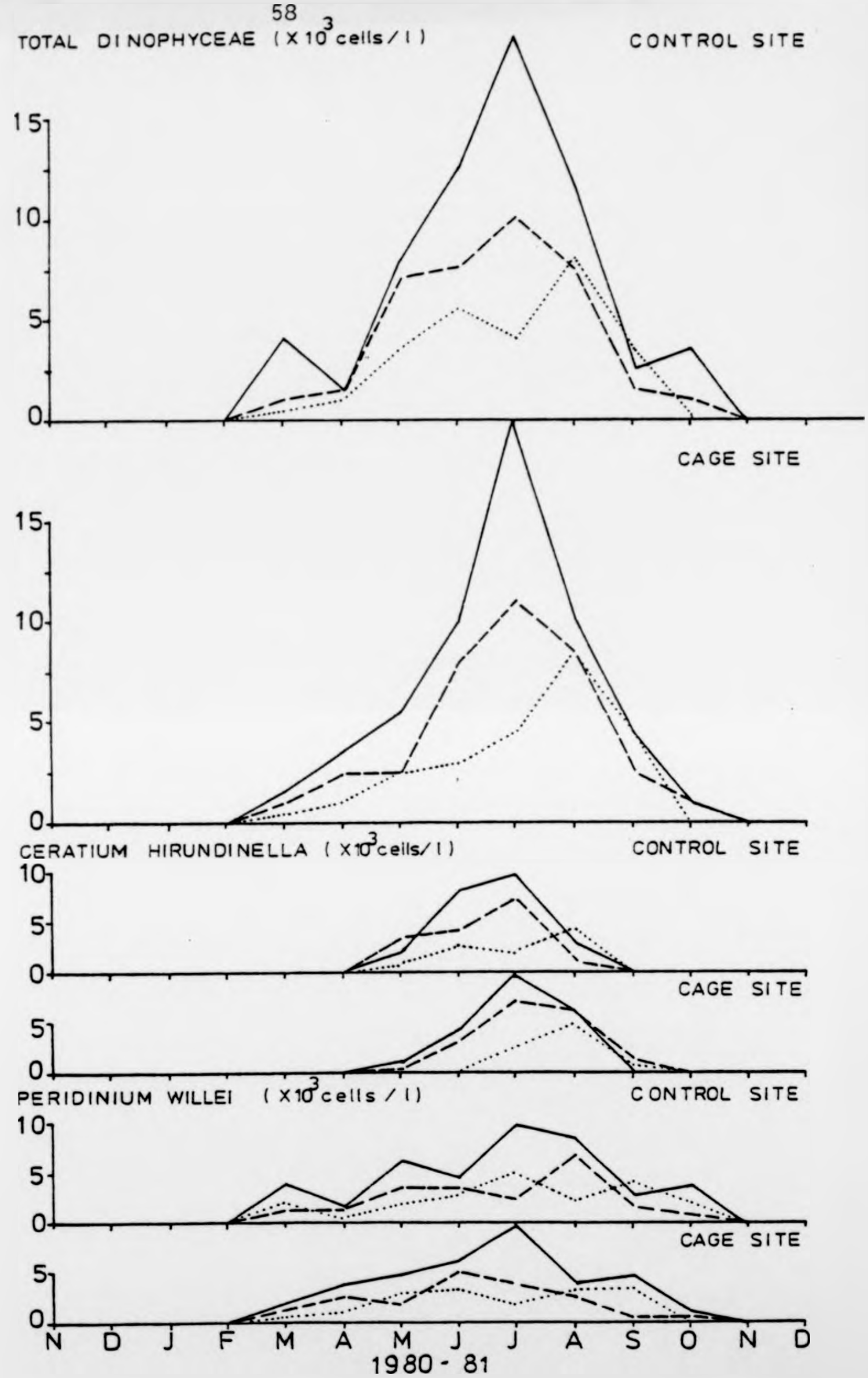

Fig.27: Seasonal changes in abundance of Dinophyceae, Ceratium hirundinella, Peridinium willei in Loch Fad at control and cage sites during 1980-81

(—— surface, – – – 4m, ... 9m)

present between cage site and control site was not significant (Table 5).

The group Dinophyceae was represented by only two species in Loch Fad, viz. Ceratium hirundinella and Peridinium willei. Their seasonal variation and vertical distribution is shown in fig. 27, both being maximum during July at both the sites.

(D) Cyanophyceae: The seasonal fluctuation and vertical distribution of Cyanophyceae is shown in fig. 28. Abundance was maximum during August at both sites, with higher numbers throughout the year at the cage site at all depths than at the control site. This difference, however, was significant only at the surface (Table 5).

Anabaena flos-aquae and Coelosphaerium naegelianum were present throughout the study period. A. flos-aquae was maximum during June-July, while C. naegelianum peaked during July-August (fig.29). Microcystis aeruginosa (fig.29) was absent for only two months at the beginning of the study, and its population had the highest peak during August at both sites. Oscillatoria agardhi was present from February to September with its highest peak during April, while Oscillatoria limosa was present from March to October, and was maximum during July (fig.30).

5.1.13.2 Relative abundance of phytoplankton:

(A) Chlorophyceae: Except during the first two months of the study when Chlorophyceae formed 7-23% at the control and 18-29% at the

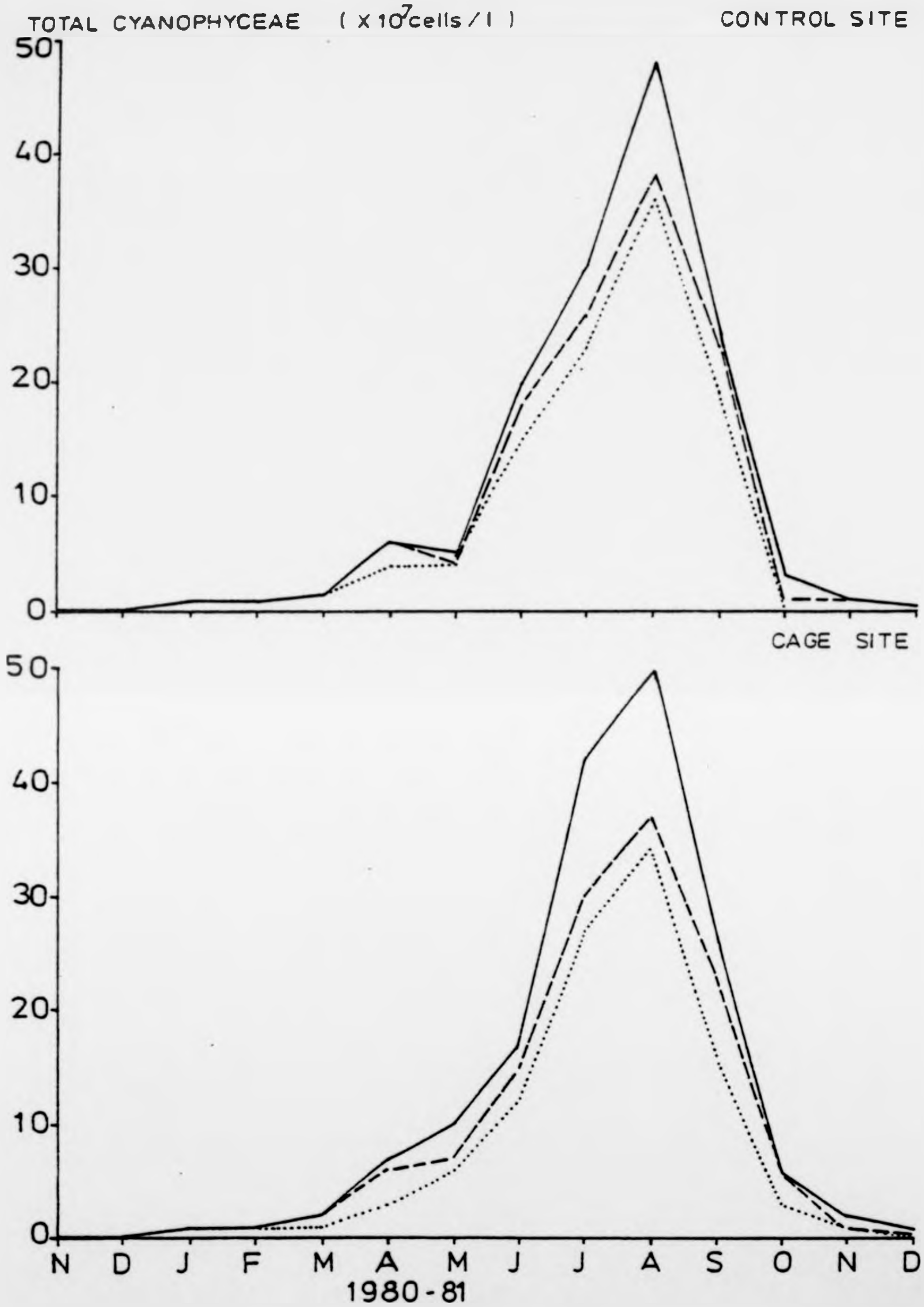

Fig.28: Seasonal changes in abundance of Cyanophyceae in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

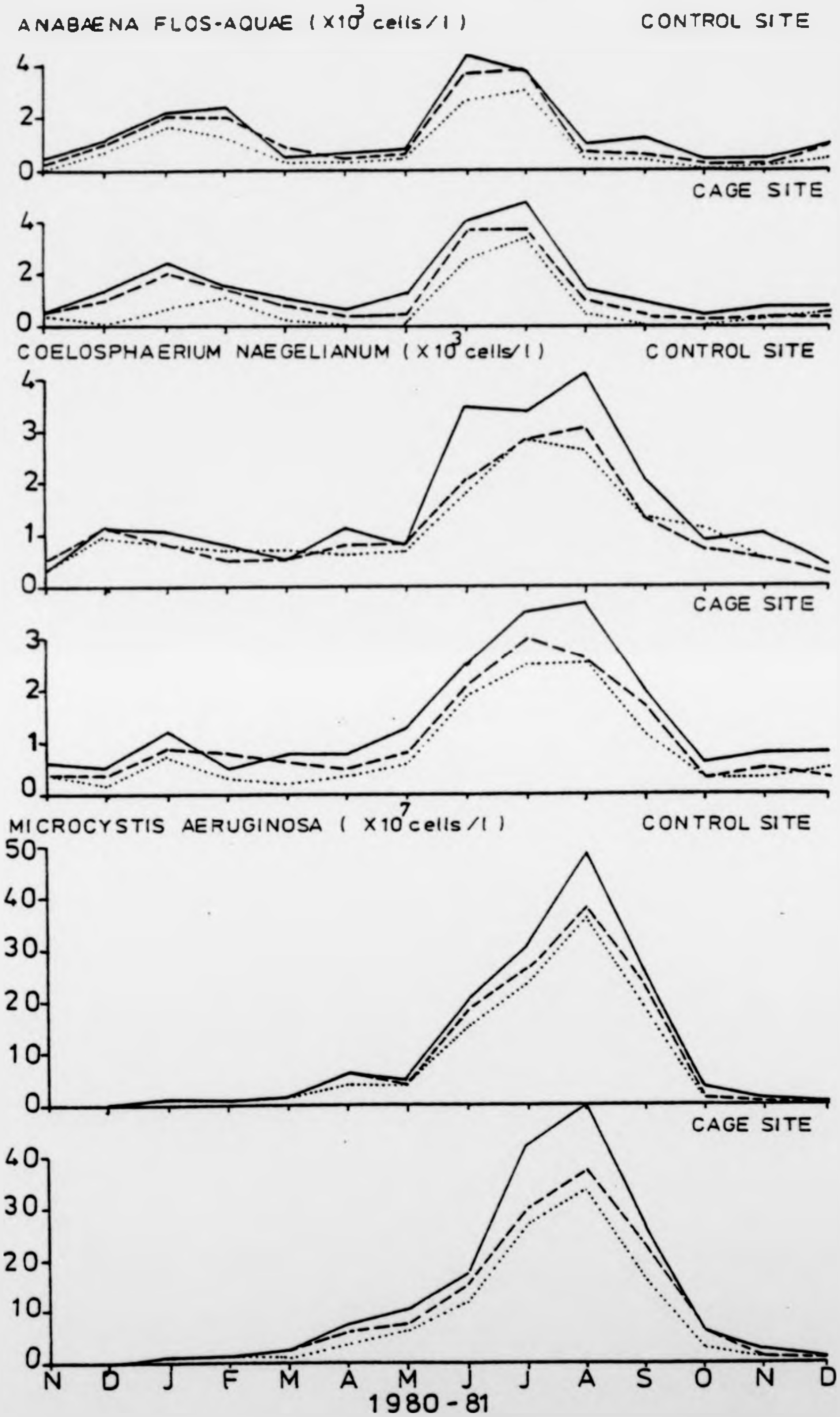

Fig.29: Seasonal changes in abundance of Anabaena flos-aquae, Coelosphaerium naegelianum and Microcystis aeruginosa in Loch Fad at control and cage sites during 1980-91

(___ surface, ---4m, ... 9m)

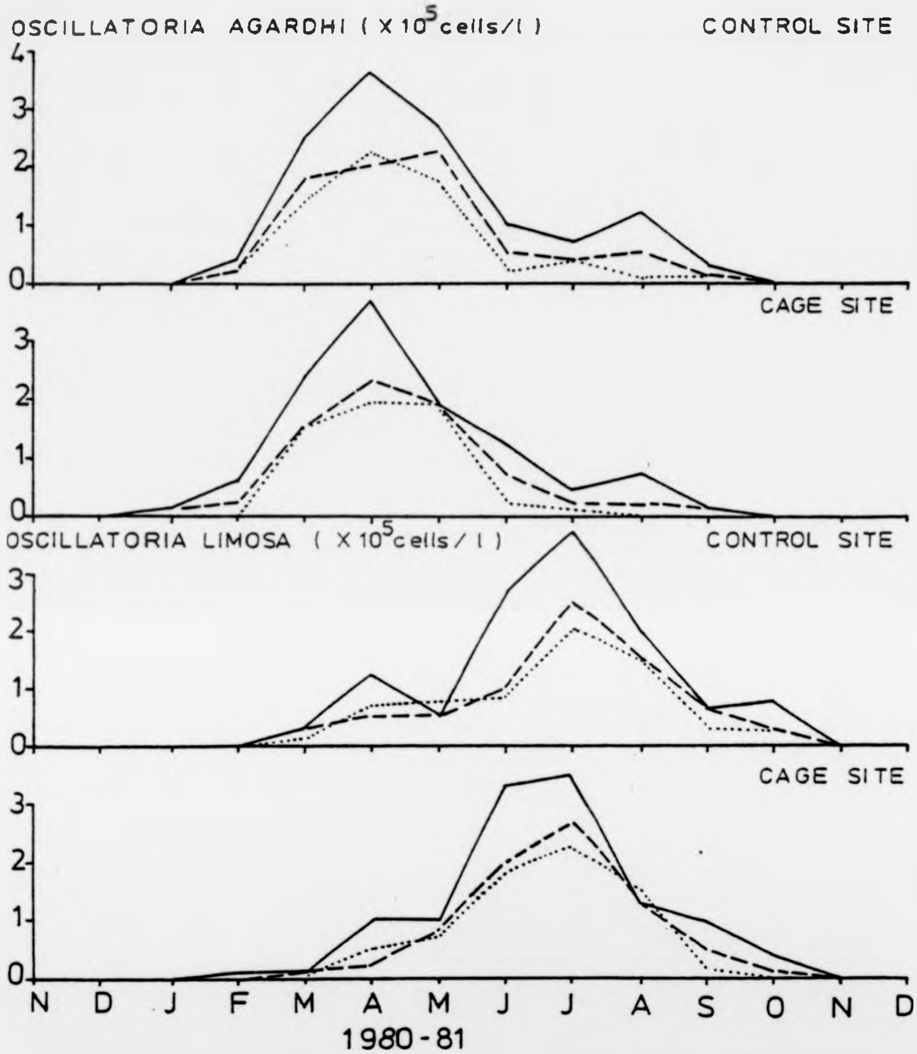

Fig.30: Seasonal changes in abundance of Oscillatoria agardhi and Oscillatoria limosa in Loch Fad at control and cage sites during 1980-81

(── surface, --- 4m, ... 9m)

cage site, this group contributed very little towards the total phytoplankton population during the rest of the period of study (fig.31).

(B) Bacillariophyceae: Of the five groups present in Loch Fad, Bacillariophyceae formed the bulk of the total phytoplankton (70-92%) during the start of the study (November and December '80) when other groups were low but from January to December '81 it formed less than 6% of the total phytoplankton at both sites (fig.31).

(C) Dinophyceae: The contribution of the group Dinophyceae towards the total phytoplankton population was negligible, with a maximum of .024%. Ceratium hirundinella was never more than .008% while Peridinium willei was maximum at .028%

(D) Cyanophyceae: The group Cyanophyceae was the most dominant group during most of the study period. In fact the peaks and troughs of the total phytoplankton were due to fluctuations in the Cyanophycean population. At the beginning of the study it formed a maximum of only 1.03%, but from January to December it contributed not less than 92% towards the total phytoplankton population, except during October-December at the control, and during December at the cage site, at 9m depth (fig. 31).

Microcystis aeruginosa was never below 92% when it was present and comprised even more than 99.5% of the total phytoplankton during its peak time. The contribution of other species of Cyanophyceae was very little, the maximum contribution throughout the study period being 0.57% for Anabaena flos-aquae, 0.62% for Coelosphaerium

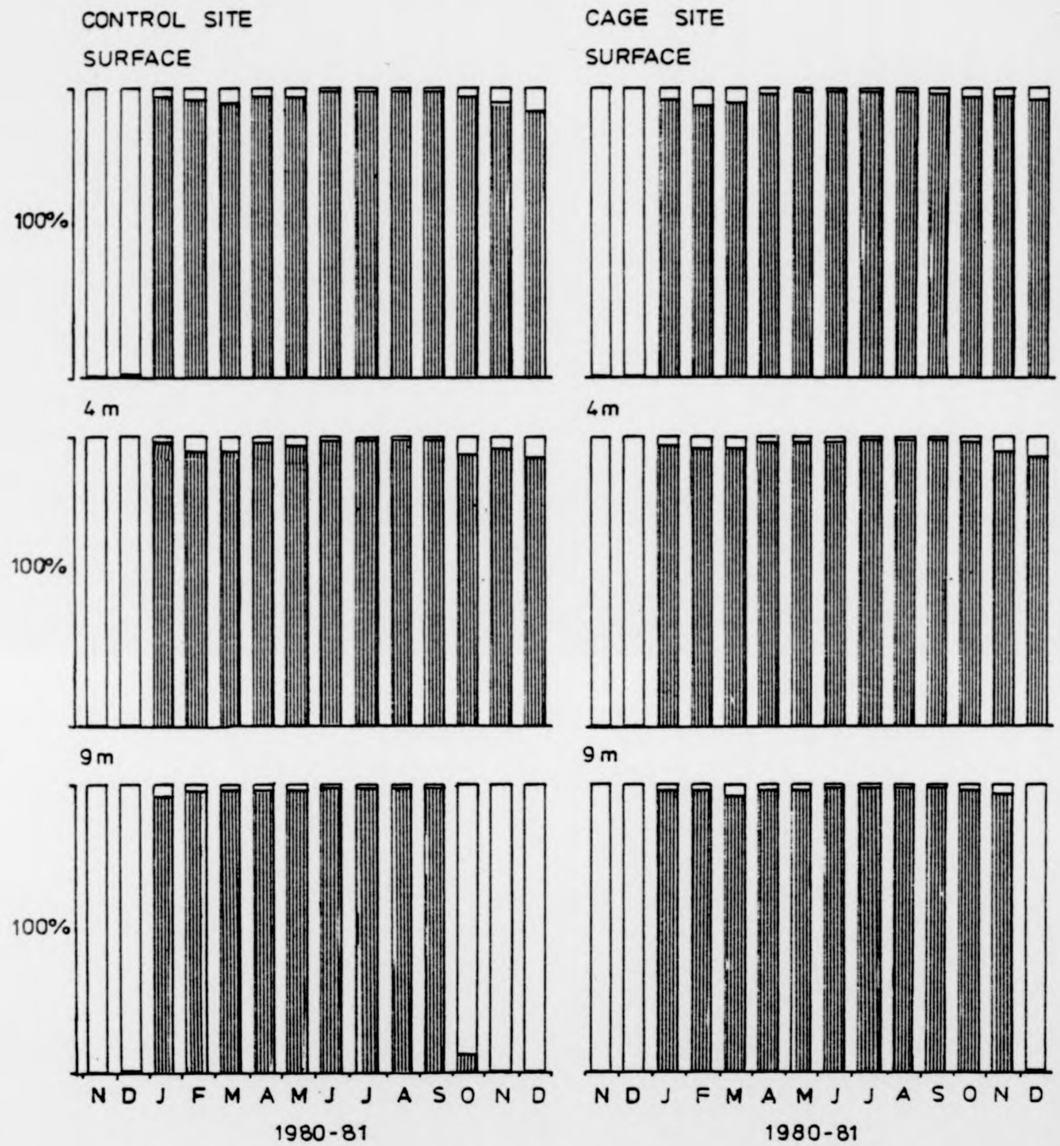

Fig. 31: Relative abundance of phytoplankton in Loch Fad at control and cage sites during 1980-81

(Cyanophyceae, Other phytoplankton)

naegelianum, 1.56% for Oscillatoria agardhi, and 0.28% for Oscillatoria limosa.

5.1.13.3 Summary of Species Succession of Phytoplankton:

During December to February, the diatoms Cyclotella comta and Stephanodiscus astraea were common together with Anabaena flos-aquae. From January Microcystis aeruginosa started appearing and remained the most dominant species until December, as has been stated earlier. By April and May, Oscillatoria agardhi with spring diatoms Melosira italica-subarctica, Asterionella formosa, Meridion circulare, Tabellaria fenestrata and Synedra ulna were at their maximum. By early summer Anabaena flos-aquae was high again with some chlorophyceans, including Sphaerocystis schroeteri. During mid summer most chlorophyceans were at their highest peak together with Navicula viridis and Oscillatoria limosa. Late summer was the time of maximum for the most abundant blue-green Microcystis aeruginosa, together with Coelosphaerium naegelianum. This was also the time when Pediastrum boryanum, Scenedesmus quadricaunda and diatoms, mainly Asterionella formosa, were maximum. By autumn, the diatom Stephanodiscus astraea was again high in number.

5.1.14 Zooplankton: The seasonal variations and vertical distribution of total zooplankton in Loch Fad are shown in fig. 32. Zooplankton numbers were mostly higher at 9m and were minimum at the surface at both sites. During the summer months (May-July) the numbers of zooplankton were highest at all depths. The mean total zooplankton population was higher at the cage site only at the surface but the

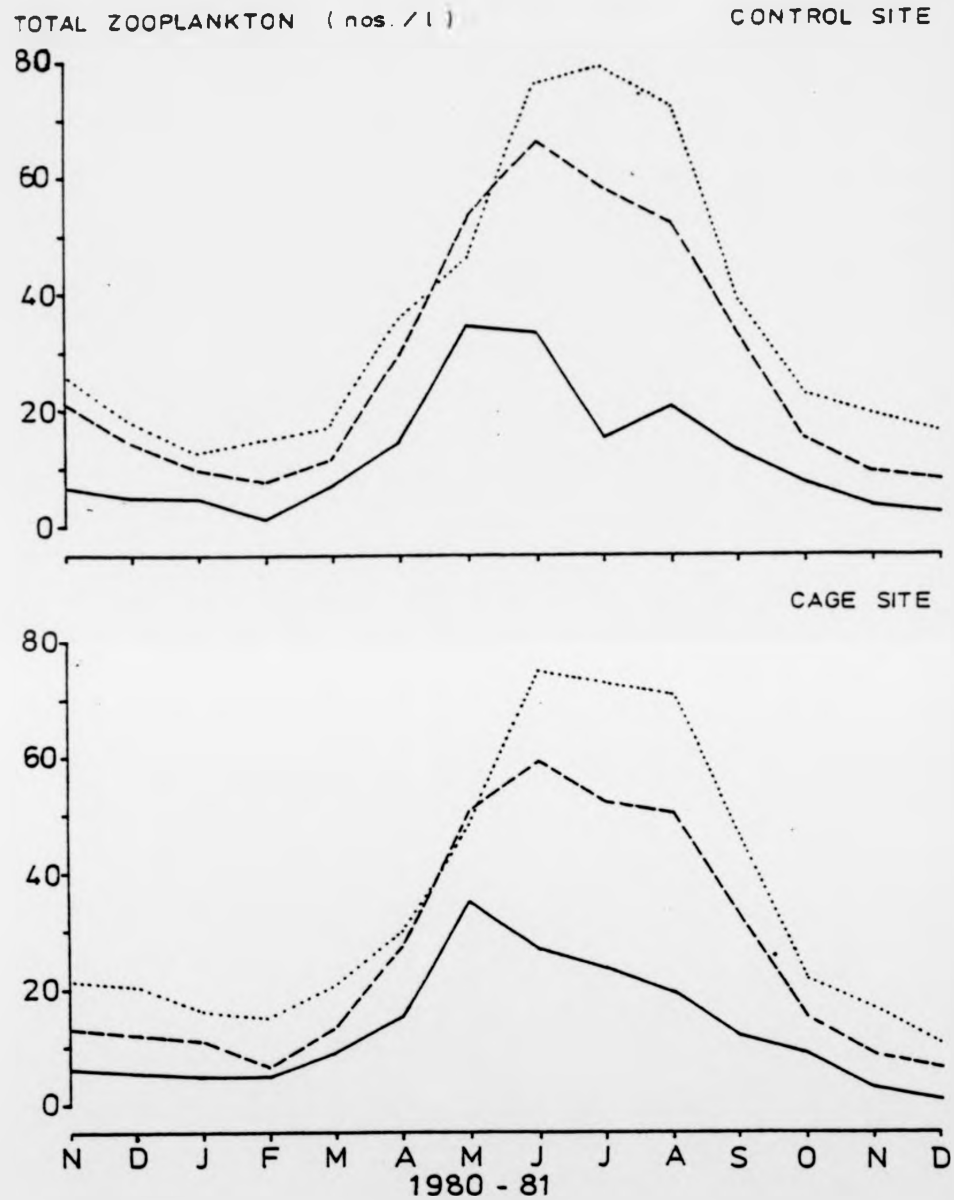

Fig. 32: Seasonal changes in abundance of total zooplankton in Loch Fad at control and cage sites during 1980-81

(—— surface, ---- 4m, ... 9m)

difference was not significant, while the population was higher at the control site at 4m and 9m depths, the difference at 4m being significant (Table 6).

Total zooplankton was positively correlated with the total phytoplankton and the correlation was highly significant (Table 1) at both sites.

A total of 11 species belonging to Cladocera, Copepoda, and Rotifera were present in Loch Fad and are listed in Table 7.

5.1.14.1 Seasonal trend of zooplankton

(A) Cladocera: The seasonal variation and vertical distribution of Cladocera are shown in fig.33. In vertical distribution the Cladocera were mostly more abundant in daytime samples at 4m than at other depths. The population of Cladocera reached its highest peak during May-June at both the sites. Cladoceran population was higher at the control site at all depths than at the cage site, but the difference was not significant (Table 6).

The group comprised 3 species in Loch Fad of which *Bosmina longirostris* and *Daphnia longispina* were present from March to August. *B. longirostris* reached its maximum during May and *D. longispina* during June. *Chydorus sphaericus* was absent only during December to February and had its highest peak during August (fig. 34)

(B) Copepoda: The seasonal fluctuation and the vertical distribution of Copepoda are shown in fig.35. The group Copepoda reached a maximum during August and were mostly higher in number at 9m and

Table 6: Results of the t-test for paired comparison of Zooplankton at each depth between control and cage site in Loch Fad over 14 months

	Depths	Average recorded at control	Average recorded at cage	t_s
Total Zooplankton (No./l)	Surface	11.71	12.04	.212
	4m	27.25	25.54	2.950*
	9m	35.25	34.68	.387
Cladocera (No./l)	Surface	9.38	8.13	1.453
	4m	13.30	11.75	2.034
	9m	10.75	10.35	.647
Copepoda (No./l)	Surface	3.32	3.25	1.580
	4m	6.93	6.75	.325
	9m	11.21	10.39	1.083
Rotifera (No./l)	Surface	3.04	4.18	2.599*
	4m	10.82	10.39	1.112
	9m	16.36	16.89	.825

where * P <.05, ** P <.01, *** P <.001

Table 7: Species of Zooplankton recorded in Loch Fad during 1980-81

CLADOCERA

Bosmina longirostris (O.F. Muler) s.str.

Chydorus sphaericus (O.F. Muler)

Daphnia longispina O.F. Muler

COPEPODA

Cyclops abyssorum Sars

Diaptomus gracilis Sars

ROTIFERA

Ascomorpha ovalis Carlin

Conochilus hippocrepis (Schrank)

Filinia terminalis (Plate)

Kellicottia longispina (Kellicot)

Keratella cochlearis (Gosse)

Trichocerca capucina (Wierzejski)

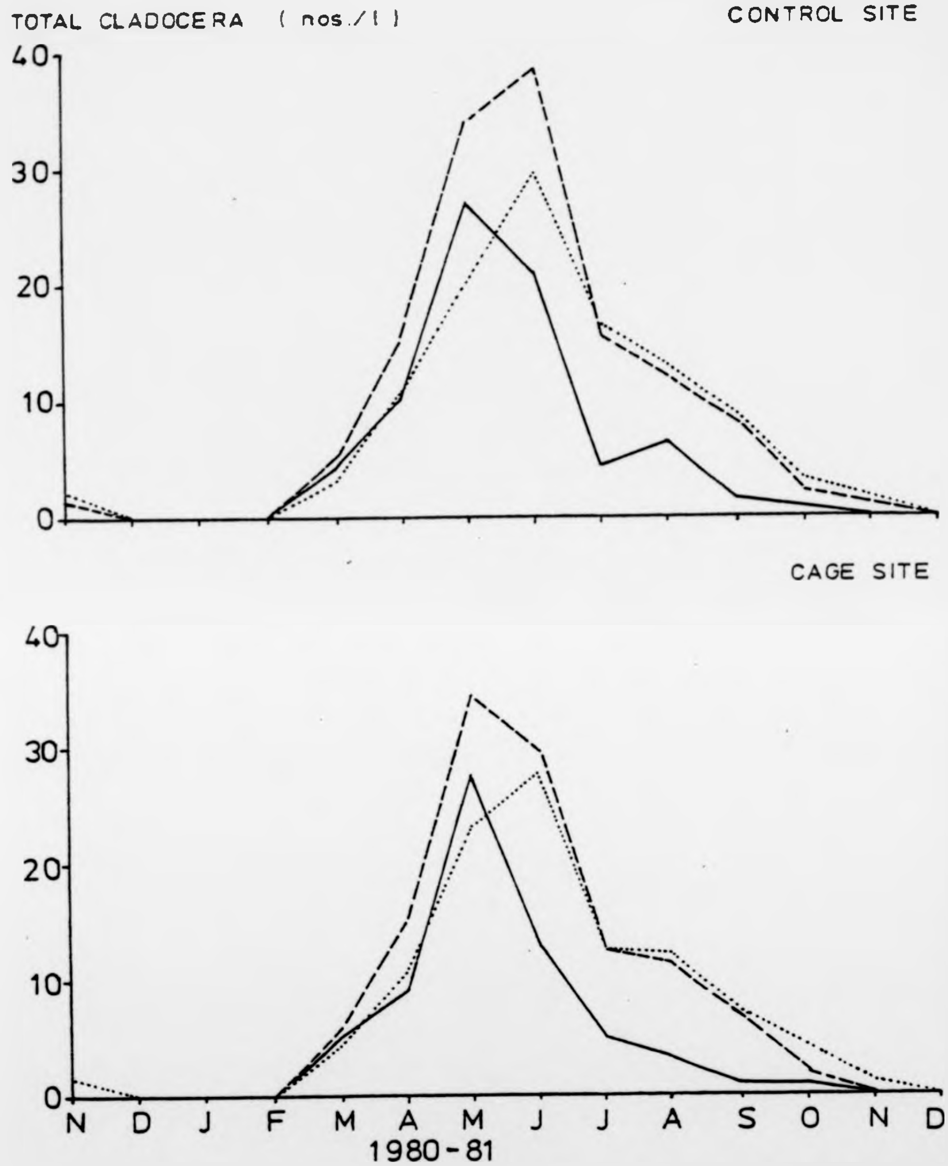

Fig.33: Seasonal changes in abundance of Cladocera in Loch Fad at control and cage sites during 1980-81

(—— surface, – – – 4m, ... 9m)

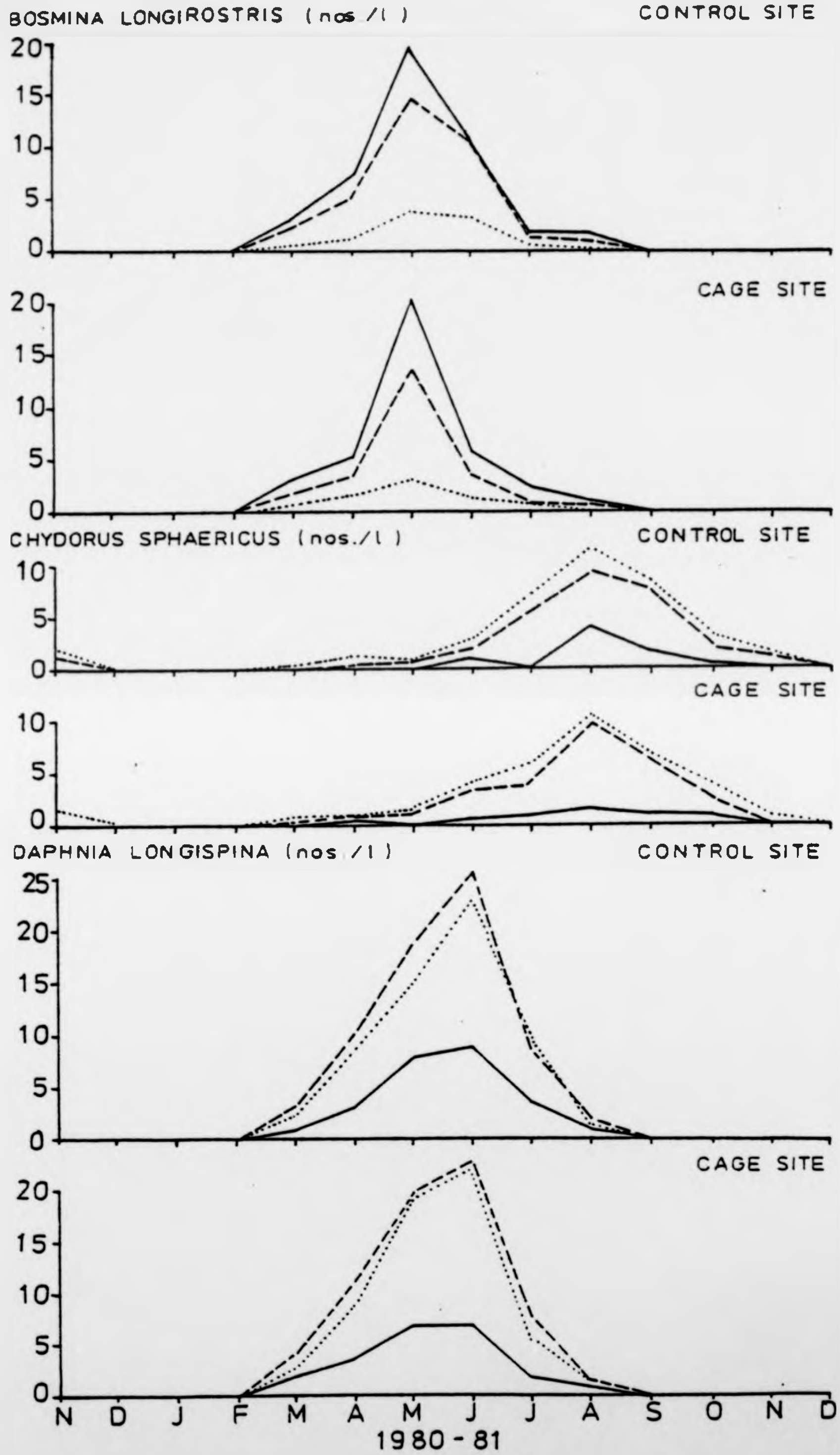

Fig.34: Seasonal changes in abundance of Bosmina longirostris, Chydorus sphaericus and Daphnia longispina in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

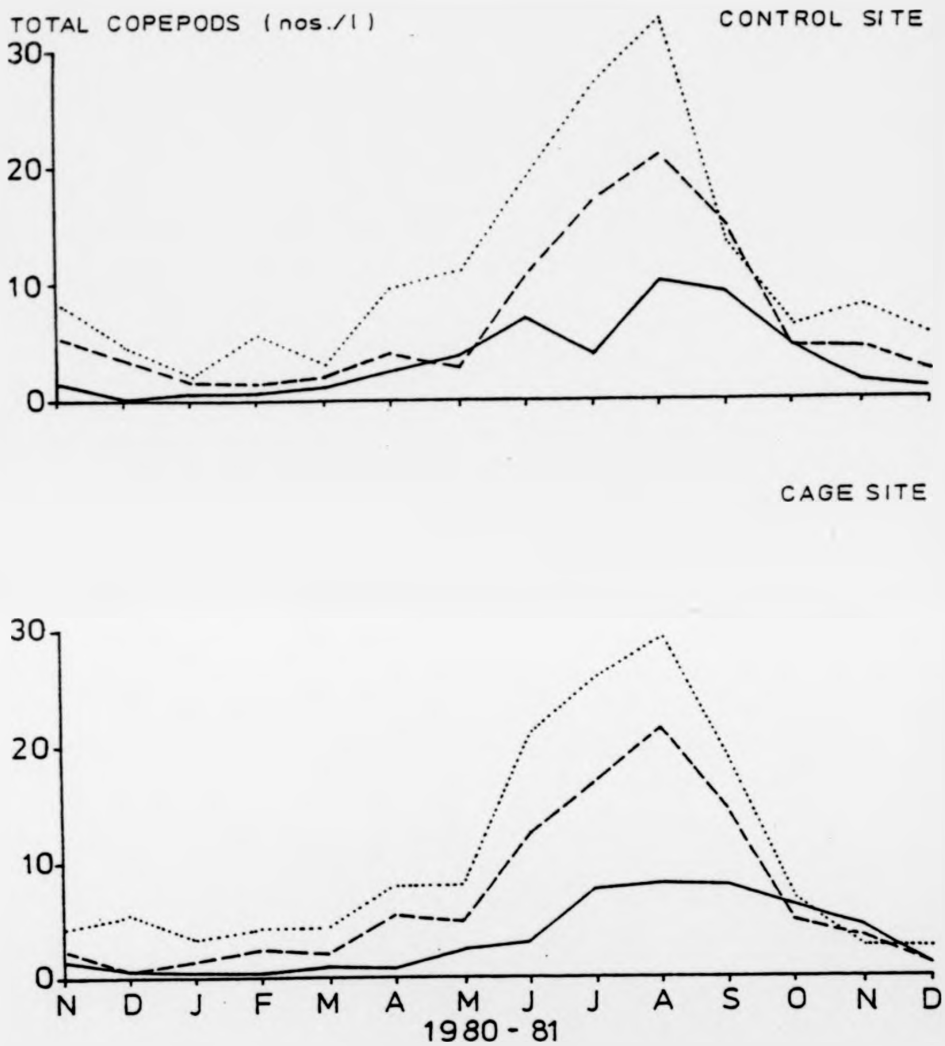

Fig. 35: Seasonal changes in abundance of Copepods in Loch Fad at control and cage sites during 1980-81

(—— surface, ––– 4m, ... 9m)

minimum at the surface throughout the study period at both the sites. Though the number of copepods was higher at the control site at all depths, this difference was not significant (Table 6).

The representatives of copepoda were Cyclops abyssorum and Diaptomus gracilis only, both of which were present throughout the study period and were more numerous at 9m than at other depths. Cyclops abyssorum had its highest peak during August and Daiptomus gracilis during June-July (fig. 36).

(C) Rotifera: The seasonal fluctuation and vertical distribution of the group Rotifera are shown in fig. 37. Rotiferan numbers increased with depth. At the cage site Rotifera were more abundant at the surface and 9m compared with the control site, but the difference was significant only at the surface (Table 6).

All Rotifera except Filinia terminalis were present throughout the study period. Ascomorpha ovalis, Conochilus hippocrepis, Kellicottia longispina, Keratella cochlearis, Trichocerca capucina, had their peak during June-August, while Filinia terminalis was at its maximum during December (fig. 38).

5.1.14.2 Relative abundance of Zooplankton:

(A) Cladocera: As a percentage of total zooplankton, Cladocera were dominant in the upper layers during March to June at both sites, while at the bottom it was dominant only during May-June, as shown in fig. 39. Daphnia longispina comprised more of the total zooplankton

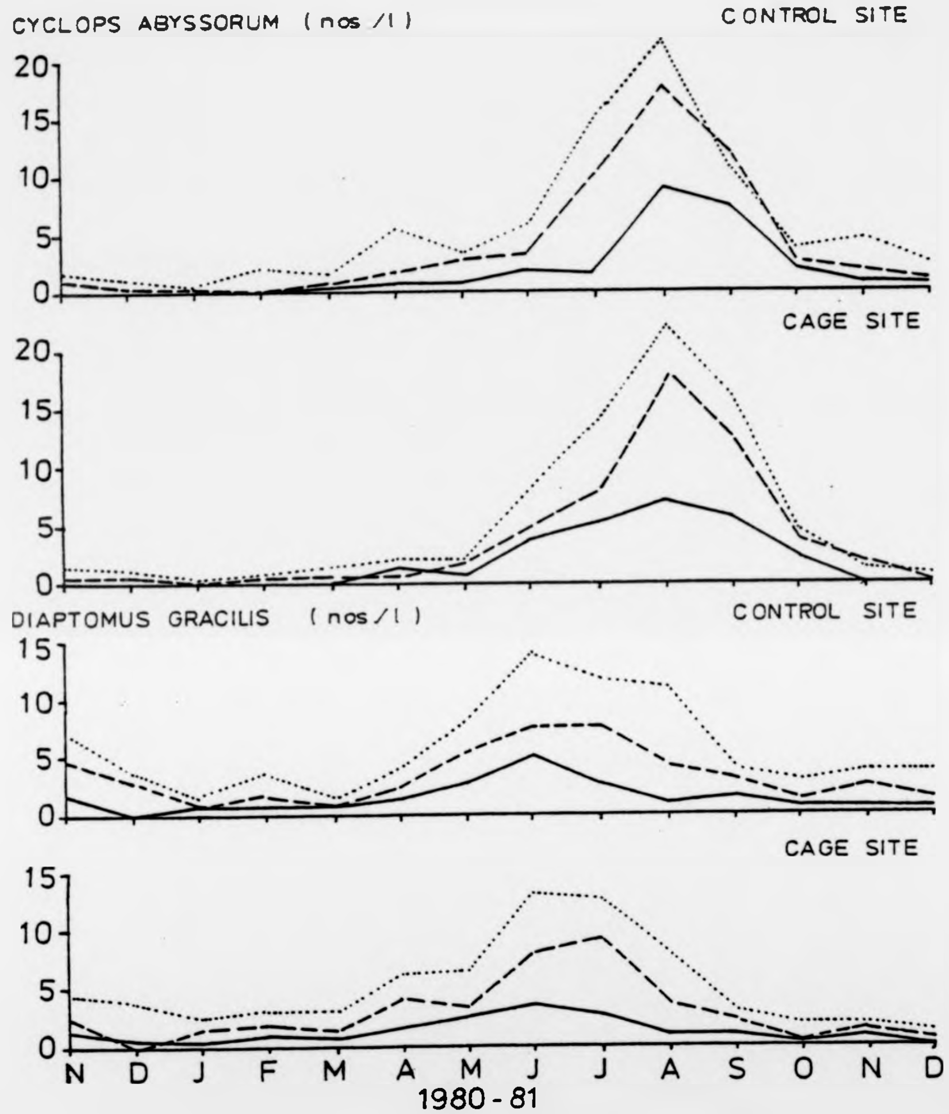

Fig.36: Seasonal changes in abundance of <u>Cyclops abyssorum</u> and <u>Diaptomus gracilis</u> in Loch Fad at control and cage sites during 1980-81

(___ surface, --- 4m, ... 9m)

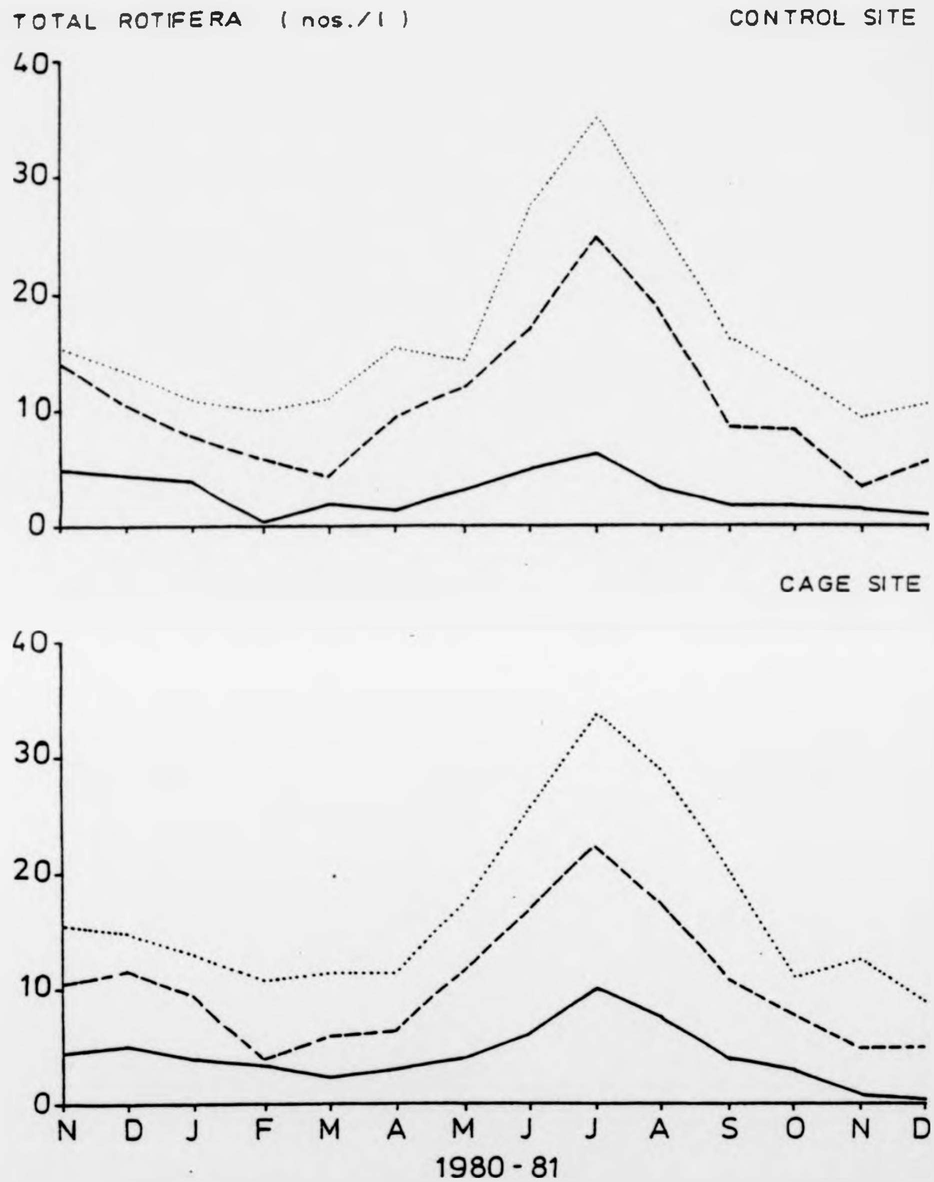

Fig.37: Seasonal changes in abundance of Rotifera in Loch Fad at control and cage sites during 1980-81

(___ surface, ___ 4m, ... 9m)

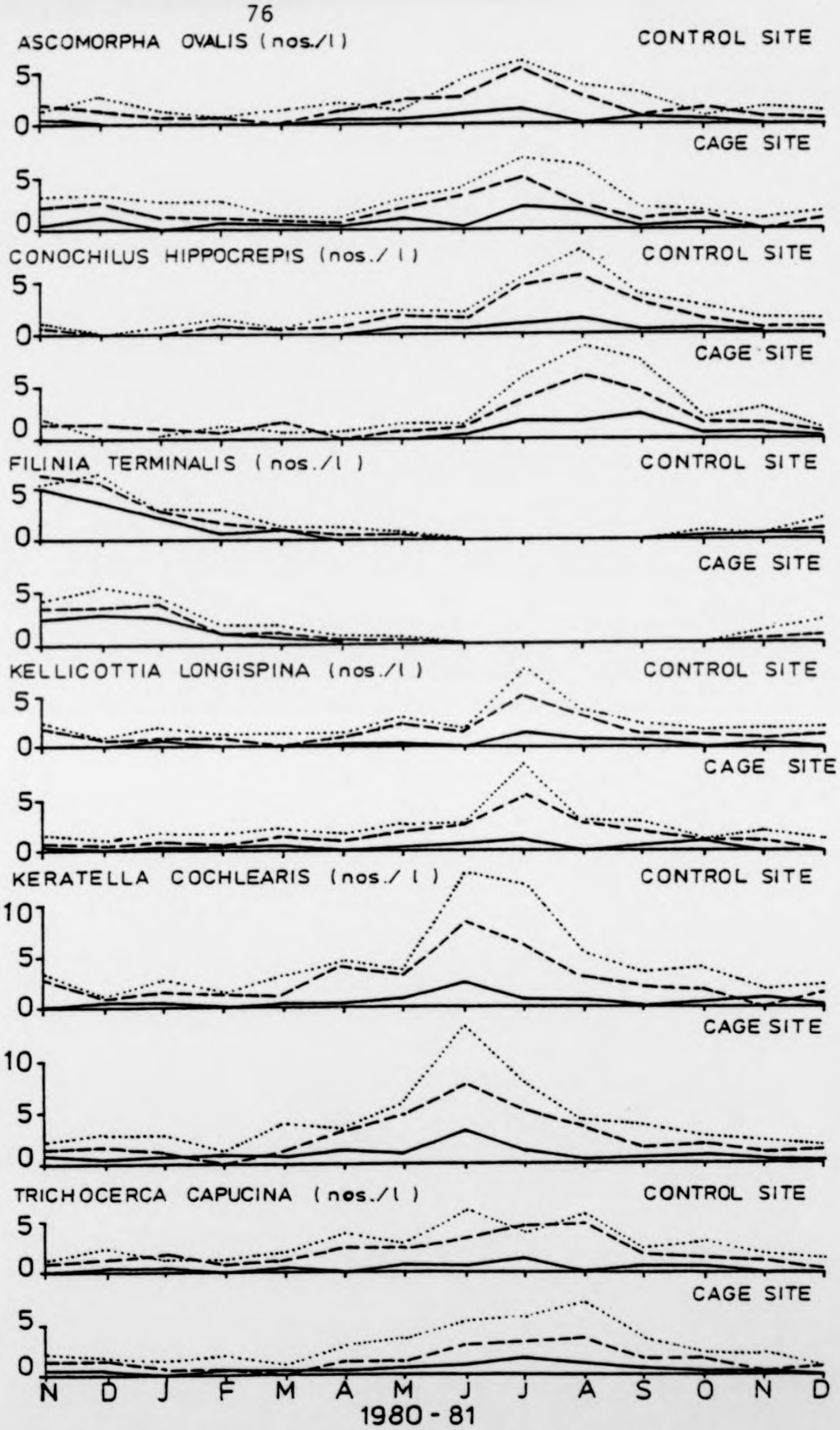

Fig.38: Seasonal changes in abundance of Ascomorpha ovalis, Conochilus hippocrepis, Filinia terminalis, Kellicottia longispina, Keratella cochlearis and Trichocerca capucina in Loch Fad at control and cage sites during 1980-91

(—— surface, ---- 4m, ... 9m)

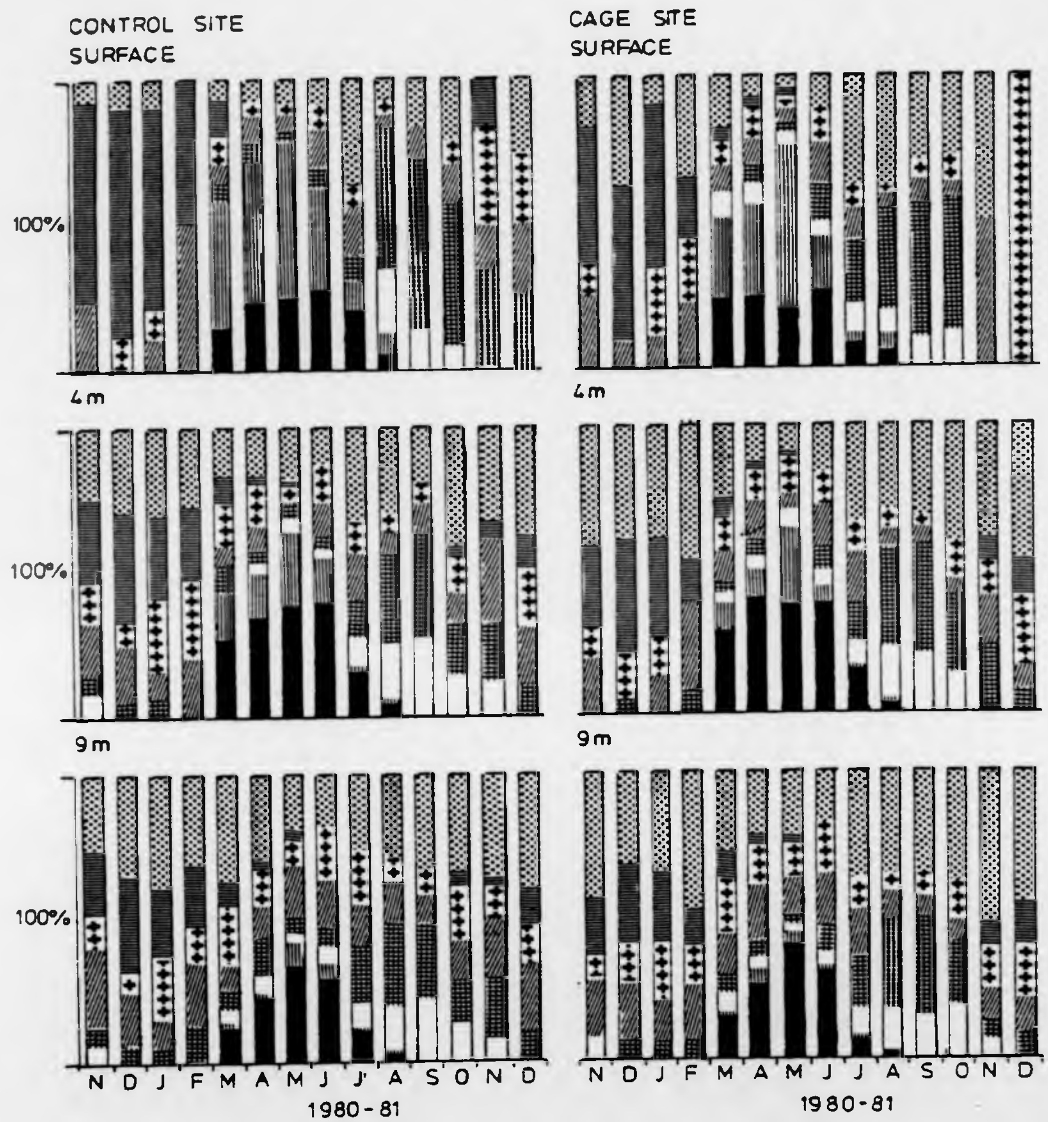

Fig.39: Relative abundance of zooplankton in Loch Fad at control and cage sites during 1980-81

(■ Daphnia longispina, ▥ Bosmina longirostris, □ Chydorus sphaericus, ▦ Cyclops abyssorum, ▨ Diaptomus gracilis, ⊞ Keratella cochlearis, ▤ Filinia terminalis, ⊡ other rotifers) at 4m depth than at other depths, with a maximum of 39% at both sites. Bosmina longirostris was the most abundant among zooplankton during March to June at the surface, reaching a maximum in May of 56% at the control and 59% at the cage site (fig. 39). Chydorus sphaericus reached a maximum in September of 25% at the control site and 20% at the cage site, when it was the only cladoceran present.

(B) Copepoda: The histograms of percent composition show that Copepoda dominated the zooplankton only during August to November in the upper layers, and during August at 9m depth as shown in fig. 39. During August to October, Cyclops abyssorum was the dominant species among the zooplanktons at all depths and at both sites, maximum being 60% at control site and 48% at the cage site (fig. 39). Fig. 39 shows that Diaptomus gracilis formed 5-50% of total zooplankton at both sites during the period of study.

(C) Rotifera: Fig. 39 shows that the group Rotifera was abundant in the zooplankton throughout the year at 9m, but at 4m and surface it was abundant only during November to February. Ascomorpha ovalis reached a maximum of 14-21% of total zooplankton. Conochilus hippocrepis and Trichocerca capucina comprised a maximum of 25% as shown in fig. 39. Filinia terminalis was dominant over other zooplankton during November to February, reaching a maximum of 56% to 78%. Keratella cochlearis reached a maximum of 33% and 100% at control and cage sites respectively.

5.1.15 Periphyton: The attached algae on the artificial surface (wooden blocks) showed seasonal fluctuations and decreased with depth (fig.40). The periphytic population started increasing from the

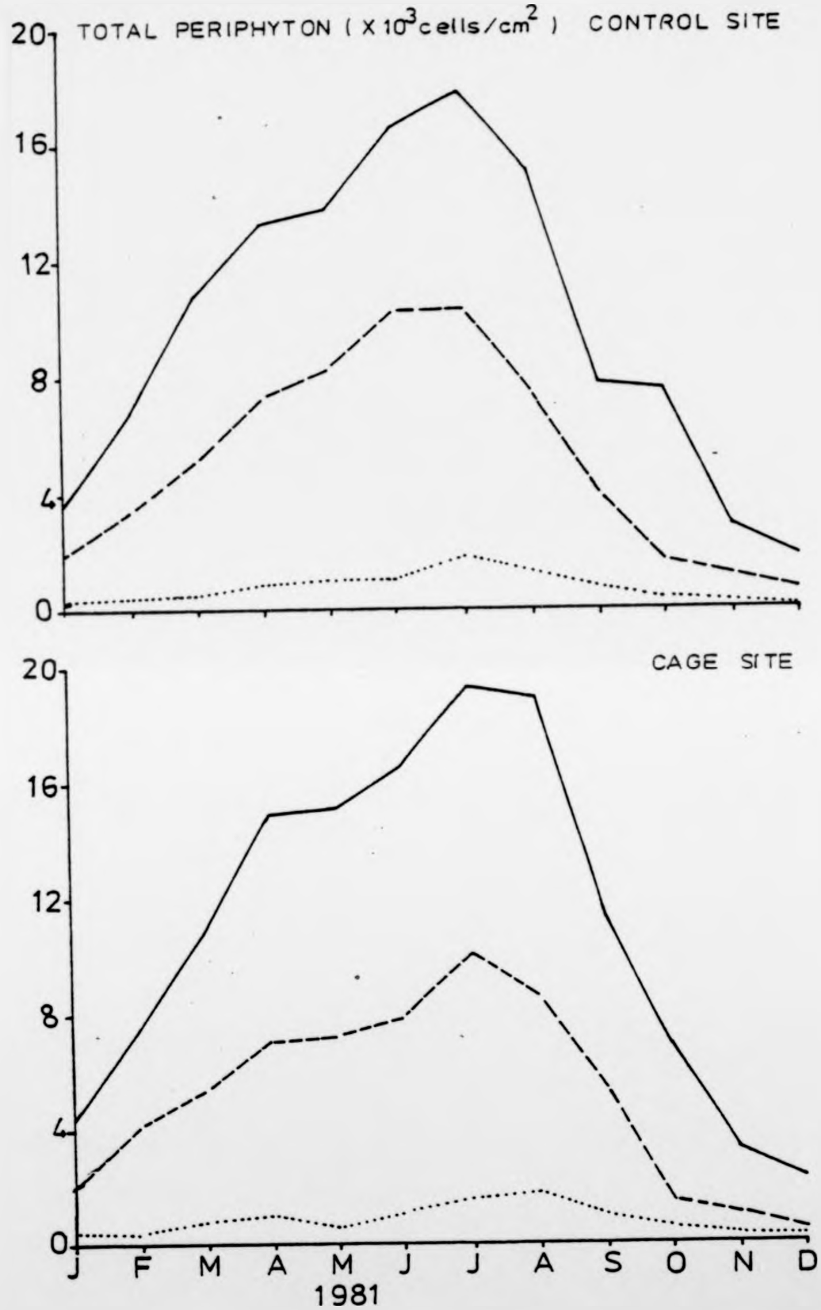

Fig.40: Seasonal changes in abundance of total periphyton in Loch Fad at control and cage sites during 1980-81

(— surface, --- 4m, ... 9m)

start of the study, reaching a maximum during July at both sites. Their numbers were mostly higher at the cage site at all depths than at the control, but the difference was significant only at the surface (Table 8).

Periphyton was positively correlated with the total phytoplankton population, the correlation coefficient being significant (Table 2).

The periphytic population in Loch Fad comprised 22 species representing Chlorophyceae, Bacillariophyceae and Cyanophyceae, which are listed in Table 9.

5.1.15.1 Seasonal trends of periphyton:

(A) Chlorophyceae: The group Chlorophyceae were at a maximum during June-July, as shown in fig. 41. The number was higher at all depths at the cage site, but the difference was significant only at the surface (Table 8).

The seasonal changes of individual chlorophycean species are shown in fig. 41 and fig. 42. Of the seven species, only *Pediastrum boryanum* and *Pediastrum duplex* were present throughout the study period and were at a maximum during June and July-August, respectively. *Ankistrodesmus falcatus* was present from February to September with a maximum during June, while *Scenedesmus quadricauda* and *Spirogyra gracilis* appeared by March and reached a maximum by June-July. *Scenedesmus abundans* and *Closterium Kutzingii* were present from May with peaks during June and August respectively.

Table 8: Results of the t-test for paired comparison of periphyton at each depth between control and cage site in Loch Fad over 12 months.

	Depths	Average recorded at control site	Average recorded at cage site	ts
Total periphytic algae ($\log_{10}$ no./cm^2)	Surface 4m 9m	3.992 3.709 2.897	4.039 3.711 2.926	2.959** 0.528 0.869
Chlorophyceae ($\log_{10}$ no./cm^2)	Surface 4m 9m	3.164 2.950 1.491	3.245 2.959 1.531	2.790* 0.109 0.561
Bacillariophyceae ($\log_{10}$ no./cm^2)	Surface 4m 9m	3.730 3.435 2.816	3.768 3.499 2.848	1.622 0.750 0.555
Cyanophyceae ($\log_{10}$ no./cm^2)	Surface 4m 9m	3.475 3.178 2.017	3.521 3.185 2.817	1.588 0.244 1.593
Fungi ($\log_{10}$ no./cm^2)	Surface 4m 9m	3.301 3.219 3.176	3.403 3.315 3.292	3.614** 3.007** 4.098**

where * $P < .05$, ** $P < .01$

Table 9: Periphytic algae recorded in Loch Fad during 1980-81

CHLOROPHYCEAE

Ankistrodesmus falcatus (Corda) Ralfs

Closterium Kutzingii Breb.

Pediastrum boryanum (Turp.) Menegh.

Pediastrum duplex Meyen

Scenedesmus abundans (Kirchn.) Chod.

Scenedesmus quadricauda (Turp.) Breb.

Spirogyra gracilis (Hass.) Kutz.

BACILLARIOPHYCEAE

Amphora ovalis Kutz.

Asterionella formosa Hass.

Cyclotella comta (Ehr.) Kutz.

Cymbella ventricosa Agardh

Gomphonema constrictum Ehrenb.

Melosira italica (Ehrenb.) Kutz *subarctica* Mull

Meridion circulare (Greville) Agardh

Navicula viridis Kutz

Nitzschia linearis (Ag.) W.Sm.

Stephanodiscus astraea (Ehr.) Grunow

Synedra ulna (Nitzsch.) Ehrenb.

Tabellaria fenestrata (Lyngb.) Kutz.

CYANOPHYCEAE

Anabaena flos-aquae (Lyngb.) Breb.

Oscillatoria agardhi Gomond

Oscillatoria limosa Ag.

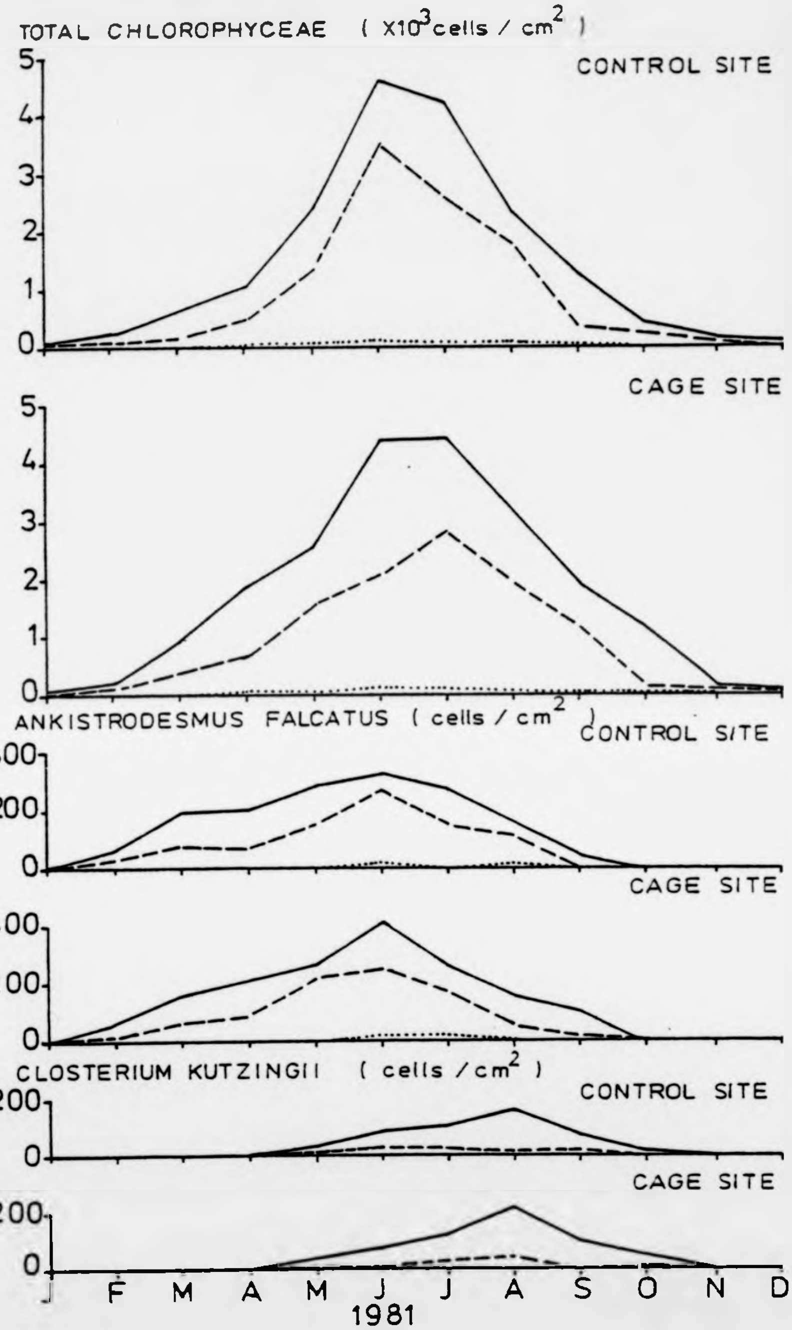

Fig. 41: Seasonal changes in abundance of total Chlorophyceae, Ankistrodesmus falcatus and Closterium Kutzingii in the periphyton at surface (——), 4m (– – –) & 9m (.........) depths in Loch Fad at control and cage sites during 1981

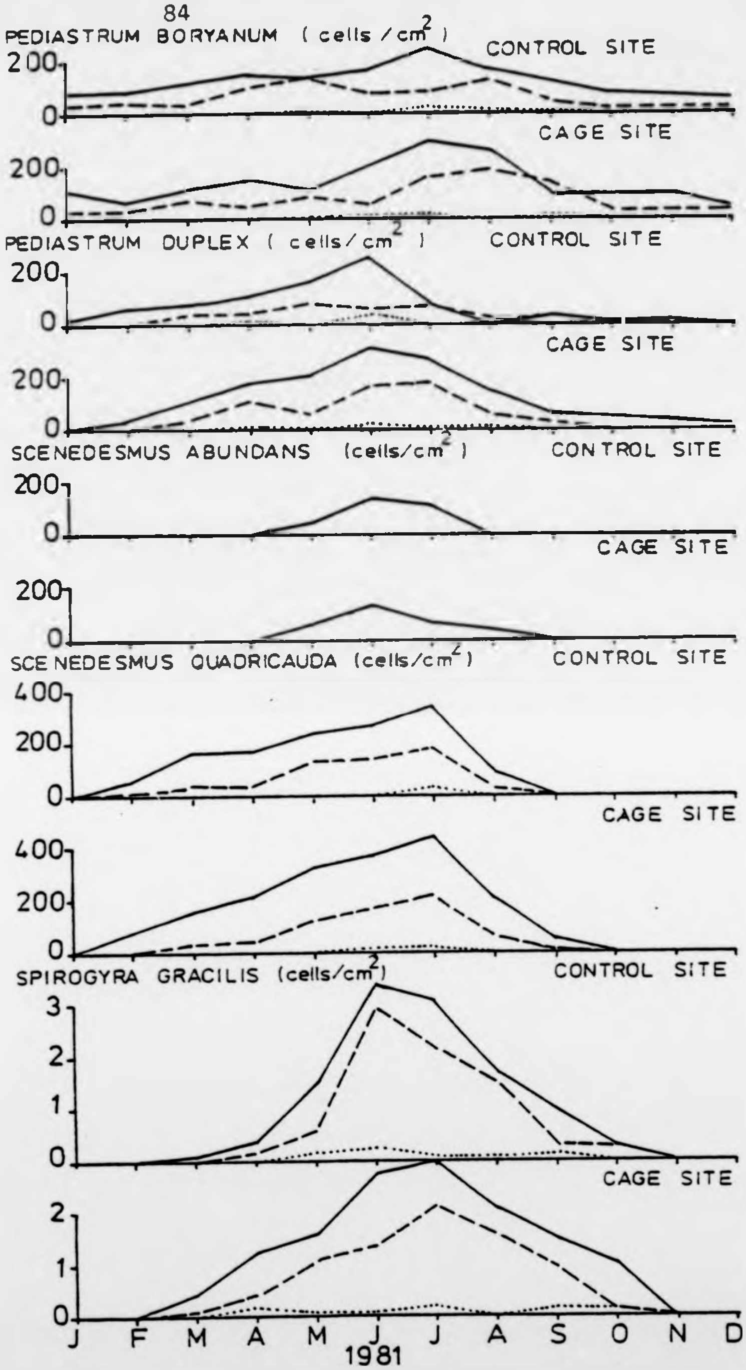

Fig.42: Seasonal changes in abundance of Pediastrum boryanum, Pediastrum duplex, Scenedesmus abundans, Scenedesmus quadricauda, and Spirogyra gracilis on wooden substrates suspended at surface (——), 4m (– – –), 9m (········) depths in Loch Fad at control and cage sites during 1981

(B) Bacillariophyceae: The seasonal changes and vertical distribution of Bacillariophyceae are shown in fig. 43. The population had its highest peak during August. The cell numbers of Bacillariophyceae were generally higher at all depths at the cage site than at the control site, but the difference was not significant (Table 8).

The seasonal changes and vertical distribution of the twelve species of Bacillariophyceae are shown in fig. 44 to fig. 46. The species, *viz.*, *Asterionella formosa*, *Cyclotella comta*, *Gomphonema constrictum*, *Melosira italica-subarctica*, *Navicula viridis* and *Stephanodiscus astraea*. were present throughout the study period, of which *A. formosa*, *G. constrictum*, and *S. astraea* were maximum during August. *C. comta* did not show any marked seasonal variation. *M. italica-subarctica* and *N. viridis* had their highest peaks during July and April, respectively. *Nitzschia linearis* and *Synedra ulna* showed peaks during May-June, while peaks of *Amphora ovalis* and *Cymbella ventricosa* occurred during August. *Meridion circulare* was present from January to July with a maximum during April.

(C) Cyanophyceae: The seasonal fluctuation in total Cyanophyceae with two peaks, one in April and the other in July, is shown in fig. 47. The cell number was mostly higher at all depths at the cage site, but the difference was not significant (Table 8).

The Cyanophyceae group comprised three species, *Anabaena flos-aquae*, *Oscillatoria agardhi*, *Oscillatoria limosa*, the seasonal changes and vertical distributions of which are shown in fig. 48. *Anabaena flos-aquae* was present throughout the year with the maximum in July. *Oscillatoria agardhi* was absent during November and December with a

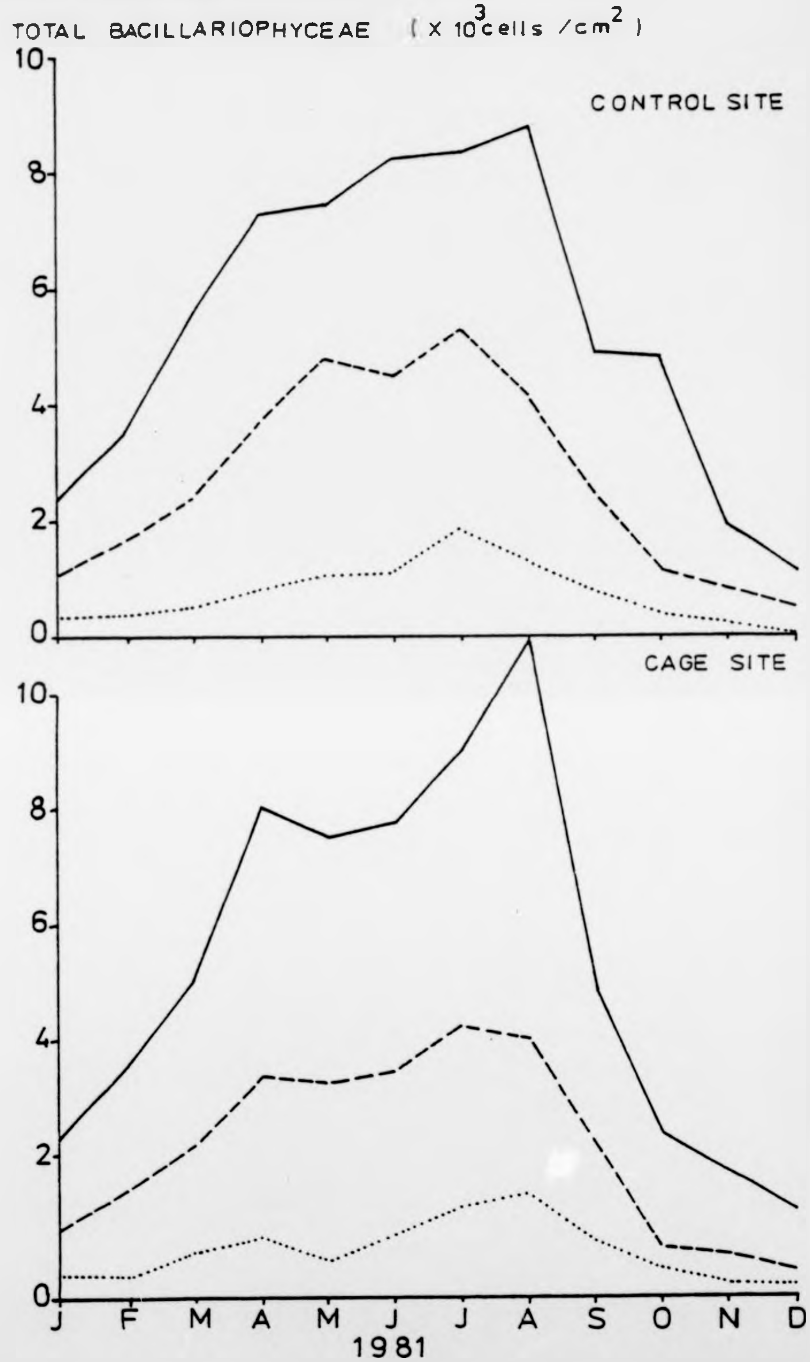

Fig.43: Seasonal changes in abundance of Bacillariophyceae on wooden substrates suspended at surface (——), 4m (–––), 9m (........) depths in Loch Fad at control and cage sites during 1981

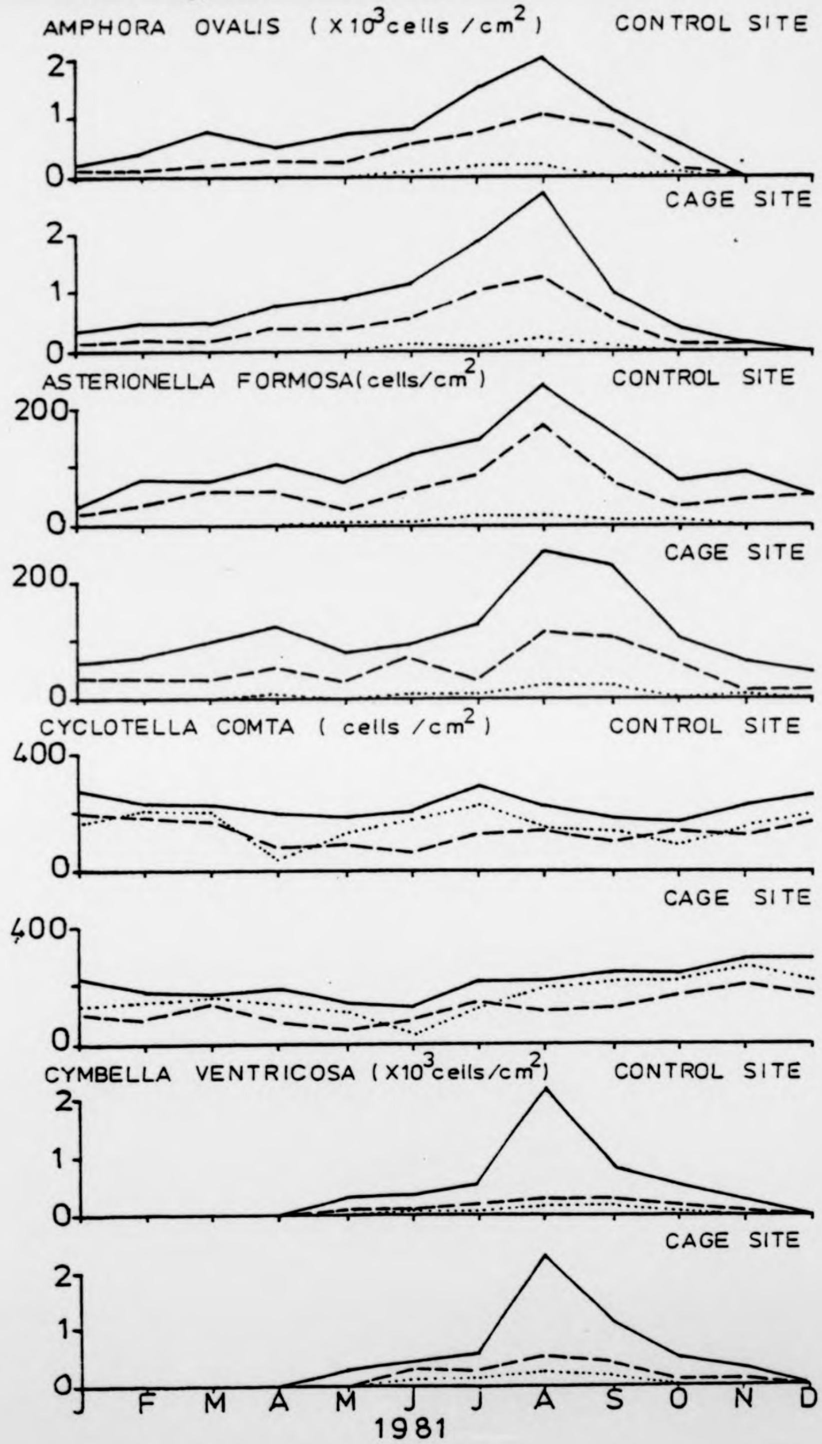

Fig.44: Seasonal changes in abundance of Amphora ovalis, Asterionella formosa, Cyclotella comta, and Cymbella ventricosa on wooden substrates suspended at surface (——), 4m (– – –), 9m (........) depths in Loch Fad at control and cage sites during 1981

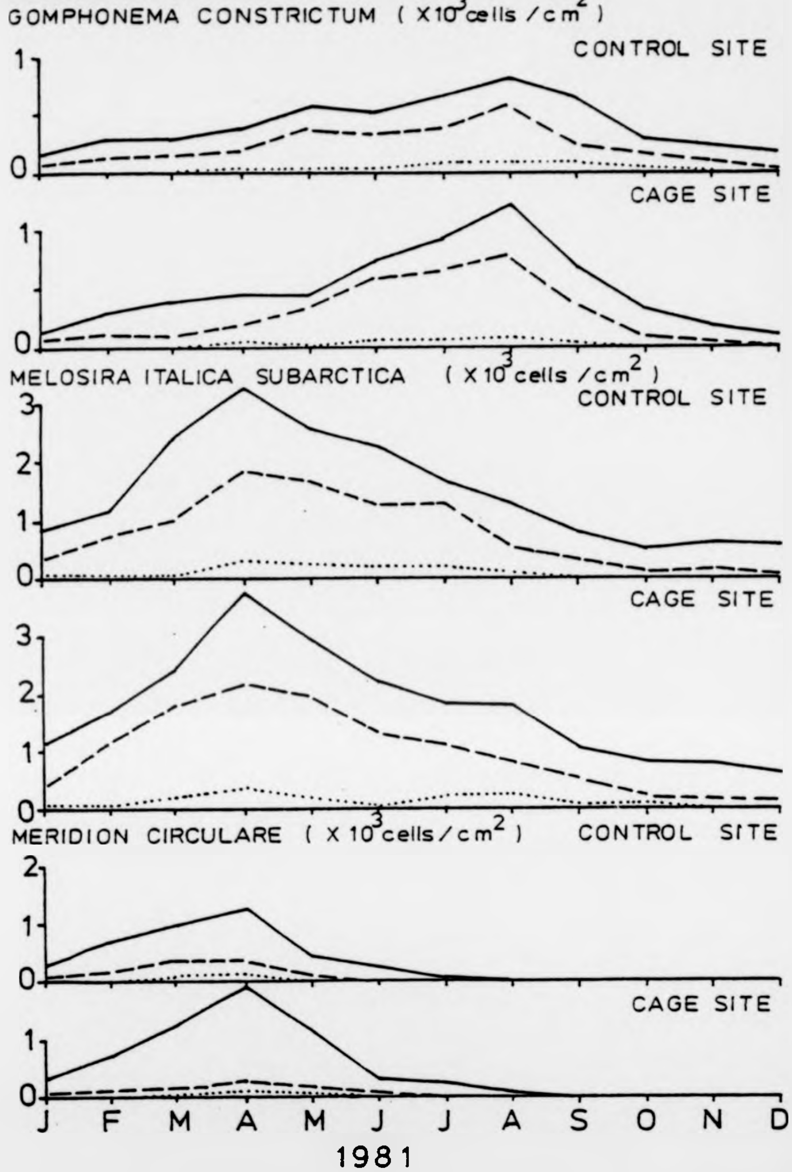

Fig.45: Seasonal changes in abundance of Gomphonema constrictum, Melosira italica-subarctica, Meridion circulare on wooden substrates suspended at surface (——), 4m (– – –), 9m (........) depths in Loch Fad at control and cage sites during 1981

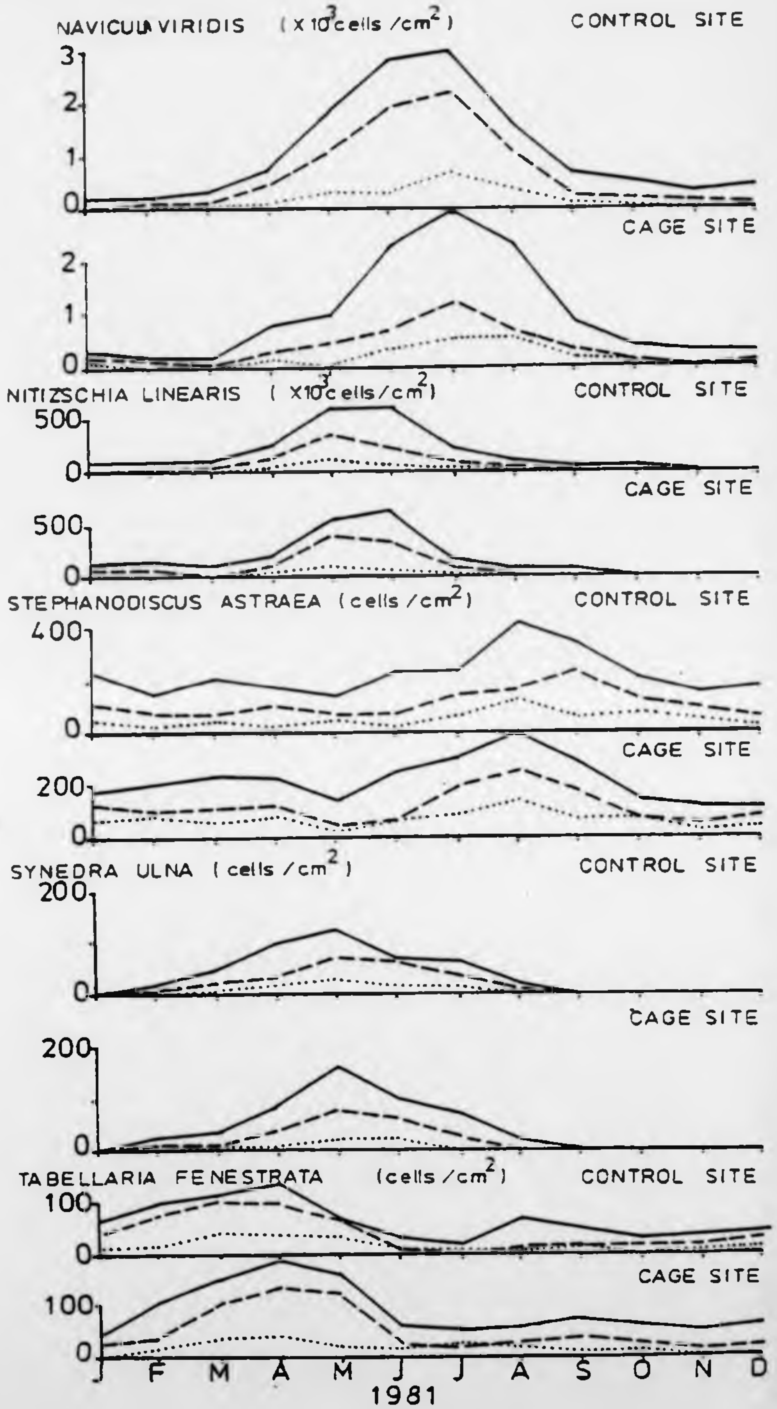

Fig. 46: Seasonal changes in abundance of Navicula viridis, Nitzscia linearis, Stephanodiscus astraea, Synedra ulna, Tabellaria fenestrata on wooden substrates suspended at surface (———), 4m (– – –), 9m (.........) depths in Loch Fad at control and cage sites during 1981

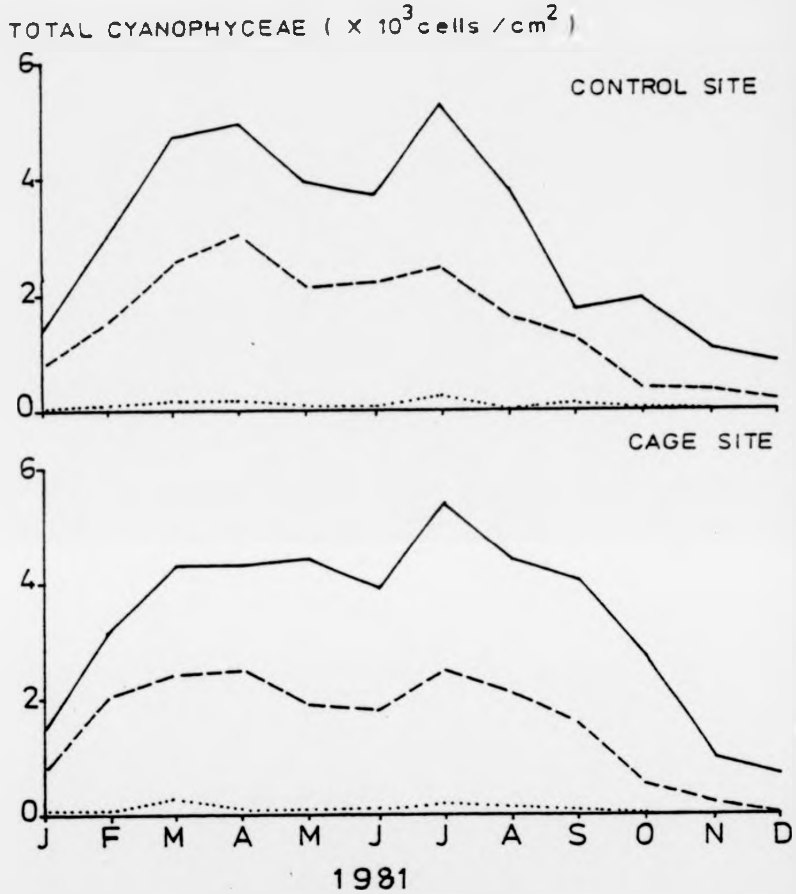

Fig. 47: Seasonal changes in abundance of Cyanophyceae on wooden substrates suspended at surface (——), 4m (----), 9m (........) depths in Loch Fad at control and cage sites during 1981

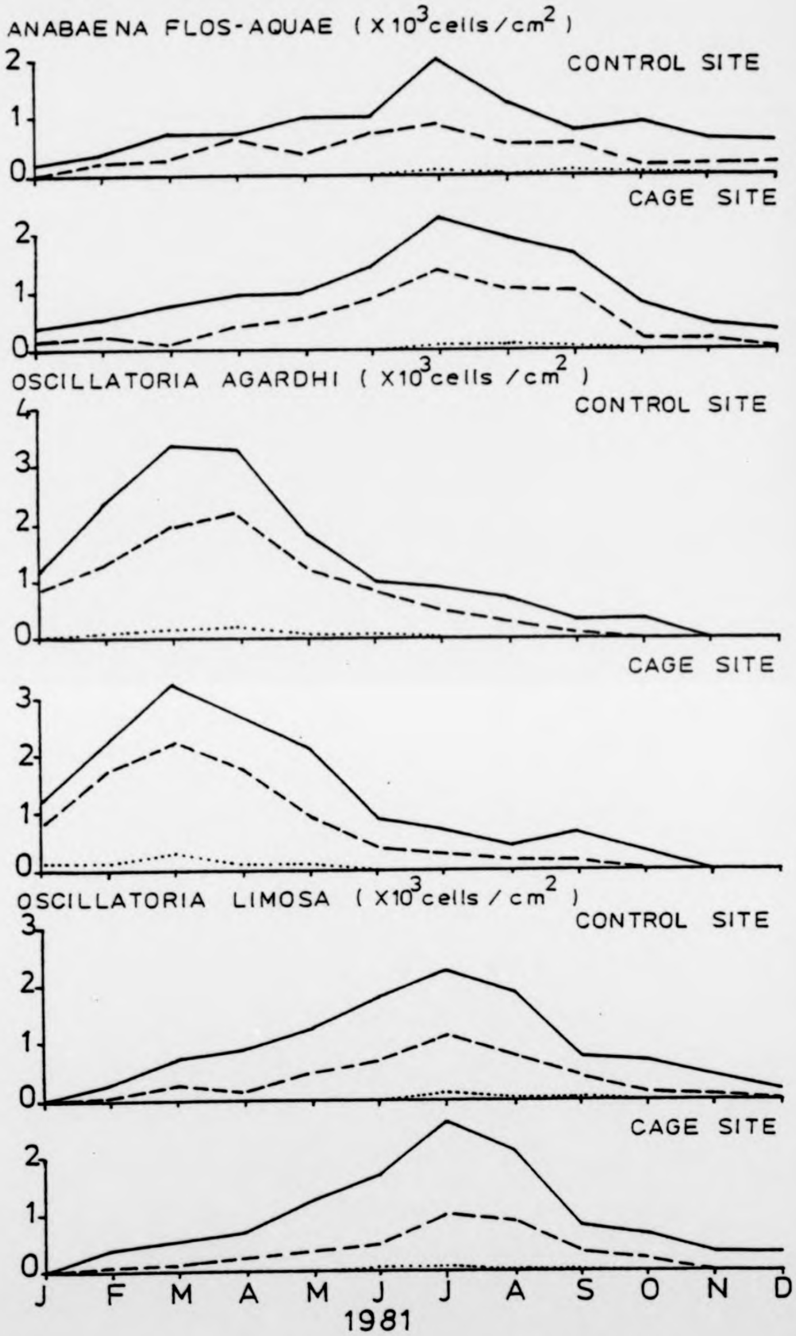

Fig.48: Seasonal changes in abundance of Anabaena flos-aquae, Oscillatoria agardhi, Oscillatoria limosa on wooden substrates suspended at surface (——), 4m (– – –), 9m (........) depths in Loch Fad at control and cage sites during 1981

peak in March, and O. limosa was absent only during January with a peak in July.

(D) Fungi: Besides the attached algae, water moulds were also observed on the wooden collector plaques. Fig. 49 shows that fungal hyphae were present from June to December with a maximum during October at all depths at both sites. The number of fungal hyphae were higher at all depths at the cage site than at the control, these differences being statistically significant (Table 8).

5.1.15.2 Relative abundance of periphyton:

(A) Chlorophyceae: Of the total periphyton, the group Chlorophyceae was never dominant over other groups (fig. 50), the maximum percentage being 35% at control and 38% at the cage site. The percentage contribution of Chlorophycean species towards the total periphyton is shown in fig. 50. *Spirogyra gracilis* was one of the dominant periphyton species, forming a maximum of 21-29% during June-July. *Pediastrum duplex*, *P. boryanum*, *Scenedesmus quadricauda*, *S. abundans*, *Closterium kutzingii*, and *Ankistrodesmus falcatus* never formed more than 4% of the total periphyton.

(B) Bacillariophyceae: The group Bacillariophyceae was the most dominant group of all, forming more than 43% of total periphyton at both sites at all depths, while at 9m depth they even formed a maximum of 100% (fig. 50). The percentage contribution to total periphyton by Bacillariophycean species is shown in fig. 50. *Amphora ovalis*, *Cymbella ventricosa*, *Stephanodiscus astraea*, and *Meridion circulare* never formed more than 20% of the total, while *Cyclotella*

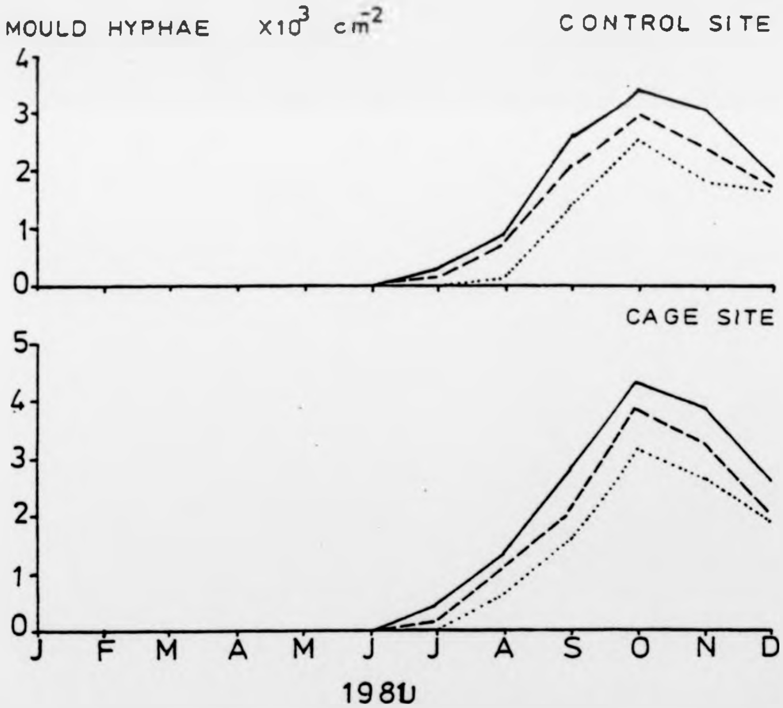

Fig.49: Seasonal changes in abundance of **Fungi** ; on wooden substrates suspended at surface (——), 4m (– – –), 9m (.........) depths in Loch Fad at control and cage sites during 1981

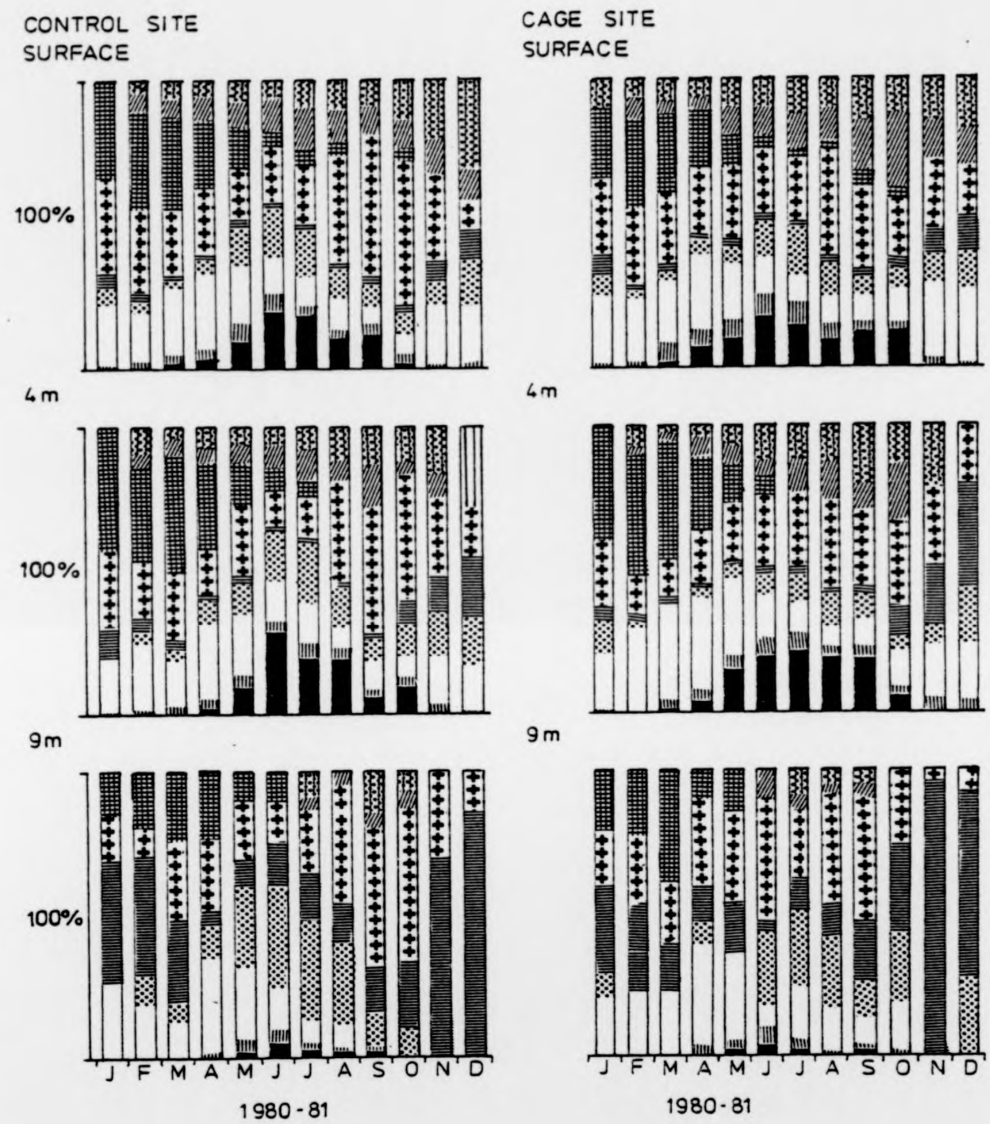

Fig.50: Relative abundance of Periphyton in Loch Fad at control and cage sites during 1981

(■ Spirogyra gracilis, ▥ other chlorophyceans, □ Melosira italica-subarctica, ⊠ Navicula viridis, ▤ Cyclotella comta, ⊞ other diatoms. ▦ Oscillatoria agardhi, ▨ Oscillatoria limosa, ▩ Anabaena flos-aquae) comta, Melosira italica-subarctica and Navicula viridis formed maxima of 24%-89%. Remaining species of Bacillariophyceans were less than 12.5% throughout the study period.

(C) Cyanophyceae: Cyanophyceae mostly comprised more of the total periphyton than Chlorophyceae, but less than Bacillariophyceae. The maximum contribution was 50% at the control site and 52% at the cage site. The seasonal changes in percentage composition of cyanophycean species are shown in fig. 50.

5.1.15.3 Species succession of periphyton:

As has already been stated, total periphyton had two peaks, one small one during spring and another high one by summer. The spring maxima of periphyton was due to Bacillariophyceans and Cyanophyceans, mainly Stephanodiscus astraea, Cyclotella comta, Melosira italica-subarctica, and Meridion circulare and Oscillatoria agardhi. By the first half of summer most chlorophyceans were high in number, together with the blue-greens Oscillatoria limosa and Anabaena flos-aquae and the diatoms Navicula viridis, Nitzschia linearis. Late summer was the time when other diatoms were in maxima, especially Stephanodiscus astraea and Asterionella formosa. With autumn, the periphyton decreased in number till winter.

5.1.16 Diurnal Studies: At Loch Fad diurnal study of physico-chemical parameters, phytoplankton and zooplankton was carried out on 2nd-3rd April, 1981, at the cage site only (fig.51 to 54).

Water temperature rose to the highest during 13.00 hrs. at all

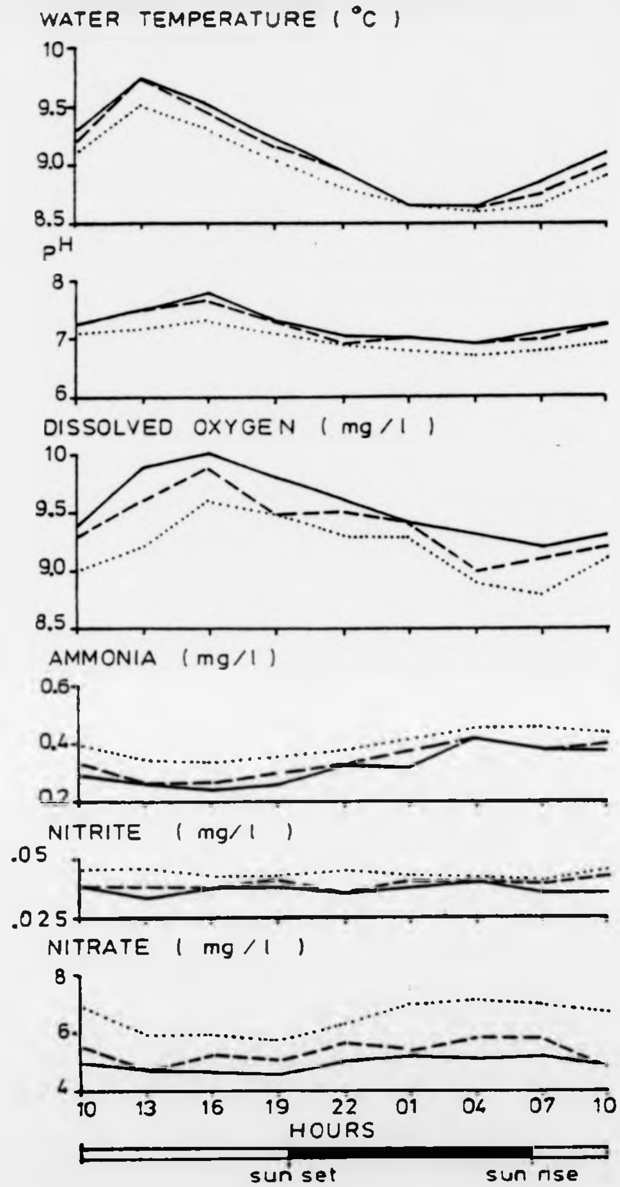

Fig.51: Diurnal changes in Water temperature, Dissolved Oxygen, Ammonia, Nitrite, and Nitrate in Loch Fad at cage site during 2nd-3rd April, 1981

(___ surface, _ _ _ 4m, ... 9m)

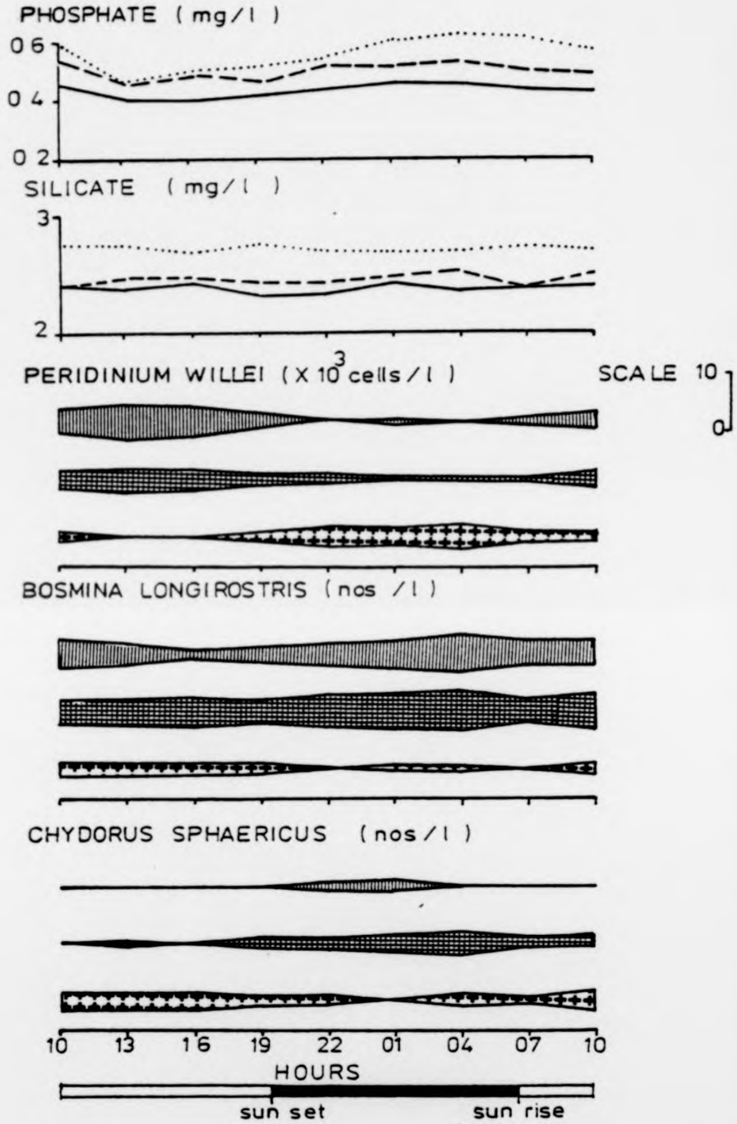

Fig.52: Diurnal changes in Orthophosphate, Silicate, Peridinium willei, Bosmina longirostris, Chydorus sphaericus, in Loch Fad at cage site during 2nd-3rd April 1981

(— ▥ surface, -- ▦ 4m, ... ⊞ 9m)

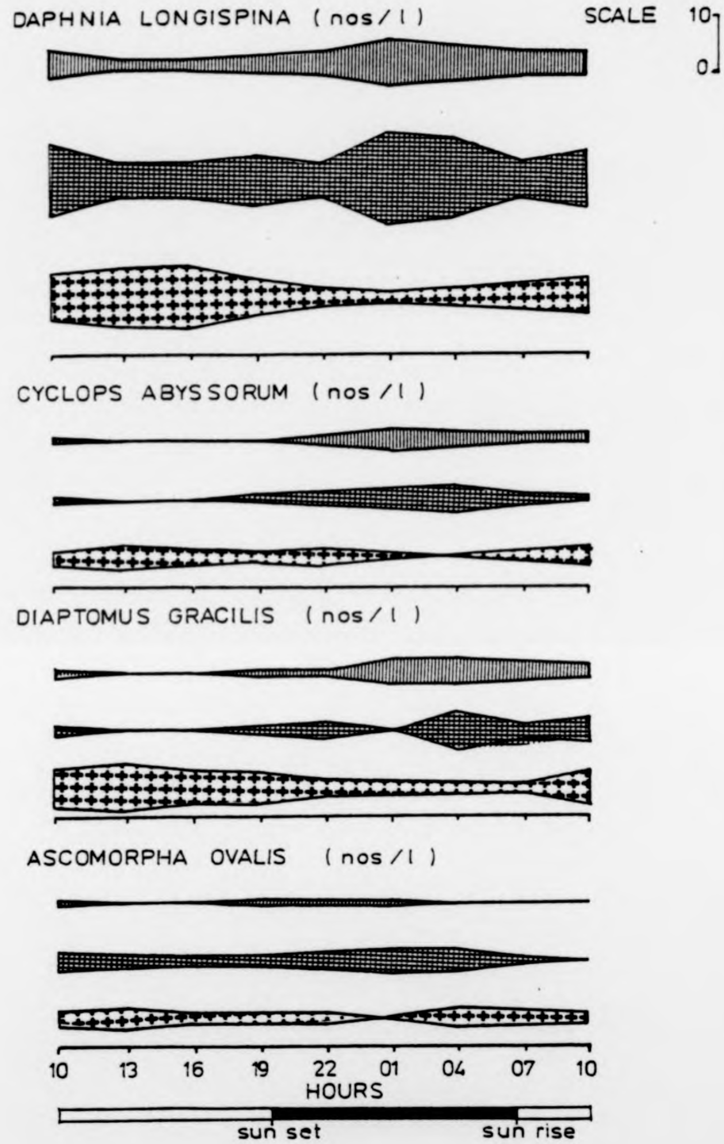

Fig.53: Diurnal changes in Daphnia longispina, Cyclops abyssorum, Diaptomus gracilis, and Ascomorpha ovalis, in Loch Fad at cage site during 2nd-3rd April 1981

(▥ surface, ▦ 4m, ⊞ 9m)

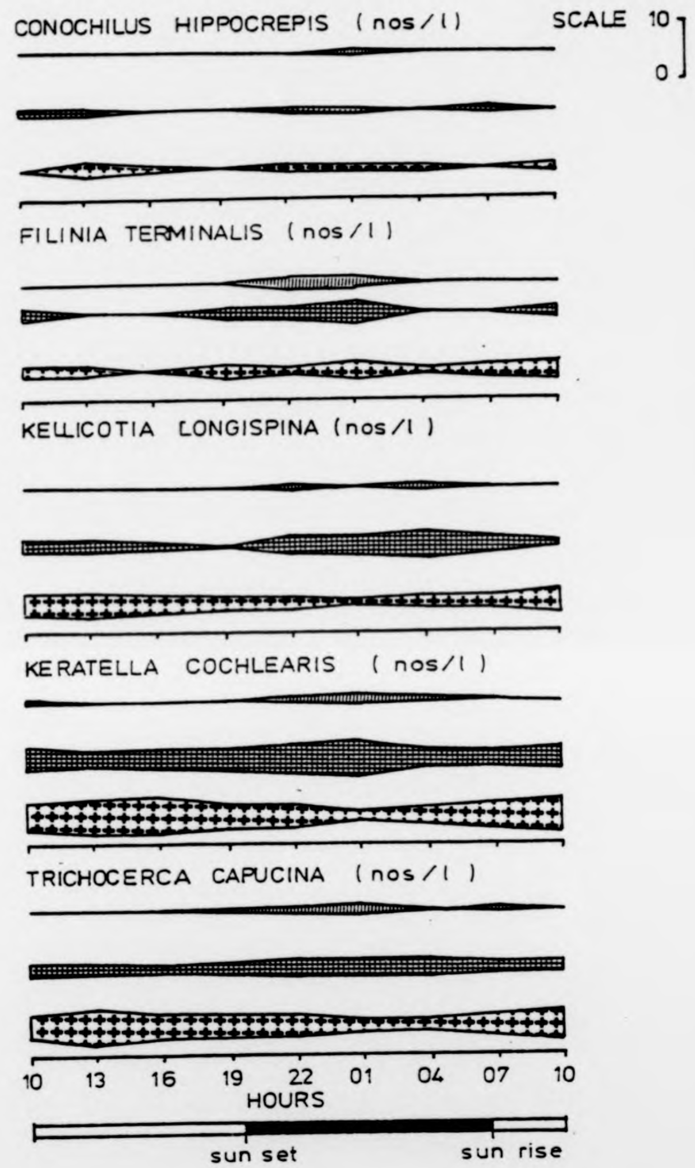

Fig. 54: Diurnal changes in Conchilus hippocrepis, Filinia terminalis, Kellicottia longispina, Keratella cochlearis, Trichocerca capucina, in Loch Fad at cage site during 2nd-3rd April 1981

(▥ surface, ▦ 4m, ⊞ 9m)

depths and then dropped to a minimum by 01.00 to 04.00 hrs. before rising again. The difference between the maximum and minimum temperatures was only 1.1°c.

pH increased until 16.00 hrs. and then started decreasing, reaching a minimum by 04.00 hrs., after which it increased until the end of study at 10.00 hrs.

Dissolved oxygen was always below 100% saturation during the period of study. It was highest during 16.00 hrs., being 10 mg/l at the surface layer, 9.9 mg/l at 4m, and 9.6 mg/l at 9m. The concentration then dropped to a minimum between 04.00 and 07.00 hrs.

Ammonia, Nitrate and Phosphate concentrations showed a decreasing trend during the day and an increasing trend during the night. Nitrite-nitrogen and silicate concentrations, however, showed no marked diurnal trends.

Except *Peridinium willei*, all other phytoplankton did not show any diel pattern in their vertical distribution in the water column; they were always higher in number in the upper layers than at the bottom. So the data of phytoplankton during diel study is not shown in figure form. *Peridinium willei* showed upward movement during the day and downward movement during the night.

All 11 zooplankton species which were recorded during the seasonal study were present. All zooplankton showed a downward migration during the day and an upward migration during the night. The maximum number recorded at the surface was during 01.00 hrs. to 04.00 hrs. and at the 9m layer it was during 13.00 hrs. to 16.00 hrs.

5.2 Howietoun Fish Farm

5.2.1 Water temperature: The water temperature rose from 4°c in February to 16°c in mid May, reaching a maximum of 17.6°c in mid July (fig. 55). The difference between the water temperature of different stations was never more than 0.5°c, which was observed during July.

5.2.2 Hydrogen-ion concentration: The seasonal fluctuation of p^H (measured between 11.00 a.m. to 12 noon) at all the stations showed a similar pattern, low during winter months and high during summer (fig. 55). p^H showed a decreasing trend during winter months from station 1 to station 6 but during the summer the trend was the reverse.

Highly significant positive correlation was observed between daytime p^H and total phytoplankton population at all the stations (Table 11) which was probably related to the photosynthetic activity of the phytoplankton.

5.2.3 Dissolved Oxygen: The seasonal fluctuation in dissolved oxygen at all the stations is presented in fig. 56. Dissolved oxygen concentration decreased from station 1 to station 6, and the difference between stations was highly significant ($P < .001$) when analysed with two way anova (Table 12).

The percentage saturation of dissolved oxygen is presented in Table 10. At station 1, it was more than 100% except on a few occasions, but at station 6 it was never more than 98%.

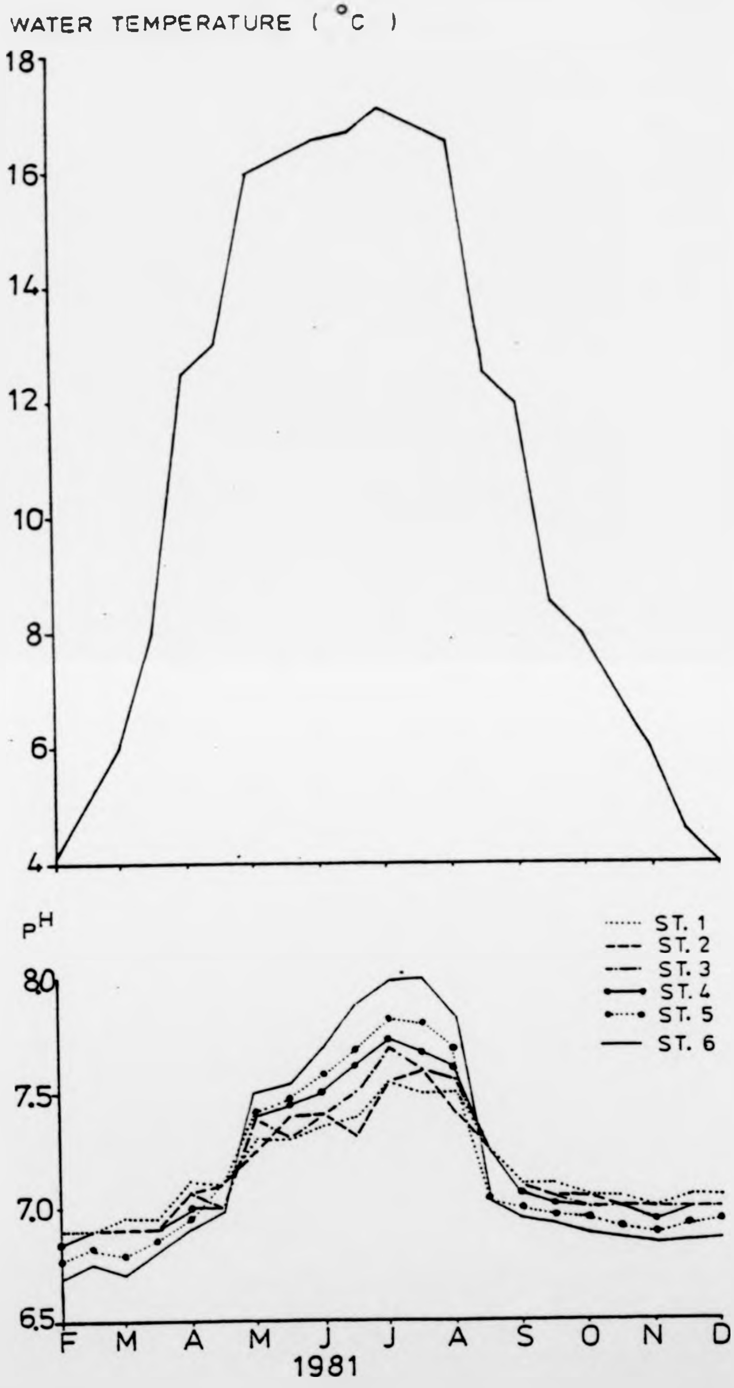

Fig.55: Seasonal changes in water temperature and pH in Howietoun Farm at six stations during 1981

Table 10: Showing Percent Saturation of Dissolved Oxygen at all six stations at Howietoun Fish Farm during 1981

	St.1	St.2	St.3	St.4	St.5	St.6
Feb.	102	100	100	98	98	97
Mar.	102 101	100 100	100 100	98 98	98 98	97 96
Apr.	101 107	100 102	100 102	97 100	97 100	95 98
May	102 105	100 100	100 97	98 100	96 97	95 96
June	102 98	100 98	100 95	98 95	95 92	95 92
July	98 96	98 95	96 97	95 96	95 97	92 95
Aug.	100 101	98 100	96 100	96 100	96 94	94 95
Sep.	101 100	98 96	97 98	96 97	88 80	86 86
Oct.	100 98	98 96	96 97	95 97	88 97	87 95
Nov.	102 101	100 101	98 100	99 99	96 98	96 97
Dec.	101 101	100 100	100 99	99 100	97 98	96 96

Table 11: Correlation coefficient between the parameters at each station at Howietoun Fish Farm

Parameters	Correlation Coefficients					
	St.1	St.2	St.3	St.4	St.5	St.6
Phytoplankton and p^H	.66**	.81***	.86***	.85***	.87***	.84***
Phytoplankton and Inorganic-N	-.51*	-.79***	-.82***	-.89***	-.95***	-.85***
Phytoplankton and Nitrate	-.53*	-.76***	-.81***	-.89***	-.94***	-.89***
Phytoplankton and Phosphate	-.52*	-.82***	-.79***	-.76***	-.92***	-.77***
Phytoplankton and Total Solids	.23	.01	.13	.01	.23	.29
Phytoplankton and Chlorophyll-a	.99***	.99***	.97***	.99***	.99***	.99***
Phytoplankton and Periphyton	.82***		.85***		.93***	
Phytoplankton and Zooplankton	.78***	.72***	.83***	.88***	.80***	.82***
Bacillariophyceae and Silicate	-.29	-.28	-.44*	-.53*	-.65**	-.43

where * $P < .05$, ** $P < .01$, *** $P < .001$

Table 12: Results of analysis of variance (2-way without replication) of different parameters between stations at Howietoun Fish Farm (Critical values of F_s = 3.2 for df = 5,100 at P = 0.01, and F_s = 5.85 for df = 2,20 at P = 0.01.)

	df	SS	MS	F_s
Dissolved Oxygen				
Stations	5	7.37	1.47	33.81
Error	100	4.36	.0436	
Inorganic Nitrogen				
Stations	5	308.043	61.609	274.21
Error	100	22.458	.225	
Ammonia				
Stations	5	31567.69	6313.54	253.56
Error	100	2419	24.19	
Nitrite				
Stations	5	2731.944	546.388	32.33
Error	100	1690.55	16.9	
Nitrate				
Stations	5	275.38	55.076	681.64
Error	100	8.07	.0807	
Phosphate				
Stations	5	76.91	15.38	15.69
Error	100	98.03	.9803	
Silicate				
Stations	5	42.51	8.5	178.99
Error	100	4.75	.0475	
Suspended Solids				
Stations	5	16.94	3.388	5.21
Error	100	64.74	.65	
Chlorophyll-a				
Stations	5	687.57	175.51	57.36
Error	100	306.2	3.06	
Total Phytoplankton				
Stations	5	7934.361	1586.8722	47.05
Error	100	3372.819	33.72819	

cont'd. over...

Table 12 cont'd...

		df	SS	MS	F_S
Chlorophyceae					
	Stations	5	260.0	52.0	16.4
	Error	100	316.47	3.17	
Bacillariophyceae					
	Stations	5	164.75	32.95	224.92
	Error	100	14.65	.1465	
Cyanophyceae					
	Stations	5	4528.59	905.72	22.61
	Error	100	4005.49	40.06	
Total Zooplankton					
	Stations	5	4109.59	821.918	296.72
	Error	100	277.08	2.77	
Cladocera					
	Stations	5	604.83	120.96	21.66
	Error	100	558.5	5.585	
Copepoda					
	Stations	5	269.87	53.97	9.78
	Error	100	552.45	5.5245	
Rotifera					
	Stations	5	525.7	105.14	80.36
	Error	100	130.67	1.31	
Total Periphyton					
	Stations	2	2358.71	1179.36	20.89
	Error	20	1129.43	56.47	
Chlorophyceae					
	Stations	2	38.19	19.095	13.17
	Error	20	28.99	1.4495	
Bacillariophyceae					
	Stations	2	115.78	57.89	147.87
	Error	20	7.83	.3915	
Cyanophyceae					
	Stations	2	1020.56	510.28	11.10
	Error	20	919.85	45.99	

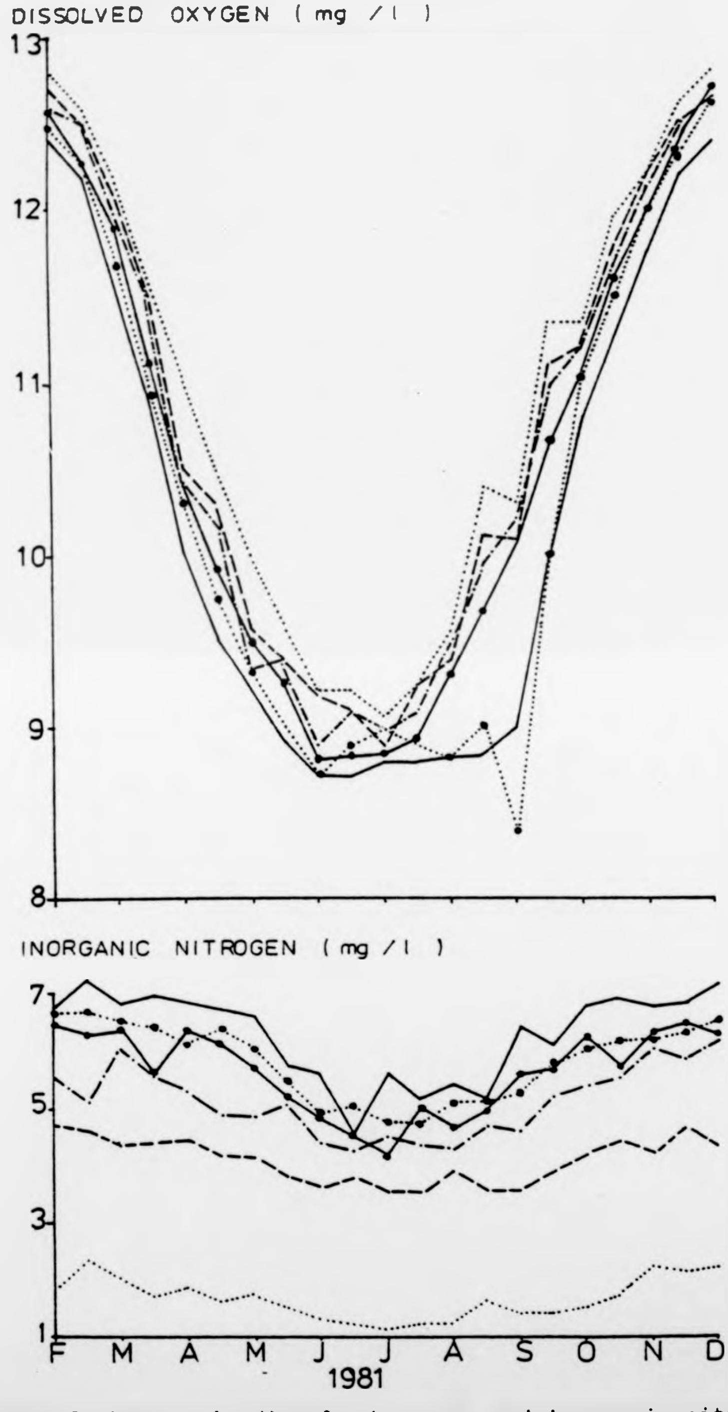

Fig.56: Seasonal changes in dissolved oxygen and inorganic nitrogen in Howietoun Farm at six stations during 1981.

(..... St.1, --- St.2, -.- St.3, —• St.4, •... St.5, — St.6)

5.2.4 Inorganic Nitrogen: Inorganic nitrogen concentrations were high at all the stations during winter and were low during summer (fig. 56). The concentration of inorganic nitrogen showed an increasing trend from station 1 to station 6, the difference between the stations being highly significant ($P<.001$) as shown in Table 12.

The negative correlation between inorganic nitrogen and the total phytoplankton population was significant as shown in Table 11.

5.2.5 Nitrite: Nitrite-nitrogen was never more than .025 mg/l at all the stations except during mid September at stations 5 and 6 (fig.57). Nitrite concentration increased through station 1 to station 6, the difference between the stations being significant (Table 12).

5.2.6 Ammonia: Seasonal fluctuations of total ammonia concentration were similar at all the stations, decreasing steadily from February to reach a minimum during July-August (fig. 57). The ammonia concentration increased from station 1 to station 6 and the difference between stations was significant (Table 12).

5.2.7 Nitrate: Nitrate-nitrogen was the dominant nutrient over ammonia, phosphate and silicate. Its concentration followed a similar pattern to that of ammonia of decreasing during the summer (fig. 57). Nitrate concentration increased from station 1 to station 6, and this difference between stations was significant (Table 12).

The negative correlation between nitrate-nitrogen and total phytoplankton population was statistically significant (Table 11) at all the stations.

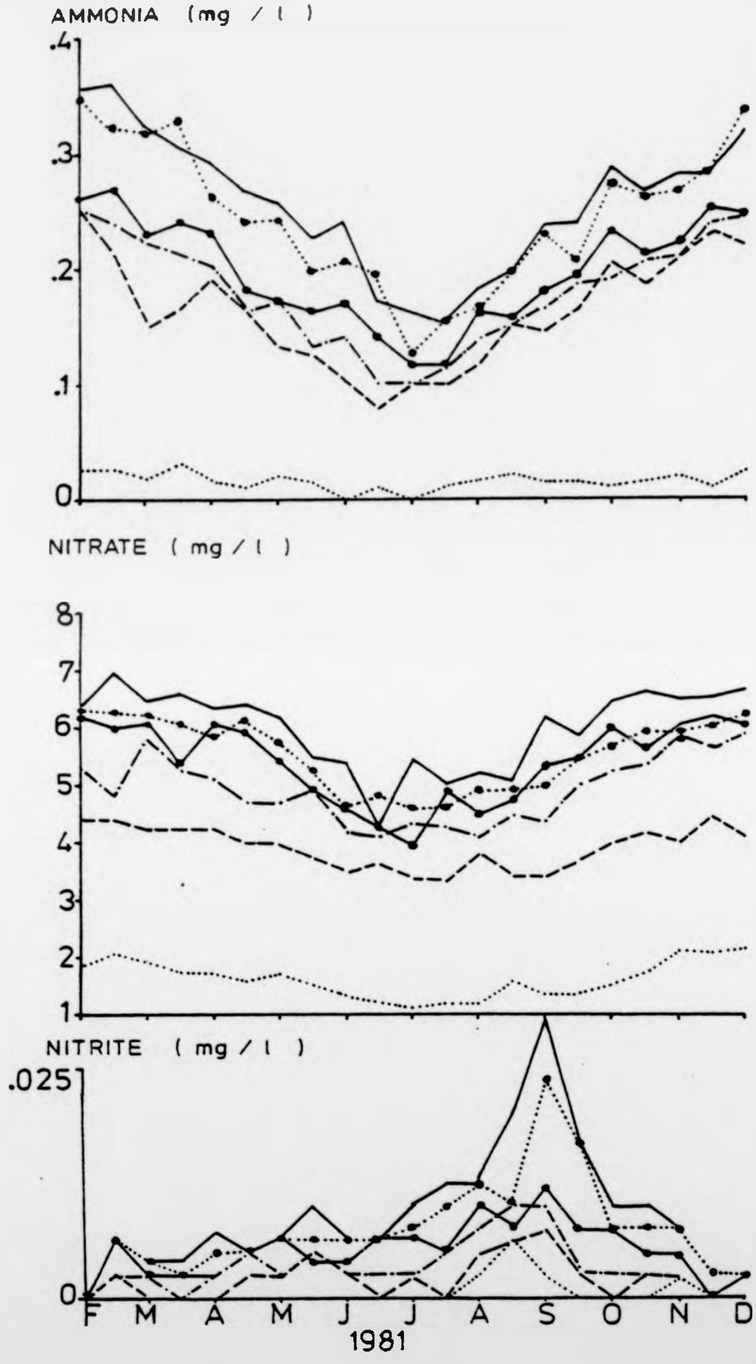

Fig.57: Seasonal changes in ammonia, nitrite, nitrate, in Howietoun Farm at six stations during 1981

(..... St.1, —— St.2, —·— St.3, —• St.4, •.....• St.5, — St.6)

5.2.8 Phosphate: Fig. 58 shows that phosphate concentration followed a similar pattern to that of nitrate-nitrogen, being low during summer months (July-August). Its concentration also increased from station 1 to station 6, the between station difference being significant (Table 12).

A significant negative correlation between phosphate concentration and the total phytoplankton population existed at all the stations (Table 11).

5.2.9 Silicate: The reactive silicate concentration showed two peaks, a smaller one during mid March and another higher one during September-October (fig. 58). Unlike other nutrients, silicate concentration decreased from station 1 to station 6, the difference between stations being highly significant (Table 12).

Though silicate concentration was correlated negatively with Bacillariophyceae population at all the stations, this correlation was significant only at stations 3, 4 and 5 (Table 11).

5.2.10 Total suspended solids: Fig. 59 shows two peaks of suspended solids one in March and the other in September-October. Total suspended solids also decreased from station 1 to station 6, except in August. The difference between the stations was still significant, though less so than with the other parameters.

The correlation between suspended solids and total phytoplankton was not significant at any station (Table 11). This contrasts with the significant positive correlation observed at Loch Fad.

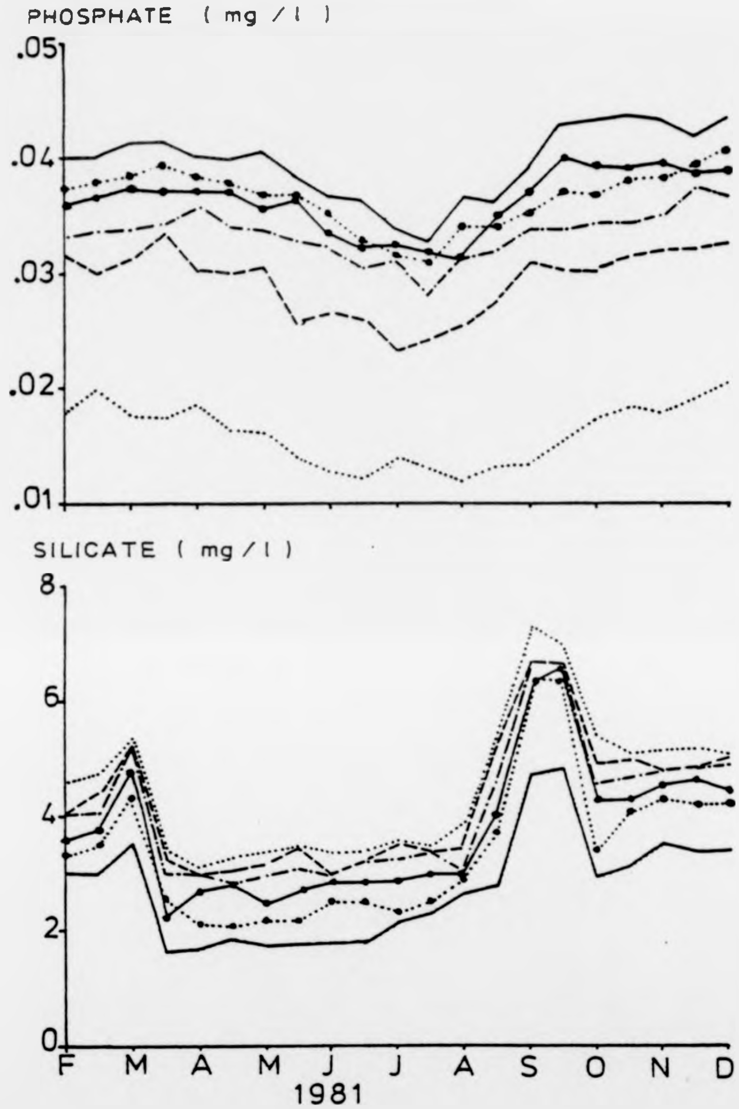

Fig.58: Seasonal changes in orthophosphate and silicate in Howietoun Farm at six stations during 1981

(..... St.1, --- St.2, -.- St.3, —•— St.4, •-•- St.5, — St.6)

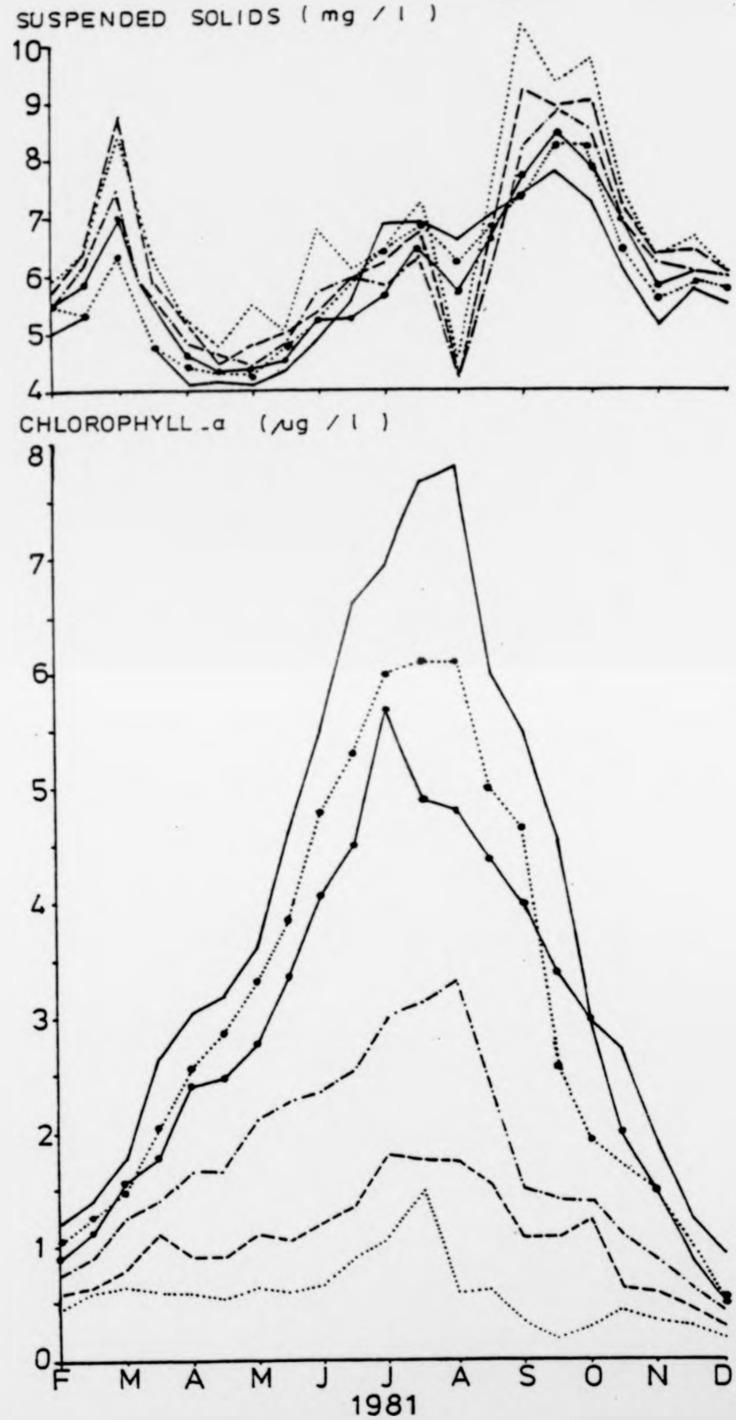

Fig.59: Seasonal changes in total suspended solids and Chlorophyll-a in Howietoun Farm at six stations during 1981

(St.1, St.2, St.3, St.4, St.5, St.6)

5.2.11 Chlorophyll-a: Chlorophyll-a concentration increased from February, reaching its maximum in July-August (fig. 59), after which it decreased to the end of the study in December. Chlorophyll-a concentration increased from station 1 to station 6 as shown in fig. 63, the difference between stations being significant (Table 12).

Chlorophyll-a concentration was positively correlated with the total phytoplankton, the correlation being highly significant (Table 11).

5.2.12 Phytoplankton: The seasonal variation of total phytoplankton at all the stations at Howietoun Fish Farm is shown in fig. 60. The population showed its highest peak during July-August. The cell numbers increased from station 1 to station 6, and the difference between stations was highly significant (Table 12).

The total phytoplankton population comprised 31 species belonging to the groups Chlorophyceae, Xanthophyceae, Bacillariophyceae, Rhodophyceae, and Cyanophyceae. They are listed in Table 13.

5.2.12.1 Seasonal Variation of Phytoplankton:

(A) Chlorophyceae: The group Chlorophyceae increased steadily from the start of the study, reaching a maximum during July at all stations (fig. 60). Chlorophyceae also showed an increasing trend from station 1 to station 6, the station difference being highly significant (Table 12).

The group Chlorophyceae comprised 10 species, the seasonal variation of which is shown in fig. 61 to fig. 64. None of the chlorophycean

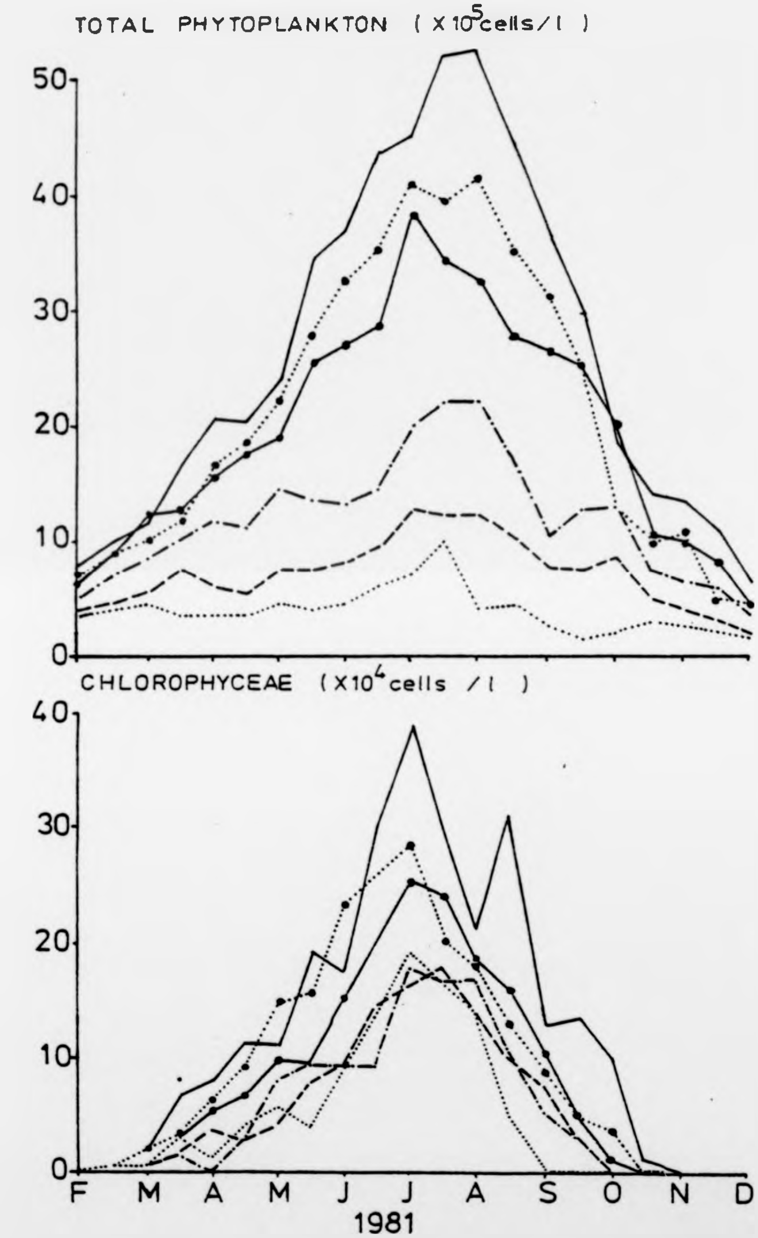

Fig.60: Seasonal changes in abundance of total phytoplankton and Chlorophyceae in Howietoun Farm at six stations during 1981

(...... St.1, —— St.2, —·— St.3, •—• St.4, •.....• St.5, — St.6)

Table 13: Phytoplankton recorded in Howietoun Fish Farm during 1981

CHLOROPHYCEAE

Ankistrodesmus falcatus (Corda) Ralfs

Ankistrodesmus sp.

Botryococcus braunii Kutz

Closterium parvulum Naeg.

Oedogonium sp.

Pandorina morum (Mull) Bory.

Scenedesmus quadricauda (Turp.) Breb

Scenedesmus obliquus (Turp.) Kutz

Spirogyra varians (Hass.) Kutz

Staurodesmus cuspidatus (Breb) Teiling

BACILLARIOPHYCEAE

Amphora ovalis Kutz

Asterionella formosa Hass.

Cyclotella meneghiniana Kutz

Diatoma elongatum Ag.

Diatoma vulgare Bory.

Gomphonema constrictum Ehrenb

Gomphonema geminatum (Lyngb.) Ag.

Melosira italica-subarctica

Meridion circulare (Greville) Agardh

Navicula cryptocephala Kutz

Navicula viridis Kutz

Nitzschia linearis (Ag.) W.Sm.

Stephanodiscus hantzschii Grunow

Table 13 cont'd.

BACILLARIOPHYCEAE cont'd...

Synedra ulna (Nitzsch) Ehrenb.

Tabellaria fenestrata (Lyngb.) Kutz

Tabellaria flucculosa (Roth) Kutz

RHODOPHYCEAE

Chantransia pygmaea Kutz

Lemanea mammillosa (Kutz)

CYANOPHYCEAE

Anabaena flos-aquae (Lyngb.) Breb

Coelosphaerium Kuetzingianum Naeg.

Oscillatoria agardhi Gomond

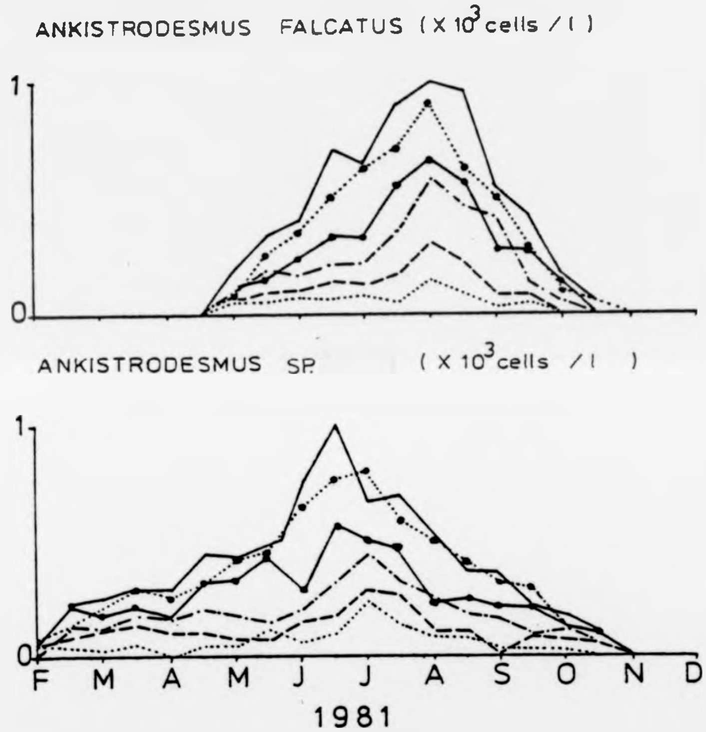

Fig.61: Seasonal changes in abundance of Ankistrodesmus falcatus and Ankistrodesmus sp. in Howietoun Farm at six stations during 1981

(..... St.1, ---- St.2, -.-.- St.3, —— St.4, ... St.5, —— St.6)

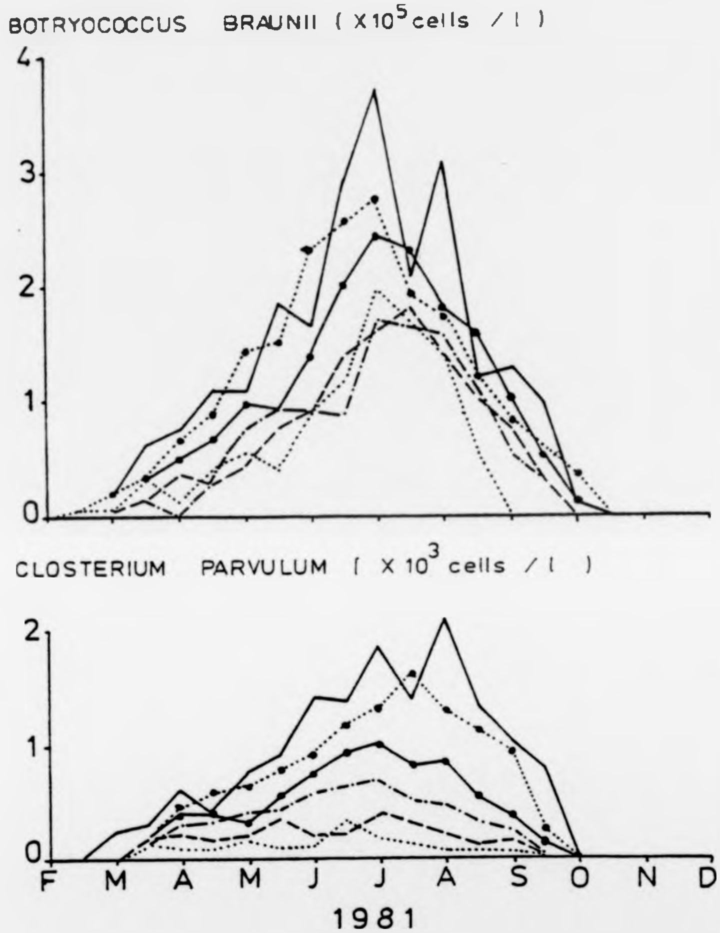

Fig.62: Seasonal changes in abundance of Botryococcus braunii and Closterium parvulum in Howietoun Farm at six stations during 1981

(...... St.1, --- St.2, _._ St.3, •—• St.4, •......• St.5, — St.6)

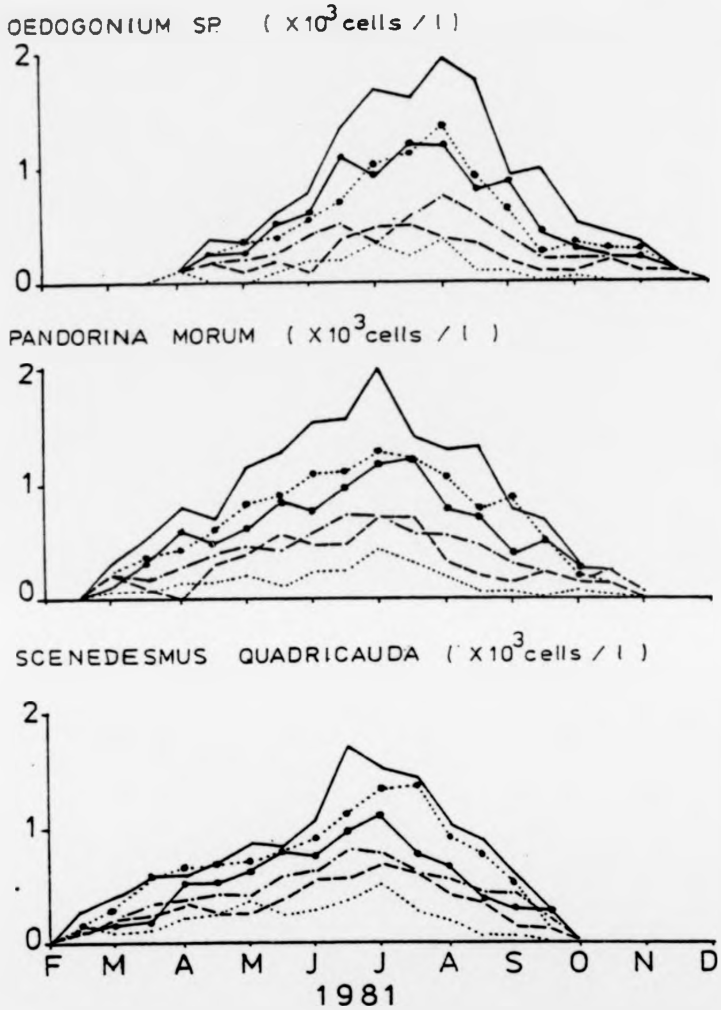

Fig.63: Seasonal changes in abundance of Oedogonium sp., Pandorina morum, and Scenedesmus quadricauda, in Howietoun Farm at six stations during 1981

(...... St.1, --- St.2, -.-- St.3, —• St.4, •....• St.5, — St.6)

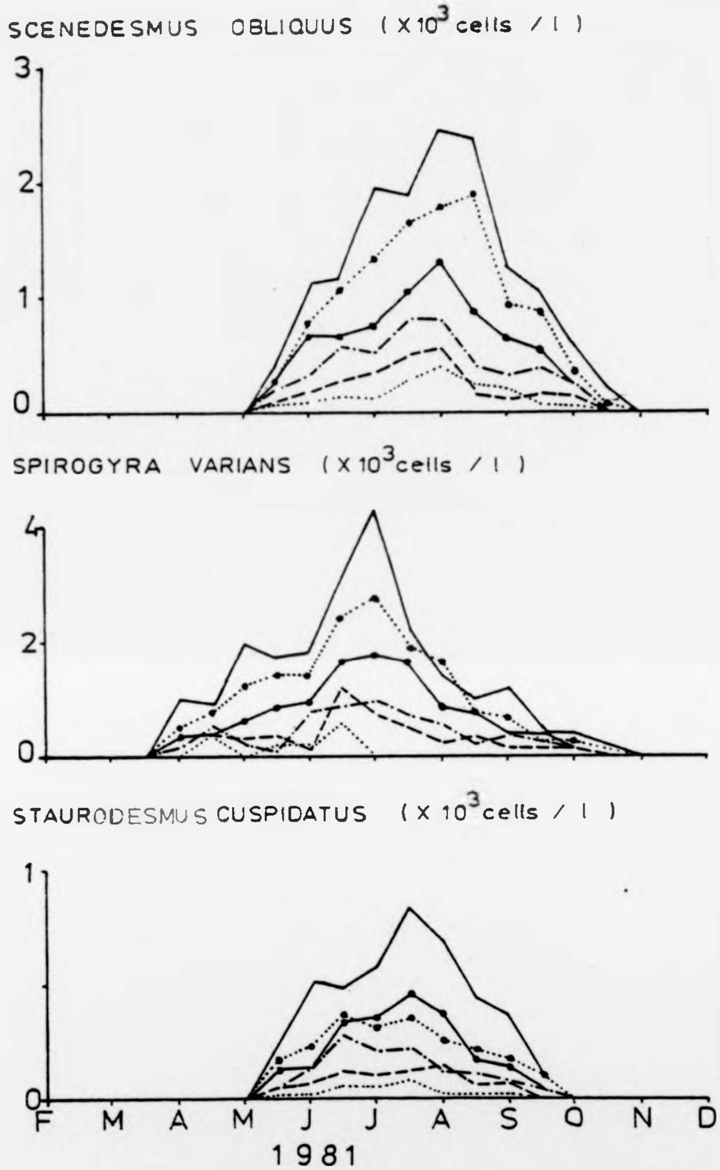

Fig.64: Seasonal changes in abundance of <u>Scenedesmus obliquus</u> and <u>Spirogyra varians</u> in Howietoun Farm at six stations during 1981

(...... St.1, ___ St.2, _._ St.3, ___. St.4, ._..... St.5, ___ St.6) species persisted throughout the study period. The population of Ankistrodesmus sp. , Botryococcus braunii, Closterium parvulum, Pandorina morum, Scenedesmus quadricauda, and Spirogyra varians had their highest peak in July, while Ankistrodesmus falcatus, Oedogonium sp., Scenedesmus obliquus, and Staurodesmus cuspidatus had their maxima in August.

(B) Bacillariophyceae: The group Bacillariophyceae showed its highest peak in March-April at all stations (fig. 65). This group also showed an increasing trend in abundance from station 1 to station 6, the difference between stations being significant as shown in Table 12.

Bacillariophyceae comprised 16 species at Howietoun, the seasonal variation of which is shown in fig. 65 to fig. 70. The population of Cyclotella meneghiniana and Navicula cryptocephala had maxima during March. By April-May Asterionella formosa, Melosira italica-subarctica, Meridion circulare, Synedra ulna, and Tabellaria fenestrata had their highest peaks. Diatoma elongatum, Diatoma vulgare, Gomphonema geminatum, and Tabellaria flucculosa showed their highest peak in June, while the maxima of Amphora ovalis, Nitzschia linearis, Navicula viridis and Stephanodiscus hantzschii occurred in July. Gomphonema constrictum was the only diatom to have a peak in August.

(C) Rhodophyceae: The group Rhodophyceae was present only at stations 1, 2 and 3, being higher in number at station 1 than at the other stations (fig. 71). It was present from February to August with the highest peak by June. This group comprised Lemanea mammillosa and Chantransia pygmaea, which showed similar seasonal

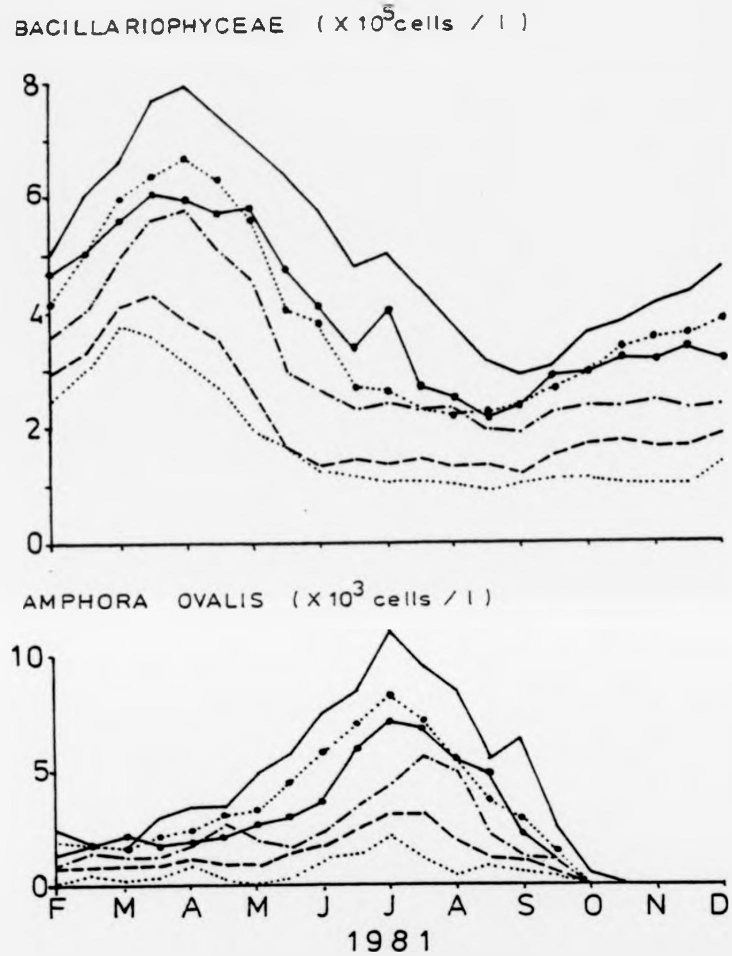

Fig.65: Seasonal changes in abundance of Bacillariophyceae and <u>Amphora</u> <u>ovalis</u> in Howietoun Farm at six stations during 1981

(...... St.1, --- St.2, -.- St.3, •—• St.4, •......• St.5, — St.6)

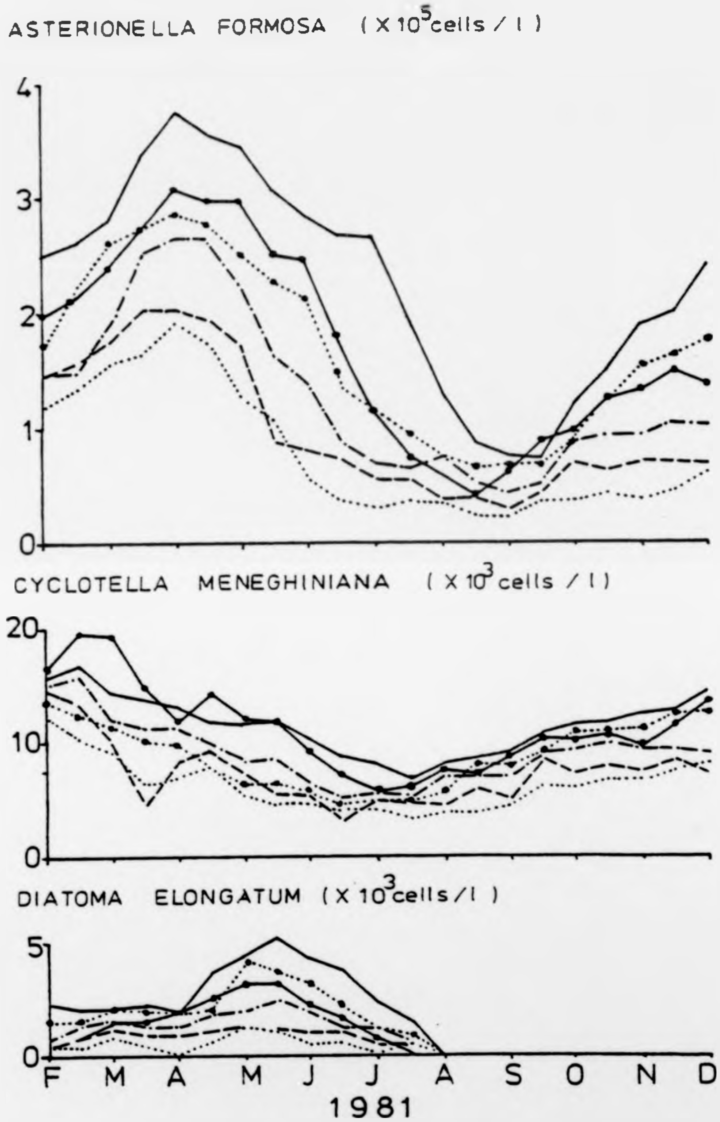

Fig.66: Seasonal changes in abundance of Asterionella formosa, Cyclotella meneghiniana, and Diatoma elongatum in Howietoun Farm at six stations during 1981

(...... St.1, --- St.2, .— St.3, —• St.4, •.... St.5, — St.6)

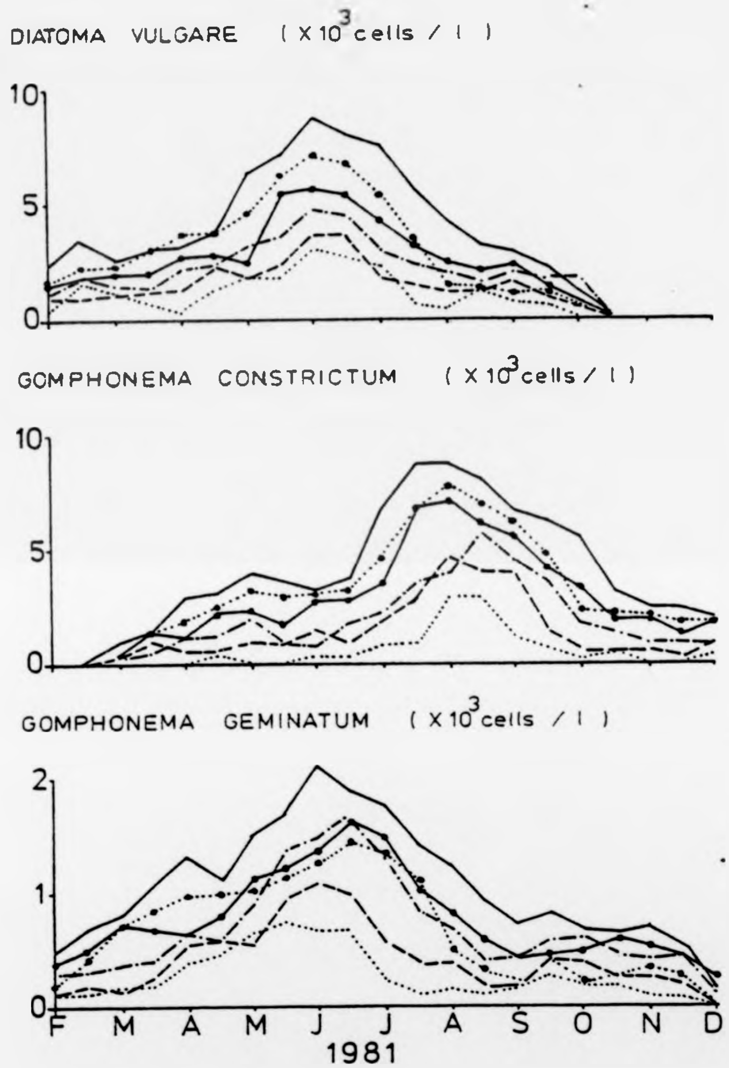

Fig.67: Seasonal changes in abundance of _Diatoma vulgare_, _Gomphonema constrictum_, and _Comphonema geminatum_ in Howietoun Farm at six stations during 1981

(...... St.1, ___ St.2, _._ St.3, ——• St.4, •......• St.5, — St.6)

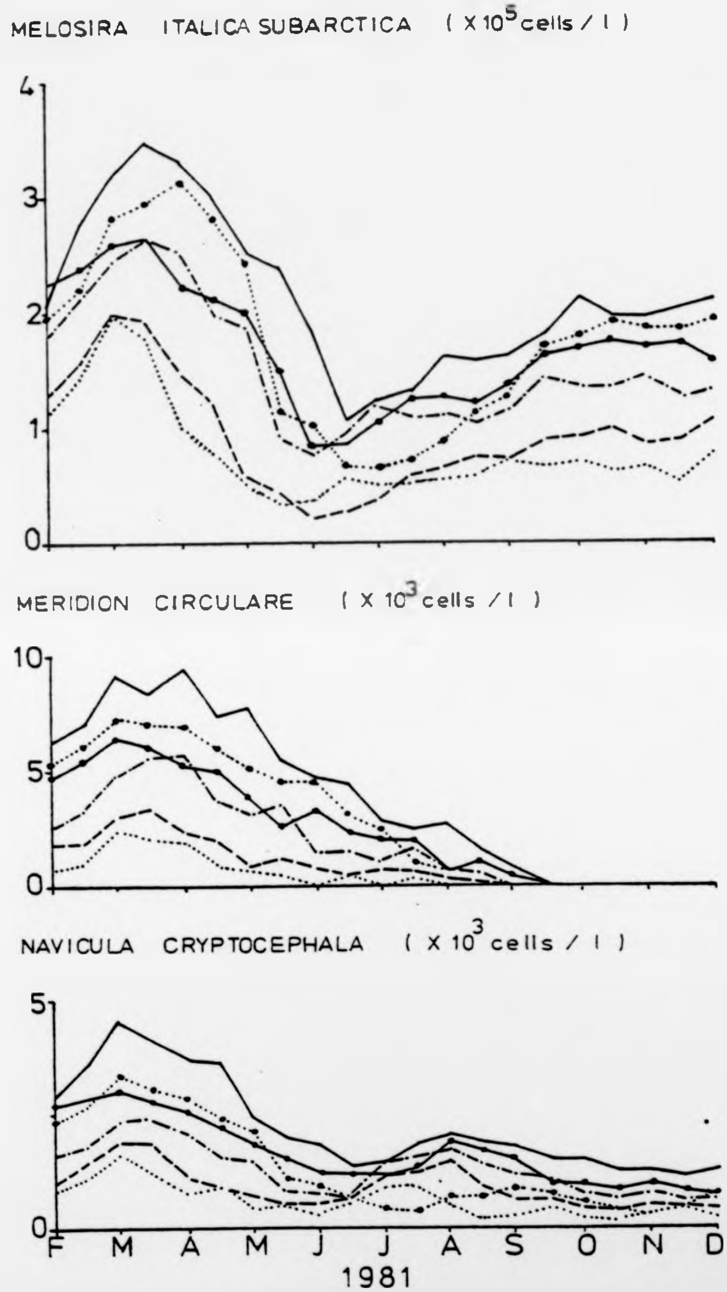

Fig.68: Seasonal changes in abundance of Melosira italica-subarctica, Meridion circulare, and Navicula cryptocephala in Howietoun Farm at six stations during 1981

(..... St.1, —— St.2, —.— St.3, •—• St.4, •.....• St.5, — St.6)

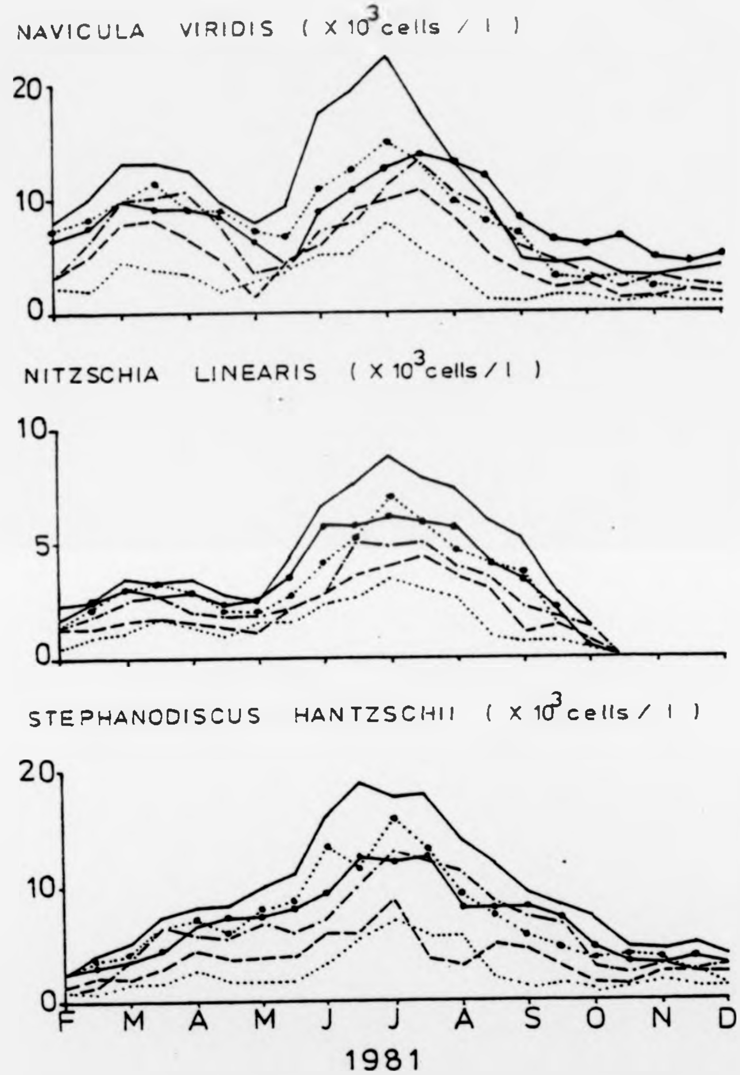

Fig.69: Seasonal changes in abundance of Navicula viridis, Nitzschia linearis, and Stephanodiscus hantzschii in Howietoun Farm at six stations during 1981

(..... St.1, ––– St.2, –·–· St.3, ——• St.4, •...• St.5, —— St.6)

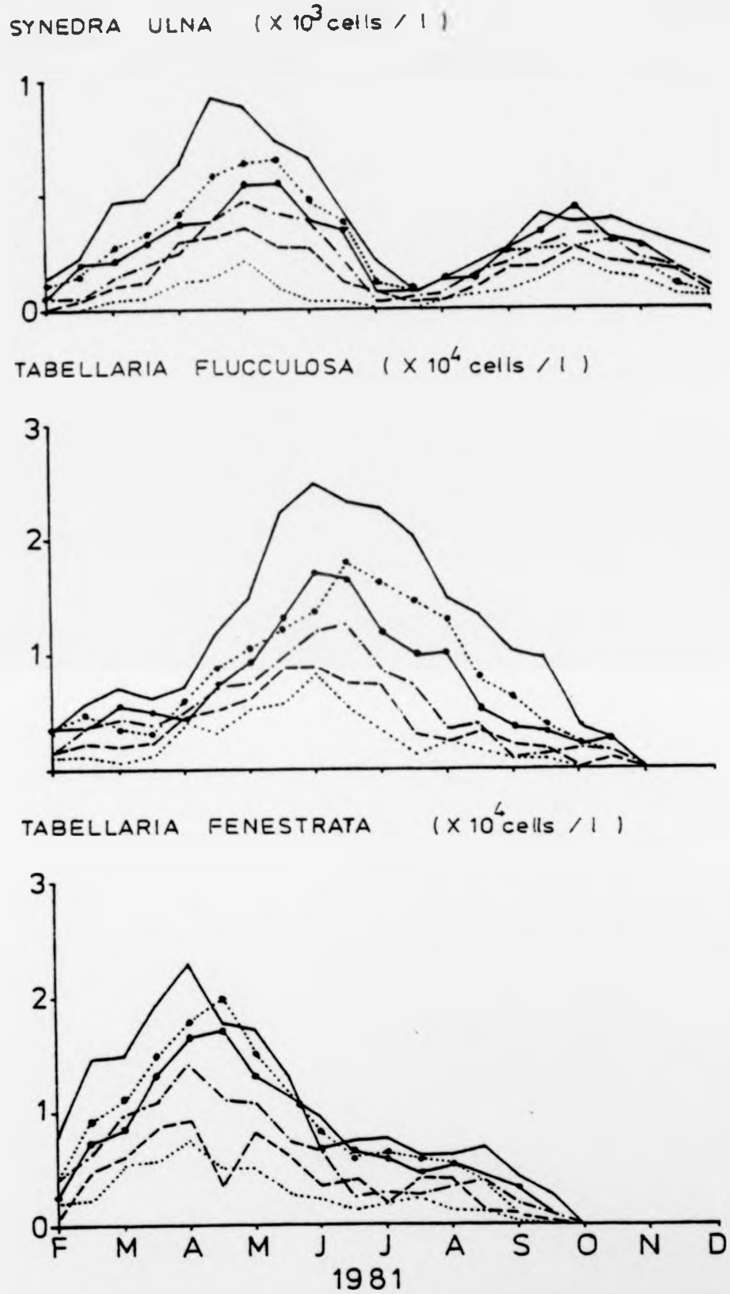

Fig.70: Seasonal changes in abundance of Synedra ulna, Tabellaria flucculosa, and Tabellaria fenestrata in Howietoun Farm at six stations during 1981

(...... St.1, ___ St.2, ._._ St.3, ___ St.4, ... St.5, ___ St.6) cycles (fig. 71).

(D) Cyanophyceae: The group Cyanophyceae showed its highest peak by July-August (fig. 72). Cyanophyceae showed an increasing trend from station 1 to station 6, and the difference between the stations was significant (Table 12).

The seasonal variation of *Anabaena flos-aquae*, *Coelosphaerium Kuetzingianum*, and *Oscillatoria agardhi* are shown in fig. 72 and fig. 73. *Anabaena flos-aquae* and *Oscillatoria agardhi* were present throughout the study period and both had their peak by July-August. *Coelosphaerium Kuetzingianum* was present from May to November with the highest peak in August.

5.2.12.2 Relative abundance of Phytoplankton:

(A) Chlorophyceae: The group Chlorophyceae formed a maximum of 7 to 36% of the total phytoplankton population during the summer months. Among chlorophyceans, *Botryococcus braunii* contributed most towards the total phytoplankton, while other chlorophyceans never formed more than 0.36%

(B) Bacillariophyceae: The group Bacillariophyceae was dominant over the other groups during February, March and December at all the stations. Of the total phytoplankton, it formed a maximum of 71% to 100% (fig. 74).

Asterionella formosa and *Melosira italica-subarctica* formed maxima of 31% to 57% and 30% to 50% respectively (fig. 74). But none of

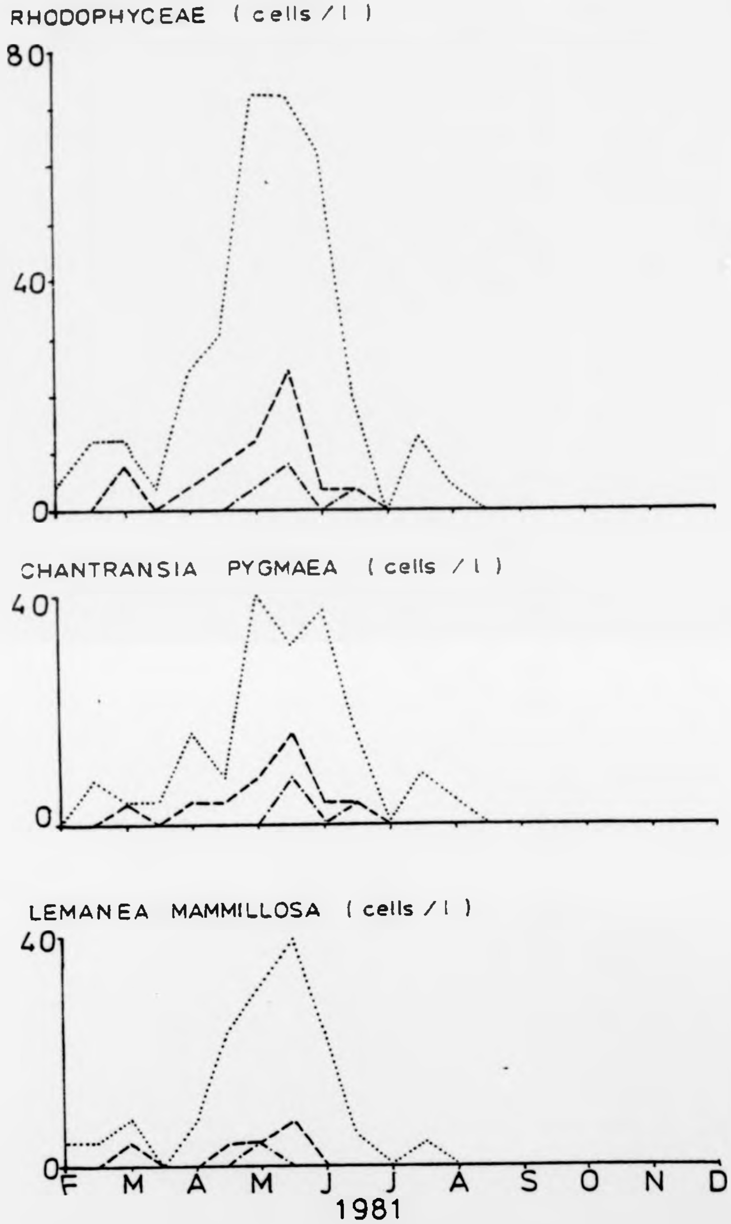

Fig.71: Seasonal changes in abundance of Rhodophyceae, Chantransia pygmaea, and Lemanea mammillosa in Howietoun Farm at six stations during 1981

(...... St.1, --- St.2, .-.- St.3, ---- St.4, ... St.5, —— St.6)

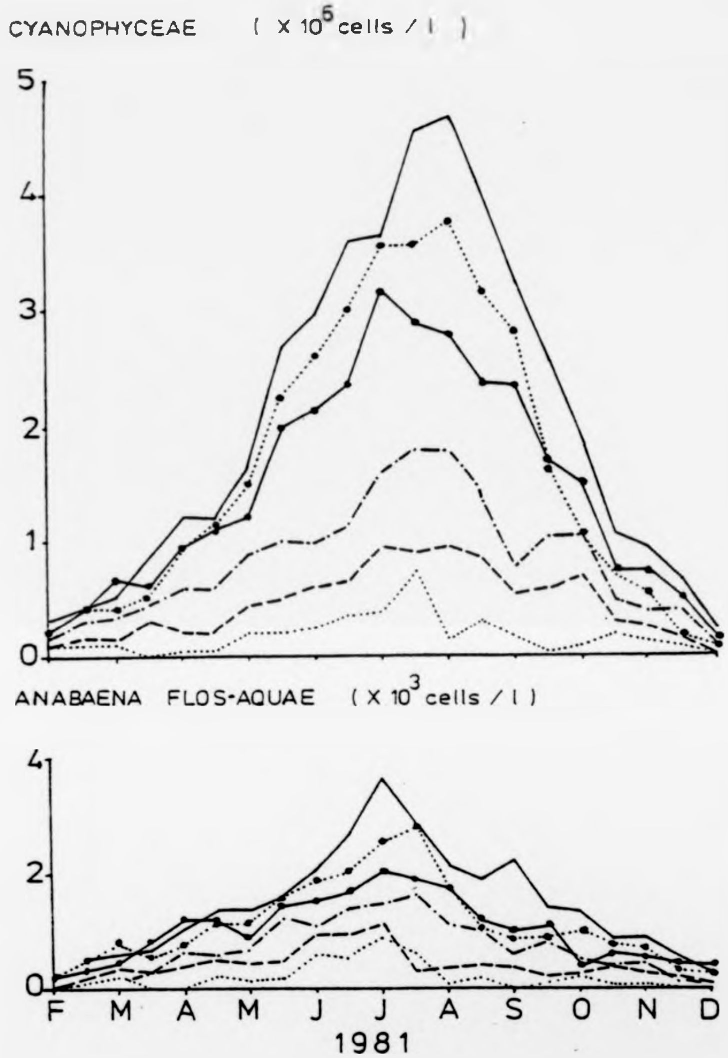

Fig.72: Seasonal changes in abundance of Cyanophyceae and <u>Anabaena flos-aquae</u> in Howietoun Farm at six stations during 1981

(....... St.1, --- St.2, .-.- St.3, —•— St.4, •.....• St.5, — St.6)

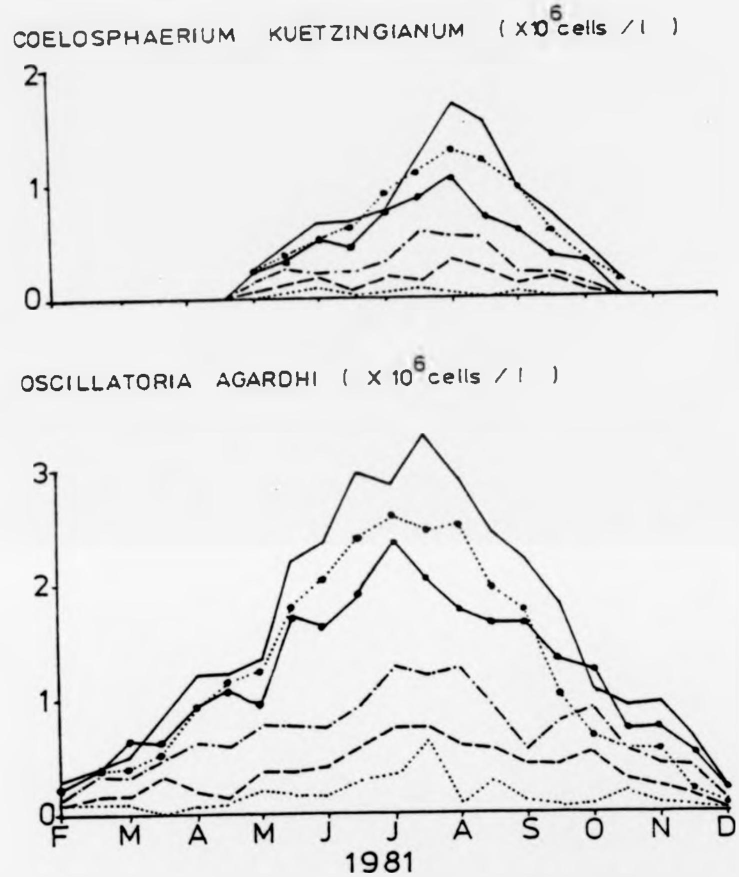

Fig.73: Seasonal changes in abundance of Coelosphaerium Kuetzingianum, and Oscillatoria agardhi in Howietoun Farm at six stations during 1981

(...... St.1, --- St.2, .— St.3, — St.4, •....• St.5, — St.6)

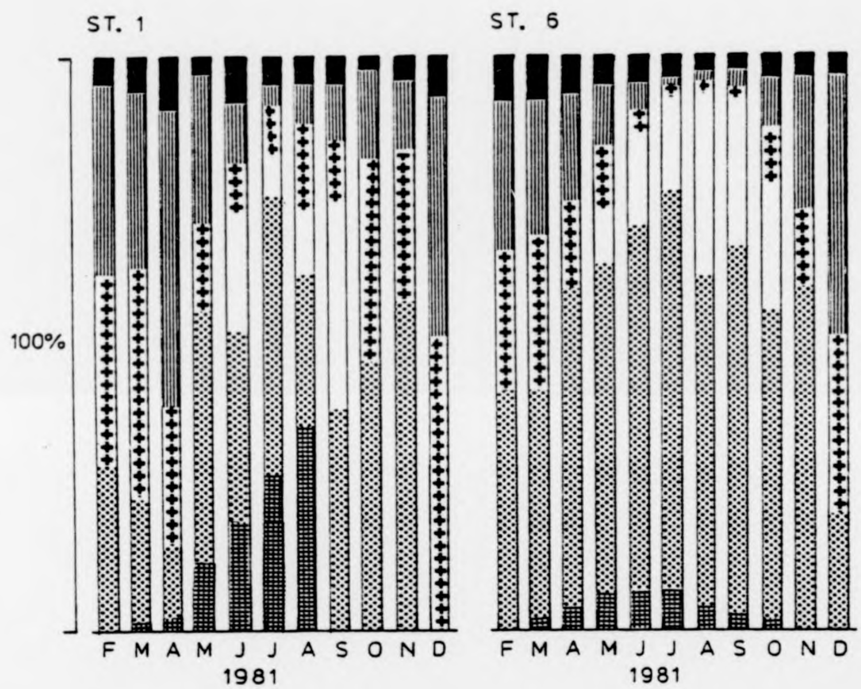

Fig.74: Relative abundance of phytoplankton in Howietoun Farm at stations 1 and 6 during 1981

(▦ Chlorophyceae, ▩ *Oscillatoria agardhi*,
□ other blue-greens, ⊞ *Melosira italica-subarctica*,
▥ *Asterionella formosa*, ■ other diatoms)

the other diatoms formed more than 2% each.

(C) Rhodophyceae: This group, when present, never formed more than 0.02% of the total phytoplankton.

(D) Cyanophyceae: The group Cyanophyceae was the most dominant group at Howietoun Fish Farm during April to November. Of the total phytoplankton, Cyanophyceae formed a maximum of 79% to 90% (fig. 74).

Anabaena flos-aquae never formed more than 0.13% at all the stations, while *Coelosphaerium Kuetzingianum* and *Oscillatoria agardhi* formed a maximum of 21% to 35% and 63% to 70%, respectively.

5.2.12.3 Species Succession of Phytoplankton:

The seasonal cycle, together with peaks of phytoplankton, have already been stated. In winter and the beginning of spring Bacillariophyceans were common, especially *Asterionella formosa* and *Melosira italica-subarctica*. By mid-summer, most of the diatoms had their maxima except *Gomphonema constrictum* which had its highest peak by August. By July-August all blue-greens, mainly *Coelosphaerium Kuetzingianum* and *Oscillatoria agardhi*, together with the chlorophyceans had their maxima which coincided with the peak abundance of total phytoplankton.

5.2.13 Zooplankton: The seasonal fluctuation of the total zooplankton population at all the six stations is shown in fig. 75. The population increased steadily from the beginning of study in February, reaching its peak during July at all the stations. The abundance of all groups of zooplankton was much lower at station 1 than at the

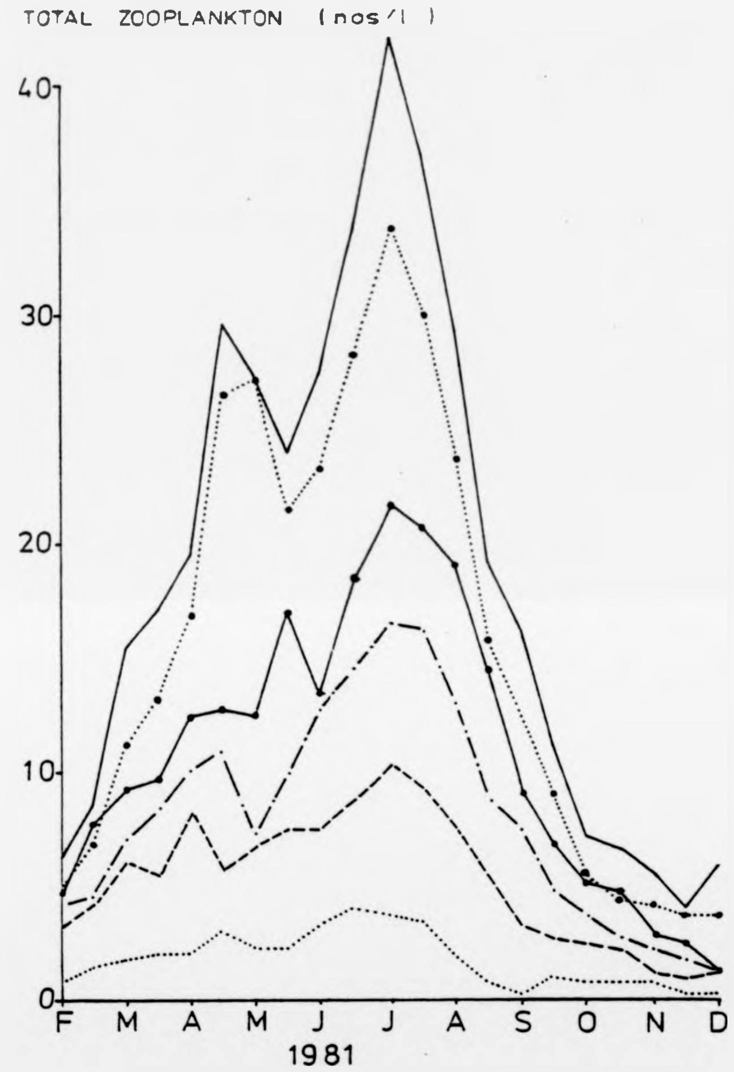

Fig.75: Seasonal changes in abundance of total zooplankton in Howietoun Farm at six stations during 1981

(...... St.1, ___ St.2, _._ St.3, ._. St.4, ... St.5, __ St.6) other stations and increased consistently to station 5, station differences being highly significant, as shown in Table 12.

Total zooplankton was positively correlated with the total phytoplankton at all the stations, the correlation being highly significant as shown in Table 11.

The total zooplankton in Howietoun Fish Farm comprised 9 species belonging to the groups Cladocera, Copepoda and Rotifera, which are listed in Table 14.

5.2.13.1 Seasonal variation of Zooplankton:

(A) Cladocera: The seasonal variation of total Cladocera is shown in fig. 76. Its population had the highest peak during May-June.

The group Cladocera comprised three species, the seasonal variation of which is shown in fig. 77. *Alonopsis elongata* was present from June to November at all the stations except where it was not recorded throughout the study period. Its population reached a maximum during August. *Bosmina longirostris* was present from the beginning of the study in February to July and had the highest peak during May at all the stations. Like *A. elongata*, *Chydorus ovalis* was also absent at station 1, and was present at all other stations from May to October with a high peak in July.

(B) Copepoda: The seasonal variation of Copepoda is shown in fig.78. It was presentfrom June to November at all stations with maxima during August.

Table 14: Zooplankton recorded in Howtoun Fish Farm during 1981

CLADOCERA

Alonopsis elongata Sars

Bosmina longirostris (O.F. Muler) s. str.

Chydorus ovalis Kurz

COPEPODA

Cyclops vicinus Uljanin

Diaptomus laciniatus Lilljeborg

ROTIFERA

Ascomorpha ecaudis Perty

Brachionus angularis Gosse

Filinia terminalis (Plate)

Keratella valga (Ehrb.)

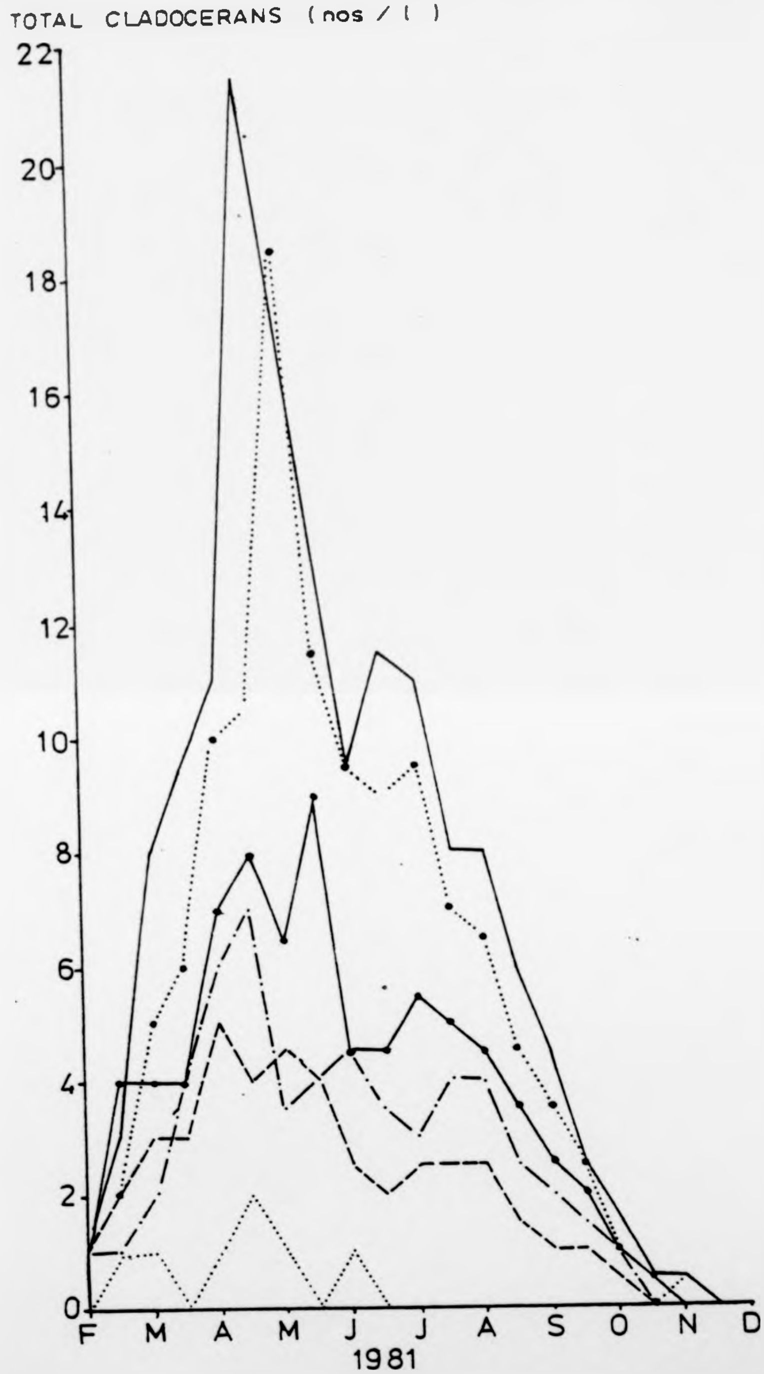

Fig.76: Seasonal changes in abundance of Cladocera in Howietoun Farm at six stations during 1981

(...... St.1, ––– St.2, –.– St.3, ––•–– St.4, •....• St.5, — St.6)

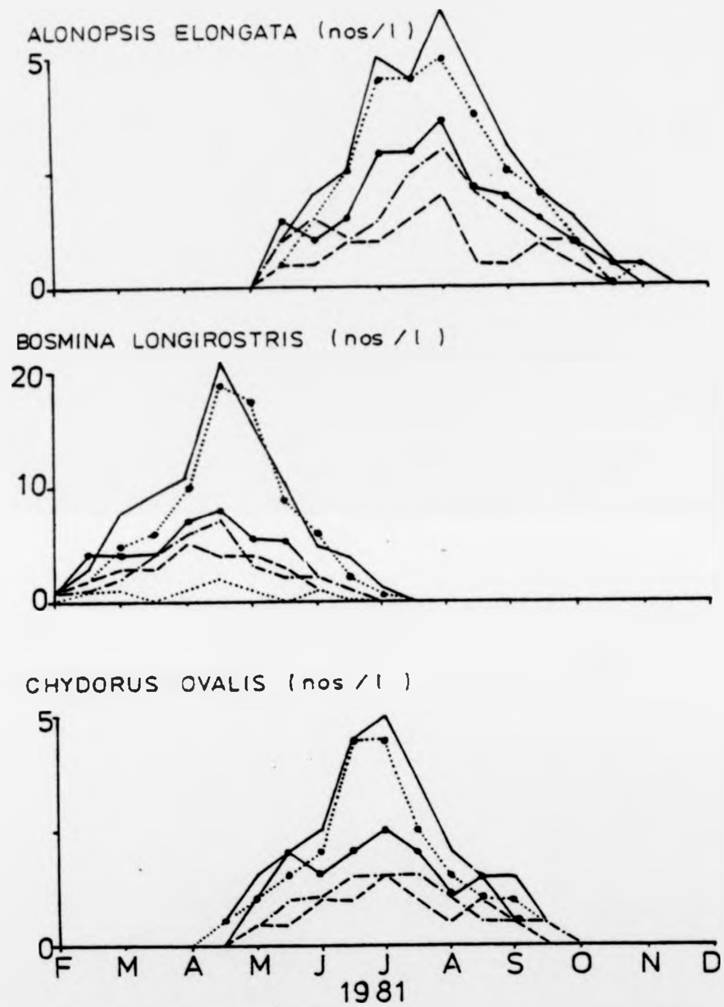

Fig.77 Seasonal changes in abundance of Alonopsis elongata, Bosmina longirostris, Chydorus ovalis, in Howietoun Farm at six stations during 1981

(..... St.1, ___ St.2, ._._ St.3, •—• St.4, •.....• St.5, — St.6)

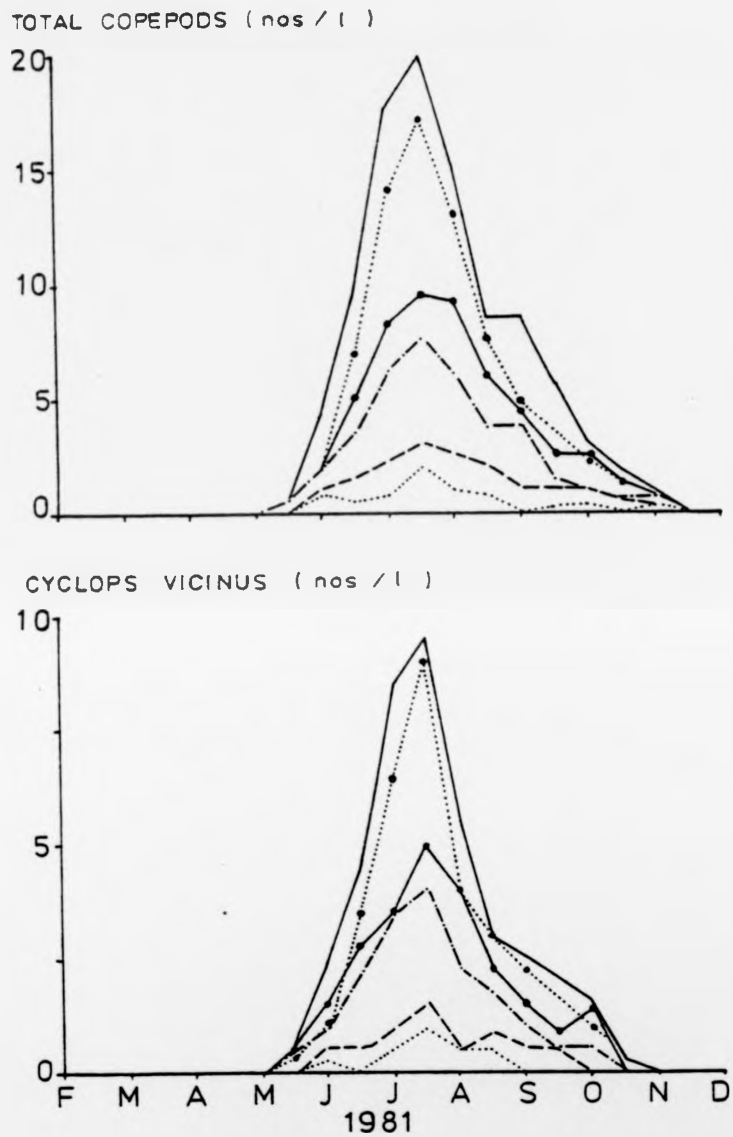

Fig.78: Seasonal changes in abundance of Copepoda and Cyclops vicinus in Howietoun Farm at six stations during 1981

(..... St.1, ___ St.2, ._._ St.3, .__. St.4, •.....• St.5, — St.6)

There were only two species of copepods, Cyclops vicinus and Diaptomus sp., the seasonal variation of which is shown in figs. 78 and 79. Both Cyclops vicinus and Diaptomus sp.started appearing from June and were present until November with the highest peak during August at all the stations.

(C) Rotifera: The group Rotifera was present throughout the study period and the seasonal variation is shown in fig. 79. Its population was maximum during July and minimum during October.

The seasonal variation of the four rotiferan species is shown in fig. 80. Only Keratella valga was present throughout the study period. Brachionus angularis was absent only during December, and Ascomorpha ecaudis was present from March to September. All three species were high in number by June-July. Filinia terminalis was the only winter species present.

5.2.13.2 Relative Abundance of Zooplankton:

(A) Cladocera: The group Cladocera was common during March to June as shown in fig. 81, forming a maximum of 63% - 73% of total zooplankton. Bosmina longirostris was the most common species when present, forming a maximum of 53% to 72% (fig. 81). Alonopsis elongata formed more of total zooplankton during August-September, forming a maximum of 22% to 36%; while Chydorus ovalis formed a maximum of 11% to 15%.

(B) Copepoda: The group Copepoda was common in total zooplankton during July to October (fig. 81). Cyclops vicinus comprised a

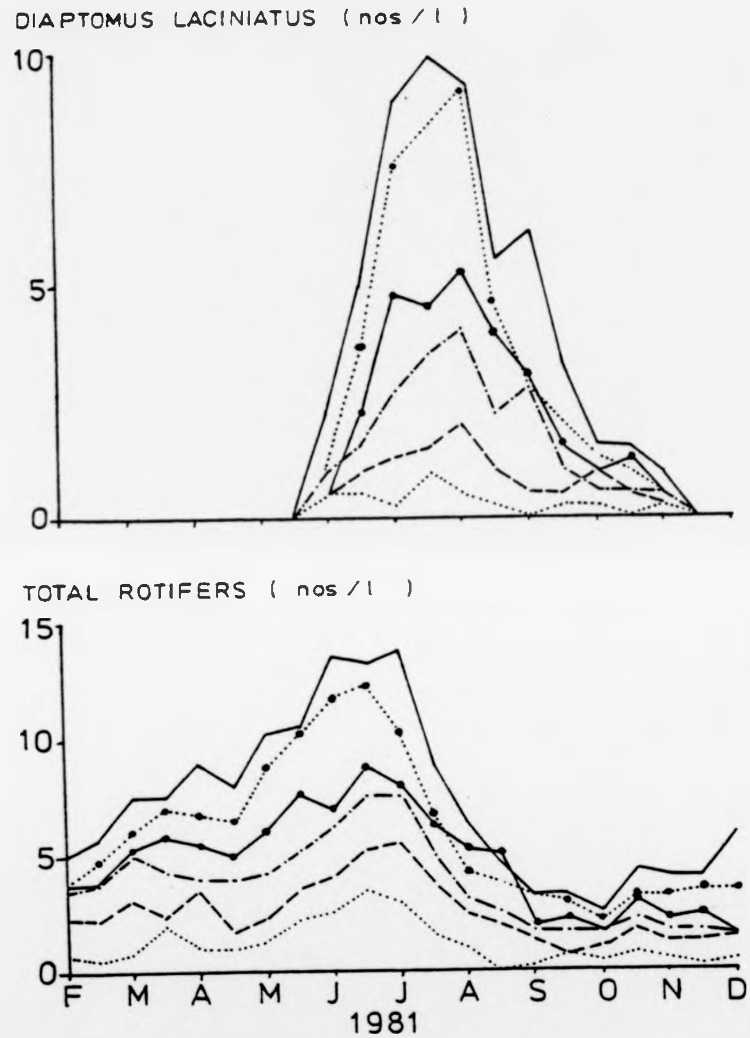

Fig.79: Seasonal changes in abundance of Diaptomus laciniatus and Rotifers in Howietoun Farm at six stations during 1981

(....... St.1, — — St.2, — . — St.3, •— St.4, •.....• St.5, —— St.6)

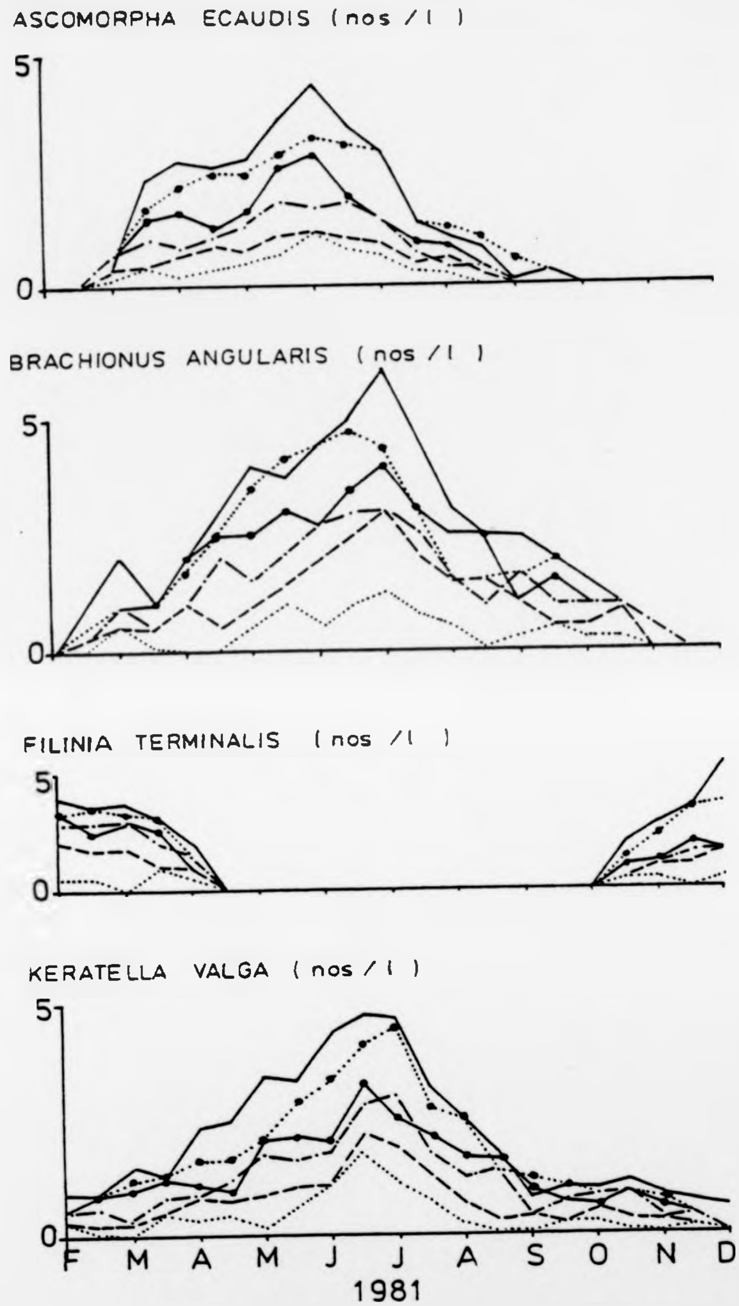

Fig.80: Seasonal changes in abundance of Ascomorpha ecaudis, Brachionus angularis, Filinia terminalis, and Keratella valga in Howietoun Farm at six stations during 1981

(...... St.1, --- St.2, -.- St.3, •— St.4, •....• St.5, — St.6)

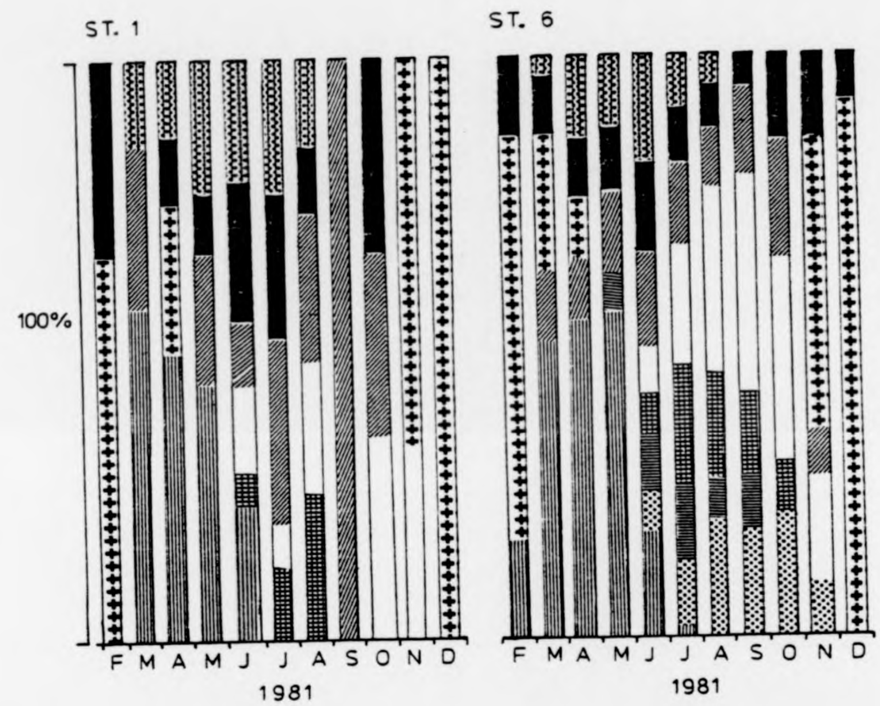

Fig.81: Relative abundance of zooplankton in Howietoun Farm at stations 1 and 6 during 1981

(Bosmina longirostris, Alonopsis elongata,
Chydorus ovalis, Cyclops vicinus,
Diaptomus laciniatus, Brachionus angularis,
Filinia terminatus, Keratella valga,
Ascomorpha ecaudis)

maximum of 24% to 67% of total zooplankton, while <u>Diaptomus</u> op. comprised a maximum of 33% to 40%

(C) <u>Rotifera</u>: The group Rotifera was most common during December (fig. 81). <u>Brachionus angularis</u> and <u>Keratella valga</u> were among the common zooplankton. <u>Filinia terminalis</u> dominated during December, when it formed 100% at most stations.

5.2.14 <u>Periphyton</u>: Total periphyton showed the highest peak during July at all stations (fig. 82). The abundance of all groups except Rhodophyceae increased from station 1 to station 5, and the difference between stations was significant (Table 12). Periphyton comprised 25 species in Howietoun Fish Farm, which are listed in Table 15.

The total periphyton was positively correlated with the total phytoplankton, the correlation coefficient being significant (Table 11).

5.2.14.1 <u>Seasonal Variation of Periphyton</u>:

(A) <u>Chlorophyceae</u>: The seasonal variation of Chlorophyceae is shown in fig. 83. It was highest in number during June-July at all the stations.

This group comprised 5 species, the seasonal variation of which is shown in fig. 83 to fig. 84. <u>Ankistrodesmus</u> sp. and <u>Scenedesmus quadricauda</u> were present from the beginning of study in February and were maximum during July. <u>Ankistrodesmus falcatus</u>,

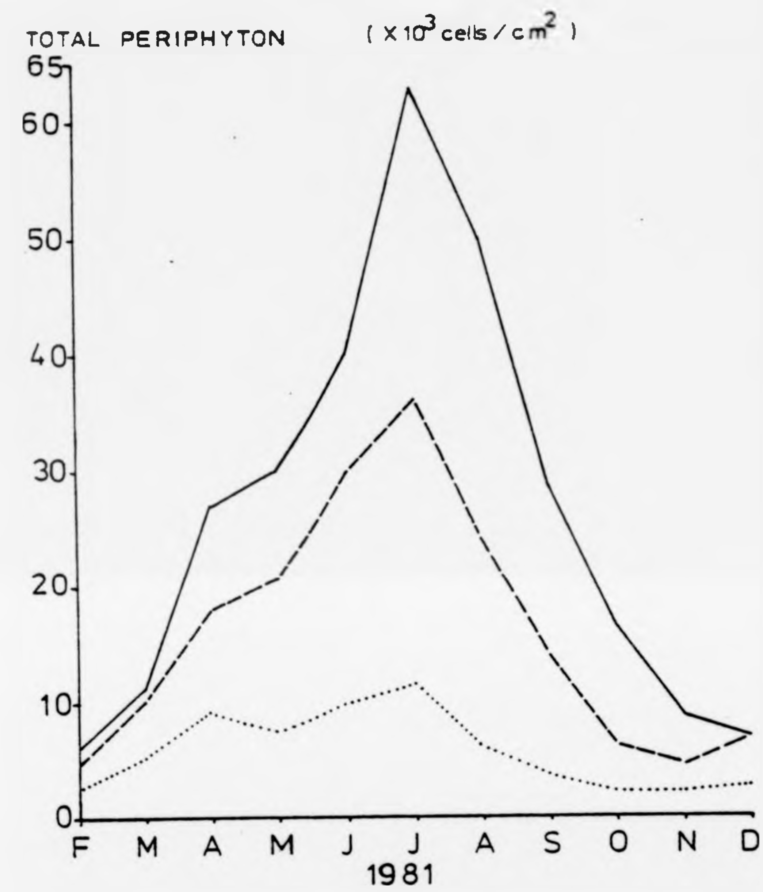

Fig.82: Seasonal changes in abundance of total periphyton in Howietoun Farm at stations 1, 3 and 5 during 1981

(....... St.1, ___ St.3, —— St.5)

Table 15: Attached algae recorded in Howietoun Fish Farm during 1981

CHLOROPHYCEAE

Ankistrodesmus falcatus (Corda) Ralfs

Ankistrodesmus sp.

Oedogonium sp.

Scenedesmus quadricauda (Turp.) Breb.

Scenedesmus obliquus (Turp.) Kutz

Spirogyra varians (Hassall) Kutz

BACILLARIOPHYCEAE

Amphora ovalis Kutz

Asterionella formosa Hass

Cyclotella meneghiniana Kutz

Diatoma elongatum Ag.

Diatoma vulgare Bory.

Gomphonema constrictum Ehrenb.

Gomphonema geminatum (Lyngb.) Ag.

Melosira italica-(Ehrenb.) Kutz *subarctica* Mull

Meridion circulare (Geville) Agardh

Navicula cryptocephala Kutz

Navicula viridis Kutz

Nitzschia linearis (Ag.) W.Sm.

Stephanodiscus hantzschii Grunow

Synedra ulna (Nitzsch) Ehrenb.

Tabellaria fenestrata (Lyngb.) Kutz

Tabellaria flucculosa (Roth) Kutz

Table 15 cont'd.

RHODOPHYCEAE

Lemanea mammillosa Kutz

CYANOPHYCEAE

Anabaena flos-aquae (Lyngb.) Breb.

Oscillatoria agardhi Gomond

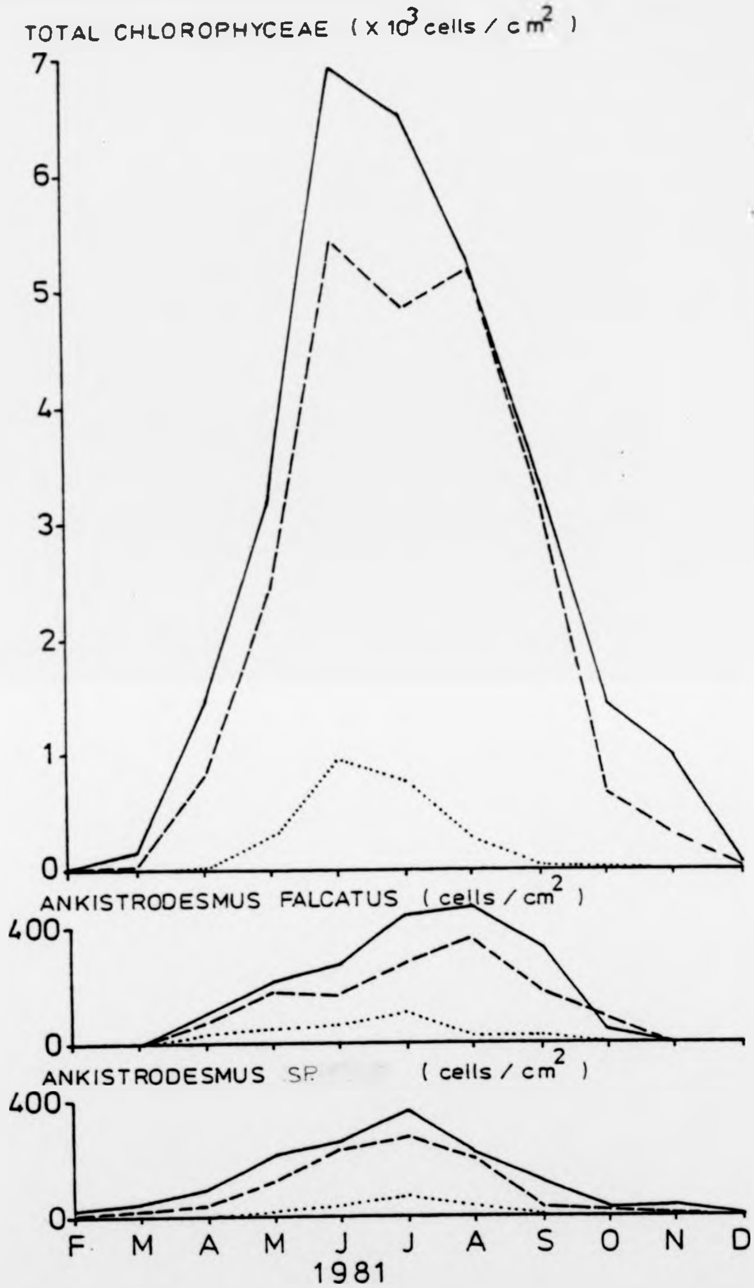

Fig.83: Seasonal changes in abundance of Chlorophyceae, Ankistrodesmus falcatus, Ankistrodesmus sp. on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981

(...... St.1, --- St.3, — St.5)

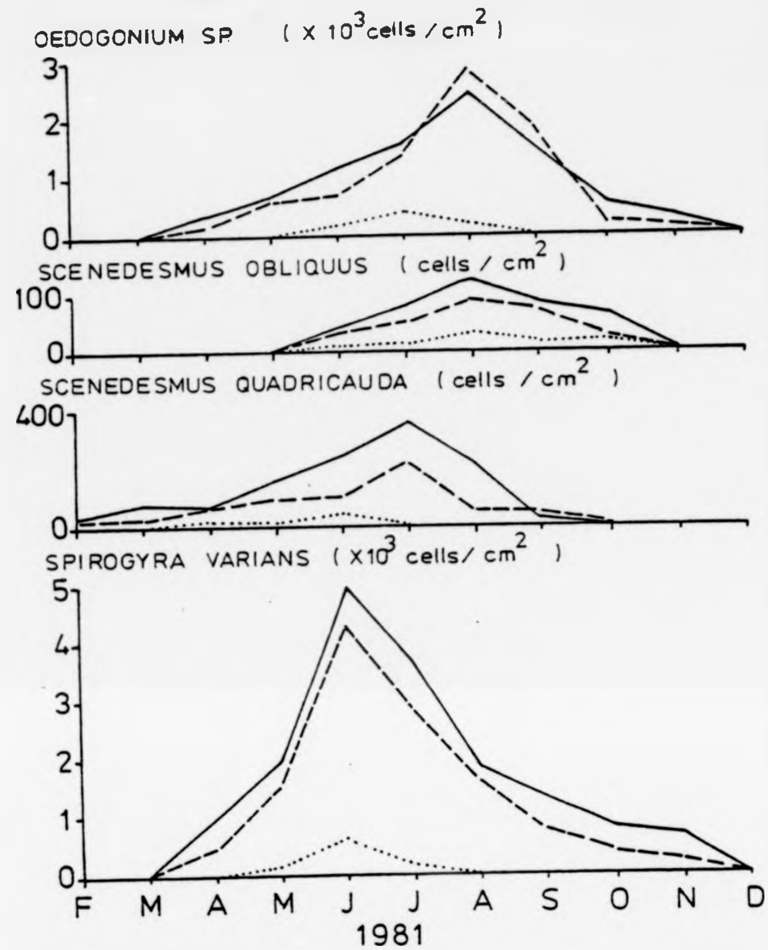

Fig.84: Seasonal changes in abundance of Oedogonium sp., Scenedesmus obliquus, Scenedesmus quadricauda, and Spirogyra varians on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981

(...... St.1, --- St.3, — St.5)

Oedogonium sp., and Spirogyra varians started appearing by April; the first two reached their maxima by August while S. varians was at a maximum during June. Scenedesmus obliquus was present only from June to October with a peak in August.

(B) Bacillariophyceae: Seasonal variation of Bacillariophyceae is shown in fig. 85. The total population reached its highest peak by April at all stations.

Bacillariophyceae comprised 16 species, the seasonal variation of which is shown in fig. 85 to fig. 88. Only 8 species, viz. Asterionella formosa, Cyclotella meneghiniana, Gomphonema geminatum, Melosira italica-subarctica, Navicula cryptocephala, Navicula viridis, Stephanodiscus hantzschii, and Synedra ulna were present throughout the study period. C. meneghiniana and M. italica-subarctica had their highest peak during March, A. formosa and N. cryptocephala were maximum by April, G. geminatum and S. ulna were maximum by June and May respectively, while N. viridis and S. hantzschii had their maxima by July. The maximum number recorded of Diatoma elongatum and Tabellaria fenestrata was during April-May; and Amphora ovalis, Diatoma vulgare, and Tabellaria flucculosa were high in number by June-July. By August, Gomphonema constrictum had its maximum.

(C) Rhodophyceae: The group Rhodophyceae was represented in periphyton only by Lemanea mammillosa. It was present only at station 1 during March, May and June (fig. 88) forming only .01% to .09% of total periphyton.

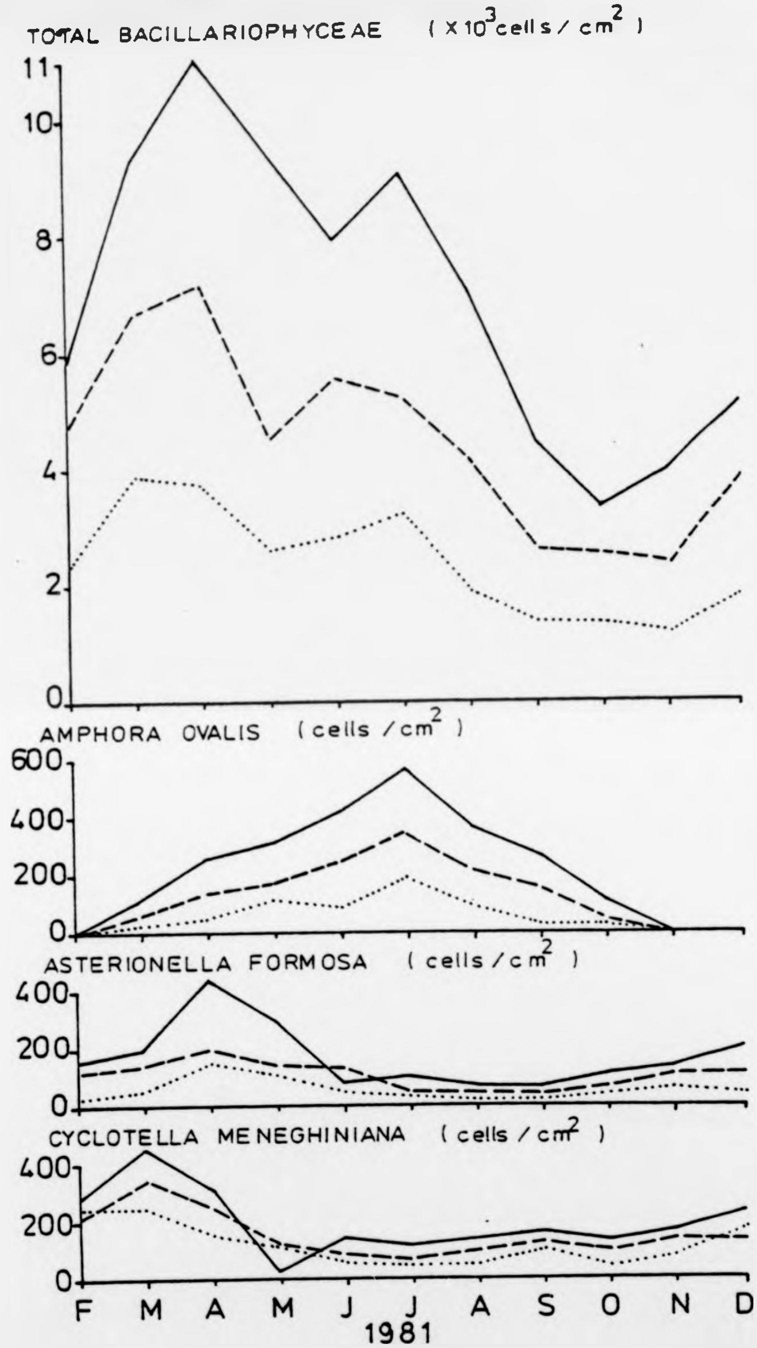

Fig.85: Seasonal changes in abundance of Bacillariophyceae, Amphora ovalis, Asterionella formosa, and Cyclotella meneghiniana on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981

(...... St.1, --- St.3, —— St.5)

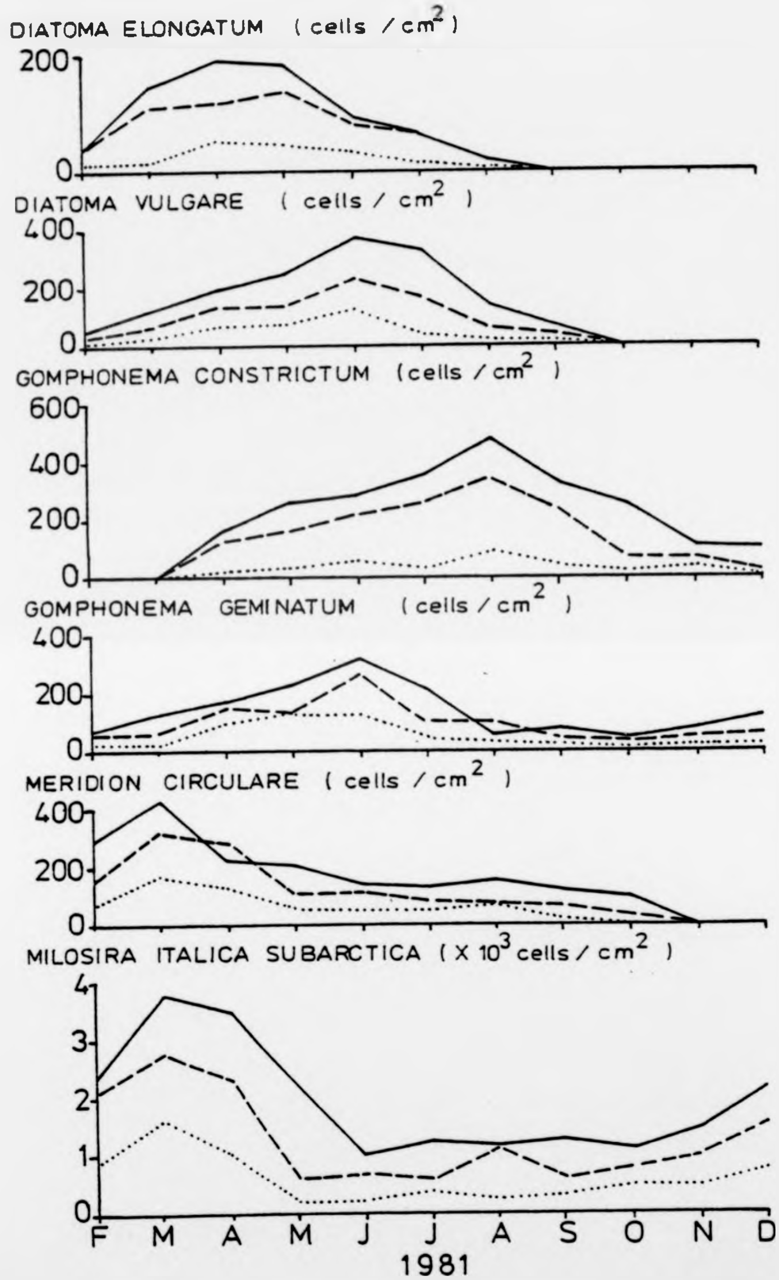

Fig.86: Seasonal changes in abundance of Diatoma elongatum, Diatoma vulgare, Gomphonema constrictum, Gomphonema geminatum, Meridion circulare, Melosira italica-subarctica on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981

(...... St.1, --- St.3, —— St.5)

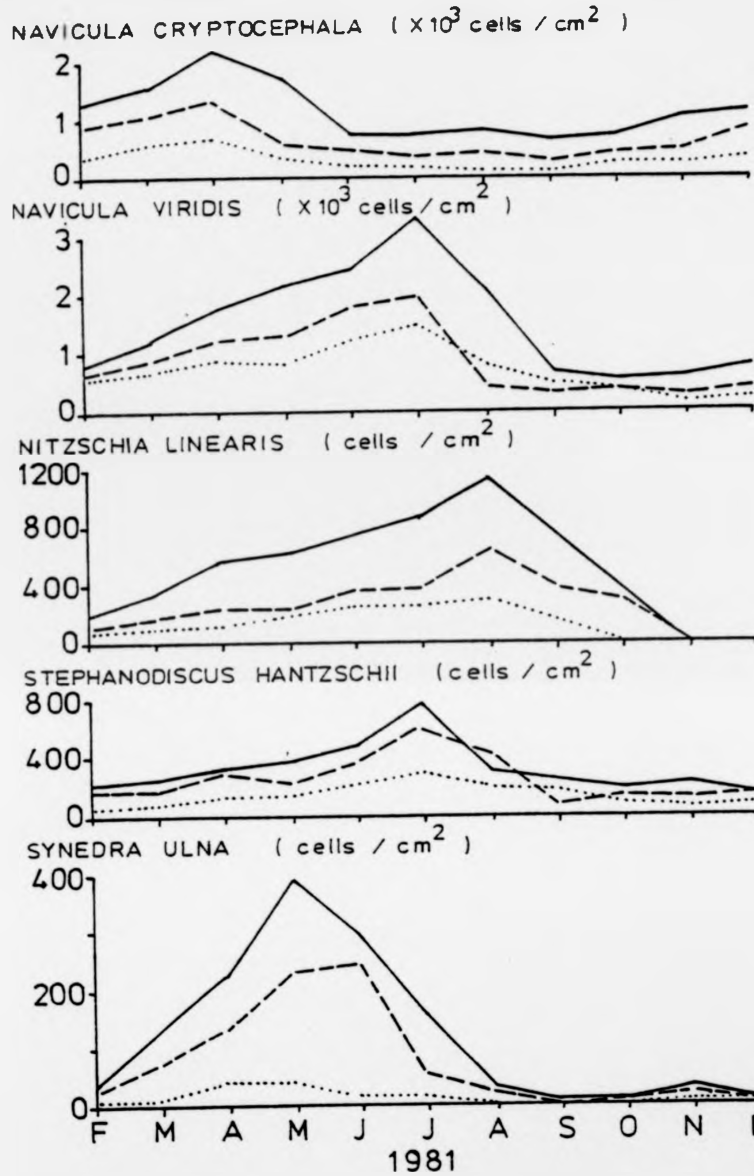

Fig.87: Seasonal changes in abundance of Navicula cryptocephala, Navicula viridis, Nitzschia linearis, Stephanodiscus hantzschii, Synedra ulna on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981

(...... St.1, ---- St.3, —— St.5)

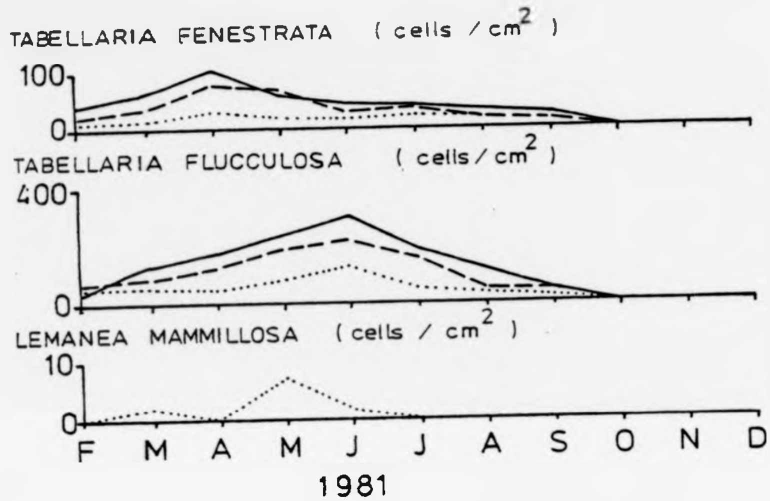

Fig. 88: Seasonal changes in abundance of Tabellaria fenestrata, Tabellaria flucculosa, and Lemanea mammillosa on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981

(....... St.1, ___ St.3, ___ St.5)

(D) Cyanophyceae: Total Cyanophyceae had its highest peak during July at all stations (fig. 89). It comprised only Anabaena flos-aquae and Oscillatoria agardhi, the seasonal fluctuations of which are shown in fig. 89. Both were mostly present throughout the study period and had their maxima by July.

5.2.14.2 Relative Abundance of Periphyton:

(A) Chlorophyceae: The percentage composition of chlorophyceae is shown in fig. 90. Of the total periphyton, it formed a maximum of 9% to 23%. Ankistrodesmus falcatus, Ankistrodesmus sp. , Scenedesmus quadricauda, and Scenedesmus obliquus never formed more than 1.5% each at all stations. Oedogonium sp. and Spirogyra varians formed maxima of 3% to 14% and 6% to 14% , respectively.

(B) Bacillariophyceae: Bacillariophyceae formed a maximum of 46% to 55% (fig. 90). Melosira italica-subarctica was the most abundant diatom, forming up to 34% to 43% of the total periphyton. The other major species were Cyclotella meneghiniana, Navicula cryptocephala, and Navicula viridis, which formed maxima of 8% to 21%. Asterionella formosa, Meridion circulare, Nitzschia linearis, and Stephanodiscus hantzschii never formed more than 5%.

(C) Cyanophyceae: The group Cyanophyceae was dominant from April to October at all stations, forming a maximum of 49% to 76% of total periphyton (fig. 90). Oscillatoria agardhi was the most common species among the periphyton, forming a maximum of 20% to 70%. Anabaena flos-aquae formed a maximum of 5% to 10% of total periphyton.

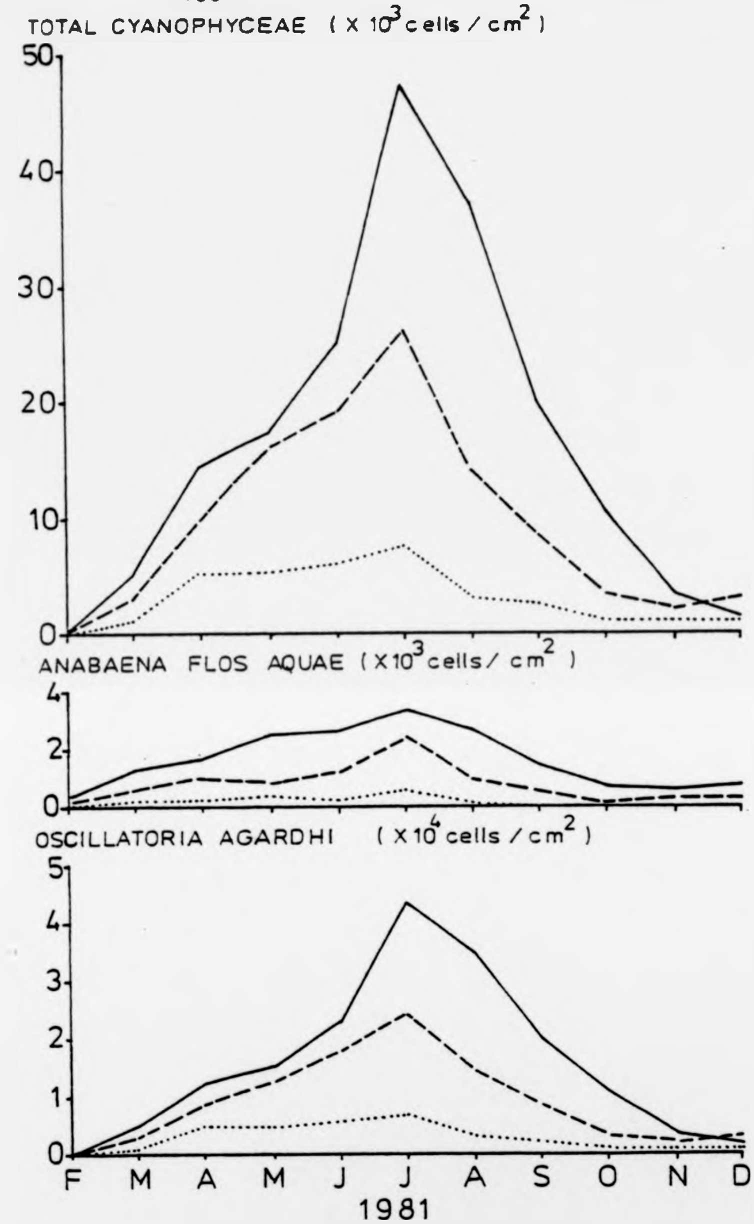

Fig.89: Seasonal changes in abundance of Cyanophyceae, Anabaena flos-aquae, Oscillatoria agardhi, on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981

(....... St.1, --- St.3, —— St.5)

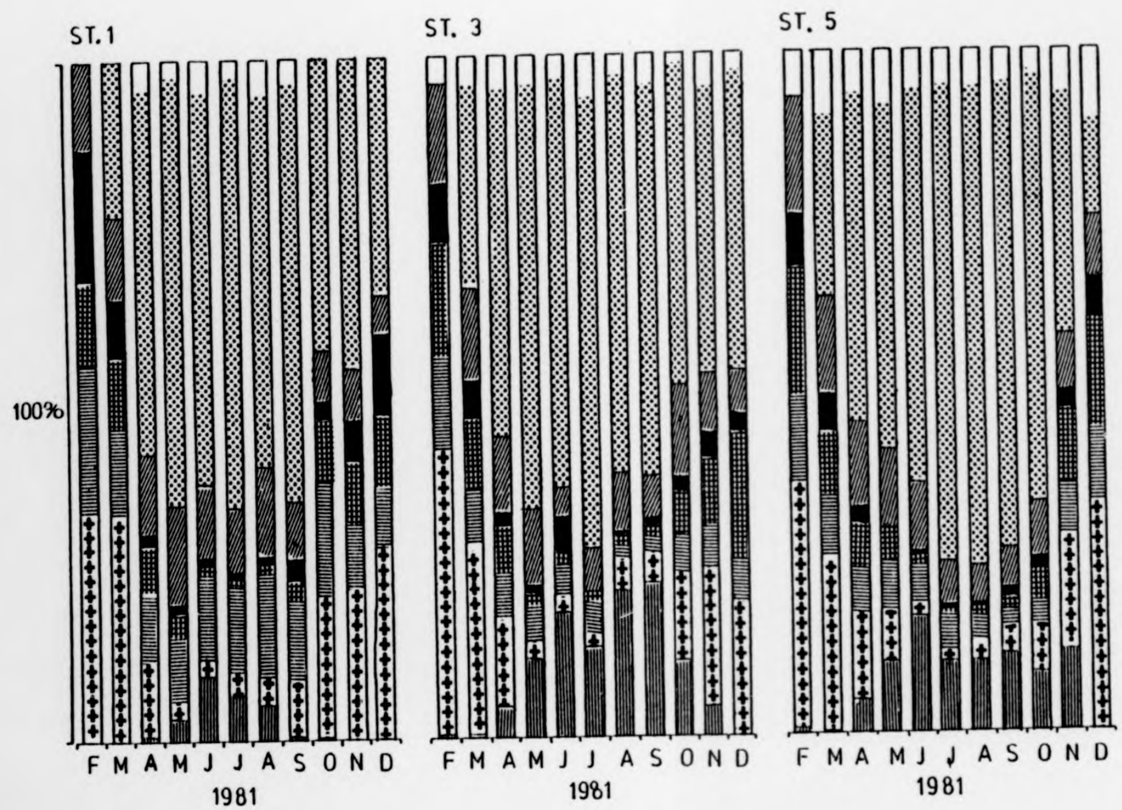

Fig.90: Relative abundance of periphyton on wooden substrates in Howietoun Farm at stations 1, 3 and 5 during 1981.

(Chlorophyceae, Melosira italica-subarctica, Navicula viridis, Navicula cryptocephala, Cyclotella meneghiniana, other diatoms, Anabaena flos-aquae, Oscillatoria agardhi)

5.2.14.3 Summary of Species Succession of Periphyton

In the spring, periphyton bacillariophyceans, mainly *Asterionella formosa*, *Cyclotella meneghiniana*, *Melosira italica-subarctica* and *Navicula cryptocephala* were common. By early summer *Spirogyra varians* together with diatoms were common. The two representatives of Cyanophyceae, *Anabaena flos-aquae* and *Oscillatoria agardhi* had peaks together with those of *Navicula viridis* and *Stephanodiscus hantzschii* etc. by July. The late summer was the time when *Ankistrodesmus falcatus*, *Oedogonium* sp., and *Scenedesmus obliquus*, together with *Gomphonema constrictum* and *Nitzschia linearis* had their peaks

5.2.15 Diurnal Studies: To study the diurnal cycle of physico-chemical parameters, phytoplankton and zooplankton samples were taken from stations 4 and 5 from the surface layer on 5th - 6th April 1981.

The diurnal changes in the physico-chemical parameters areshown in figs. 91 and 92. Water temperature was highest at 16.00 hrs. and lowest at 01.00 hrs. The difference in the maximum and minimum temperature was only 2°c.

p^H was lower at station 5 than at station 4 at the start of study but rose to equal that at station 4 at 16.00 hrs., when it was maximum at both stations, after which it decreased during night hours.

Dissolved oxygen concentration was higher at station 5 than at station 4 only during daylight hours. At both stations it showed an increasing

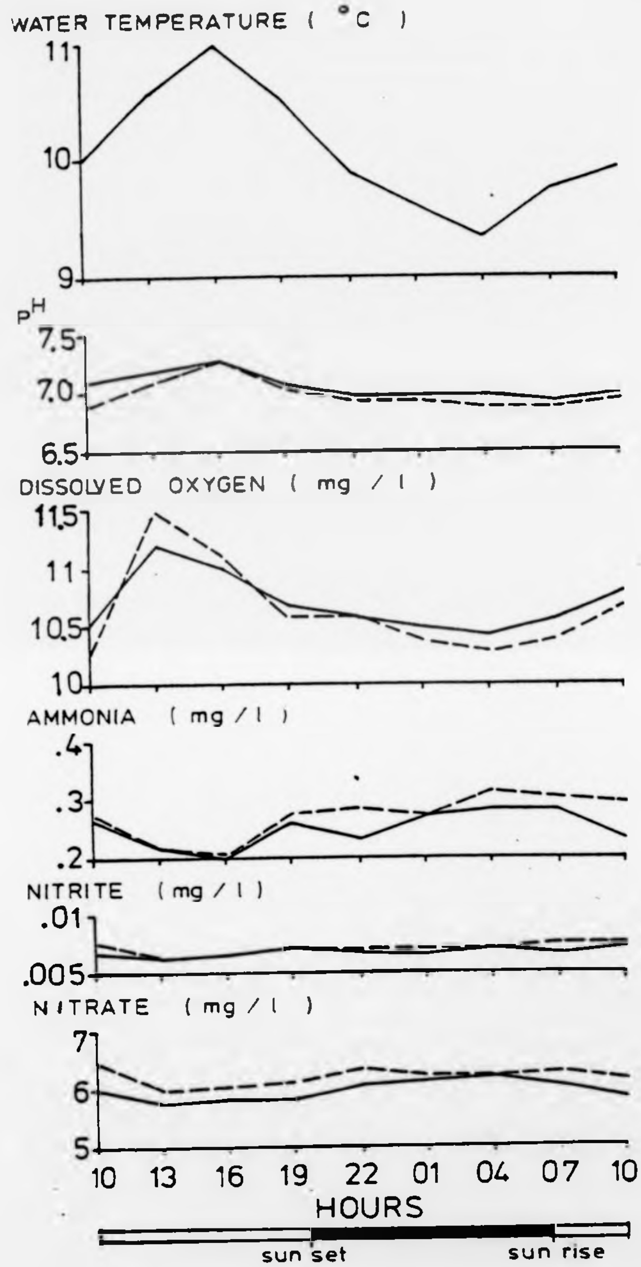

Fig.91: Diurnal changes in water temperature, pH, dissolved oxygen, ammonia, nitrite, nitrate in Howietoun Farm at stations 4 and 5 during 5th-6th April 1981

(___ St.4, _ _ _ St.5)

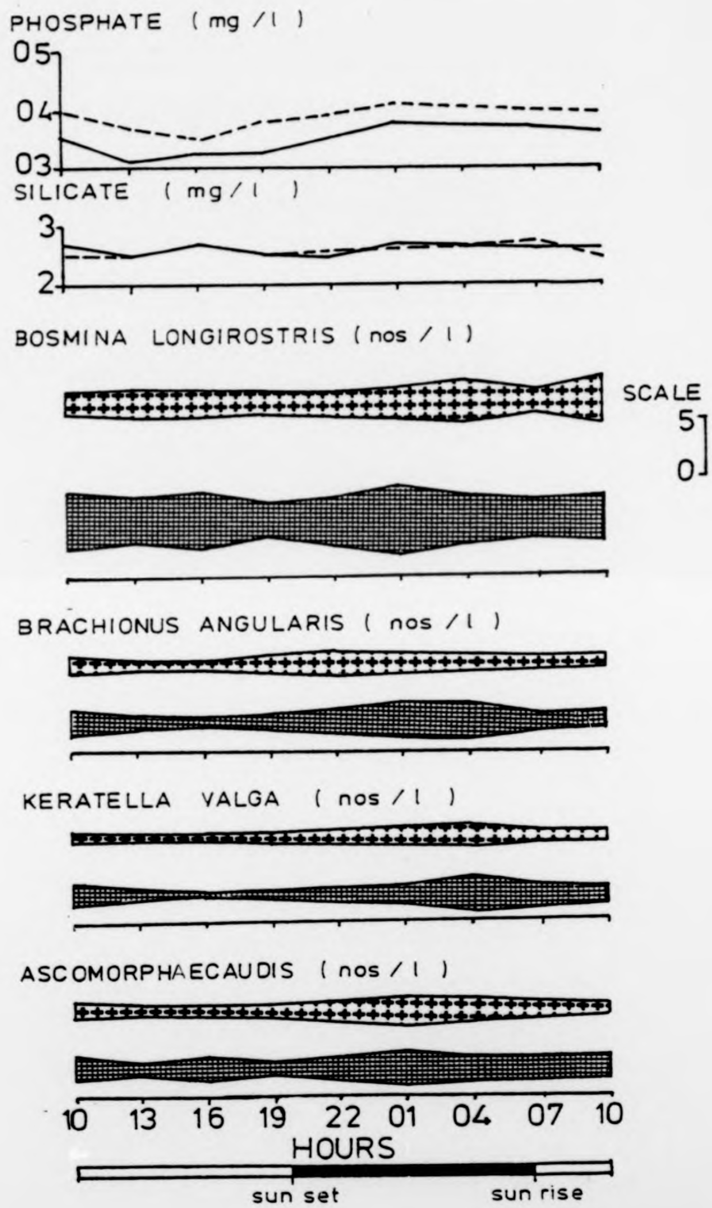

Fig.92: Diurnal changes in orthophosphate, silicate, Bosmina longirostris, Brachionus angularis, Keratella valga, Ascomorpha ecaudis, in Howietoun Farm at stations 4 and 5 during 5th-6th April 1981

(__ ⊞ St.4, __ ▦ St.5)

trend during the day, reaching a maximum at 13.00 hrs. and a decreasing trend during the night, being minimum at 04.00 hrs.

Ammonia, Nitrate and Phosphate concentrations decreased during the day and increased at night at both the stations. But Nitrite and Silicate concentrations showed no marked pattern of diel changes.

None of the phytoplankton showed any diurnal pattern during the period of study, so their data is not presented.

Only four zooplankton species were present during the study period. Bosmina longirostris was maximum in number at 04.00 hrs. at station 4, and at 01.00 hrs. at station 5, but its diurnal variation pattern was not very marked. Brachionus angularis, Keratella valga, and Ascomorpha ecaudis showed diurnal variation, decreasing during daytime and increasing at night (fig. 92). in surface samples.

6. DISCUSSION

Water Temperature:

Water temperature is one of the most studied parameters in aquatic biological investigations. At both Loch Fad and Howietoun Fish Farm the water temperature followed the same pattern as that of air temperature. At Loch Fad thermal stratification was never noticed, and the maximum temperature difference between the surface and bottom layers was 0.6°c. This absence of thermal stratification was due to the shallowness of the loch and the prevailing wind action which mixes the loch water thoroughly. At the cage site the mixing is aided by the movements of the cage rafts as they are anchored at one single point and free to move in a circle of 82m diameter according to the wind direction. At Howietoun, any difference of water temperature between the stations (maximum being 0.5°c) was mainly due to the irradiation during the period of sample collections.

Temperature is perhaps the factor most constant in its effect on the various species of phytoplankton and zooplankton. Although some species prefer colder temperatures, most of them show their highest peak during the warmer months of the year. At both Loch Fad and Howietoun Fish Farm the highest peak of phytoplankton and zooplankton were seen during the warmer months.

Transparency:

The fluctuations of transparency (Secchi disc depths) in a water body are indicative of either the phytoplankton population or the turbidity due to the colloidal soil particles and the suspended solids. The greater the density of either, the lower will be the Secchi disc readings. Chandler (1942), Bachmann and Jones (1974), Dillon and Rigler (1975), Bales et al (1980), Canfield and Bachmann (1981), Blaauboer (1982), etc. have demonstrated the inverse relation between transparency and the suspended matter (autochthonous/allochthonous). The inverse relation between transparency and the chlorophyll-a concentration was reported by Edmondson (1972), Bachmann and Jones (1974), Carlson (1977), Forsberg and Ryding (1980), and Canfield and Bachmann (1981).

In Loch Fad the Secchi disc reading was low during summer months; the lowest reading coincided with the highest peaks of phytoplankton and the suspended solids at both the sites. The lower Secchi disc reading at the cage site rather than at the control site during most of the study period can be ascribed to the higher phytoplankton population, together with suspended fish faecal material and fish food particles.

In addition to other parameters, the Secchi disc transparency is often used for its simplicity to describe the trophic situation of water bodies (Rawson, 1960; Pennak, 1968). If the turbidity is primarily the product of autochthonous, particulate organic matter, living or dead, one might expect a negative relationship between Secchi disc values and degree of eutrophication. If, on the other hand, significant fractions of the turbidity are caused by allochthonous materials, such a relationship would not necessarily be in evidence. In Loch Fad, as has already been said, the transparency was affected mainly by the presence of the phytoplankton population and suspended organic materials. The contribution of rainfall in adding the soil particles washed from the catchment area did not have much effect on the Secchi disc reading, as the Secchi disc reading was low when the rainfall was also low.

Table 16: Suggested trophic states related to transparency compiled from the literature

Authors	Transparency (m)		
	Oligotrophic	Mesotrophic	Eutrophic
U.S.E.P.A. (1974)	>3.7	2.0 - 3.7	<2.0
Carlson (1977)	>4.0	2.0 - 4.0	<2.0
Rast and Lee (1978)	>4.6	2.7 - 4.6	<2.7
Forsberg and Ryding (1980)	>4.0	2.5 - 4.0	<2.5

Considering the above classifications, Loch Fad could be classified as a eutrophic system as the Secchi disc transparency was never more than 2.5m and dropped to 0.6 - 1.0m during the summer months.

Hydrogen-ion concentration:

Hydrogen ion concentrations of aquatic systems are conditioned by the biological activity of synthesis and respiration and mineralisation. The close link between pH and the photosynthetic activity of chlorophyll bearing plankton has been recorded by Juday et al (1924,1934), Ruttner (1931), Weiss and Oglesby (1960), Elwaked and Wahby (1970), King (1970), Sreenivasan (1970, 1976), Arumugam and Furtado (1980), Bales et al (1980), DeHann (1982), Rimmon and Shilo (1982); they reported the photoassimilation of free CO_2 caused the elevation of p^H of water bodies. At both Loch Fad and Howietoun Farm, p^H increase during summer months was due to the photosynthetic activity of the high phytoplankton population prevailing during that period.

Vertical distribution of p^H is determined by the utilization of CO_2 in the trophogenic layers and its liberation in the tropholytic layers. At Loch Fad, p^H decreased with depth, the result of photosynthetic activity at the upper layers and the release of CO_2 at the bottom. The lower p^H values at the cage site at all depths than at the control site was due to the production of CO_2 by respiratory activity of fishes and the high rate of decomposition of organic matter at the cage site. The greater difference between the p^H of surface and 9m layers at the cage site compared with the control site was also the result of more CO_2 production at the bottom at the cage site.

During diurnal studies at both Loch Fad and Howietoun Farm, p^H increased during the day due to algal photosynthesis utilizing CO_2, and dropped during the night because of community respiration; such day time increase and night time decrease of p^H value was also reported by George (1961), Michael (1964), Verma (1967), Bales et al (1980), Rimmon and Shilo (1982).

Dissolved Oxygen:

The concentration of no substance present in lake water, except perhaps in a rough way the hydroxonium ion, has been studied as much as that of oxygen. The seasonal trend of dissolved oxygen is under the influence of other factors such as temperature and rate of photosynthesis. At Loch Fad, the lower oxygen concentration at the cage site than at the control site throughout most of the study period, in spite of the higher phytoplankton population, was due to respiration of cage fishes and the decomposition of the larger quantities of organic matter at the bottom at the cage site. A similar lower dissolved oxygen at a cage site than at a control site was reported by Yamagishi *et al* (1972) in Lake Suwa in Central Japan. The minimum dissolved oxygen concentration at both sites during the month of September was due to decay of dead phytoplankton. The percent saturation in the upper layers of Loch Fad was more than 100% only during June to August, and this further suggests the contribution of photosynthetic activity of the high phytoplankton population prevailing then.

At Howietoun Farm, the decrease in the dissolved oxygen concentration when the water passed through successive fish ponds was caused by the respiration of fishes and the decomposition of organic matter at the bottom, despite the photosynthetic activity of phytoplankton. Similar results were reported by Warrer-Hansen and Wood-Petersen (1976) and Bergheim *et al* (1982) in Danish and Norwegian fish ponds, respectively.

During diurnal study at both Loch Fad and Howietoun Farm, dissolved oxygen increased during day time due to photosynthetic production of oxygen and dropped gradually during night because of respiration. Bohra (1976), Nasar (1977), Dwivedi et al (1977), Rimmon and Shilo (1982), reported similar situations.

Inorganic nitrogen:

Inorganic nitrogen exists in natural bodies of water in the form of ammonia, nitrites and nitrates. Of these compounds, only the first and last have been found to be the main sources of inorganic nitrogen used by plankton algae. The nitrites are, as a rule, chemically unstable and occur in concentrations which are too low to be of any significance in phytoplankton periodicity. Total inorganic nitrogen concentration in Loch Fad and Howietoun Farm was high during winter and low during summer, showing negative correlation with the phytoplankton population, which was probably related to inorganic nitrogen utilization by the phytoplankton.

Total Ammonia-nitrogen:

Ammonia reaches water in fertilizers, in fish excrement, and from microbial decay of nitrogenous compounds. Plants rapidly absorb ammonia, certain bacteria oxidize ammonia to nitrate, and ammonia may be lost through other ways. Total ammonia concentration at Loch Fad and Howietoun Farm was high during winter when the phytoplankton population was lowest, and decreased during summer when phytoplankton was high in number, suggesting the utilization of ammonia by phytoplankton.

Eppley *et al* (1969), Strickland *et al* (1969), Prochazkova *et al* (1970), Brezonik (1972), Bienfang (1975), Larsen (1975) and Conway (1977) have reported the utilization of ammonia by phytoplankton.

In water bodies where high densities of fish are fed supplemented feeds, ammonia concentration may increase to undesirably high levels. In water, unionized ammonia exists in a p^H and temperature dependent equilibrium with ammonium ion. Un-ionized ammonia is highly toxic to fish, but ammonium ion is relatively non-toxic. The proportion of the total ammonia nitrogen existing as un-ionized ammonia increases with increasing temperature and p^H. The un-ionized ammonia concentration was very little at both Loch Fad and Howietoun Farm, never more than .005 mg/l, suggesting very little toxic effect on fishes.

The higher concentration of total ammonia at the cage site than at the control site at Loch Fad, and the progressive increase in total ammonia when the water passes through the Howietoun Farm, were the result of fish excretion and the bacterial decomposition of organic matter at the bottom.

In the diurnal study, the increase in total ammonia during the night and the decrease during the day might be due to its utilization by phytoplankton during the day, while lack of ammonia utilization by phytoplankton during night time resulted in the accumulation of ammonia.

Nitrite-nitrogen:

Nitrite nitrogen usually occurs at much lower concentration than does nitrate nitrogen and this ion accumulates to appreciable levels only in low oxygen tension. Nitrite can be formed by bacterial activity through either the oxidation of ammonium or the reduction of nitrate (Goering, 1968; Carlucci and Schubert, 1969, Kline and Richards, 1972; Wada and Hattori, 1972).

Nitrite-nitrogen concentration did not show any seasonal trend. The increase in its concentration during the month of September at both Loch Fad and Howietoun Farm may have been due to the decomposition of dying phytoplankton population.

Several workers (e.g. Smith & Williams, 1974; Russo et al, 1974; Konikoff, 1975; Russo and Thunston, 1977; and Tomasso et al, 1979) have reported the nitrite toxicity of fishes. The toxic nitrite concentrations they reported were much higher than the maximum concentration recorded in Loch Fad and Howietoun Farm.

Nitrate-nitrogen:

As nitrogen is transferred to higher trophic levels, particulate organic material such as organism fragments or faeces descends into deep water where the nitrogen which is not permanently locked up in sediments is remineralized to nitrate via bacterial oxidative activity (Redfield et al, 1963; Harvey, 1966).

The high nitrate-nitrogen concentration during winter and low concentration during summer, was the result of biological activity at both Loch Fad and Howietoun Farm. The higher nitrate concentration at the cage site than at control was the result of fish waste decomposition at the cage bottom. Nitrate concentration also increased when water passed through the ponds at Howietoun Farm. A similar increase in nitrate at the outlet at some trout hatcheries was reported by Hinshaw (1973). No increase in nitrate, however, was observed by Markmann (1977) in a Danish investigation, or Bergheim et al (1982) in a Norwegian fish farm.

Strickland et al (1970) observed a consistent negative correlation between nitrate concentration and temperature, which is also true in the case of Loch Fad and Howietoun Farm. This negative relation of nitrate and temperature was probably the result of utilization of nitrate by phytoplankton. In the diel study, the lower concentration of nitrate during daytime was also due to utilization by phytoplankton. Toetz (1976) in his study of diel periodicity in uptake of nitrate and nitrite by using ^{15}N technique in reservoir phytoplankton, reported that the rate of nitrate uptake generally paralleled changes in irradiance, uptake of nitrate and nitrite also occurring in the dark, but at low rates.

Orthophosphate:

Phosphorus occurs in the biosphere almost exclusively in a fully oxidized state. Orthophosphate is the form of phosphorus preferred by all organisms, including the phytoplankton, and in natural waters is the major source of this element with other dissolved forms, e.g. organic phosphorus compounds.

Like inorganic nitrogen, orthophosphate concentration in Loch Fad and Howietoun Farm increased during winter and decreased during summer, these changes being due to the utilization of phosphorus by phytoplankton. In Loch Fad, the higher phosphate concentration at the cage site than at the control site could be attributed to excretion by fish and the decomposition of faeces and excess food at the cage site. In Howietoun Farm the increase in phosphate as the water passed through the farm was also due to the addition of phosphorus from the metabolic waste; a similar increase in phosphate concentration was also reported by Bergheim et al (1982) in a Norwegian fish farm.

During diel study, phosphate concentration decreased during the day due to the phytoplankton utilization, and accumulated during the night from the fish excretion.

Numerous authors have shown that the summer chlorophyll concentrations in lakes are closely correlated with concentration of total phosphorus at the spring overturn (Sakamoto, 1966; Edmondson, 1970; Anon, 1973; Dillon, 1975 and Schindler, 1976). One of the most convincing relationships between the maximum phosphate content at lake overturn and the phytoplankton bloom has been shown in Lake Washington (Edmondson, 1970, 1972). During the years when algal density progressed to nuisance level, maximum total phosphorus in winter increased from 10-20 mg/l up to 57 mg/l. In Loch Fad the phosphate concentration reached nearly 70 mg/l during winter, and was followed by a heavy phytoplankton bloom during summer (with maximum chlorophyll-a concentration of 200 mg/l).

Silicate:

Silicon is present in most natural waters as solid or colloidal silicate polymers, derived from catchment soils or 'recycled' from biogenic sources (e.g. dead diatoms). Depolymerization leads directly to the formation of soluble monomeric orthosilicic acid $Si(OH_4)$, the 'soluble reactive silicon' SRS) that is detected colorimetrically by standard analytical technique . This is probably the only fraction available to diatoms and other phytoplankton. Apart from its quantitative importance, silica is of immense significance as one of the major nutrients for diatoms, and some other phytoplankton (such as yellow-brown algae that form siliceous cysts) and siliceous sponges. Silica is present in solution in natural waters in the form of monomeric orthosilicic acid, $Si(OH)_4$. The silicate content of surface waters shows considerable variation even within a restricted region (Hutchinson, 1957). This variation is due to utilization by diatoms and perhaps in some cases by other types of precipitation in the lake. Lower silicate concentrations occur in temperate than in tropical regions. This is in line with theoretical expectation and with the averages for the rivers of the world.

Pearsall(1932) first suggested that silica (at a concentration of approximately 500μg SiO_2 (l^{-1}) limited diatom growth in the English Lake District. Weimann (1933) also showed that blooms of Stephanodiscus hantzschii depleted silica. In Lake Windermere, Lund (1950), and Lund et al (1963) found that Asterionella formosa ceased to grow at a concentration of less than 0.5mg SiO_2(l^{-1}).

Diatom population limited by the silicon supply was also reported by Belcher _et al_ (1966), Tessenow (1966), Happey (1970), Bailey-Watts and Lund (1973), Bailey-Watts (1976) and Parker _et al_ (1977). In Loch Fad the lowest concentration of silicate was 1.6 mg/l to 1.8 mg/l, while in Howietoun Fish Farm it was never below 1.6 mg/l.

Silicate concentration shows seasonal fluctuations during the periods of diatom growth, and tends to decline during or just after the peak level of diatom population (Tessenow, 1966; Bailey-Watts, 1976 a, b; Conway _et al_, 1977; and Bailey-Watts and Duncan, 1981). In Loch Fad and Howietoun Farm the silicate concentration was lowest during the highest peak of diatoms and was highest in concentration when diatoms were low; this change was mostly due to utilization of silicate by the diatoms present. The high peaks of silicate concentration at both Loch Fad and Howietoun Farm also coincided with the rainfall, suggesting the input of silicate by rainwater from the catchment area. The vertical distribution of silicate resembled that of other substances that can be derived from the sediments, being highest at the bottom.

Corbet _et al_ (1980), in Lake Poukowa, New Zealand, during a 24 hour study have reported that silicate concentration decreased during the day due to more utilization of silicate by diatoms during day-time. But in the present study at both Loch Fad and Howietoun Farm, no marked trend was noticed in the silicate concentration during the diel study.

Suspended Solids:

The seasonal pattern of suspended solids at Loch Fad followed the seasonal cycle of the phytoplankton population, being maximum during the summer months. The heavy rain during the month of September also contributed to suspended solids through the addition of soil particles washed down from the catchment area. The suspended solids were always higher at the cage site than at the control site because of the production of fish faeces and uneaten fish food, together with higher numbers of phytoplankton at the cage site.

In Howietoun Farm, the suspended solids followed strictly the pattern of rainfall in that area. Soil particles formed most of the suspended solids in Howietoun Farm which sedimented as the water passed through the farm, resulting in lower suspended solids at the outlet of the farm. Higher suspended solids at the inlet than at the outlet were also reported by Bergheim et al (1982) in Norwegian fish farms.

Chlorophyll-a:

Chlorophyll-a is considered the most specific and versatile measure of algal biomass. At both Loch Fad and Howietoun Farm the seasonal fluctuation of Chlorophyll-a followed that of the total phytoplankton population, being minimum during winter months and maximum during summer. Carlson (1977), Forsberg and Ryding (1980), and Canfield and Bachmann (1981) show the negative relation of transparency with chlorophyll-a concentration in lakes, and a similar relation was found in Loch Fad.

Chlorophyll is both a useful and a simple estimator of phytoplankton standing crop and is now more generally used than cell number or cell volume. Sakamoto (1966), Dillon & Rigler (1974), Jones and Bachmann (1976), Forsberg & Ryding (1980), and Canfield & Bachmann (1981), after collecting data from several different lakes, reported the linear relationship between total phosphorus and Chlorophyll-a concentration. And Forsberg & Ryding (1980) reported the linear relationship between total nitrogen and Chlorophyll-a concentrations. At Loch Fad, the Chlorophyll-a concentration was higher at the cage site than at the control site, phosphorus and nitrogen nutrients were also higher at the cage site than at the control site. At Howietoun Farm, too, Chlorophyll concentration was highest at the station (station 6) where the nutrient concentration was also highest.

A number of attempts have been made to establish a trophic state criterion as a function of commonly measured water quality variables. In Table 17 a comparison is made between some investigations on Chlorophyll-a level versus trophic states. The background data from the investigated lakes differ widely regarding both lake basin and water characteristics as well as sampling techniques and observation period (mostly the data are summer averages). Loch Fad could be classified as eutrophic according to the classification of lakes suggested by the above authors, on the basis of Chlorophyll-a concentrations of 202 μg/l. The classification of lakes, however, based only on Chlorophyll-a levels may inadequately reflect their trophic status.

Table 17: Suggested trophic states based on Chlorophyll-a (mg/m^3) compiled from the literature

Authors	Oligotrophic	Mesotrophic	Eutrophic
Rast and Lee (1978)	0 - 2	2 - 6	> 6
Sakamoto (1966)	0 - 2.43	2.43 - 5	> 5
Carlson (1977)	0 - 2.57	2.57 - 6.5	> 6.5
Forsberg and Ryding (1980)	0 - 3	3 - 7	> 7
National Academy of Sciences (1972)	0 - 4	4 - 10	>10
Dobson et al (1974)	0 - 4.36	4.36 - 8.71	> 8.71
U.S.E.P.A. (1974)	0 - 7	7 - 12	>12

Phytoplankton:

Phytoplankton encompasses a surprising range of cell size and cell volume from the largest forms which are visible to the naked eye, e.g. Volvox (500-1500 μm) in freshwater, to algae as small as 1 μm in diameter and to even smaller bacteria. Phytoplankton constitutes the greater part of the photosynthetic producers in most water bodies, and the whole of the rest of the biological community therefore depends to a very large extent on the planktonic plants. The seasonal changes of phytoplankton are controlled by many environmental factors, the main ones being temperature, light, nutrient concentrations, predation and competition.

Phytoplankton populations in both Loch Fad and Howietoun Farm were low during the winter months and high during the warm months. Although temperature and light contribute to species dominance and succession, they do not tell the whole story because the available nutrient supply and other factors are also elements in the adaptation of species to sub- or supra-optimum temperature and light. The blue-green species that usually prefer warm summer temperature can apparently out-compete other algae for the available nutrients at that time; however, they can also adapt to other seasons when nutrient availability is high. The occurrence of blue-green algae tends to be initially confined to late summer or autumn in moderately enriched lakes, but as enrichment proceeds, they begin to dominate even in spring, which is the case in early spring in Pine Lake, Washington, at a temperature of 8°c (Welch, 1980). Microcystis aeruginosa was usually the most dominant species throughout the year in Loch Fad,which was enriched with the continuous addition of fish wastes from the farm established.

Thunmark (1945) and Nygaard (1949) have suggested the classification of lakes based on the composition of the phytoplankton. These were merely numerical attempts to express the degree of oligotrophy and eutrophy from a consideration of species complement rather than from nutrient cycle. Thunmark devised an index based on the ratio of the number of species of chlorococcales and desmids, and Nygaard devised several indices, e.g. a Cyanophycean index, a diatom index, a Euglenophycean index, and a compound index. These indices will vary somewhat according to the type and time of collection, and Coessel (1975) warns of the dangers involved in using desmids which are more widely distributed in waters of all types than is usually recognised. In general the compound index:

$$\frac{\text{Cyanophyceae + Chlorococcales + centric diatoms + Euglenophyceae}}{\text{desmids}}$$

seems to be the most useful. If this is less than 0.2 it indicates a dystrophic state, up to 1.0 an oligotrophic water, 1.0 - 3.0 mesotrophic, and above 3.0 eutrophic. Round and Brook (1959) combined the compound index with an analysis of the dominant species and showed the trend from Cyanophyceae in eutrophic to desmids in oligotrophic. In Loch Fad the compound index was 7.0 with Cyanophyceae as the most dominant group, suggesting the eutrophic nature of the loch. Brooks (1956) and Holden (1959) reported the change in the compound index from oligotrophic to eutrophic after the enrichment of Sutherland lochs with mineral fertilizers.

The representation of certain species of freshwater plankton is often a sensitive indicator of the trophic state. Weimann (1951), Rawson (1956), Liebmann (1962), Kolkwitz (1950), Sladeček (1973), Wetzel (1975) and Persoone & De Paun (1979), have suggested an approximate distribution of algae over the range of trophic state, but their list is obviously not appropriate world-wide, as some species have a wide range, e.g. *Asterionella*. In general, the presence and dominance of blue-green algae, such as *Aphanizomenon*, *Microcystis*, *Anabaena*, *Coelosphaerium* or *Aphanocapsa*, are strong indicators of eutrophy (Welch, 1980). In Loch Fad the phytoplankton bloom occurred during warmer months and *Microcystis aeruginosa* formed 92 to 99% of the total phytoplankton, even throughout much of the year.

The literature concerning the growth and metabolism of blue-green algae is large and much of it has been described and reviewed by Fogg (1969), Fogg *et al* (1973), Wolk (1973) and by Carr & Whitton (1973). The major factors that influence the growth of blue-green algae are the same as for other planktonic algae, viz. light, temperature and the chemical composition of the water. In some tropical lakes growth of blue-green algae can take place throughout the year (Burgis _et al_, 1973). In temperate regions, filamentous forms (e.g. _Anabaena_) appear first between April and July, while colonial species (e.g. _Microcystis aeruginosa_) develop a little later, between June and September (Nauwerek, 1963; Reynolds, 1971, 1973; Davis, 1972). In both Loch Fad and Howietoun Farm filamentous and colonial blue-green forms were maximum during July-August except _Oscillatoria agardhi_ in Loch Fad which was maximum during April. In some shallow, temperate lakes, subject to long periods of isothermal mixing in winter, small populations of _Microcystis_ spp. (Davies, 1972; Reynolds, 1973) and occasionally _Anabaena_ spp. (Reynolds, 1975) may be maintained in suspension throughout the winter, and may form the basis of a spring bloom. In Loch Fad, a small population of _Microcystis aeruginosa_ and _Anabaena flos-aquae_ was present during winter months. In Howietoun Farm ponds _Anabaena flos-aquae_ and _Oscillatoria agardhi_ were present in winter months as well.

Most blue-green algae grow best in the range of p^H 7.5 - 9.0 (Gerloff _et al_, 1950; Kratz & Myers, 1955; Holm Hansen, 1968). Shapiro (1973) found that they became dominant over green algae at High p^H values, indicating that the algae are efficient in deriving carbon from very low concentrations of free carbon dioxide. p^H values much below 6 appear to prevent blue-green algal growth (Allison, Hoover & Morris, 1937, quoted by Fogg _et al_, 1973; and Brock, 1973). Reynolds and Allen (1968) observed the formation and growth of blue-green algal populations in a natural lake (Oak Mere) after a rise in p^H from 4.7 to 6.5 In both Loch Fad and ponds at

Howietoun Farm p^H never fell below 6.7 and reached 7.5 to 8.0 during summer time.

The presence of organic solutes in natural water may be of considerable indirect benefit to blue-green algae. Apart from maintaining trace elements in solution, substantital quantities of oxidizable organic matter lower the concentration of dissolved oxygen, and blue-green algae grow and fix nitrogen more actively under such conditions (Topachevskii et al, 1969; Stewart and Pearson, 1970). Organic substances are absorbed by bacteria which frequently occur in a close relationship with blue-green algae (Kuentzel, 1969; Hudson and Marsson, 1970). Carbon phosphorus, nitrogen and perhaps other organically bound elements are metabolized by the bacteria and may be made available to algae in exchange for photosynthetic oxygen (Kuentzel, 1969; Lange, 1970; May, 1972). In both Loch Fad and Howietoun Farm ponds organic compounds were in abundance in the form of fish faeces, metabolites and uneaten food, and this could be one of the factors for blue-green abundance.

The Rhodophyceans Chantransia pygmaea and Lemanea mammillosa, which were recorded at Howietoun Farm, are usually found attached to rocks or stones in rapidly flowing streams and rivers (West and Fritsch, 1928). Its presence in small numbers in the Phytoplankton at the inlet, and stations 2 and 3 might be due to the presence of thallus detached from upstream habitats and carried into the inlet.

Dinoflagellates, Ceratium hidundinella and Peridinium willei are regarded as typical in oligotrophic waters (Naumann, 1917; Pearsall, 1921, 1932). Höll (1928) regarded P. willei as one of the most eurytopic species. Pearsall (1932) found these two dinoflagellates to be common only in summer and autumn in waters of the English Lake District, while Maulood and Boney (1981a), in Loch Ard, reported the maxima of these two in summer months only (July - August). In Loch Fad, P. willei and C. hirundinella also had their maxima during summer (July).

Asterionella formosa is one of the phytoplanktonic species which has a wide range of tolerance to the trophic state of a lake. This is clear in the study by Round and Brooks (1959) on Irish loughs of various water type, where it was one of the dominant species in eutrophic lakes (e.g. Loughs Rea, Bunny, Cullin, Caherglassan Talf), in mesotrophic lakes (e.g. Lough Lerally), and also in oligotrophic lakes (e.g. Loughs Ardderry, and Ballynahinch). Liebmann (1962) considered A. formosa as an indicator of moderately polluted water, while Rawson (1956) and Sparling & Nalewajko (1970) found it to be common in oligotrophic waters. The timing of the population peak varies between Scottish lochs, being May in Loch Lomond, June in Loch Awe, and July in Loch Ness (Bailey-Watts and Duncan, 1981). Maulood and Boney (1981a) found its peak during April in Loch Ard. In Lake Menteith it was during May and August (Maulood and Boney, 1981b). In Loch Fad, A. formosa had peaks during both April and August, while in Howietoun Farm ponds it was during April only, which is similar in timing to the smaller shallower Scottish lake mentioned above.

Observation of a maximum number of Melosira italica-subarctica during April in Loch Fad and in Howietoun Farm ponds corresponds to that in Loch Lomond and Lake Menteith (Bailey-Watts and Duncan

1981; Maulood and Boney, 1981b). In Loch Ard the peak of M. italica-subarctica was during June (Maulood and Boney, 1981a).

Lindstrom et al (1973) reported Diatoma elongatum to be co-dominant with Asterionella formosa during a bloom in a lake-river system in Norway. In Loch Leven, Scotland, Bailey-Watts (1976) observed that the maximum abundance of D. elongatum occurred just after the decline of Asterionella formosa populations, when silicate concentrations were rapidly declining. Moed and Hoogveld (1975) reported that D. elongatum became dominant in Tjeukemeer, Netherlands, when silicate levels fell below 4uM SiO_2 - Si. In Howietoun Farm ponds D. elongatum had its peak during May-June just after the peak of Asterionella formosa, when the silicate concentration was at its lowest (2.0 to 3.5 mg/l).

Liebmann (1962) suggested that Stephanodiscus hantzschii is an indicator of highly polluted waters. This species was present in Howietoun Farm ponds with a maximum number during July.

Rawson (1956), Liebmann (1962) and Sparling and Nalewajko (1970) reported that Tabellaria flucculosa is common in oligotrophic waters, but it was present in Howietoun Farm ponds with peak numbers during June-July. Maulood et al (1978) reported its peak in Loch Lomond during March, while Maulood and Boney (1981a) found its peak during May in Loch Ard. Tabellaria fenestrata, common in eutrophic water (Rodhe , 1958) was present at both Loch Fad and Howietoun Farm ponds with a peak during April. In Loch Lomond and in Lake Menteith, however, it had a peak during July (Maulood et al, 1978; Maulood &

Boney, 1981b).

Botryococcus braunii is considered to be characteristic of oligotrophic waters by Naumann (1931), Rawson (1956) and Hutchinson (1967). B. braunii was present from April to November in Loch Fad and from March to October in Howietoun Farm ponds, with its maxima during July at both places. Maulood and Boney (1980) have also reported its peak during June-July in Loch Lomond, but in Lake Menteith they found it to be high in number by January (Maulood & Boney, 1981b).

Oocystis spp., which were considered to be characteristic of oligotrophic waters by Hutchinson (1967) was present in Loch Fad with a peak during July-August. Moss (1973) reported that Pandorina will not grow at 5°c or below and grows optimally at temperatures between 10°c and 20°c under laboratory conditions. In Loch Fad and Howietoun Farm ponds it was never recorded below 5°c and was maximum during July when the temperature was around 17°c. Hutchinson (1967) considered Pediastrum duplex to be characteristic of eutrophic waters, while Rawson (1956) and Persoone and De Paun (1979) considered it to be a mesotrophic indicator. Rawson (1956) considered P. boryanum also to be characteristic of mesotrophic waters. Both P. boryanum and P. duplex were present in Loch Fad with peaks in August and July respectively.

Sphaerocystis schroeteri was common in spring and autumn in English Lake District waters as reported by Pearsall, in Hutchinson (1967). In Hogan Pond, Newfoundland, it was common in mid summer (Davis, 1972), and Klarer (1978) also reported its peak during summer in Dubh Lochan. In Loch Fad, S. schroeteri was present from March to October with a peak during June.

Zooplankton

The important groups represented in the zooplankton belong to the free-living non-photosynthetic Protista, to the Rotifera, and to the Crustacea. The zooplankton population is regulated by numerous factors, the most important being temperature, food and predators. The zooplankton and phytoplankton population peaks are generally considered to be coincident or immediately following each other. Annual and seasonal cycles seem to be of a highly variable nature from lake to lake and from year to year within the same lake. There are many papers in which different authors give examples of irregularities, particularly concerning the phytoplankton-zooplankton relationship. Anderson et al (1955), Sladecek (1958), Losos and Hetesa (1973), Barthelmes (1975), have reported the grazing effect of zooplankton which controls the phytoplankton population. While Gliwicz (1975), Gliwicz and Hillbricht-Ilkowska (1973), Pederson et al (1976) in their studies found that zooplankton populations were small and did not control the phytoplankton population. Gliwicz (1975) has shown that the filtering rate of zooplankton increases from ultraoligotrophy, through mesotrophy but decreases in eutrophic lakes, so that the efficiency of phytoplankton removal was poor with eutrophy, resulting in an increasing amount of net phytoplankton and bacteria/detritus.

In both Loch Fad and Howietoun Farm, zooplankton were high in number during warmer months (June-July) when phytoplankton were also high (the highest peak being during July-August), but the results did not show any evidence of a controlling effect on phytoplankton by zooplankton grazing.

With enrichment of lakes and ponds an increase in the standing crop of phytoplankton and of the planktivores has been reported by several authors (Chandler, 1940; Hrbacek, 1962; Bradshaw, 1964; Davis, 1964; Beeton, 1965). Wiebe (1929), McIntire & Bond (1962), Hall et al (1970), and Boyd (1982) have reported a higher number of zooplankton in fertilized ponds than in unfertilized ones. Among the array of phytoplanktonic organisms, the blue-green algae respond most noticeably to enrichment. Apart from the possible chemical unacceptability of cells of certain blue-greens to herbivores (Monakov and Sorokin, 1961; Hrbacek, 1964), large colonies cannot be utilized by true planktonic herbivores. Saunders (1969) has suggested that bacteria often dominate the planktonic biomass during a bloom of blue-green algae and, at such times, the bacteria provide a concentrated and important food source for zooplankton. Peterson et al (1978) have shown that Daphnia do utilize bacteria as a food source under natural conditions.

Loch Fad and Howietoun Farm water is enriched with the uneaten fish food supplements and with fish waste products, and exhibited a high phytoplankton population with a heavy bloom in the case of Loch Fad. Zooplankton in Howietoun Farm increased as the water became enriched as it passed through the Farm. In Loch Fad zooplankton abundance was generally higher than those reported by Maitland et al (1981) in oligotrophic and mesotrophic Scottish lochs (Lochs Lomond, Awe, Ness, Morar, and Shiel) but was lower than those found by Johnson and Walker (1974) in shallow eutrophic Loch Leven, Kinross.

The crustacean herbivores constitute one of the chief trophic links between the algae and bacteria and the fish that dominate the higher trophic levels of lacustrine ecosystems. Nearly all fish subsist on zooplankton shortly after they hatch and commence feeding. Some continue to find much food in the open-water zooplankton (e.g. roach). There are fewer obligate planktivores in freshwater than there are in the sea, undoubtedly because only scattered lakes can continuously provide an adequate supply of plankton. Most freshwater fish are facultative planktivores; they feed on zooplankton when large forms are plentiful, but switch to some other food source when the supply of large zooplankton fails. Large zooplankton are preferred to small ones, and Cladocera are preferred to Calanoid Copepods of the same size. Cyclopoids are an intermediate choice (Ivlev, 1961; Berg and Grimaldi, 1965, 1966; Brooks, 1968). In Loch Fad the cladocerans and copopods were lower in number at the cage site than at the control. This may have been due to predation by the fish population in the cages together with the wild fish populations of the Loch which congregate around the cages (principally pike, *Esox lucius*; perch, *Perca fluviatilis*; roach.*Rutilus rutilus*; and escaped rainbow trout *Salmo gairdneri*) which are attracted to the cage site by the uneaten fish food pellets. Forbes (1981) reported the higher density of wild fishes around the cages than at the southern end of Loch Fad. The gut content of rainbow trout, roach, young pike and fry and yearling of perch showed that zooplankton formed part of their diet. He also reported that perch fry were more abundant at the cage site, the primary source of these perch fry being zooplankton. Phillips

(1983) found the cages in Loch Fad act as supplementary feeding points, and have a significant effect on the distribution of the rainbow trout within the Loch. Large fish (> 300mm) occupied and remained confined to the area close to the cages. The stomachs of these large fish contained Daphnia sp., chironomid pupae and unidentified insects, together with the cage food. The dietary components of adult trout and perch populations at Loch Leven have been studied by Thorpe (1974). His work has shown that when these fish species fed upon zooplankton, they selectively predated upon Daphnia hyalina and Bythotrephes longimanus. The copepods Cyclops s. abyssorum and Diaptomus gracilis appeared to be insignificant in the diet. Additionally, Daphnia spp. were recorded in the gut contents of Loch Leven trout (Balmain and Shearer, 1953; Morgan, 1970).

In contrast, rotifers were more abundant at the cage site which might be due to their possible escape from fish predation due to their smaller size and to the lower number of cyclopoid copepod predators (Cyclops abyssorum) at the cage site. Rutkowski (1981) observed that Rotifera constituted the major animal group in the diet of Cyclops s. abyssorum in Loch Leven. In Howietoun Farm any predatory effect of fish on the zooplankton was not evident, zooplankton numbers increased as the water passed through the farm.

The zooplankton in both Loch Fad and Howietoun Farm belonged to the groups Cladocera, Copepoda and Rotifera. Though the composition of dominant planktonic herbivores need not reflect enrichment, there is always the possibility that some minor component of the zooplankton might be especially sensitive to some aspect of enrichment. Such a species might then be a biotic indicator of enrichment. Several studies have indicated that *Bosmina coregoni* disappears as a lake is enriched and is replaced by the rather smaller *Bosmina longirostris* (Deevey, 1942; Hasler, 1947). Such shifts in *Bosmina* species could result from changes in the level of predation on the zooplankton. If predation on zooplankton greatly increases, a population of the larger *B. coregoni* might not be able to persist. *B. coregoni*, which is 2 to 3 times larger than *B. longirostris*, disappeared from the zooplankton of Crystal Lake after a population of *Alosa aestivalis* became established (Brooks and Dodson, 1965) and *B. longirostris* became the dominant planktonic herbivore. Thus the presence of *B. longirostris* may not indicate the trophic state of a water body. In both Loch Fad and Howietoun Farm *B. longirostris* was present during spring and summer with the highest peak during late spring. Elgmork (1964) also reported its peak in spring, while Moore (1977) reported its peak during autumn.

Chydorus sphaericus was present in Loch Fad with its highest peak during summer when the phytoplankton, comprising 99% of blue-green algae, were also maximum. The large colonies of blue-greens cannot be utilized by true planktonic herbivores. These large clumps, however, produce food and substrate for *C. sphaericus* (Brooks, 1969). According to Hutchinson (1967) the species is generally acknowledged to be perennial in the littoral zones but may appear in quantity in the open water only during the summer, usually July and August (Birge, 1898; Wesenburg-Lund, 1904; Patalas, 1954). Berg and Nygaard (1929) showed that *Chydorus* sp. reached a peak of of abundance in August during an Anacystis bloom in the Frederiksborg Slotsø, this being thought to be associated with an increase in the back-scattering of light from open water in which much seston was suspended. Similarly Chydorus sp. in Lake Mendota, Wisconsin, became planktonic during blue-green algal blooms (Apstein 1896, Birge 1898).

Daphnia longispina was considered to be an indicator of high productivity of ponds by Langhans (1936) and Ziegelmeier (1940), but Nordquist (1921) reported that in oligotrophic ponds D. longispina predominated during summer, while Bosmina longirostris dominated eutrophic ones. In Loch Fad, D. longispina was present from March to August with a high peak by June when phytoplanktons were also high. Elgmork (1964) also reported its high peak during June in inundated ponds in Southern Norway. It is widely acknowledged that Daphnia spp. are filter-feeders which depend for their nutrition on a wide variety of fine particles suspended in the surrounding medium, such as algae, detritus, bacteria, protozoa and fungi. Daphnia utilize particles within a fairly restricted size spectrum of 1 <20 um (Brooks, 1969; Nadin-Hurley and Duncan, 1976). Saunders (1969) noted that in highly productive lakes the correspondingly high level of detritus provided an important food source to filter-feeders and occupied a dominant role in zooplankton feeding along with phytoplankton.

Cyclops abyssorum was present in Loch Fad throughout the year with its highest peak during summer, as reported by Maitland et al (1981) in Lochs Lomond, Awe, Ness, Morar, Shiel, and by Johnson and Walker (1974) in Loch Leven. In Loch Leven, Rutkowski (1981) reported that in the diet of *Cyclops abyssorum* diatoms represented the major food intake (68%), the second most abundant category of food ingested was Chlorophyceae (16%), the blue-greens were 9% and the Euglenophyceae 2%. Rotifera constituted the major animal group in the diet of *C. abyssorum*. Planktonic crustacea appears to constitute a relatively minor food source. In Loch Fad, diatoms and chlorophyceans were also high during the peak abundance of *C. abyssorum*. *Cyclops vicinus* in Howietoun Farm was present from June to October with a peak during August. It increased as the water passed through the farm, showing no evidence of fish predation. Hutchinson (1967) observed that *Cyclops vicinus* was confined to localities with small fish populations so that predation is avoided.

Diaptomus gracilis in Loch Fad was present throughout the year with a high peak in summer, which agrees with studies on Lochs Lomond, Morar and Shiel, by Maitland *et al* (1981), but in Loch Awe and Loch Ness they reported its peak during October. Johnson and Walker (1974) and Jones (1980, per.comm.) reported its peak during autumn in Loch Leven. *Diaptomus laciniatus* was present in Howietoun Farm only during summer and autumn with the highest peak in summer. Murray and Pullar (1910) and Maitland *et al* (1981) have also observed the short summer season of this species in Loch Lomond and Loch Shiel, respectively.

Ascomorpha ecaudis was present in Howietoun Farm from March to October with a peak by June, and a similar cycle was reported by Hutchinson (1967) in the Motala system. *Brachionus angularis* in Howietoun Farm had a peak by July, while Schuurman (1932) reported its high peak in August in a warm monomictic lake. *Conochilus* hippocrepis was present in Loch Fad throughout the year with a peak during August. Pejler (1957) reported that the appearance of a population peak of Conochilus sp. in any lake was dependent upon presence or absence of a phytoplankton bloom, peaks occurring in early summer in lakes with a bloom and in late summer in those without a bloom. This does not agree with the present observation of a peak in Loch Fad in late summer, even though the phytoplankton population was in bloom. Filinia terminalis is seemingly a cold-water species, usually recorded from waters below 20°c, and usually in much colder water. Typically it is present in the plankton of temperate lakes at all depths during winter but only in the hypolimnion in summer, except at extreme altitudes in which the water is perennially cold (Edmondson and Hutchinson, 1934; Hutchinson 1967). As would be expected, F. terminalis was never present in Loch Fad at temperatures above 15°c, while in Howietoun Farm it was present only at temperatures up to 12.5°c.

Kellicottia longispina is the commonest planktonic rotifer in temperate regions and is characteristic of oligotrophic waters (Pejler,1957a). It was, however, recorded throughout the year in eutrophic Loch Fad. This species was common during summer months, in agreement with the studies of Pejler (1957 a & b) and Larson (1971). Pejler (1957b) considered it to be sensitive to high light levels and so confined to lower depths during summer months, but it was present in the surface layers in Loch Fad during summer, as has been reported by Klarer (1978) in Dubh Lochan.

Keratella cochlearis is likely to occur in the open water of deep lakes, and is a widespread temperate form (Hutchinson, 1967). In Loch Fad *K. cochlearis* was present throughout the year with a peak during summer. Eddy (1934), Larson (1971) and Doohan (1973) have also observed its presence throughout the year. Pejler (1957b) observed a similar summer peak to that in Loch Fad, but Doohan (1973) reported its peak only during spring, while Bricker and Gannon (1976) observed its peak only during autumn. *K. valga* is characteristic of smaller water bodies than those in which *K. cochlearis* and *K. quadrata* occur (Hutchinson 1967). It was present in Howietoun Farm throughout the year with peaks in summer, while *K. cochlearis* was not observed.

Trichocerca spp. are considered rather generally as species of eutrophic waters. Like *Chydorus sphaericus*, some species of *Trichocerca* become planktonic at times of blue-green algal blooms (Hutchinson, 1967). *T. capucina* was present in Loch Fad throughout the year at all depths with a peak in summer when the phytoplankton population was in bloom.

Diurnal Vertical Migration in Zooplankton:

Diurnal variation in the self-directed, vertical positioning of zooplankton has evoked a relatively large number of investigations into its causes and adaptive significance. Initiation, control and direction appear to be primarily regulated by exogenous changes in the intensity and angular distribution of light (Ringelberg, 1964; McNaught and Hasler, 1964) apparently based upon an endogenous rhythm (Harris, 1963; Enright and Hamner, 1967; Ringelberg and Servaas, 1971). A profusion of speculations exist as to the adaptive value of diurnal migration (Hutchinson 1967; McLaren 1963), often implicating competition (Dumont, 1972) and predation (Zaret and Suffern, 1967) as selective forces. In both Loch Fad and Howietoun Farm ponds, a single diurnal study was conducted to study the diurnal vertical variation of zooplankton in the month of April, but due to the lack of precise descriptions of vertical movement of migrating zooplankton at very short time intervals, records of light intensity and lack of supportive laboratory experiments; the causal factors for the vertical migration observed in the present study could not be investigated.

Typical daytime downward and nighttime upward migrations were observed in Loch Fad by Bosmina longirostris, Chydorus sphaericus, Daphnia longispina, Cyclops abyssorum, Diaptomus gracilis, Ascomorpha ovalis, Conochilus hippocrepis, Filinia terminalis, Kellicottia longispina, Keratella cochlearis, Trichocerca capucina; and at Howietoun Farm ponds by Ascomorpha ecaudis, Brachionus angularis and Keratella valga. Bosmina longirostris at Howietoun Farm did not show any marked trend of movement in diurnal study.

Kikuchi (1930) noticed in Bosmina longirostris and Daphnia longispina a slight tendency to upward movement during the night. Southern and Gardiner (1926, 1932) in Lough Derg reported that the young Daphnia longispina start moving upwards before or shortly after sunset reaching the upper layer and descend again as the sky begins to lighten in early morning, but adult D. longispina exhibited the reverse movement. Similar diurnal migration of Chydorus Sphaericus to that observed in Loch Fad was reported by Berg and Nygaard (1929), Whiteside (1974), Buchanan (1975) and Meyers and

Strickler (1978) in their study. Hutchinson (1967) found *Cyclops abyssorum* to move from 50m up to 20m at night in Lake Lucerne. Kikuchi (1930), in Japanese Lake Aoki, and Schindler and Noven (1971) in a Canadian Lake, reported slight upward nocturnal movement of *Keratella cochlearis*, but Pennak (1944) reported its reverse movement in Silver Lake.

Periphyton:

Young (1945) defined the term periphyton as "The assemblage of organisms growing upon free surfaces of submerged objects in water". Periphytic algae should provide good indicators of productivity of the particular system because algae in such communities are fixed in position, unlike the planktonic algae which can easily be moved into and out of an area. To study periphyton, workers have used the natural substrata and the artificial substrata. Among the natural substrata, the most common substrata for periphyton in natural conditions are stones, wood and inorganic or dead materials of any kind. The other natural substrata often used in the study of periphyton are submerged leaves and stems of aquatic plants and the aquatic animals (e.g. shells of molluscs and turtles). Many difficulties with the quantitative removal of periphyton from uneven and rough surfaces of natural substrata have caused the introduction of artificial substrata, which can either be objects of natural origin with modified surfaces or artificial objects of various shapes, made of various materials. According to the literature, the most common materials are glass, wood, concrete and various sheets of metals and plastics.

Smooth surfaced wooden blocks were used in the study of periphyton at both Loch Fad and Howietoun Farm. In Loch Fad the higher periphytic population at the cage site than at the control site presumably was the result of higher nutrient concentrations at the cage site, due to decomposition of cage fish faeces, metabolites and uneaten fish food pellets. In Howietoun, the periphyton population increase from the inlet of the farm to the outlet might also be the result of increased nutrients as the water passes through the farm. All the algal species present in the periphyton were also represented in the plankton population. Though the seasonal variations of the periphytic algal species were mostly similar to that of the plankton population, the growth cycles of some periphytic species were either slightly lengthened or shortened. Weber and Raschke (1970) compared the plankton and glass-slide flora and came to the conclusion that the composition of the communities was very different throughout the entire exposure period. One of the possible causes of this difference could be the artificial substrate. Tippett (1969, 1970) showed that, in both lakes and flowing waters, the seasonal succession of diatom species on natural substrata and glass slides differs considerably with the growth cycles either lengthened or shortened, while Patrick _et al_ (1954) and Brown & Austin (1971, 1973) reported that algal communities growing on glass slides and natural substrata are very similar. Foerster and Schlichting (1965) and Brown (1976) showed that glass slides support a smaller diversity of algae than the natural substrata.

In Howietoun Farm ponds, the relative abundance of algal groups in the periphyton was mostly similar to that in the phytoplankton. In Loch Fad, however, the periphyton was dominated by the group

Bacillariophyceae, whereas the group Cyanophyceae dominated the phytoplankton throughout most of the year. This difference in the relative abundance was mostly because Microcystis aeruginosa, the most abundant phytoplankton species in Loch Fad, was absent in the periphytic population.

The fungal hyphae also observed on the periphyton blocks is worthy of comment. The stimulated organic production that accompanies eutrophication often manifests itself in blooms of aquatic micro-organisms. These blooms can be particularly annoying when they cause taste and odour problems in drinking water and fishes. A wide range of taste and odour may be contributed by a variety of microorganisms, including Actinomycetes and specific types of algae. Adam (1929, 1933) apparently was the first to ascribe the problem of earthy odour in water to Actinomycetes. Other researchers, Egorova and Issotchenko (1944), Ferramola (1949), and Morris (1962); also have come to similar conclusions. In 1965, Gerber and Le Chevalier isolated a strong earthy odour compound which they named Geosmin. Henley (1970) also isolated Geosmin from the blue-green algae. In Loch Fad the earthy flavour in fish has on occasions caused complaints from consumers. Stewart (1984) reported that the earthy flavour rating was low in samples taken in July and the beginning of August, then rose sharply to a peak in early September-October. This could be interpreted as a result of the presence of the breakdown product of algal cells, and was strong following the collapse of the blue-green algal bloom by September. Alternatively, it could have been produced by fungi , either in association with or independent of the presence of dead algal materials. In the present study fungi ; in the periphyton increased steadily from June, and reached a peak at the beginning of October. Without more information, however, no definite conclusions can be drawn.

7. SUMMARY AND CONCLUSION

A study of the plankton (phytoplankton and zooplankton) together with some physico-chemical parameters and periphyton was carried out on an intensive cage fish-farm in Loch Fad, Isle of Bute, and in earthen ponds at Howietoun Fish Farm, Bannockburn.

Loch Fad: This shallow, eutrophic, unstratified loch exhibited low Secchi disc readings (0.6m to 1.0m) during summer due to the high phytoplankton population and high suspended solids. p^H was slightly on the alkaline side of neutrality throughout most of the study period, and photosynthetic activity resulted in the summer elevation of p^H during daytime. p^H and dissolved oxygen concentrations were lower at the cage site than at a control station situated at the opposite end of the loch to the fish farm. This was due to the high respiratory demands of the cage fishes and high densities of feral fishes in the vicinity of the cages, and the decomposition of larger quantities of organic matter in the water column and on the bottom at the cage site. Nutrient concentrations were higher at the cage site than at the control, resulting from the decomposition of fish faeces, metabolites and uneaten fish food pellets. Nutrient concentrations decreased during summer at all depths, indicating their utilization by the growing phytoplankton population. Chlorophyll-a concentration was generally high (maximum 202 mg/l), and was higher at the cage farm site than at the control, reflecting the denser phytoplankton population at this site.

Blooms of Microcystis aeruginosa were one of the principal characteristics of Loch Fad phytoplankton. It formed 92% to 99% of the total phytoplankton cell numbers. Presumably because of higher availability of nutrients at the cage site, the total phytoplankton population density was higher there. The other common phytoplankters were: Oscillatoria agardhi, Oscillatoria limosa, Asterionella formosa, Melosira italica-subarctica, Botryococcus braunii, Pediastrum boryanum and Pediastrum duplex.

Similarly to the phytoplankton, the zooplankton population was maximum during the summer months. Predation by cage fish and wild fishes in the loch, which tended to concentrate at the cage site to feed upon surplus fish food, may have been responsible for reducing the populations of the larger Cladocera and Copepoda at the cage site. Rotifers, however, were higher at the cage site than at the control, presumably because they were successful in escaping from predation by fishes on account of their smaller size and because of the lower population density of crustacean cyclopoid predators (particularly Cyclops abyssorum) at the cage site compared with the control. The common zooplankton in Loch Fad were: Bosmina longirostris, Chydorus sphaericus, Daphnia longispina, Cyclops abyssorum, Diaptomus gracilis and Keratella cochlearis. All the zooplankton present showed the typical diurnal migration cycle of daytime downward and night time upward movements.

The development of periphytic algal populations on suspended wooden blocks was maximum during summer and was higher at the cage site than at the control, presumably due to higher available nutrient concentrations at the cage site. In contrast to the dominance of Cyanophyceae in the phytoplankton, the group Bacillariophyceae was dominant over the other groups in the periphyton. The common algal species in the periphyton species were: Spirogyra gracilis, Melosira italica-subarctica, Navicula viridis, Amphora ovalis, Oscillatoria agardhi, Oscillatoria limosa, Anabaena flos-aquae. Also a higher number of fungal ascomycete species was present at the cage site than at the control. The presence of ascomycetes in Loch Fad may have contributed to the reported earthy taint of farmed fish.

Howietoun Fish Farm: Water temperature ranged seasonally from 4 °c to 16°c. Elevation of daytime pH at all the stations during summer was observed, due presumably to the photosynthetic activity of the higher phytoplankton population prevailing then. Dissolved oxygen concentration decreased as the water passed through the farm, principally because of the respiratory activity of the cultured fish and the decomposition of fish wastes and uneaten food. Ammonia, nitrite, nitrate and orthophosphate concentrations also increased from the water supply inlet to the farm to the outlet, which caused a progressive increase in the phytoplankton population. Suspended solids, however, decreased from the inlet to the outlet of the farm; this might be due to the sedimentation of inorganic suspended solids from the stream supply water as the water passed through the farm ponds.

The phytoplankton population reached a maximum during the summer.

The group Cyanophyceae was dominant over other groups of phytoplankton from April to November. The most dominant species, however, was Oscillatoria agardhi, as opposed to Microcystis aeruginosa which dominated Loch Fad phytoplankton. The other common species were: Coelosphiarium Kuetzingianum, Asterionella formosa, Melosira italica-subarctica, Tabellaria fenestrata, Tabellaria flucculosa, Botryococcus braunii and Spirogyra varians.

Total zooplankton reached maximum densities by summer and increased from the inlet to the outlet of the farm. The predation of zooplankton by the cultured fish was not evident. The most dominant zooplankter was Bosmina longirostris, and the other common species were Cyclops vicinus and Diaptomus laciniatus. Ascomorpha ecaudis, Brachionus angularis and Keratella valga, were present during a diurnal study and showed the expected daytime downward and night time upward movements, but Bosmina longirostris did not show any marked diurnal movement pattern.

The periphytic population in Howietoun Farm was also maximum during summer, and also increased from the inlet to the outlet of the farm, which could be the result of increased nutrient concentrations. As in the phytoplankton, the group Cyanophyceae was dominant from April to October. Oscillatoria agardhi was the most dominant species, the other common species were Anabaena flos-aquae, Navicula cryptocephala, Navicula viridis, Melosira italica-subarctica and Spirogyra varians.

Concluding Remarks

Comparison of eutrophication criteria

Different criteria were considered in the above discussion to describe the trophic state of Loch Fad, *viz*. transparency, chlorophyll-*a*, phytoplankton compound index and the presence of indicator species. All these indices pointed towards the highly eutrophic nature of the loch. Transparency is very often used to indicate the degree of eutrophication on the basis that it decreases with enrichment due to increasing abundance of phytoplankton. This criterion will hold good in the situation where transparency is mainly limited by autochthonous sources and organic matter, but transparency could also be affected by suspended soil particles washed in by rain or upmixing of the bottom sediments by wind action. Chlorophyll-*a* concentration is a very good indicator of the trophic state of a particular waterbody as it is a simple estimator of the phytoplankton, but to compare the chlorophyll-a data with other lakes, it is essential to use the same techniques for sampling during the same period of the year and time of day. In trophic state classification, many workers have used various phytoplankton indices, using desmids as characteristic of oligotrophic lakes. The most common index used is the compound index, which involves Cyanophyceae, Chlorophyceae, centric diatoms, Euglenophyceae and desmids, but desmids are sometimes widely distributed in all types of water rather than only in oligotrophic ones. Lastly, the indicator species criterion has also been widely used to determine the trophic state of lakes, but again some species have a wide range of distribution, making the classification difficult. In general, the presence and dominance of blue-green algae seems to be a strong indicator of eutrophy. In trophic state determination, all possible different criteria should be considered before reaching any conclusion. Perhaps the most simple and preliminary observations for alerting the fish farmer to increasing enrichment will be the deep green water colour, low transparency, high abundance of blue-green algae which could be detected by the naked eye with experience, and low dissolved oxygen during night-time.

Factors limiting phytoplankton on fish farms

Temperature, light, nutrients and grazing by zooplankton are considered to be among the main controlling factors of phytoplankton growth. The metabolic response of all organisms follows a general law of doubling with each 10°c increase up to a certain limit. This is approximated in most phytoplankton studies of photosynthesis and respiration if other factors are not severely limiting, though certain species of phytoplankton are more suited to low temperatures. Phytoplankton growth is affected by both quality and quantity of light. In highly productive systems, maximum productivity is near the surface and the photic zone may be only a metre or two deep due to high abundance of phytoplankton. In such a situation the productivity is limited by insufficient light, or in other words limited by self-shading. One of the important limiting factors for the growth of phytoplankton in the natural environment is the nutrient availability. In both Loch Fad and Howietoun Farm the high nutrient concentrations were unlikely to limit phytoplankton growth. Zooplankton populations were also not in such high abundance as to limit the phytoplankton. Moreover blue-greens were dominant in the phytoplankton population in both places, which are generally unacceptable to these herbivores. Thus water temperature and self-shading appear to play major roles in limiting the phytoplankton in Loch Fad. In Howietoun Farm, flushing might have played an important role in limiting phytoplankton. The greater the flushing rate, the shorter the period of time available for use and reuse of the nutrient income and, if the flushing rate is high enough, plankton buildup may be prevented because of cell washout. Further investigation of the flow rate of water through Howietoun farm ponds and retention time in each pond will be of great help in understanding the phytoplankton dynamics in ponds.

Workers in Canada studying small eutrophic prairie lakes found that those which reached an algal biomass of 100 mg/l chlorophyll-a had a 50% chance of a summer fish kill following a collapse in the algal population, while for those exceeding 200 mg/l chlorophyll-a, the probability increased to above 80%. These lakes were smaller and shallower than Loch Fad so the conditions are not directly comparable, but the example highlights the serious level of eutrophication in Loch Fad, with summer chlorophyll-a levels well above 100 mg/l for a sustained period and reaching a maximum of 202 mg/l.

Practical lessons for the fish farmer

The fish farmer should monitor dissolved oxygen, ammonia concentration and suspended solids regularly. During calm weather conditions the risk of low oxygen levels is greatest when algal levels are high. Dissolved oxygen could also drop drastically during the autumnal breakdown of the algal population. Un-ionized ammonia is highly toxic to fish, but the ammonium ion is relatively non-toxic. In the literature, several authors have discussed the LC50 concentration of un-ionized ammonia in salmonids. In general, a concentration of more than 0.02 mg/l of un-ionized ammonia causes significant depression of growth in fish. A decrease in the dissolved oxygen content in water increases the toxicity of several poisons to fish, and this has also been found for ammonia. There is no evidence that concentrations of suspended solids less than 25 mg/l have any harmful effect on fisheries. High levels of suspended solids reduce the resistance of fish to diseases, poisons, or to low dissolved oxygen, high temperature and extreme pH values. If low dissolved oxygen, high ammonia concentration and high suspended solids persist for a prolonged period, it is advisable to employ aeration of the water, lower the stocking density and/or use low-pollution feeds. Low-pollution feeds are more digestible, have lower total phosphorus, and contain phosphorus in a more digestible form. These feeds are more expensive than the ordinary market available feeds. However, an economic study of low-pollution feeds and their use is required in order to fully evaluate profitability.

Application of a number of conventional lake and reservoir restoration techniques could be used for reducing net phosphorus loading. Diversion of wastes from the waterbody is a common method of reducing loadings. The particulate waste faction from cages could be trapped and pumped out, but this method would be expensive and impractical in commercial scale operations. Sediment removal has also been used in restoration programmes. This method would cause more problems than it would solve in cage culture in lakes/reservoirs, as resuspension of sediments would stimulate algal production through increasing dissolved nutrient levels and destroying the thermocline. The sediment removal method, however, would be very useful and simple in pond culture systems as it is easier to manage. It is advisable to remove the pond sediments every two years at least. Other, more practical methods of reducing the environmental impact from intensive farms include removal of mortalities and increased harvesting pressure. Another method, given sufficient land area, would be to combine extensive settlement and oxidation ponds with intensive operation. This method is used in some tropical developing countries and could be used in temperate countries.

8. REFERENCES

Adams, B.A. (1929) The Cladothrix dichotoma and allied organisms as a cause of an "Indeterminate" taste in chlorinated water. Water and Water Eng.(London), 31, 309.

Adams, B.A. (1933) The role of Actinomycetes in producing earthy tastes and smell in potable water. Paper 14 Rept. of Public Works, Roads and Transport Cong., London

Anderson, G.C., C.W. Comita and V. Engstrom-Heg (1955) A note on the phytoplankton-zooplankton relationships in two lakes in Washington. Ecology, 36, 757-759.

Anon (1973) Water quality criteria 1972. United States Environmental Protection Agency Ecological Research Series R3.73.033.

Apstein, C. (1896) Das Susswasser plankton. Method und Resultate der quantitativen Untersuchung. Kiel, vi + 200 pp.

Arumugam, P.T. and J.I. Furtado (1980) Physico-chemistry, destratification and nutrient budget of a lowland eutrophicated malaysian reservoir and its limnological implications. Hydrobiologia, 70, 11-24.

Bachman, H. (1907) Vergleichende studien uber das Phytoplankton von Seen Schottlands und der Schweiz. Arch. Hydrobiol. Planktonk, 3, 1-91.

Bachmann, R.W. and J.R. Jones (1974) Phosphorous inputs and algal blooms in lakes. Iowa State J. Res., 49(1), 155-160.

Bailey-Watts, A.E. (1974) The algal plankton of Loch Leven, Kinross. Proc. R. Soc. Edin., B 74, 135-156.

Bailey-Watts, A.E. (1976a) Planktonic diatoms and some diatom-silica relations in a shallow eutrophic Scottish Loch. Freshwat. Biol. 6: 69-80.

Bailey-Watts, A.E. (1976b) Planktonic diatoms and silica in Loch Leven, Kinross, Scotland: a one month silica budget. Freshwat. Biol., 6, 203-213.

Bailey-Watts, A.E. (1978) A nine-year study of the phytoplankton of the eutrophic and non-stratifying Loch Leven (Kinross, Scotland). J. Ecol., 66, 741-771.

Bailey-Watts, A.E. & P. Duncan (1981) The phytoplankton in The Ecology of Scotland's largest lochs: Lomond, Awe, Ness, Morar and Shiel. Ed. P.S. Maitland, Dr. W. Junk Publishers, The Hague.

Bailey-Watts, A.E. & J.W.G. Lund (1973) Observations on a diatom bloom in Loch Leven, Scotland, Biol. J. Linn.Soc., 5, 235-253.

Bales, J.L. G.R. Curtin, I.C. Campbell and B.T. Hart (1980) Eutrophication study of lake Daylesford, Victoria. Aust. J. Mar. Freshwat. Res., 31, 573-587.

Balmain, K.H. and W.H. Shearer (1953) Further notes on the Fisheries of Loch Leven. Scott. Home Dep. North Scot. Hydro-electric Bds. Brown Trout Res. Lab. BTSC83.

Barthelmes, D. (1975) Elemente der Sauer-stoffbilanz in Karpfenteichen, ihre Wirkungsweise sowie die Optimirungsmoglichkeiten durch Silberkarpfen (Hypophthalmichthys molitrix) Z.Binnenfisch. DDR, 22, (12), 355-363.

Beeton, A.M. (1965) Eutrophication of the St. Lawrence Great Lakes. Limnol. Oceanogr., 10, 240-254.

Belcher, J.H., E.M.F. Swale and J. Heron (1966) Ecological and morphological observations on a population of Cyclotella pseudostelligera Hustedt., J. Ecol., 54, 335-340.

Berg, A. and E. Grimaldi (1965) Biologia delle due formi di coregene (Coregorius sp.) del Lago Maggiore. Mem. 1st Ital. Idrobiol.,18, 25-196.

Berg, A. and E. Grimaldi (1966) Biologia dell'agone (Alosa ficta lacustris) del Lago Maggiore. Mem. 1st Ital. Idrobiol.,20, 41-83.

Berg, K. and Nygaard, G. (1929) Studies on the plankton in the lake of Frederiksborg Castle. Mem. de l'Acad. Roy. Res. Sci. et des Lett. de Denmark, Sec. des Sci., Ser. 91, 223-316.

Bergheim, A, A Sivertsen and A.R. Selmer-Olsen, (1982) Estimated pollution leading from Norwegian fish farms. 1. Investigations 1978-1979. Aquaculture, 28, 347-361.

Beveridge, M. (1981) The environmental impact of cage fish culture on Loch Fad, Bute. Report commissioned by Rothesay Sea-foods Ltd.

Bienfang, P.K. (1975) Steady state analysis of nitrate-ammonium assimilation by phytoplankton. Limnol. Oceanogr., 20, 402-411.

Bindloss, M.E. (1976) The light-climate of Loch Leven, a shallow Scottish lake, in relation to primary production by phytoplankton. Freshwat. Biol., 6, 501-518.

Birge, E.A. (1898) Plankton studies on Lake Mendota. II The crustacea of the plankton from July 1894 to December 1896. Trans. Wis. Acad. Sci. Arts Lett., II, 274-451. In: Hutchinson, 1967.

Blaauboer, M.C.I. (1982) The phytoplankton species composition and the seasonal periodicity in Lake Vechter from 1956-1979. Hydrobiologia, 95, 25-36.

Bohra, O.P. (1976) Some aspects of Limnology of Padamsagar and Ranisagar, Jodhpur: Ph.D. Thesis, University of Jodhpur.

Boney, A.D. (1978) Microscopic plantlife in Loch Lomond. Glasg. Nat. 19, 391-402.

Bourrelly, P. (1966) Les Algues d'Eau Douce. I. Les Algues Vertes. Paris: Boubee et Cie.

Bourrelly, P. (1968) Les Algues d'Eau Douce. II Les Algues Jaunes et Brunes. Chrysophycees, Pheophycees, Zanthophycees et Diatomees. Paris: Boubee et Cie.

Bourrelly, P. (1970) Les Algues d'Eau Douce. III Les Algues Bleues et Rouges, Les Eugleniens, Peridiniens et Cryptomonadines. Paris: Boubee et Cie.

Boyd, C.E. (1982) Water quality management for pond fish culture. Elsevier Scientific Publishing Co.

Bradshaw, A.S. (1964) The crustacean zooplankton picture: Lake Erie 1939-49-59, Cayuga 1910-51-61. Verh. Internat. Verein. Limnol., 15, 700-708.

Brett, J.R. and T.D.D. Groves (1979) Physiological energetics. In: W.S. Hoar, D.T. Randall and J.R. Brett (Editors), Fish Physiology, Vol. V111, Bioenergetics and Growth. Academic Press, New York, NY, San Francisco, Ca, London, pp. 280.352.

Brezonik, P.L. (1972) Nitrogen: sources and transformations in natural waters. In: Allen, H.E. & Kramer, J.R. (eds), Nutrients in Natural Waters,pp. 1-47. Wiley, New York.

Bricker, F.J. and J.E. Gannon (1976) Limnological investigation of Hoop Lake - a northern Michigan bog. Mich. Academician, 9, 25-42.

Brock, T.D. (1973) Lower p^H limit for the existence of blue-green algae. Evolutionary and ecological implications. Science, New York, 179, 480-482

Brook, A.J. (1958) Changes in the phytoplankton of some Scottish hill lochs resulting from their artificial enrichment. Verh. internat. Ver. Limnol. XIII, 298-305

Brook, A.J. & A.v. Holden (1957) Fertilization experiments in Scottish freshwater lochs I. Loch Kinardochy Sci. Invest. Freshw. Salmon Fish Res. Scot Home Dep., 17, 39pp.

Brooks, J.L. (1968) The effects of prey-size selection by lake planktivores. Syst. Zool., 17, 272-291.

Brooks, J.L. (1969) Eutrophication and changes in composition of the zooplankton. In Eutrophication causes, consequences, correctives. National Academcy of Science, Washington, D.C.

Brooks, J.L. and S.I. Dodson (1965) Predation, body size and composition of plankton. Science, 150, 28-35.

Brown, H.D. (1976) A comparison of the attached algal communities of a natural and an artificial substrate. J. Phycol., 12, 301-306.

Brown, S.D. and A.P. Austin (1971) A method of collecting periphyton in lentic habitats with procedures for subsequent sample preparation and quantitative assessment. Int. Rev. ges. Hydrobiol., 56, 557-580.

Brown, S.D. and A.P. Austin (1973) Spatial and temporal variation in periphyton and physiochemical conditions in the littoral of a lake. Arch. Hydrobiol., 71, 183-232.

Buchan, A. (1872) Remarks on the deep-water temperature of Lochs Lomond, Katrine and Tay. Proc. R. Soc. Edinb., 1871-72, 791-795.

Buchanan, C. (1975) A biological study of the Lakes of the Clouds (with emphasis on zooplankton) M.S. Rep. Dep. Zool. Univ. New Hampshire.

Burgis, M.J., J.P.E.C. Darlington, I.G. Dunn, G.G. Ganf, J.J. Gwahaba and L.M. McGowan (1973) The biomass and distribution of organisms in Lake George, Uganda. Proc. R. Soc. Land., B. 184, 271-298.

Canfield, D.E. Jr. and R.W. Bachmann (1981) Prediction of total phosphorus concentrations, Chlorophyll-a, and secchi depth in Natural and Artificial lakes. Can. J. Fish Aquat. Sci., 38, 414-423.

Carlson, R.E. (1977) A trophic state index for lakes Limnol. Oceanogr., 22, 361-369.

Carlucci, A.F. and H.R. Schubert (1969) Nitrate reduction in seawater of the deep nitrite maximum off Peru. Limnol. Oceanogr., 14, 187-193.

Carr, N.G. and B.A. Whitton (eds) (1973) Biology of the blue-green algae. Oxford: Blackwell.

Chandler, D.C. (1940) Limnological studies of western Lake Erie. I. Plankton and certain physical-chemical data of the Bass Islands Region, from September 1938 to November 1939. Ohio J. Sci., 40, 291-336.

Chandler, D.C. (1942) Limnological studies of western Lake Erie II. Light penetration and its relation to turbidity Ecology, 23, 41-52.

Chapman, M.A. (1965) Ecological studies on the zooplankton of Loch Lomond. Ph.D. Thesis, University of Glasgow.

Chapman, M.A. (1969) The bionomics of Diaptomus gracilis Sars (Copepoda, Calanoida) in Loch Lomond, Scotland. J. Anim. Ecol., 38, 257-284.

Chapman, M.A. (1972) The annual cycles of the limnetic cyclopoid Copepoda of Loch Lomond, Scotland. Int. Revue ges. Hydrobiol. Hydrogr., 57, 895-911.

Christison, R. (1871) Observations on the fresh-waters of Scotland Proc. R. Soc. Edinb., 7, 567.

Coche, A.G., (1976) A general review of cage culture and its application in Africa. FAO Technical Conference on Aquaculture, Kyoto Comm.FIR. AQ/CONF/76/E.72.

Coche, A.G. (1977) Preliminary results of cage rearing of Tilapia nilotica in Lake Kossou, Ivory Coast. Aquaculture, 10(2), 109-140.

Coesel, P.F.M. (1975) The relevance of desmids in the biological typology and evaluation of freshwaters. Hydrobiol. Bull., 9, 93-101.

*

Conway, H.L. (1977) Interactions of inorganic nitrogen in the uptake and assimilation by marine phytoplankton Mar. Biol., 39, 221-232.

Conway, H.L., J.I. Parker, E.M. Yaguchi and D.L. Mellinger (1977) Biological utilization and regeneration of silica in Lake Michigan. J. Fish Res. Bd. Can., 34, 537-544.

Corbet, S.A., R.M.S. Perrin, D.R. Hartly, P.D. Lancashire, H.A.F. Mace, A.S. McClay, J.R. Morton, R.E. Parfitt, D.G. Reid, R. H.H. Tomiak, K. Wheatly, P.G. Willmer and R.I. Willows (1980) Diel changes in plankton and water chemistry in Wicken Brickpit. Hydrobiologia, 74, 249-271.

Davis, C.C. (1964) Evidence for the eutrophication of Lake Erie from phytoplankton records. Limnol. Oceanogr., 9, 275-283.

Davis, C.C. (1972) Plankton dynamics in a Newfoundland lake Verh. Internat. Verein. Limnol., 18, 278-283.

Deevey, E.S. Jr. (1942) Studies on Connecticut lake sediments III Biostronomy of Linsley Pond. Amer. J. Sci., 240, 233-264.

De Haan, H. (1982) Physico-chemical environment in Tjeukemeer with special reference to speciation of algal nutrients. Hydrobiologia, 95, 205-221.

Dillon, P.J. (1975) The phosphorus budget of Cameron Lake, Ontario: The importance of flushing rate to the degree of eutrophy of lakes. Limnol. Oceanogr., 20, 28-39.

Dillon, P.J. and F.H. Rigler (1974) The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr., 19, 767-773.

Dillon, P.J. and F.H. Rigler (1975) A simple method for predicting the capacity of a lake for development based on lake trophic status. J. Fish Res. Bd. Can., 32(9), 1519-1531.

Dobson, H.F.H., M. Gilbertson and P.G. Sly (1974) A summary and comparison of nutrients and related water quality in Lakes Erie, Ontario, Huron and Superior. J. Fish Res. Bd. Can., 31, 731-738.

Doohan, M. (1973) Energetics of planktonic rotifers applied to populations in reservoirs. Ph.D. Thesis, Univ. London.

Dumont, H.J. (1972) A competition-based approach of the reverse migration in zooplankton and its implications, chiefly based on a study of the interactions of the rotifer Asplanchna priodonta (Gosse) with special Crustacea Entomostraca. Int. Rev. Gesamten Hydrobiol., 57, 1-38.

Dwivedi, S.N., O.P. Bohra, D.V. Reddy and K.K. Pillai (1977). Diurnal observations of abiotic factors at Kakinada Bay, main feeder channel and stocking pond of brakish water fish farm, Kakinada (A.P). Comp. Physiol. Ecol., 2(4), 248-250.

Eddy, S. (1934) A study of fresh-water plankton communities. Illinois Biological Monographs, 12(4), 1-93.

Edmondson, W.T. (1965) Freshwater Biology. John Wiley & Sons, Inc., New York.

Edmondson, W.T. (1970) Phosphorus, nitrogen and algae in lake Washington after diversion of sewage. Science, New York, 169, 690-691.

Edmondson, W.T. (1972) Nutrients and phytoplankton in Lake Washington. In Nutrients and Eutrophication: The limiting nutrient controversy. G.E. Likens (ed.) Spec. Symp. Limnol. and Oceanogr. 1, 173-193.

Edmondson, W.T. and Hutchinson, G.E. (1934) Report on Rotatoria of Yale North India Expedition. New Haven. Mem. Conn. Acad. Arts Sci., 10, 153-186.

Egorova, A.A. and V.L. Issotchenko (1944). The cause of earthy odor and flavor in water basins. Microbiol., 13, 216.

Elgmork, K. (1964) Dynamics of zooplankton communities in some small inundated ponds. Folia limnol. Scand., 12, 83 pp.

Elwaked, S.K. and Wahby, S.D. (1970) Hydrography and chemistry of Lake Manzalah, Egypt. Arch. Hydrobiol., 67, 173-200.

Enell, M. (1981) Miljokonsekuenser au akvakultur-sedimentation fran fiskkasseodlingar. Redogorelse av hittills uppnadda resultat for perioden 1/7 - 31/12 - 1981. Limnologiska Institutionen, Universitetet i Lund. 28p.

Enright, J.T. and W.M. Hamner (1967) Vertical diurnal migration and endgenous rhythmicity. Science, 157, 937-941.

Eppley, R.W., J.L. Coatsworth and L. Solorzano (1969) Studies of nitrate reduction in marine phytoplankton Limnol. Oceanogr.,14, 194-205.

Farramola, R. (1949) Odors produced by Streptomyces in water. Jour. Interam. Assoc. San. Eng., 2, 371.

Foerster, J.W. and H.E. Schlichting (1965). Phycoperiphyton in an oligotrophic lake. Trans. Am. micros. Soc., 84, 485-502.

Fogg, G.E. (1969) The physiology of an algal nuisance Proc. R. Soc. Land., B, 173, 175-189.

Fogg, G.E., W.D.P. Stewart, P. Fay and A.E. Walsby (1973) The blue-green algae. London and New York: Academic Press.

Forbes, I.J. (1981) A preliminary investigation into the effects of cage culture on the wild fish of Loch Fad, Bute. B.Sc.(Hons) Thesis, University of Stirling, Stirling.

Forsberg, C. and Ryding, S.O. (1980) Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. Arch. Hydrobiol., 89(½), 189-207.

George, M.G. (1961) Diurnal variations in two shallow ponds in Delhi, India. Hydrobiologia, 18, 265-273.

Gerber, N.N. and H.A. Le Chevalier (1965) Geosmin, an earthy-smelling substance isolated from Actinomycetes. Appl. Microbiol., 13, 935.

Gerloff, G,C., G.P. Fitzgerald and F.Skoog (1950). The isolation, purification and culture of blue-green algae. Amer. J. Bot., 37, 216-218.

Gibson, P. (1981) Comparison of normal and low pollution grower diets for brown trout (Salmo trutta). M.Sc. Thesis, University of Stirling, Stirling.

Gilwicz, Z.M. (1975) Effect of zooplankton grazing on photosynthetic activity and composition of phytoplankton. Verh. Internat. Verein. Limnol., 19, 1490-1497.

Gliwicz, Z.M. and A. Hillbricht-Ilkowska (1973) Efficiency of the utilization of nanoplankton primary production by communities of filter-feeding animals measured in situ. Verh. Internat. Verein. Limnol, 18, 197-212.

Goering, J.J. (1968) Denitrification in the oxygen minimum layer of the eastern tropical Pacific Ocean. Deep Sea Res., 15, 157-164.

Goldspink, C.R. & D.B.C. Scott (1971) Vertical migration of *Chaoborus flavicans* in a Scottish loch. *Freshwat. Biol.*, *1*, 411-421.

Golterman, H.L., R.S. Clymo and M.A.M. Ohnstad (1978) *Methods for physical and chemical analysis of fresh waters.* Blackwell Scientific Publications.

Gulati, R.D. (1982) The zooplankton: its community structure, food and feeding, and role in the ecosystem of Lake Vechten. *Hydrobiologia*, *95*, 127-163.

Hall, D.J., W. Cooper and E. Werner (1970) An experimental approach to the production dynamics and structure of freshwater animal communities. *Limnol. and Oceanog.*, *15*, 839-928.

Happey, C.M. (1970) The effects of stratification on phytoplanktonic diatoms in a small body of water. *J. Ecol.*, *58*, 635-651.

Harding, J.P. and W.A. Smith (1974) *A key to the British Freshwater Cyclopid and calanoid Copepods.* FBA Scientific Publication No.18.

Harris, J.E. (1963) The role of endogenous rhythms in vertical migration. *J. Mar. Biol. Assoc. U.K.*, *43*, 153-166.

Harvey, H.W. (1966) *The Chemistry and Fertility of Sea Waters.* Cambridge University Press, London.

Hasler, A.D. (1947) Eutrophication of lakes by domestic drainage. *Ecology3*, *28*, 383-395.

Henley, D. (1970) *Odorous metabolites and other selected studies of Cyanophyton.* Ph.D. Thesis, North Texas State University.

Hinshaw, R.N., (1973) *Pollution as a result of fish culture activites* Ecological Research Series, U.S. Environmental Protection Agency, Washington, DC, 53pp.

Höll, K. (1928) Oekologie der Peridineen Studien uber den Einfluss chemischer und physikalischer Faktoren auf die Verbreitung der Dinoflagellaten im Susswasser. Pflanzenforschung, II, vi, 105pp.

Holden, A.V. (1959) Fertilization experiments in Scottish freshwater lochs. I Sutherland, 1954, 1. Chemical and Botanical observations. Sci. Invest. Freshw. Salmon Fish. Res. Scot. Home Dep. 24, 42pp.

Holden, A.V. & L.A. Caines (1974) Nutrient chemistry of Loch Leven, Kinross, Proc. R. Soc. Edinb., B,74, 101-21.

Holm, J.C., D. Møller, J. Thorsen and T. Hansen (1982) Stettefiskoppdrett i vassdrag-Virksomheten i Kvernavatnet 1979-1981. Fiskeridirektoratets Havforskningsinstitutt. L.nr.14/82.

Holm-Hansen, O. (1968) Ecology, physiology and biochemistry of blue-green algae. A. Rev. Microbiol., 22, 47-70.

Hrbaček, J. (1962) Relations of planktonic Crustacea to different aspects of pollution, p.53-57. In Biological problems in water pollution. Robert A. Taft Sanitary Engineering Center, U.S. Public Health Service, Cincinnati, Ohio.

Hrbaček, J. (1964) Contribution to the ecology of water-bloom forming blue-green algae - Aphanizomenon flos-aquae and Microcystis aeruginosa. Vert. Int. Verein Limnol. 15, 837-846.

Hudson, E.J. and H.W. Marsson (1970) Eutrophication, with particular reference to the role of phosphate. Chem. Ind. 14 Nov., 1449-1458.

Hutchinson, G.E. (1957) A treatise on Limnology, Vol.1, Wiley.

Hutchinson, G.E. (1967) A treatise on Limnology, Vol.2, Wiley.

Ivlev, V.S. (1961) Experimental ecology of the feeding of fishes (trans. from Russian) Yale Univ. Press, New Haven, Conn., 302p.

Johnson, D. and A.F. Walker (1974) The zooplankton of Loch Leven, Kinross. Proc. R. Soc. Edinb. B, 74, 285-294.

Jones, J.R. and R.W. Bachmann (1976) Prediction of phosphorus and chlorophyll levels in lakes. J. Water Poll. Control. Fed. 48; 2176-2182

Juday, C., E.B. Fred and F.C. Wilson (1924) The Hydrogen ion concentration of certain Wisconsin Lake Waters. Trans. Amer. Micros. Soc., 33, 177-190.

Juday, C., J.M. Blair and E.F. Wilder (1934) Photosynthetic activity of the aquatic plants of Little John Lake, Vilas County, Wisconsin. Amer. Midland Naturalist., 30, 426-446.

Kairesalo, T. (1979) Effects of rainbow trout breeding on phytoplankton productivity in lake Langelmavesi, South Finland, Ann. Bot., 16, 35-42.

**

Kikuchi, K. (1930) A comparison of the diurnal migration of plankton in eight Japanese Lakes. Mem. Coll. Sci. Kyoto Imp. Univ., B, 5, 27-74.

Kilambi, R.V; C.E. Hofman, A.V. Brown, J.C. Adams and W.A. Wickizer (1976) Effects of cage culture fish production upon the biotic and abiotic environment of Crystal Lake, Arkansas. Final report to the Arkansas Game and Fish Commissioners and United States Department Commissioners, NOAA National Marine Fisheries Service Project Number 2-166R.

King, D.L. (1970) The role of carbon in Eutrophication. J. Water Pollut. Contr. Fed., 42, 2035-2051.

Klarer, D.M. (1978) Some studies on the plankton of the Dubh Lochan. Ph.D. Thesis, University of Glasgow.

Kline, J.D. and R.A. Richards (1972) Oxygen-deficient conditions and nitrate reduction in the eastern tropical north Pacific Ocean. Limnol. Oceanogr., 17, 885-900.

Kolkwitz, R. (1950) Okologie der Saprobien. Schr. Ver Wasser Bodem- und Luflhygiene, 4, 1-64.

Komàrek, J. and H. Ettl (1958) Algologische Studien. Prague.

Konikoff, M. (1975) Toxicity of nitrite to channel catfish. Prog. Fish-Cult., 37, 96-98.

Korycka, A. and B. Zdanowski (1980) Some aspects of the effect of cage fish culture on lakes, with special reference to heated lakes. EIFAC Symposium on new developments in the utilization of heated effluents and of recirculation systems for intensive aquaculture, 28-30 May 1980, Stavanger, Norway, 10p.

Kratz, W.A. and J. Myers (1955) Nutrition and growth of several blue-green algae. Amer. J. Bot., 42, 282-287.

Kuentzel, L.E. (1969) Bacteria carbon dioxide and algal blooms. Journal of the Water Pollution Control Federation, 41, 1737-1747.

Lange, W. (1970) Cyanophyta-bacteria systems: effects of added carbon compounds or phosphate on algal growth at low nutrient concentrations. J. Phycol., 6, 230-234.

Langhans, V. (1936) Planktonorganismen als Indikatoren zur Beurleilung von Karpfenteichen. Zeitschr. f. Fischerei, 34, 385-399.

Larsson, P. (1971) Vertical distribution of planktonic rotifers in a meromictic lake: Blankvatn near Oslo, Norway. Norw. J. Zool., 19, 47-75.

Larsen, V. (1975) Nitrogen transformation in lakes. In: Conference on Nitrogen as a Water Pollutant. I.A.W.P.R. specialized Conference, Copenhagen, Denmark, August, 1975.

Liao, P.B. (1970) Pollution potential of salmonid fish hatcheries. Water Sewage Works, 117, (8), 291-297.

Liebmann, H. (1962) Handbuch der Frischwasser - und Abwasserbiologie, Vol.1, 2nd edit., R. Oldenbourg, Munchen, 588pp.

Lindstrom, E.A., R. Skulberg and O.M. Skulberg (1978) Observations on planktonic diatoms in the lake-river system Lake Mjosa-Lake Oyeren-River Gloma, Norway. Norw. J. Bot., 20, 183-195.

Losos, B. and J. Hetesa (1973) The effect of mineral fertlization and carp fry on the composition and dynamics of plankton. Hydrob. Stud., 3, 173-217.

Lund, J.W.G. (1950) Studies on Asterionella formosa Hass. II Nutrient depletion and the spring maximum, Pt.1 J. Ecol., 38, 1-14.

Lund, J.W.G., F.J.H. MacKereth and C.H. Mortimer (1963) Changes in depth and time of certain chemical and physical conditions and of the standing crop of Asterionella formosa Hass. in the North Basin of Windermere in 1947. Phil. trans. R. Soc., B246, 731, 255-290.

Lund, J.W.G. (1971) The Fritsch collection of illustrations of freshwater algae. Mitt. int. Verein theor. angew. Limnol., 19, 314-316.

Maitland, P.S. (1981) The ecology of Scotland's largest Lochs: Lomond, Awe, Ness, Morar and Shiel. Dr W. Junk Publishers, The Hague.

Maitland, P.S; B.D. Smith and G.M. Dennis (1981) The crustacean zooplankton In:the ecology of Scotland's largest lochs: Lomond, Awe, Ness, Morar and Shiel. Ed. P.S. Maitland, Dr W Junk Publishers, The Hague.

Markmann, P.N. (1977) Status over dambrugsproblematikken pr. 1977 11.30. Udført for Vejle, Viborg ag Arhus Amtskommune, 162pp.

Markmann, P.N. (1978) Bergraensning af dambrugsforureningen. Vand, 9(1), 29-34.

Maulood, B.K. and A.D. Boney (1980) A seasonal and ecological study of the phytoplankton of Loch Lomond, Hydrobiologia, 71, 239-259.

Maulood, B.K. and A.D. Boney (1981a) Phytoplankton ecology of Loch Ard, Scotland. Hydrobiologia, 83, 485-490.

Maulood, B.K. and A.D. Boney (1981b) Phytoplankton ecology of the lake of Menteith, Scotland. Hydrobiologia, 79, 179-186.

Maulood, B.K., G.C.F. Hinton and A.D. Boney (1978) Diurnal variation of phytoplankton in Loch Lomond. Hydrobiologia, 58(2), 99-117.

May, V. (1972) Blue-green algal blooms at Braidwood, New South Wales (Australia). New South Wales Department of Agriculture, Sydney.

McIntire, C.D. and C.E. Bond (1962) Effects of artificial fertlization on plankton and benthos abundance in four experimental ponds. Trans. Amer. Fish. Soc., 91, 303-312.

McLaren, I.A. (1963) Effects of temperatures on growth of zooplankton and the adaptive value of vertical migration. J. Fish. Res. Bd. Can., 20, 685-727.

McNaught, D.C. and A.D. Hasler (1964) Rate of movement of populations of Daphnia in relation to changes in light intensity J. Fish. Res. Bd., Can., 31, 291-316.

Michael, R.G. (1964) Limnological investigations on ponds plankton, macrofauna and chemical constituents of water and their bearing on fish production. Ph.D. Thesis, University of Calcutta.

Meyers, D.G. and J.R. Strickler (1978) Morphological and behavioral interactions between a carnivorous aquatic plant (Utricularia vulgaris L.) and a chydorid cladoceran (Chydorus sphaericus O.F.M.). Int. Ver. Theor. Angew. Limnol. Verh., 20, 2490-2495.

Moed, J.R. and H.L. Hoogveld (1975) Dominant diatoms in Tjeukemeer. The appearance of Diatoma elongatum (Lyngb.) Agardh. Freshwat. Biol., 5, 159-165.

Monakov, A.V. and Yu. I. Sorokin (1961) Quantitative data on the feeding of Daphnia. Trav. Inst. Biol., Vodokhr., 4, 251-261.

Moore, J.W. (1977) Some factors influencing the density of subarctic populations of Bosmina longirostris, Holopedium gibberum, Codonella eratera and Ceratium hirundinella. Hydrobiologia, 56(3), 199-207.

Morgan, N.C. (1970) Changes in the fauna and flora of a nutrient enriched lake. Hydrobiologia, 35, 545-553.

Morris, R.L. (1962) Investigations of Actinomycetes as taste and Odor sources. Water and Sewage Works, 109, 76.

Mortimer, C.H. (1941) The exchange of dissolved substances between mud and water in lakes. J. Ecol. 30, 147-201.

Mortimer, C.H. (1941) The exchange of dissolved substances between mud and water in lakes. J. Ecol., 29, 280-529.

Moss, B. (1973) The influence of environmental factors on the distribution of freshwater algae - an experimental study. Part 3. Effects of temperature, vitamin requirements, and inorganic nitrogen compounds on growth. J. Ecol., 61, 179-192.

Murray, J. and L. Pullar (1910) Bathymetrical survey of the freshwater lochs of Scotland. Edinburgh Challenger Vols. 1-6.

Nadin-Hurley, C.M. and A. Duncan (1976) A comparison of daphnid gut particles with the sestonic particles present in two Thames Valley reservoirs throughout 1970 and 1971. Freshwat. Biol., 6, 109-123.

Nasar, S.A.K. (1977) Diurnal variations in some physico-chemical factors in a pond in Bhagalpur, India. Comp. Physiol. Ecol. 2(3), 145-149.

National Academy of Science and National Academy of Engineering (1972) Water quality criteria. A report of the Committee on Quality Criteria. Washington, D.C. 594pp.

Naumann, E. (1917) Undersokningar ofver fytoplankton och under den pelagiska regionen forsiggaende gytjeoch dybildningar inom vissa syo och mellasvenska ubergsvatten. Kunn. svenska Vegtensk. Akad. Handl., 56, 1-165.

Naumann, E. (1931) Limnologische Terminologie E. Abderhalden: Handbuch der biologischen Arbeitsmethoden. Berlin and Wien, Urban and Schwarzenberg, Abt. Ix, Teil 8: 776pp.

Nauwerck, A. (1963) Die Beziehungen Zwischen Zooplankton und Phytoplankton in See Erken. Symbolae Botanical Upsaliensis, 17, 1-163.

Nordquist, H. (1921) Studien uber das Teichzooplankton Lunds Univ. Aarskrift. N.F., 17, 5:3 - 123, Lund.

North, D.H. (1983) Sediment chemistry and nutrient exchange in intensively farmed Loch Fad. B.Sc. (Hons.) Thesis, University of Stirling, Stirling.

Nygaard, G. (1949) Hydrobiological studies of some Danish ponds and lakes II. Kon. danske Vidensk. Selsk. Biol. Skr., 7, 293 pp.

Parker, J.I., H.L. Conway and E.M. Yaguchi (1977) Seasonal periodicity of diatoms and silicon limitation in offshore Lake Michigan J. Fish. Res. Bd. Can., 34, 552-558.

Patalas, K. (1954) Quantitative investigations on the diurnal and seasonal variations in the distribution of the pelagic crustacea in the Charzykowo Lake. Pol. Arch. Hydrobiol., 2, 31-155.

Patrick, R., M.H. Hohn and J.H. Wallace (1954). A new method for determining the pattern of the diatom flora. Not. Nat., 259, 12 pp.

Pearsall, W.H. (1921) The development of vegetation in the English Lakes, considered in relation to the general evolution in glacial lakes and rock basins. Proc. R. Soc., B 92, 259-284.

Pearsall, W.H. (1932) Phytoplankton in the English Lakes II The composition of the phytoplankton in relation to dissolved substances. J. Ecol., 20, 241-262.

Pearsall, W.H. & L. Loose (1937) The growth of Chlorella vulgaris in pure culture. Proc. Roy. Soc. (London), B, 121, 451-501.

Pederson, G.L., E.B. Welch and A.H. Litt (1976) Plankton secondary productivity and biomass: their relation to lake trophic state. Hydrobiol. 50, 129-144.

Pejler, B. (1957a) Taxonomic and ecological studies on planktonic Rotatoria from central Sweden, K. Svenska Vetensk Akad., Handl., Ser.4, band 6, No.7, 52pp.

Pejler, B. (1957b) Taxonomic and ecological studies on planktonic Rotatoria from Northern Swedish Lapland. K. Svenska Vetensk Akad., Handl., Ser.4, band 6, No.5, 68pp.

Penczak, T; W. Galicka, M. Molinski, E. Kusto and M. Zalewski (1982) The enrichment of a mesotrophic lake by carbon, phosphorus and nitrogen from the cage aquaculture of a rainbow trout, Salmo gairdneri. J. Appl. Ecol., 19, 371-393.

Pennak, R.W. (1944) Diurnal movements of zooplankton organisms in some Colorado mountain lakes. Ecology, 25, 387-403.

Pennak, R.W. (1968) Field and experimental winter limnology of three Colorado mountain lakes. Ecol., 49, 505-520.

Persoone, G. and N. De Paun (1979) Systems of biological indicators for water quality assessment in Biological Aspects of Water pollution. Ed. O. Ravera, London: Pergamon.

Peterson, B.J., J.E. Hobbie and J. Haney (1978) Daphnia grazing on natural bacteria Limnol. Oceanogr., 23, 841-1088.

Phillips, M. (1983) The attraction of free ranging rainbow trout to a feeding station. Ph.D. Thesis, University of Stirling, Stirling.

Pollock, J.B. (1981) Studies on the parasite fauna of the caged and wild fish of Loch Fad. B.Sc. (Hons.) Thesis, University of Stirling, Stirling.

Pontin, R.M. (1978) A key to the freshwater planktonic and semi-planktonic Rotifera of the British Isles. F.B.A. Scientific Publication No.38.

Procházková, L., P. Blazka and M. Kralova (1970) Chemical changes involving nitrogen metabolism in water and particulate matter during primary production experiments. Limnol. Oceanogr., 15, 797-807.

Rast, W. and G.F. Lee (1978) Summary analysis of northern American (U.S. portion) OECD Eutrophication Project: Nutrient loading. Lake response relationships and trophic state indices. EPA-600/3-78-008.

Rawson, D.S. (1956) Algal indicators of trophic lake types Limnol. and Oceanog., 1, 18-25.

Rawson, D.S. (1960) A limnological comparison of twelve large lakes in northern Saskatchewan. Limnol. Oceanogr., 5, 195-211.

Redfield, A.C., G.H. Ketchum and F.A. Richards (1963) The influence of organisms on the composition of sea water. In Hill, M.N. (ed.), The Sea, Vol.2, pp. 26-77. Wiley-Interscience, New York.

Reynolds, C.S. (1971) The ecology of the planktonic blue-green algae in the North Shropshire meres. Field Studies, 3, 409-432.

Reynolds, C.S. (1973) Growth and buoyancy of Microcystis aeruginosa Kutz. emend. Elenkin in a shallow eutrophic lake. Proc. R. Soc. Lond., B 184, 29-50.

Reynolds, C.S. (1975) Interrelations of photosynthetic behaviour and buoyancy regulation in a natural population of a blue-green alga. Freshwat. Biol.,5, 323-338.

Reynolds, C.S. and S.E. Allen (1968) Changes in the phytoplankton of Oak Mere, following the introduction of base-rich water. Brit. Phycol. Bull.,3, 451-462.

Rimon, A. and M. Shilo (1982) Factors which affect the intensification of fish breeding in Israel. I. Physical, chemical and biological characteristics of the intensive fish ponds in Israel. Bamidgeh, 34, 87-100.

Ringelberg, J. (1964) The positively phototactic reaction of Daphnia magna Straus. A contribution to the understanding of vertical migration. Neth. J. Sea. Res., 2, 319-406.

Ringelberg, J. and H. Servaas (1971) A circadian rhythm in Daphnia magna. Oecologia, 6, 289-292.

Rodhe, W. (1958) Crystallization of eutrophication concepts in Northern Europe. In: Eutrophication: causes, consequences and correctives. Nat. Acad. Sci./Nat. Res. Council. Publ. 1700.

Round, F.E. and Brook, A.J. (1959) The phytoplankton of some Irish Loughs and an assessment of their trophic status. Proc. Roy. Ir. Acad.,60, 168-191.

Russo, R.C., C.E. Smith and R.V. Thurston (1974) Acute toxicity of nitrite to rainbow trout (Salmo gairdneri). J.Fish. Res. Bd., Can., 31, 1653-1655.

Russo, R.C. and R.V. Thurston (1977) The acute toxicity of nitrite to fishes. In R.A. (ed). Recent advances in fish toxicology, EPA Ecol. Res. Ser. EPA-600/3-77-085, U.S. Environmental Protection Agency, Corvallis, OR.

Ruttner, F. (1931) Die Schichutung in tropischen seen Verhandi. d. Internat. Vereingt Theort. V. angwad. Limnologie, B.V. 44-67.

Safferman, R.S. (1967) Earthy smelling substances from a blue-green algae. Environ. Sci. and Tech., 1, 429.

Sakamoto, M. (1966) Primary production by phytoplankton community in some Japanese lakes and its dependence on lake depth. Arch. Hydrobiol., 62, 1-28.

Saunders, G.W. (1969) Some aspects of feeding of zooplankton. In Eutrophication, causes, consequences, correctives. National Academy of Sciences, Washington, DC.

Schindler, D.W. and B. Noven (1971) Vertical distribution and seasonal abundance of zooplankton in two shallow lakes of the Experimental Lake Area, Northwestern Ontario. J. Fish. Res. Bd. Can., 28, 245-256.

Schindler, D.W. (1976) Biogeochemical evolution of phosphorus limitation in nutrient-enriched lakes of the Precambrian Shield. In J.O. Nriagu (ed). Environmental biochemistry. Ann Arbor Science Publishers, Ann Arbor, Mich.

Schuurman, J.F.M. (1932) A seasonal study of the microflora and microfauna of Florida Lake, Johannesburg, Transvaal. Trans. Roy. Soc. South-Africa, 20, 333-386.

Scourfield, D.J. and J.P. Harding (1966) A key to the British species of freshwater Cladocera. FBA Scientific Publication No.5.

Shapiro, J. (1973) Blue-green algae: why they become dominant. Science, New York, 179, 382-384.

Skogheim, O.K. and A. Bergheim (1981) Miljøeffekter av fiskoppdrett-sanlegg i ferskvann. Notat fra Fiskeforskningen, Direktoratet for vilt og Ferskvannsfisk. 10p.

Skogheim, O.K., S. Sanni and A. Bergheim (1982) Some ecological effects of a fish-cage farm in a Norwegian Lake. EIFAC Twelfth Session, Budapest, 31 May-5 June 1982. Working Party on fish-farms effluents.

Sládeček, V. (1958) A note on the phytoplankton-zooplankton relationship. Ecology, 39(3), 547-549.

Sládeček, V. (1973) System of water quality from the biological point of view. Arch. Hydrobiol. B. Ergebn. Limnol., 7, 1-14, 1-218.

Smith, I.R. (1974) The structure and physical environment of Loch Leven, Scotland. Proc. R. Soc. Edinb., B, 74, 81-100.

Smith, C.E. and W.G. Williams (1974) Experimental nitrite toxicity in rainbow trout and chinook salmon. Trans. Amer. Fish. Soc., 2, 389-390.

Smith, I.R., A.A. Lyle, & A.J. Rosie (1981) Comparative physical limnology in The ecology of Scotland's largest lochs: Lomond, Awe, Ness, Morar and Shiel. Ed. P.S. Maitland. Dr. W. Junk Publishers, The Hague.

Solberg, S.O. and F. Bregnballe (1977) Dambrug som forureningskilde. Medd. Forsøgsdambruget, No.58, 71pp.

Southern, R. and A.C. Gardiner (1926) A preliminary account of some observations on the diurnal migration of the crustacea of the plankton of Lough Derg. Int. Revue ges. Hydrobiol., Hydrogr., 15, 323-326.

Southern, R. and A.C. Gardiner (1932) Reports from the limnological laboratory. II The diurnal migrations of the crustacea of the plankton in Lough Derg. Proc. R. Ir. Acad., 40, 121-159.

Sparling, J.H. and C. Nalewajko (1970) Chemical composition and phytoplankton of lakes in Southern Ontario. J. Fish. Res. Bd., Can., 27(8), 1405-1428.

Sreenivasan, A. (1970) Limnology of tropical impoundments. A comparative study of major reservoirs in Madras State. Hydrobiologia, 36(3/4), 443-460.

Sreenivasan, A. (1976) Limnological studies and primary production in temple pond ecosystem. Hydrobiologia, 48(2), 117-123.

Stewart, J.A. (1984) Water quality and fish health at Rothesay Sea Foods cage farm, Loch Fad, Bute. Report, University of Stirling, Stirling.

Stewart, W.D.P. and H.W. Pearson (1970) Effects of aerobic and anaerobic conditions on growth and metabolism of blue-green algae. Proc. R. Soc. Lond.,B, 175, 293-311.

Strickland, J.D.H., O. Holm-Hansen, R.W. Eppley, and R.J. Linn (1969), The use of a deep tank in plankton ecology. I, Studies of the growth and composition of phytoplankton at low nutrient levels. Limnol. Oceanogr., 14, 23-34.

Strickland, J.D.H., L. Solorzano and R.W. Eppley (1970) Part I: General introduction hydrography and chemistry. In: Strickland, J.D.H. (ed), The Ecology of the Plankton off La Jolla, California, in the period April through September, 1967. Scripps Institution of Oceanography Bulletin, 17, 1-21.

Strickland, J.D.H., and Parsons, T.R. (1972) A practical handbook of sea water analysis. Fish. Research Board of Canada Publication, Bull. no. 167

Talling, J.F. and D. Driver, (1963) Some problems in the estimation of Chlorophyll-a in phytoplankton. Proc. conference on primary productivity measurements, marine and fresh-water; held at Univ. Hawaii, 1961. U.S. Atomic Energy Comm. TID-7633, 142-146.

Tessenow, U. (1964) Experimentaluntersuchungen zur Kieselsaurehaushalt der Binnengewasser. Arch. Hydrobiol., 32, 136.

Thorpe J.E. (1974) Trout and perch populations at Loch Leven, Kinross. Proc. Roy. Soc., Edinb., B, 74, 295-313.

Thunmark, S. (1945) Zur Soziologie des Susswasser-planktons. Fine methodologisch-okologische studie. Folia Limnol., Scand., 3, 66pp.

Tippett, R. (1969) Studies on the ecology of attached diatoms from two ponds and two springs in North Somerset. Ph.D. Thesis, University of Bristol.

Tippett, R. (1978) The effect of the Cruachan Pumped-Storage hydro-electric scheme on the limnology of Loch Awe. University of Glasgow, unpublished report.

Tippett, R. (1970) Artificial surfaces as a method of studying populations of benthic microalgae in freshwater. Br. phycol. J., 5, 187-199.

Toetz, D. (1976) Diel periodicity in uptake of nitrite and nitrate by reservoir phytoplankton. Hydrobiologia, 49, 49-53.

Tomasso, J.R., B.A. Simco and K.B. Davis (1979). Chloride inhibition of nitrite-induced methemoglobinemia in channel catfish (Ictalurus punctatus). J. Fish Res. Bd. Can., 36, 1141-1144.

Topachevskii, A.V., L.P. Braginskii & J.A. Sirenko (1969) Massive development of blue-green algae as a product of the ecosystem of a reservoir. Hydrobiol. J., 5,(6), 1-10.

U.S.E.P.A. (1974) The relationship of phosphorus and nitrogen to the trophic state of northeast and northcentral lakes and reservoirs. National Eutrophication Survey, Working paper No.23.

Verma, M. (1967) Diurnal variation in a fish pond in Seoni, India. Hydrobiologia., 30(1), 129-137.

Wada, E. and A. Hattori (1972) Nitrite distribution and nitrate reduction in deep sea waters. Deep Sea Res., 19, 123-132.

Walker, A.F. (1970) The zooplankton of Loch Leven. M.Sc. Thesis University of Stirling, Stirling.

Warrer-Hansen, I. and J. Wood-Petersen (1976) Forskellige driftsparameters indflydelse po foruréningen fram dambrug, VI & JTI, Danmark, September 1976, 107pp.

Watson, E.R. (1903) Internal oscillation in the waters of Loch Ness. Nature, Lond. 49: 174.

Weber, C.J. and R.L. Raschke (1970) Use of a floating periphyton sampler for water pollution surveillance, 22pp Fed. Wat. Poll. Control Admin., U.S. Dept. Int. Reprint.

Wedderburn, E.M. (1907) The temperature of the freshwater lochs of Scotland, with special reference to Loch Ness, Proc. R. Soc., Edinb., 27: 14-15.

Weimann, R. (1933) Hydrobiologische und hydrographische Untersuchungen an zwei teichartigen Gewassern. Botan. Centr. Beih., 51, 397-476.

Weimann, R. (1951) Zur Gewasseruberwachung - Tech. Volkswirtsch. Ber. Wirtschafts-u. Verkehrsministerium Nordrhein-Westfalen, Dusseldorf: 1-221.

Weiss, C.M. and Oglesby (1960) Limnology of a North Carolina reservoir and its use in water treatment. J. Amer. Water Works Ass., 54, 671-683.

Welch, E.B. (1980) Ecological effects of waste water. Cambridge University Press.

Welch, P.S. (1952) Limnology, New York : McGraw-Hill Book Co.

Welch, P.S. (1948) Limnological Methods. McGraw-Hill Book Co., New York.

Wesenburg-Lund, C. (1904) Plankton investigations of the Danish Lakes Special Part. Copenhagen, 223 pp.

West, G.S. and F.E. Fritsch (1927) A treatise on the British freshwater algae. Cambridge University Press.

West, W. & G.S. West (1903) Scottish freshwater plankton - No.1 Lin. Journ. - Biology, 35, 519-556.

West, W. & G.S. West (1905) Further contribution to the freshwater plankton of the Scottish lochs. Trans. R. Soc. Edinb. 41, 477.

Wetzel (1975) Limnology, W.B. Saunders, Philadelphia.

Whiteside, M.C. (1974) Chydorid (Cladocera) ecology: seasonal patterns and abundance of populations in Elk Lake, Minnesota. Ecology, 55, 538-550.

Wiebe, A.H. (1929) The effects of various fertilizers on plankton production. Trans. Amer. Fish. Soc., 59, 1-8.

Wolk, C.P. (1973) Physiology and cytological chemistry of blue-green algae. Bacteriological Reviews, 37, 32-101.

Yamagishi, H., H. Hayashi, T. Okina, H. Fukuhara and K. Aoyama (1972) Ecological studies on dissolved oxygen and bloom of Microsystis in Lake Suwa - II Carp culture in floating nets and its influence on the distribution of dissolved oxygen during the season of Microcystis bloom. Bull. Jap. Soc. Sci. Fish., 38(1), 1237-1245.

Young, O.W. (1945) A limnological investigation of periphyton in Douglas Lake, Michigan. Trans. Amer. Micros. Soc., 64, 1-20.

Zaret, T.M. and J.S. Suffern (1976) Vertical migration in zooplankton as a predator avoidance mechanism. Limnol. Oceanogr., 21, 804-813.

Zieglmeier, E. (1940) Die qualitative und quantitative Verteilung des Zooplanktons in einigen grossen Fischteichen der Bartschniederung mit besonderer Rucksicht der Cladoceren und Copepoden. Arch. f. Hydrobiol., 36, 495-551.

---

*Colby, P. J., G.R. Spangler, D.A. Hurley & A.M. McCombie (1972). Effects of eutrophication on salmonid communities in oligotrophic lakes. J. Fish Res. Bd. Can., 29, 975-983

**Kajak, Z. (1979). Eutrofizacja jezior. Panstwowe Wydawnictwo Naukowe, Warszawa.

***Rutkowski, E.W. (1981). Studies on feeding of Cyclops abyssorum, Sars 1862 in Loch Leven, Kinrossshire Scotland. MSc. Thesis, University of Stirling