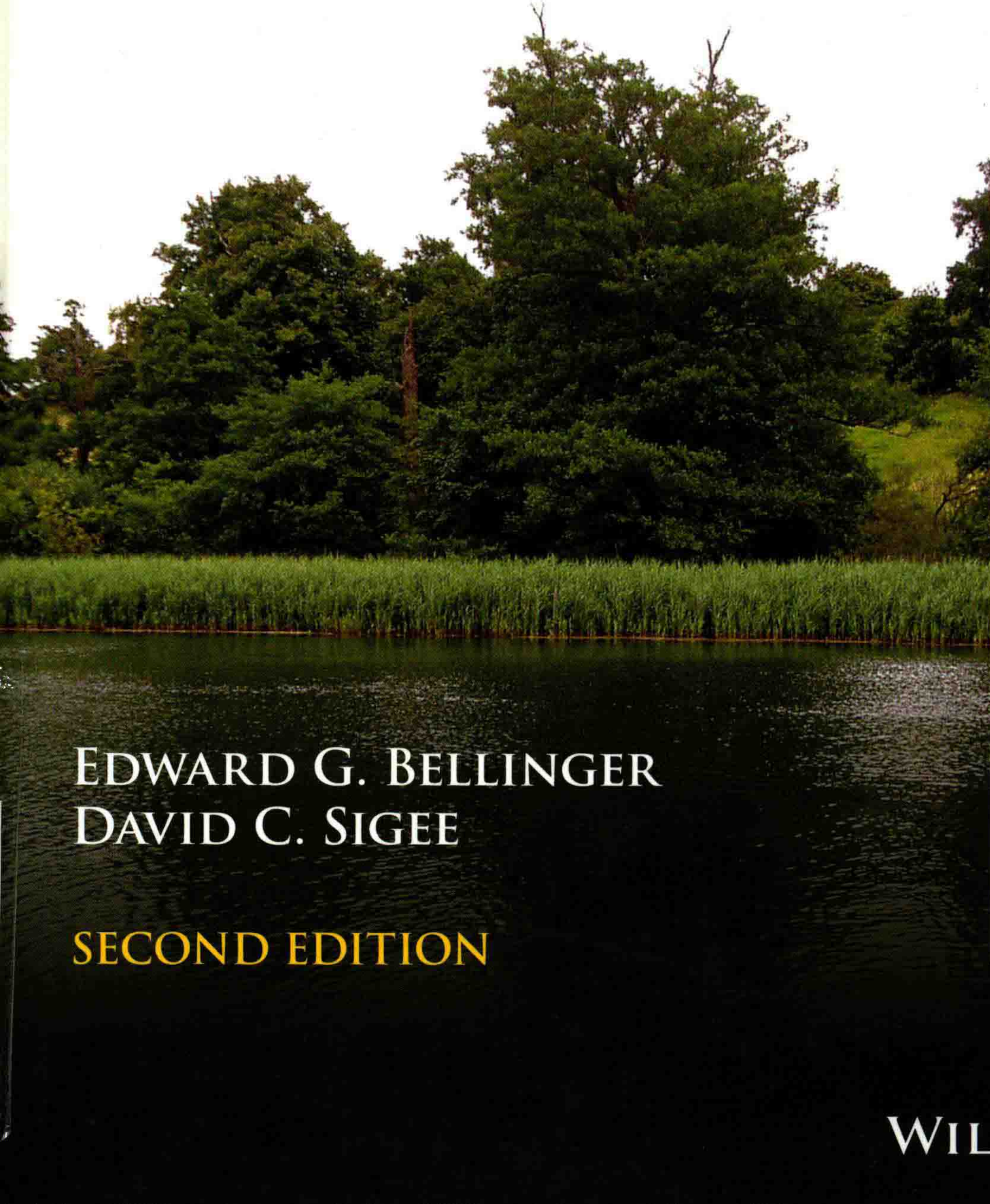
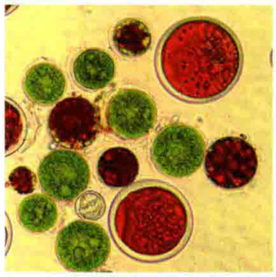
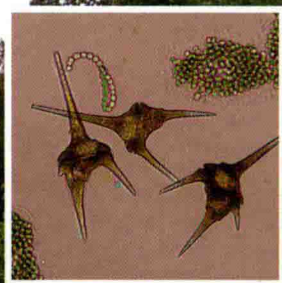
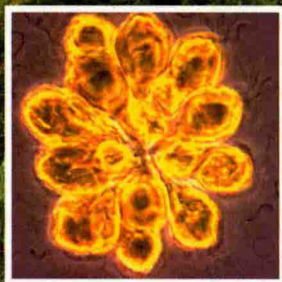
FRESHWATER ALGAE

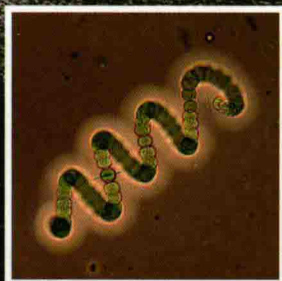
IDENTIFICATION, ENUMERATION AND USE AS BIOINDICATORS











EDWARD G. BELLINGER
DAVID C. SIGEE

SECOND EDITION

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Freshwater Algae

Identification, Enumeration and Use as Bioindicators

Second Edition

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Freshwater Algae

Preface to the First Edition

Almost any freshwater or brackish water site will contain one or many species of algae. Although they are mainly microscopic and therefore not as visually apparent as larger aquatic organisms, such as higher plants or fish, algae play an equally important role in the ecology of these water bodies. Their presence can sometimes be noticed when they occur as dense populations, colouring the water and in some cases forming massive surface scum.

Freshwater algae constitute a very diverse group of organisms. Their range of shapes and beauty, when viewed through a microscope, has delighted biologists for more than a hundred years. They have an enormous range of size from less than one micrometre to several centimetres (for the stoneworts) – equalling the size span (10^4) for higher plants seen in a tropical rainforest. Algal morphology is diverse, ranging from single cells to complex colonies and filaments. Some species are capable of active movement. The term 'algae' embraces a number of phyla (e.g. Cyanophyta, Bacillariophyta and Chlorophyta) of chlorophyll-containing organisms with different growth forms and cytologies. Algae are important primary producers in both freshwater and marine systems. In many lakes and rivers, they generate biomass which is the foundation of diverse food chains. Although algae have beneficial impacts on aquatic ecosystems, they can also have adverse effects. When present in very large numbers they can produce 'blooms' that, on decomposition, deoxygenate the water – causing fish death and other ecological problems. Some algae produce toxins that are lethal to both aquatic and terrestrial organisms. It is important to be aware of these impacts and to monitor waters for the presence of these potentially harmful organisms. Algae can be used to flag up and assess a range of human and natural impacts in aquatic systems because of their often rapid response to changes in the environment. Examples include nutrient enrichment (eutrophication), industrial pollution and changes to the hydrological regime of the water body. Some groups of algae preserve well as fossils in geological deposits such as lake sediments, analysis of which gives us information on past environmental changes.

This book comes at a time of increasing concern over the widespread effects of human activities on the general environment of this planet. Monitoring shifts in algal population gives us an insight into these changes. We need to be able to assess the 'health' of aquatic systems such as lakes and rivers, since water is vital to both human and general ecosystem survival. Knowledge of algal population dynamics can help us develop effective management strategies for those systems. Included in this book are sections on the general features of the main freshwater algal groups with notes on their ecology, methods of sample collection and enumeration, using algae as indictors of environmental conditions and, finally, a key to the identification of the more frequently occurring genera. The authors have tried to combine descriptive material with original colour photographs and line drawings, where possible, to help the reader. We would also like to gratefully acknowledge the help and encouragement of colleagues and students, and particularly appreciate the direct contributions of postdoctoral workers and research students mentioned under Acknowledgements. We would also like to thank our families for their understanding and patience during the preparation of this text.

We hope that all those using the book will find it useful, and will enjoy the numerous colour photographs of these very beautiful organisms.

Preface to the Second Edition

Revisions of the first edition have been carried out to give a general update and to broaden the global perspective. In Chapter 4, particularly, a substantial number of new photographs have been contributed from the United States and China (see Acknowledgements), and various plates have been redrawn to provide greater detail. The key has been extensively modified to give greater clarity and to provide additional information on several genera.

Acknowledgements

We are very grateful to Andrew Dean (Tables 2.3 and 2.4), Matt Capstick (Figs. 4.8, 4.10–4.12, 4.42, 4.62, 4.64, 4.66, 4.68–4.70a and 4.73a) and Huda Qari (Fig. 2.8) for allowing us to present previously unpublished data.

We also thank Academic Press, American Health Association, Cambridge University Press, Journal of Plankton Research, McGraw-Hill, Phycologia and Prentice Hall for giving us permission to use previously published data.

With the incorporation of a substantial amount of new material into the second edition of the book, we would particularly like to thank two colleagues from the United States and the Republic of China for their contributions:

Dr. Robin A. Matthews (Western Washington University, Bellingham, WA) – Figs. 4.2a, 4.2b, 4.4b, 4.18, 4.19, 4.24d, 4.29, 4.36, 4.45, 4.49, 4.51a, 4.51b, 4.52a, 4.53, 4.54 and 4.55.

Dr. Gaohua Ji (Shanghai Ocean University, Shanghai, China) – Figs. 4.8, 4.31, 4.42, 4.47, 4.48, 4.53 and 4.63.

Contents

1

Introduction to Freshwater Algae

1.1 General introduction

Algae are widely present in freshwater environments, such as lakes and rivers, where they are typically present as microorganisms – visible only with the aid of a light microscope. Although relatively inconspicuous, they have a major importance in the freshwater environment, both in terms of fundamental ecology and in relation to human use of natural resources.

This book considers the diversity of algae in freshwater environments and gives a general overview of the major groups of these organisms (Chapter 1), methods of collection and enumeration (Chapter 2) and keys to algal groups and major genera (Chapter 4). Algae are considered as indicators of environmental conditions (bioindicators) in terms of individual species (Chapter 1) and as communities (Chapter 3).

1.1.1 Algae – an overview

The word 'algae' originates from the Latin word for seaweed and is now applied to a broad assemblage of organisms that can be defined both in terms of morphology and general physiology. They are simple organisms, without differentiation into roots, stems and leaves – and their sexual organs are not enclosed within protective coverings. In terms of physiology, they are fundamentally autotrophic (obtaining all their materials from inorganic sources) and photosynthetic – generating complex carbon compounds from carbon dioxide and light energy. Some algae have become secondarily heterotrophic, taking up complex organic molecules by organotrophy or heterotrophy (Tuchman, 1996), but still retaining fundamental genetic affinities with their photosynthetic relatives (Pfandl *et al.*, 2009).

The term 'algae' (singular alga) is not strictly a taxonomic term but is used as an inclusive label for a number of different phyla that fit the broad description noted earlier. These organisms include both prokaryotes (cells lacking a membrane-bound nucleus; see Section 1.3) and eukaryotes (cells with a nucleus plus typical membrane-bound organelles).

Humans have long made use of algal species, both living and dead. Fossil algal diatomite deposits, for example, in the form of light but strong rocks, have been used as building materials and filtration media in water purification and swimming pools. Some fossil algae, for example *Botryococcus*, can give rise to oil-rich deposits. Certain species of green algae are cultivated for the purpose of extracting key biochemicals for use in medicine and cosmetics. Even blue-green algae have beneficial uses. Particularly, *Spirulina*, which was harvested by the Aztecs of Mexico, is still used by the people around Lake Chad as a dietary supplement. *Spirulina* tablets may still be obtained in some health food shops. Blue-green algae are, however, better known in the freshwater environment as nuisance organisms, forming dense blooms. These can have adverse effects in relation to toxin build-up

Freshwater Algae: Identification, Enumeration and Use as Bioindicators, Second Edition. Edward G. Bellinger and David C. Sigee.

and clogging filters/water courses – affecting the production of drinking water and recreational activities.

1.1.2 Algae as primary producers

As fixers of carbon and generators of biomass, algae are one of three major groups of photosynthetic organism within the freshwater environment. They are distinguished from higher plants (macrophytes) in terms of size and taxonomy and from photosynthetic bacteria in terms of their biochemistry. Unlike algae (eukaryotic algae and cyanophyta), photosynthetic bacteria are strict anaerobes and do not evolve oxygen as part of the photosynthetic process (Sigee, 2004).

The level of primary production by algae in freshwater bodies can be measured as fixed carbon per unit area with time (mg C m^{-3} h^{-1}) and varies greatly from one environment to another. This is seen, for example, in different lakes – where primary production varies with trophic status and with depth in the water column (Fig. 1.1). Eutrophic lakes, containing high levels of available nitrogen and phosphorus, have very high levels of productivity in surface waters, decreasing rapidly with depth due to light absorption by algal biomass. In contrast, mesotrophic and oligotrophic lakes have lower overall productivity – but this extends deep into the water column due to greater light penetration.

Although algae are fundamentally autotrophic (photosynthetic), some species have become secondarily heterotrophic – obtaining complex organic compounds by absorption over their outer surface or by active ingestion of particulate material. Although such organisms often superficially resemble protozoa in terms of their lack of chlorophyll, vigorous motility and active ingestion of organic material, they may still be regarded as algae due to their phylogenetic affinities.

1.1.3 Freshwater environments

Aquatic biology can be divided into two major disciplines – limnology (water bodies within continental boundaries) and oceanography (dealing with oceans and seas, occurring between continents). This book focuses on aquatic algae present within continental boundaries, where water is typically fresh (non-saline), and where water bodies are of two main types:

- Standing (lentic) waters – particularly lakes and wetlands.
- Running (lotic) waters - including streams and rivers.

The distinction between lentic and lotic systems is not absolute, since many 'standing waters' such as lakes have a small but continuous flow-through of water, and many large rivers have a relatively low rate of flow at certain times of year. Although the difference between standing and running waters is not absolute, it is an important distinction in relation to the algae present, since lentic systems are typically dominated by planktonic algae and lotic systems by benthic organisms.

Although this volume deals primarily with algae present within 'conventional freshwater systems' such as lakes and rivers, it also considers algae present within more extreme freshwater environments such as hot springs, algae present in semi-saline (brackish) and saline conditions (e.g. estuaries and saline lakes) and algae present within snow (where the water is in a frozen state for most of the year).

1.1.4 Planktonic and benthic algae

Within freshwater ecosystems, algae occur as either free-floating (planktonic) or substrate-associated (largely benthic) organisms. Planktonic algae drift freely within the main body of water (with some species able to regulate their position within the water column), while substrate-associated organisms are either fixed in position (attached) or have limited movement in relation to their substrate. These substrate-associated algae are in dynamic equilibrium with planktonic organisms (Fig. 2.1), with the balance depending on two main factors – the depth of water and the rate of water flow. Build-up of phytoplankton populations requires a low rate of flow

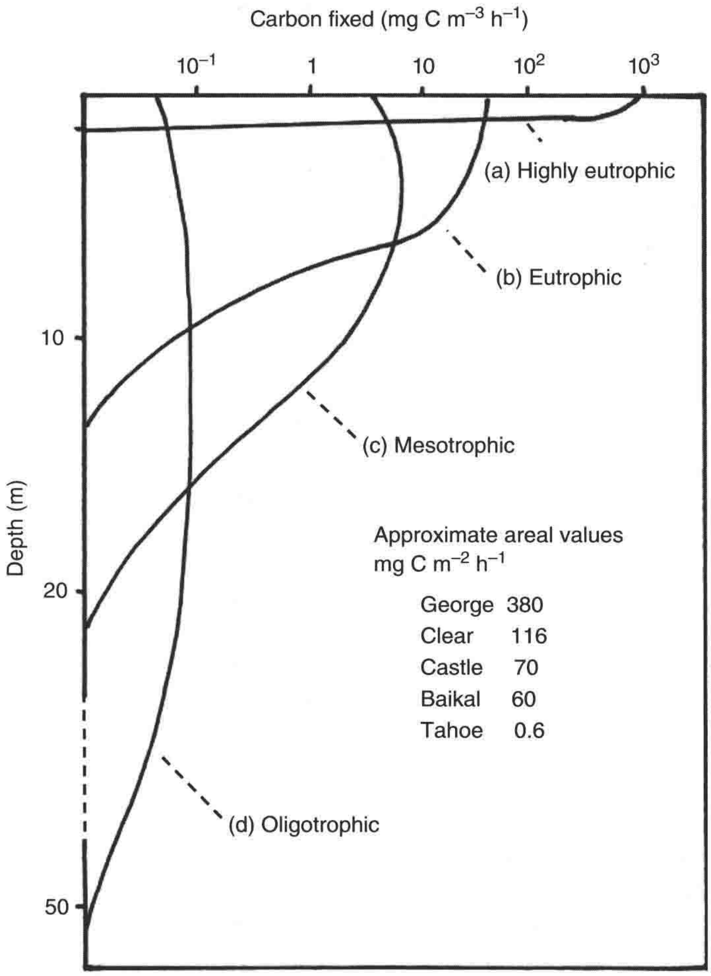

Figure 1.1 Examples of algal primary production in lakes of different trophic status, showing how rates of production typically change with depth. Examples of each lake type include (a) highly eutrophic; Lake George (Uganda). (b) eutrophic; Blelham Tarn (English Lake District), Clear Lake (USA), Erken (Sweden). (c) mesotrophic; Grasmere (English Lake District), Castle Lake (USA). (d) oligotrophic; Lake Tahoe (USA), Lake Baikal in part (Russia), Wastwater (English Lake District). Adapted from Horne and Goldman (1994)

(otherwise they flush out of the system) and adequate light levels, so they tend to predominate at the surface of lakes and slow-moving rivers. Benthic algae require adequate light (shallow waters) and can tolerate high rates of water flow, so predominate over phytoplankton in fast-flowing rivers and streams. Benthic algae also require adequate attachment sites – which include inorganic substrate, submerged water plants and emergent water plants at the edge of the water body. The distinction between planktonic and non-planktonic algae is ecologically important and is also relevant to algal sampling and enumeration procedures (see Chapter 2).

Planktonic algae

Planktonic algae dominate the main water body of standing waters, occurring as a defined seasonal succession of species in temperate lakes. The temporal sequence depends on lake trophic status (see Section 3.2.3; Table 3.3) with algae forming dense blooms in eutrophic lakes of diatoms (Fig. 1.16), colonial blue-green algae (Fig. 1.5) and late populations of dinoflagellates (Fig. 1.10). During the annual cycle, phytoplankton blooms correspond to peaks in algal biovolume and chlorophyll-*a* concentration and troughs in 'Secchi depth' – the inverse of turbidity (Fig. 2.8).

Benthic algae

Benthic algae occur at the bottom of the water column in lakes and rivers and are directly associated with sediments – including rocks, mud and organic debris. These algae (usually attached) may form major growths on inorganic surfaces or on organic debris, where they are frequently present in mixed biofilms (bacteria, fungi and invertebrates also present). Under high light conditions, the biofilm may become dominated by extensive growths of filamentous algae – forming a periphyton community (Fig. 2.23). Attached algae may also be fixed to living organisms as epiphytes – including higher plants (Fig. 2.29), larger attached algae (Fig. 2.28) and large planktonic colonial algae (Fig. 4.35). Some substrate-associated algae are not attached, but are able to move across substrate surfaces (e.g. pennate diatoms), are loosely retained with gelatinous biofilms or are held within the tangled filamentous threads of mature periphyton biofilms. (Fig. 2.29).

Many algal species have both planktonic and benthic stages in their life cycle. In some cases, they develop as actively photosynthetic benthic organisms, which subsequently detach and become planktonic. In other cases, the alga spends most of its actively photosynthetic growth phase in the planktonic environment, but overwinters as a dormant metabolically inactive phase. Light micrographs of the distinctive overwintering phases of two major bloom-forming algae (*Ceratium* and *Anabaena*) are shown in Fig. 2.7.

1.1.5 Size and shape

Size range

The microscopic nature of freshwater algae tends to give the impression that they all occur within a broadly similar size range. This is not the case with either free floating or attached algae.

In the planktonic environment (Table 1.1), algae range from small prokaryotic unicells (diameter < 1 μm) to large globular colonies of blue-green algae such as *Microcystis* (diameter reaching 2000 μm) – just visible to the naked eye. This enormous size range represents four orders of magnitude on a linear basis (×12 as volume) and is similar to that seen for higher plants in terrestrial ecosystems such as tropical rainforest.

Table 1.1 Size Range of Phytoplankton.

Category	Linear Size (Cell or Colony Diameter) (μm)	Biovolume[a] (μm^3)	Unicellular Organisms	Colonial Organisms
Picoplankton	0.2–2	4.2×10^{-3}–4.2	Photosynthetic bacteria Blue-green algae *Synechococcus* *Synechocystis*	-
Nanoplankton	2–20	4.2–4.2×10^3	Blue-green algae Cryptophytes – *Cryptomonas* *Rhodomonas*	
Microplankton	20–200	4.2×10^3–4.2×10^6	Dinoflagellates *Ceratium* *Peridinium*	Diatoms *Asterionella*
Macroplankton	>200	$>4.2 \times 10^6$	-	Blue-green algae *Anabaena* *Microcystis*

[a]Biovolume values are based on a sphere (volume 4/3Πr^3).

Planktonic algae are frequently characterised in relation to discrete size bands – picoplankton (<2 μm), nanoplankton (2–20 μm), microplankton (20–200 μm) and macroplankton (>200 μm). Each size band is characterised by particular groups of algae (Table 1.1).

In the benthic environment, the size range of attached algae is even greater – ranging from small unicells (which colonise freshly exposed surfaces) to extended filamentous algae of the mature periphyton community. Filaments of attached algae such as *Cladophora*, for example, can extend several centimetres into the surrounding aquatic medium. These macroscopic algae frequently have small colonial algae and unicells attached as epiphytes (Fig. 2.28), so there is a wide spectrum of sizes within the localised microenvironment.

Diversity of shape

The shape of algal cells ranges from simple single non-motile spheres to large multicellular structures (Fig. 1.2). The simplest structure is a unicellular non-motile sphere (Fig. 1.2b), which may become elaborated by the acquisition of flagella (Fig. 1.2c), by a change of body shape (Fig. 1.2a) or by the development of elongate spines and processes (Fig. 1.2d). Cells may come together in small groups or large aggregates but with no definite shape (Figs. 1.2d and 1.2e), or may form globular colonies that have a characteristic shape (Figs. 1.2f and 1.2g). Cells may also join together to form linear colonies (filaments), which may be unbranched or branched (Figs. 1.2h and 1.2i).

Although motility is normally associated with the possession of flagella, some algae (e.g. the diatom *Navicula* and the blue-green alga *Oscillatoria*) can move without the aid of flagella by the secretion of surface mucilage. In many algae, the presence of surface mucilage is also important in increasing overall cell/colony size and influencing shape.

Size and shape, along with other major phenotypic characteristics, are clearly important in the classification and identification of algal species. At a functional and ecological level, size and shape are also important in terms of solute and gas exchange, absorption of light, rates of growth and cell division, sedimentation in the water column, cell/colony motility and grazing by zooplankton (Sigee, 2004).

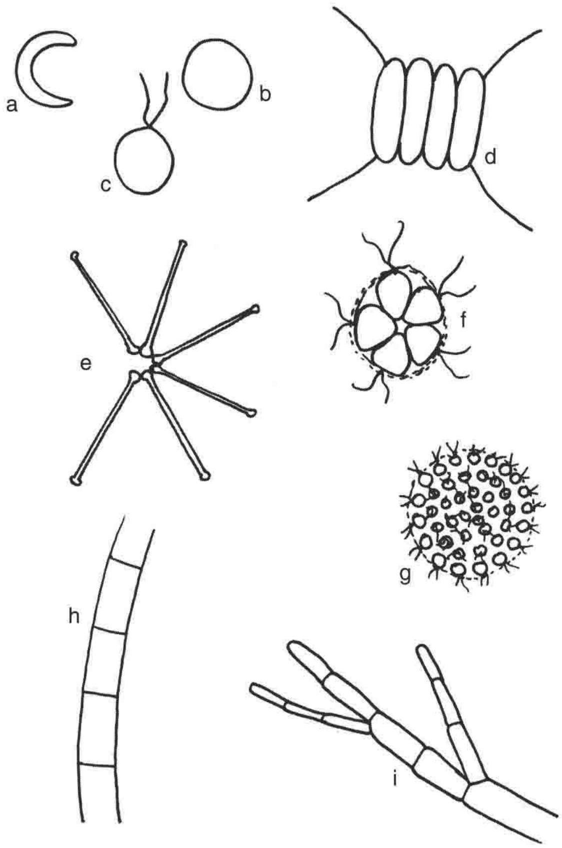

Figure 1.2 General shapes of algae. Non-motile unicells: (a) *Selenastrum*; (b) *Chlorella*. Motile unicells: (c) *Chlamydomonas*. Non-motile colony: (d) *Scenedesmus*; (e) *Asterionella*. Motile colony: (f) *Pandorina*; (g) *Volvox*. Unbranched filament: (h) *Spirogyra*. Branched filament: (i) *Cladophora*.

1.2 Taxonomic variation – the major groups of algae

Freshwater algae can be grouped into 10 major divisions (phyla) in relation to microscopical appearance (Table 1.2) and biochemical/cytological characteristics (Table 1.3). Some indication of

Table 1.2 Major Divisions of Freshwater Algae: Microscopical Appearance.

Algal Division (Phylum)	Index of Biodiversity[a]	Typical Colour	Typical Morphology of Freshwater Species	Motility (Vegetative Cells/Colonies)	Typical Examples
1. Blue-green algae (**Cyanophyta**)	297	Blue-green	Microscopic or visible – usually colonial	Buoyancy regulation Some can glide	*Synechocystis* *Microcystis*
2. Green algae (**Chlorophyta**)	992	Grass-green	Microscopic or visible – unicellular or filamentous colonial	Some unicells and colonies with flagella	*Chlamydomonas* *Cladophora*
3. Euglenoids (**Euglenophyta**)	124	Various colours	Microscopic – unicellular	Mostly with flagella	*Euglena* *Colacium*
4. Yellow-green algae (**Xanthophyta**)	73	Yellow-green	Microscopic – unicellular or filamentous	Flagellate zoospores and gametes	*Ophiocytium* *Vaucheria*
5. Dinoflagellates (**Dinophyta**)	54	Red-brown	Microscopic – unicellular	All with flagella	*Ceratium* *Peridinium*
6. Cryptomonads (**Cryptophyta**)	15	Various colours	Microscopic – Unicellular	Mostly with flagella	*Rhodomonas* *Cryptomonas*
7. Chrysophytes (**Chrysophyta**)	115	Golden brown	Microscopic – unicellular or colonial	Some with flagella	*Mallomonas* *Dinobryon*
8. Diatoms (**Bacillariophyta**)	1652	Golden brown	Microscopic – unicellular or filamentous colonies	Gliding movement on substrate	*Stephanodiscus* *Aulacoseira*
9. Red algae (**Rhodophyta**)	22	Red	Microscopic or visible – unicellular or colonial	Non-motile	*Batrachospermum* *Bangia*
10. Brown algae (**Phaeophyta**)	2	Brown	Visible – multicellular cushions and crustose thalli	Non-motile	*Pleurocladia* *Heribaudiella*

[a]Biodiversity: number of species of freshwater and terrestrial algae within the British Isles.