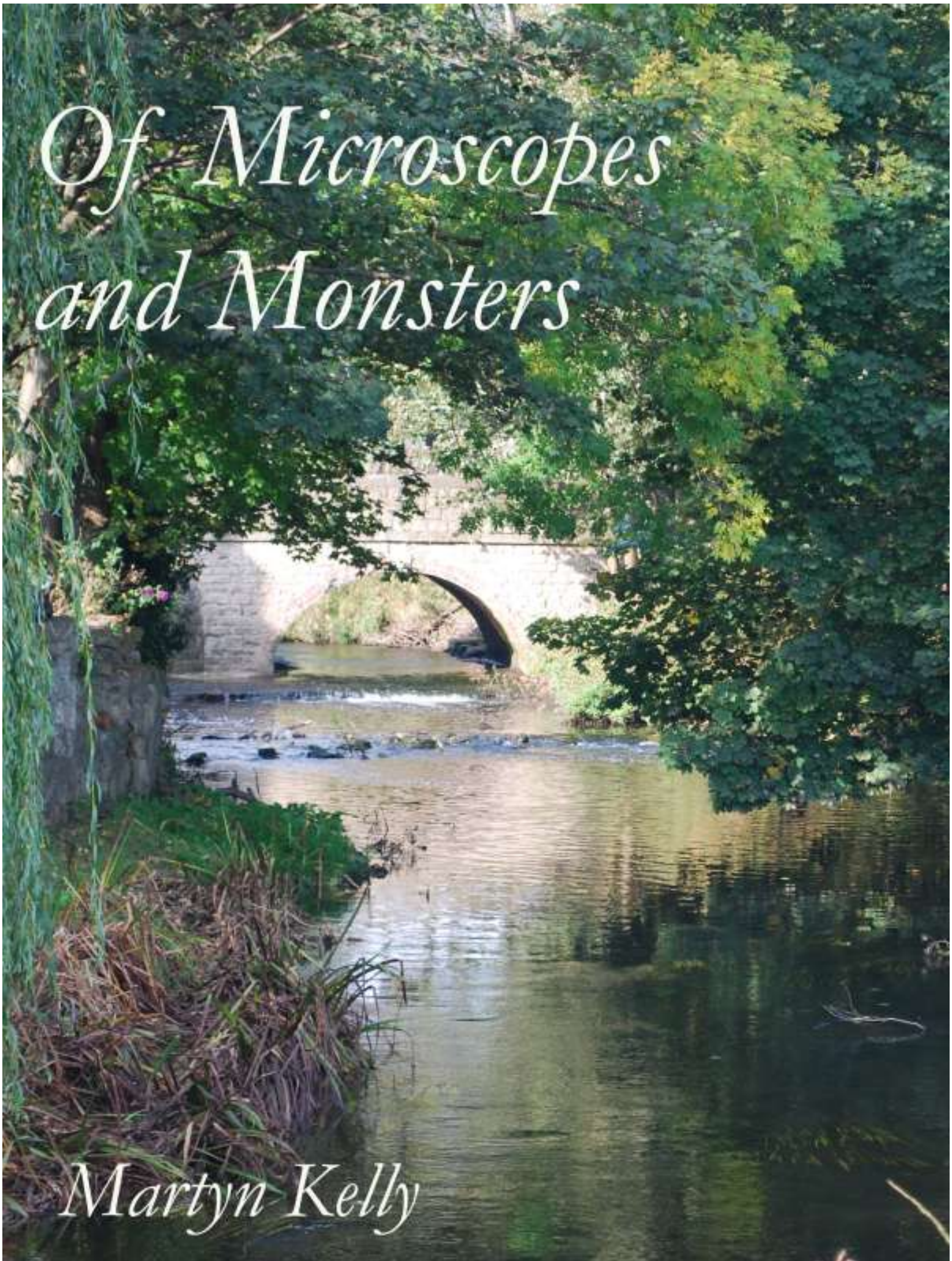
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Who looks upon a river in a meditative hour and is not reminded of the flux of all things?

Ralph Waldo Emerson

Of Microscopes and Monsters

Journeys through the hidden world of Britain's freshwaters

Martyn Kelly

Contents

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Let us start with the familiar: about 1500 species of flowering plants have been recorded from Britain and Ireland, along with about 600 mosses and liverworts, three native conifers and seventy species of fern. By contrast, over 5000 species of algae – the simplest of all plants - have been recorded from freshwaters along with a further 725 seaweeds from around our coastline. These figures are almost certainly under-estimates of the true situation as many algae are microscopic and, consequently, far less obvious as well as harder to identify than larger plants. A conservative estimate would probably be to double the existing figure for freshwater algae, which means that four out of every five plant species recorded from Britain and Ireland is an alga.

The superlatives continue. The smallest of these algae are less than a thousandth of a millimetre long, whilst the largest seaweeds may have fronds extending over ten metres in length. A single drop of water from just below the surface of Windermere in the spring contains about 2000 individuals of the most common alga and a twenty kilometre stretch of the River Wear, my local river, contains about a trillion individuals of the most abundant species alone. Algae suspended in the world's oceans are responsible for about half of all the productivity on the planet.

Yet most people know almost nothing about them.

The journeys described in this book started in the seventeenth century in the town of Delft in the Netherlands. A draper named Anton van Leuwenhoek, a close friend of the painter Jan Vermeer, invented the first microscope. It would, presumably, have been a useful tool as he checked the quality of the fabrics he was buying, but it also piqued his curiosity and he used his primitive microscope to peer at all sorts of materials including his own sperm and drops of water from the canals that surrounded Delft. He communicated his findings with the Royal Society in London and, in so doing, he became the unwitting inventor of microbiology.

Were van Leuwenhoek to walk into a modern biological laboratory, he would be amazed at how far his original idea has been developed, at the magnification achievable, at the clarity of the resulting images and at our ability to capture these using digital cameras and video equipment. However, modern science prides itself on being a dispassionate, wholly objective method for understanding the world around us and the price we pay is sometimes a loss of the awe and wonder that van Leuwenhoek would have experienced. So, rather than start this book with some background information on the biology of algae, to help you understand what follows, I want to approach the microscopic world by first considering the dinosaurs.

No-one has seen a living dinosaur. A few specialists have examined their bones and, from this evidence, built up a picture of what a living dinosaur might have looked like. More importantly, from 1830 onwards, scientists have worked with artists to convey a vision of the prehistoric world to the wider public. For a child growing up in twenty-first century Europe, with access to television programmes such as *Walking With Dinosaurs* and *Dinosaur*

Planet, Tyrannosaurus Rex may seem almost as real as a lion or an elephant. What we have here is a curious symbiosis between science and art, to create a world that is imagined but not entirely imaginary. Why not, I wondered, apply the same approach to microscopic organisms and reconstruct the worlds they inhabit from the highly artificial views that scientists see when they peer into their microscopes. Maybe this will breathe life into what comes across, too often, as curious shapes with long, technical names? In the process, maybe, I will be able to explain the importance of this hidden aspect of Britain's natural history.

The artists responsible for the reconstructions of dinosaurs and their habitats have taken us on journeys through time. My starting point for what is a journey where we traverse not just time and space but also scale, is to ask you to see the microscope not as a shiny piece of apparatus in a sterile laboratory, but as the bottle which Alice encountered when she followed the White Rabbit into his burrow. A bottle whose label consists of just two words:

Drink Me.

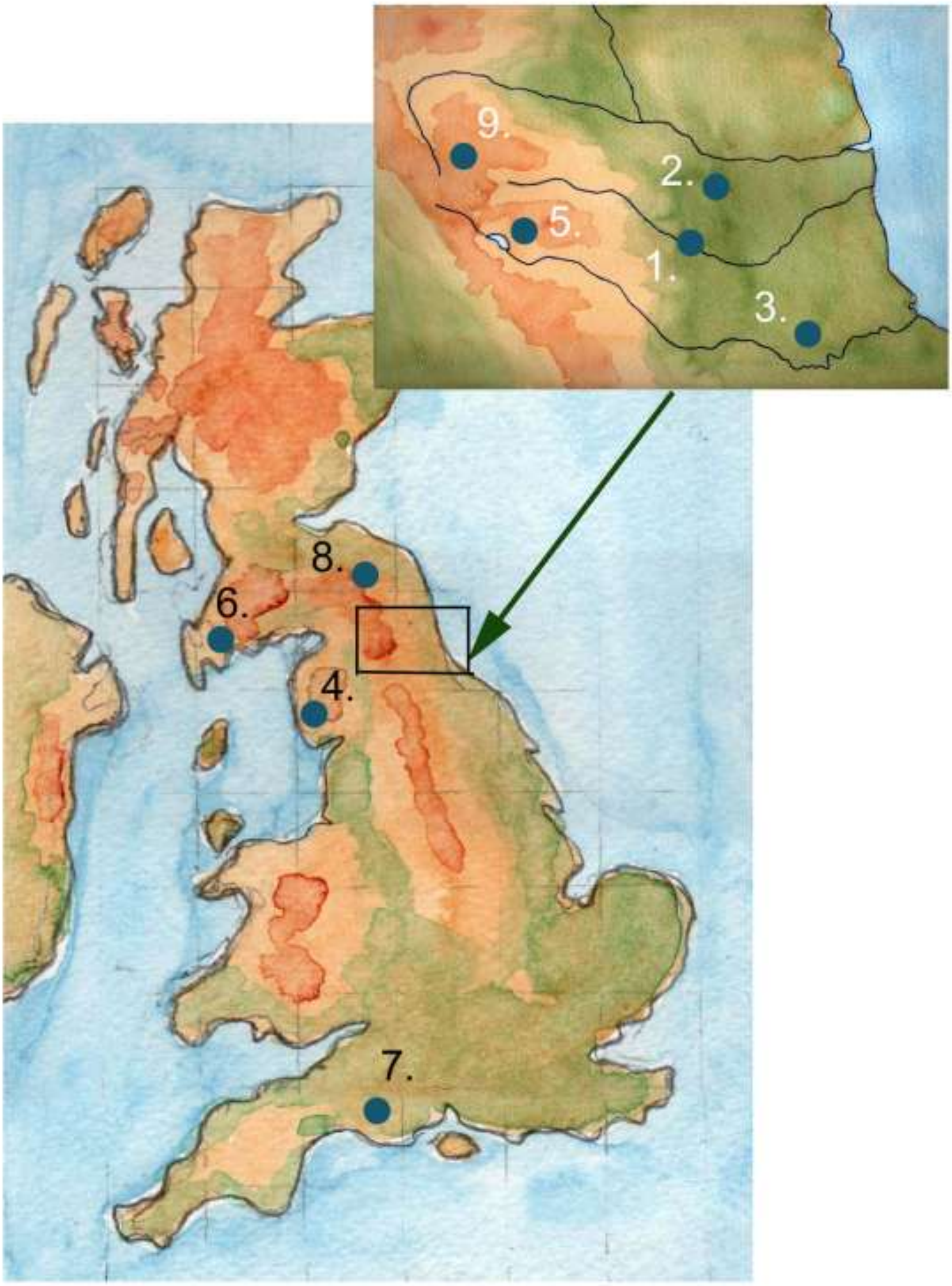

Fig. 1. Locations of sites described in this book: 1. River Wear, Wolsingham; 2. River Team, Causey; 3. River Skerne, Coatham Mundeville; 4. Wastwater; 5. Upper Teesdale; 6. Round Loch of Glenhead; 7. River Wylye, Kingston Deverill; 8. River Coquet, Chew Street; 9. River Nent, Nentsberry.

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Journeys have to start somewhere, and this one starts at Wolsingham, a market town in Weardale, on the edge of the northern Pennines with a front street lined with houses made from the local Millstone Grit. A "B" road leading off this street goes down a short hill then flattens, until an ugly metal cantilever bridge takes it across the River Wear. Stand on the bridge and look upstream and you can see the Pennine fells rising above the trees that line the river. Look the other way and the valley broadens out as it flows across the plain of the Durham Coalfield towards the North Sea at Sunderland.

Ecologists are creatures of habit, returning to the same location time after time. This point on the River Wear is one such place for me. An element of pragmatism lies behind the choice: it is less than an hour's drive from my home and I can park a car nearby so that I don't need to lug sample bottles and meters any distance. Also, it is easy to get to the river bank (no fences or walls to cross, no nettles to fight through) plus the river here is shallow enough, and the bank low enough, to make getting in and out straightforward. But there is a deeper reason behind these many return trips: by visiting the same site again and again, I get to see the river in all its moods. I have seen it in winter, in summer, in drought, in flood. Slowly, over time, a picture of how the plants and animals that live there knit together formed in my mind: who thrives when, what season each organism prefers. Some of this I could have gleaned from books, but I still need to experience it myself because words – scientific prose especially – has no vitality. When I read a scientific paper which contains new ideas, or on those occasions when I had a new idea myself, I could bring myself to Wolsingham – or even just summon up images of the river in my mind – and see if the idea might work when tested against what I already knew.

There is one more reason why the Wear at Wolsingham is ideal for my purposes. My work over the past twenty years has involved looking at the effect that man's activities have on freshwaters. The central concept, now enshrined in EU legislation, is that a river with a healthy ecosystem is a sign that the local population is using that river in a sensible and sustainable manner. "Sustainable", in this context, simply means that we do nothing to a river that will prevent future generations from using it as we do. The focus for my work has been to discover the point at which human use of a river or lake crosses a threshold from "sustainable" to "unsustainable" and to help the Environment Agency, and the UK's other environmental regulators, to understand the reasons, and to bring the river back to a sustainable state. The Wear at Wolsingham is certainly not a pristine river – there are lead mines in the fells, and the river also contains sewage from a small town and several villages upstream – but it has clear water, a rich variety of plant and animal life, including salmon and sea trout, and represents, for many British rivers, an ideal of what a river could be. Understand the ecology of the River Wear at Wolsingham, in other words, and we may learn some lessons we can apply to rivers elsewhere in the country.

Standing in the Wear at Wolsingham, the fast, cold water pressing against my waders, this rich variety of plant and animal life was not evident. There are fish, but these are elusive, fast-swimming species that are difficult to spot. In order to see the rest of the life here we need to adjust our focus. Pick up a cobble-sized stone during the warmer parts of the year, and you may see a flat insect-like creature scuttle to one side as you turn it over. These are the juvenile stages of mayflies, and are quite common in clean rivers, but they tend to inhabit the edges and undersides of the stones, protected from the current and hidden from the sharp eyes of predatory trout. On the top surface during the summer months there are tiny (about a centimetre long), cylindrical agglomerations of gravel and sand particles which turn out, on closer inspection, to be protective shelters for the larvae of another type of insect – the caddis flies. Imagine these as caterpillars (they are close relatives of the butterflies) busily feeding until the day when they pupate prior to the emergence of the adult flies.

On what are they feeding? We now need to adjust our focus again. If the caddis larva is no more than a centimetre in length, then its food is likely to be at least one or two orders of magnitude smaller, which means that we can no longer rely on the naked eye, or even on a magnifying glass, but need to turn to a microscope.

This brings with it an added complication: we can no longer view the organisms *in situ*. The top surface of a cobble is often slimy to the touch. If we want to see what makes this thin slimy film so interesting to a caddis larva we have to remove a portion (brushing with a toothbrush is an effective method) then put a drop of the gunk we remove onto a glass microscope slide, lay a very thin piece of glass, called a coverslip, on top of this, and then put the slide plus coverslip under the microscope. It is a highly disruptive process for the organisms involved, akin to taking all the plants out of a garden, laying them out on the

Fig. 2. The field biologist at work: examining stones for attached algae.

patio, and then asking someone else to imagine what the garden actually looked like. Individual organisms can be described, drawn, photographed or counted, but we have little idea of what the submerged microscopic world actually looks like. There are microscopes that can be taken into the field but, mostly, this examination has to take place back in the laboratory.

I mentioned in the previous section that if we understood the ecology of a river, we could learn lessons that could then be applied elsewhere. To use a medical analogy, my colleagues and I were trying to understand what constituted a "healthy" ecosystem, so that we could prescribe treatments that could be used to heal polluted (i.e. "sick") ecosystems. In many cases, the prescription will be tighter regulation of existing sources of pollution, such as the sewage works which discharge into our rivers. The costs for any such improvements will then be passed onto consumers via their water bills. The tough requirements of new environmental legislation could translate into increased costs for the average household of up to £100 for the average household over the next few years. As one of the scientists involved in doing the work there is, obviously, a heavy responsibility to make sure that tighter regulation actually brings tangible ecological benefits. The challenge is that water quality in Britain has improved greatly over the last two decades. There are now fewer rivers that look or smell obviously polluted to the layman yet an experienced biologist, looking closely at the plants and animals, will often find indications that the pollution is still there, albeit less obviously.

And here is the crux of the problem: my colleagues and I were good at distilling the ecology of rivers into graphs and tables and making a reasoned case to our fellow professionals, but the impact of this work was now going to affect the pockets of almost everyone. What is more, people were now going to be paying for benefits that they might not even notice. As I tried to explain my work to family and friends I realised that I needed to try to explain how freshwater ecosystems worked, and why they would benefit from extra investment.

A new phrase has entered the vocabulary of ecologists over the past few years: "ecosystem services" are defined as the benefits humankind gets from ecosystems. Take rivers as an example: it is tempting for a professional biologist such as me to see these as repositories of rare and unusual organisms, and to lapse into the loose terminology of "biodiversity" when justifying expenditure. However, our rivers provide us with drinking water, they transport away our waste materials, their water can be used to irrigate fields or to cool industrial plants and we all use rivers and their immediate environs for leisure, even if only for walking the dog. All of these are "ecosystem services" and the task of environmental regulators such as the Environment Agency is to understand what "sustainable" means with respect to the services that rivers provide for us. How much water can farmers be allowed to remove for irrigation, for example, before other "ecosystem services" (e.g. angling) starts to suffer?

Angling is a good example: many people gain pleasure – and essential relaxation – through fishing. A few, even, find their livelihood from this activity which is intricately connected with the river ecosystem. The fish sit close to the top of a food chain, sustained by organisms that are, in turn, vulnerable to the activities of man and to the substances we discharge to rivers. Everything is connected but, in the case of rivers, few of these connections are obvious. It takes place not just below the surface but also, for the most part, at a scale that we cannot see with the naked eye. The danger is that the small number of specialists who do understand river ecology will become a "priesthood", making decisions that affect many people, simply because the debate has become too esoteric for lay people to follow. Rather than just communicate to fellow professionals, I wanted to look at the process from a different perspective, and try to breathe some life back into our sterile data, in order to help lay people understand where their money was going.

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The first of these microscopic journeys involves a sample collected from the River Wear in February 2009, when the water was still bitingly cold and the trees lining the riverbank were still gaunt leafless skeletons. The underwater world, however, was surprisingly rich, with a two or three millimetre thick slimy film on top of the submerged cobbles. Sitting in front of my microscope a few hours later, I dipped a pipette into the brown gunk that had settled to the bottom of the sample bottle and withdrew a millilitre or so, then gently squeezed the bulb of the pipette to deposit one drop onto a glass slide. I carefully lay a thin glass coverslip over the drop, letting its weight flatten the drop out to form a thin film. I put the slide under my microscope, swung the lowest power objective into place and, peering through the eyepiece, adjusted the focus until the image was crisp. What I could see, at 100× magnification, was some brownish patches of varying densities and hues, within which light glinted off a few angular rock crystals. In the spaces between these patches were tiny, barely resolvable, needle-like objects. I swung the next objective into place and adjusted the focus again. My sample was now magnified 400 times. The brownish patches were still there, resolving now into agglomerations of material of indeterminate origin but the tiny needle-like objects were now clearer. They had distinct, mostly symmetrical outlines, sometimes contained one or more distinct spheres and a yellow-brown structure. These were microscopic algae called "diatoms"; the distinct symmetrical outlines were their silica shells (the technical term is "frustule"), the spheres are droplets of a carbohydrate which acts as an energy store, and the yellow-brown structures are chloroplasts, the engine-rooms of photosynthesis. When the sun shines, even in early February, these chloroplasts use the sun's energy to convert water and carbon dioxide into carbohydrates and the surface of the stones on the river bed are covered with tiny bubbles of the oxygen formed as a by-product. We expect plants to be green but the diatoms are more closely-related to the brown seaweeds than to land plants and the green of the chlorophyll is masked by other pigments (which act as "turbochargers" for the photosynthetic "engine"). If you think of the caddis flies as the cattle of the underwater world of the River Wear, then the diatoms form the pastures on which they graze. Another expectation is that plants are stationary, yet many of the diatoms I can see in this sample – the boat-shaped ones especially - are moving around, gliding first in one direction, then stopping and gliding off in a different direction.

In order to appreciate the beauty and diversity of the diatoms one really needs even more magnification, and I have the potential, on my microscope, to increase from 400× to 1000×. But, to make the most of this enormous magnification, I will need to add chemicals to burn away all the soft organic matter in the sample, and then mount the empty silica cell walls that remain on a slide using special cement. When I have done this, I can see that each of the tiny frustules is covered with regular patterns of yet finer lines, the whole giving the impression of a miniscule piece of crystal glass. Even at 400× I can see a dozen different forms: some shaped like tiny clubs, the line of symmetry running along the long axis; others like segments of an orange, with a line of symmetry running across the centreline.

It is common to find thirty or more species at any site and the River Wear at Wolsingham is no exception. However, as I searched across the slide, recording what I saw, it became clear that only a few of these species were abundant. When I had counted about 300 individuals, I sat back and looked at my list, and then started to think about how these must have been organised before I had scraped them off their stone. The lowermost diagram on Figure 3 and Figure 5 are the outcomes of these meditations. On the left hand side of Figure 5 there is a "bush" of the club-shaped cells, which belong to a species called *Gomphonema olivaceum*. Each cell sits at the end of a long stalk and these stalks, plus all of the other organic and inorganic detritus that accumulates in these thin films on the tops of rocks shades the rock surface, putting those diatoms which don't have long stalks at a disadvantage. Those diatoms which are able to move around can move up and through the matrix of *Gomphonema* stems and other detritus and search out areas where they are best able to grow. They can sit at the top of the film and soak up as much of the weak winter sun as they can and, if the *Gomphonema* "bush" grows more, so they, too, can adjust their position. Sometimes, the slimy film that grows on rocks in the spring has dark-brown, almost black patches on it and if you scrape them off carefully and look at them under the microscope, they are composed almost entirely of a species of gliding diatom called *Navicula lanceolata*.

There were also a few chains of green cells of a different alga, called *Ulothrix zonata*, which is much more closely related to the land plants than the diatoms. This species is extremely well adapted to the cold waters of early Spring: When I returned a month later, it formed bright green slimy patches on the submerged stones, sometimes even extending into long flowing tendrils. People have done experiments in the laboratory to show that it does actually grow much better in cold water than in warm and, when I returned in early April all but a few weary fragments had disappeared.

Fig. 3. Top left: The River Wear at Wolsingham, looking downstream from the bridge; top right: a cobble from Thropton Burn, Northumberland, showing the dark brown patches of diatoms common in early Spring (with a pound coin to indicate scale); centre left: the view down the microscope looking at the February sample; bottom: schematic view of the biofilm: a) "bushes" of *Gomphonema olivaceum*; b) cells of *Navicula lanceolata*; c) *Achnanthidium minutissimum*; d) a filament of *Ulothrix*. The vertical bar is 10 micrometres long (one micrometre is 1000th of a millmetre).


a.
b.
c.
d.

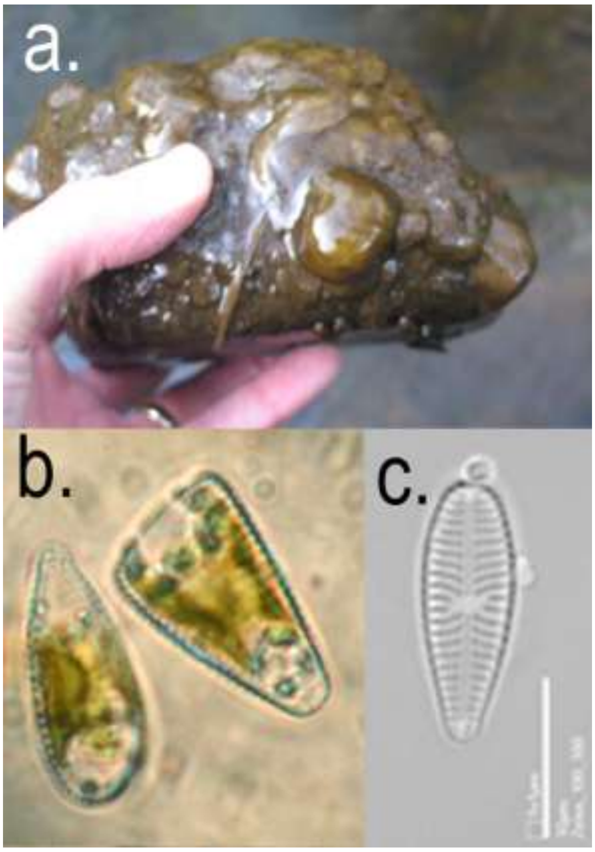

Fig.4. A question of scale: a. shows growths of diatoms (*Gomphonema olivaceum*) from a stream in County Fermanagh in Apri 2007 (photo: Lydia King); b. shows the same sample viewed under the microscope at high magnification, with the yellow-brown chloroplast clearly visible; c. shows the same species after cell contents had been removed and it has been mounted onto a slide, revealing the fine ornamentation on the cell surface. The vertical bar is 10 micrometres long (one micrometre is 1000th of a millmetre) (photo: Micha Bayer).

Fig. 5. The underwater landscape of the River Wear in February, with individual motile cells of *Navicula lanceolata* moving through "bushes" of *Gomphonema olivaecum*. There are some cells of another diatom, *Achnanthidium minutissimum* in the foreground, and a filament of *Ulothrix zonata* in the background.

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I'm not the only ecologist who came to the subject as a refugee fleeing from the physical sciences. I survived school days with a fascination for the natural world intact but perpetually befuddled by all but the most basic equations. However, when contemplating life in rivers, I cannot but notice the sheer brute physical force of water. If the River Wear in flood is powerful enough to sweep mature trees downstream, how can a tiny algal cell survive? In order to answer this, we need to understand a little of the physics of water. We also need to learn to see the world from the perspective of a microscopic organism.

Again, let's start from the familiar: you know that it is harder to walk or wade through water than it is to walk on dry land. You can feel your thigh muscles working to overcome the resistance offered by the water. You also know that water offers support so that a human body can float at or near the surface. These properties relate to the greater density of water compared to air. Imagine an even denser fluid - a pond of treacle for example – you would expect this to be even harder to move through. You might express the difference between water and treacle as a difference in their viscosity. The relevance to our present topic is that viscosity is as much a property of the size of the organism as it is of the density of the fluid, so a small organism – such as the *Navicula* which we met above - may find it as hard to move through water as we do to move through treacle. To put it another way, we cannot look at a microscopic organism as it moves and assume that it is experiencing the world in the same way as we do.

But how, given the enormous power of a river, can this rich underwater community avoid being swept away by the current? How can thirty or more different species survive and thrive whilst clinging on rocks in stretches of rivers when I struggle to keep my footing? The answer, again, is that the world that these organisms experience is very different to ours. Most importantly, the velocity of water in a river is not uniform. The water pushing against my waders may be moving at half a metre per second or more but this velocity drops as it approaches a surface. Right at the interface between water and a solid surface there is so much frictional drag that the current velocity is zero and there is a narrow layer of water directly above the surface where the friction is so great that the current is still very close to zero. The thickness of this "boundary layer" depends on various factors, including the current velocity but we are talking here of a layer considerably less than a millimetre thick. Nonetheless much of the microscopic life I will be describing is one or two orders of magnitude smaller than a millimetre and can live quite comfortably in this "boundary layer". River beds are often very heterogeneous and the larger boulders, even patches of plants, can create sheltered areas where the current velocity is lower than in the main channel and algae and other life can proliferate.

Rivers such as the Wear at Wolsingham are active examples of the old saying that "a rolling stone gathers no moss". Looking around, you notice that it is just the larger stones that tend to have growths of submerged mosses and the larger algae on them and this illustrates another principle of the physics of rivers. The size of stone that can be moved by a river is determined by "shear stress" - water flowing over a surface generates lift, just as air flowing over the wings of an aeroplane does. If the stress is large enough, particles are set in motion. The greater the current velocity, the greater the size of particle that may be moved. At normal flow conditions, it may be just sand particles that can be moved in this way but when the river is in spate, then cobbles and even boulders can be moved. The shear stress can also work directly on the algae growing on the stones too: as the current velocity increases, so the boundary layer shrinks and the algae are subject to greater stress. There are, in other words, fairly brief windows of opportunity – no more than a few weeks - for algae to grow on submerged stones in the Wear before the British climate intervenes, the river floods and the communities of algae are ripped away or their substrata overturned. In order to survive in these habitats, organisms need to be fast-growing opportunists who can colonise a bare surface quickly.

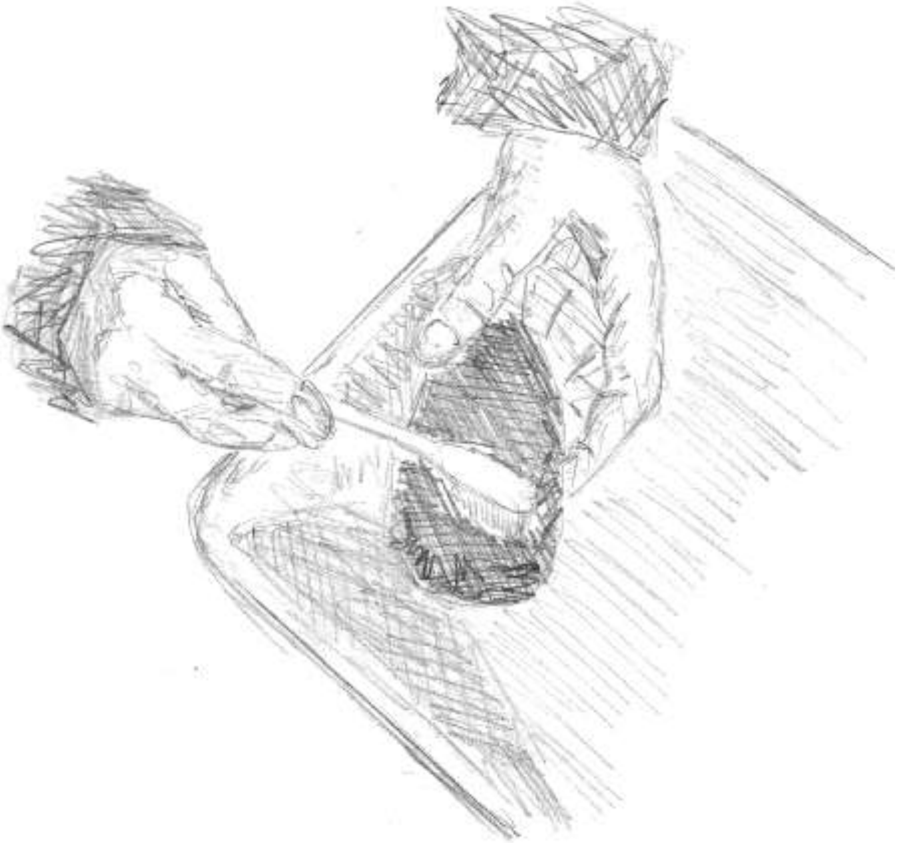

Fig. 6. Removing attached diatoms from a stone by brushing with a toothbrush.

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During 2009 I visited the River Wear at Wolsingham every month and recorded changes in the algal communities growing on the stones. As the water warmed up and Spring gave way to Summer, I started to see some interesting changes in the algae. Whereas my sample from February had contained many of the bush-forming *Gomphonema* along with motile diatoms such as *Navicula*, the summer samples were dominated by a different species of diatom altogether: *Achnanthidium minutissimum*, along with some long, slender blue-green filaments. The *Achnanthidium* is tiny: about a hundredth of a millimetre long, and is attached to the stone surface by a stalk, much shorter than that of *Gomphonema*. It is also a fast-growing species and, therefore, a typical diatom of disturbed habitats. You have probably seen how a patch of open land is quickly colonised by plants – we might call them weeds – and ecologists recognise that some plants – Rosebay willow herb for example - are well-adapted to establishing themselves in such situations. *Achnanthidium minutissimum* is one of the algal equivalents of these "ruderal" species because it grows fast and can colonise empty surfaces. More importantly, there are so many *Achnanthidium* cells upstream from Wolsingham that there are always going to be a few dislodged cells drifting down in the current and settling on the stones.

One other difference between the stones in February and June is that I could see, with the naked eye, tiny invertebrate larvae on the stone in June but not in February and here is another clue to explain why the composition of algae had changed: *Achnanthidium* is a low-growing species compared to the *Gomphonema* in particular, and grows so fast that it is less susceptible to the attentions of grazing invertebrates. This is analogous to the grasses we know from terrestrial habitats, which are adapted to grow despite heavy grazing. So, over the course of two or three months, I saw the "shrubbery" of *Gomphoenema, Navicula* and *Ulothrix* replaced by a short, tightly-cropped "turf" dominated by *Achnanthidium minutissimum.*

The other consituents of this underwater landscape were blue-green filaments. These belong to a group of organisms known as blue-green algae, or Cyanobacteria, which were amongst the very first organisms to appear on this planet. Fossils, similar in appearance to species that can still be found today have been found in rocks over 2000 million years ago, over 1700 million years before the dinosaurs walked the earth. But my interest in these particular Cyanobacteria has less to do with their evolutionary history than with what they are telling me about life in the River Wear.

The term "Cyanobacteria" needs a little explanation: the earliest microscopists who described them saw simple unicellular or filamentous organisms that appeared to resemble other algae but had distinct blue-green coloration due, it was later found, to a different type of photosynthetic "turbocharger" to those that give diatoms their yellow-brown colour. Hence the name "blue-green algae" came to be applied to the group. However, as more observations accumulated, it became clear that there were also properties of other algae that blue-green algae did not share. For example, the pigments responsible for

Fig. 7. Top left: a chironomid larva from the River Wear in May 2009 (length approximately 1 mm); middle left: a cobble from the same place in July, covered with caddis larvae; middle right: the view down the microscope in June; bottom: schematic view of the algal community in June.

photosynthesis are, in most algae, packaged into chloroplasts. In blue-green algae, by contrast, there are no such inclusions and the photosynthetic pigments, and all the cell's other biochemical machinery are spread throughout the cell. In evolutionary terms, this is a primitive characteristic, which blue-green algae shared with bacteria. Indeed, the current thinking is that the lineage of all modern plants actually started when a primitive organism ingested an ancestor of the blue-green algae and instead of digesting it, harnessed the energy-producing capabilities of the cell for itself. As knowledge of the biology of blue-green algae increased, so other bacteria-like properties were found and eventually, from approximately the late 1970s onwards, scientists came to regard them as being more closely aligned to bacteria than to plants, and advocated the term "Cyanobacteria" as a way of emphasising this.

Cyanobacteria are common as part of the "plankton", the plants and animals that live suspended in water. Many have the capability to produce toxins, and this has brought Cyanobacteria to public awareness as warm summers lead to their proliferation. As a consequence, dogs and cattle that lap water from the edge of a lake have been killed and people engaged in water sports such as swimming and canoeing have developed rashes. In one particularly tragic case, water from a lake contaminated with these toxins was used in a kidney dialysis machine. The toxins were, presumably, originally produced by the algae as a means of deterring grazing animals and it is possible that some of the Cyanobacteria that we find in rivers and streams also do this, though there is little evidence. However, looking down my microscope, I can see a different explanation for relative success of blue-green algae here: the larva of a non-biting midge, belonging to the family Chironomidae, is moving around the drop of water trapped under the coverslip, feeding relatively indiscriminately on the diatoms and other organic matter. It is about half a millimetre long, so bears the same relationship to a cell of *Achnanthidium* as does a cow to a blade of grass. The filaments of blue-green algae are, however, much harder for it to manipulate into its mouth parts and I wonder if this is at least part of the reason why these are able to thrive at this time of year?

Two months later there was very heavy rainfall in the region, and the River Wear flooded. Whole tree trunks were swept downstream and the road between my village and Durham became impassable for a time. I had assumed that this would have devastated the algal communities in the river but when I next went to collect a sample, I was surprised to find a thick coating of algae on the cobbles, and a very different collection of species. The chironomids and caddis flies were notable by their absence: I assume that both they and their algal food supply had been scoured off as the stones rolled and bumped around the river bed. However, the algae, with their ability to multiply rapidly, especially in the relatively warm waters of the summer, had recovered very quickly. As their numbers increased, so it was fast-growing species that could exploit the light which were at an advantage, and my August sample was dominated by individuals of a small, motile diatom called *Nitzschia archibaldii,* exuberantly scrambling over each other in a competition to reach the available light. Over the next couple of months, the slower-growing invertebrates had returned and the status quo was resumed. But it was a salutary lesson for me: until this storm I had thought that I was beginning to understand the forces that shaped the algae in the River Wear. By the autumn, my musings were laced with a renewed sense of humility.

Fig. 8. The underwater landscape of the River Wear in June, with "bushes" of the cyanobacterium *Homeothrix varians* and individual filaments of *Phormidium* scattered amongst a "lawn" of *Achnanthidium minutissimum*, with scattered cells of *Encyonema silesiacum*. In the distance, chironomid larvae graze on the algae.

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Idyllic is a difficult word. It has the same root in Greek as "ideal" yet has a subtly different meaning. Whilst the definition of "ideal" in my dictionary is of something that answers to "one's highest conception, perfect or supremely excellent…", an idyll is "a short description, in verse or prose of a picturesque scene or incident, especially in rustic life…". An idyll is, in other words, an idealised view of rural life. Weardale, viewed from my position on the bridge at Wolsingham, fitted the bill almost perfectly.

The painter Joseph Mallord William Turner (1775 – 1851) visited this area several times, and the rivers of north east England feature in many of his landscapes. Most of his early paintings featured an antiquity of some sort – Barnard Castle and Egglestone Abbey a few kilometres to the south on the River Tees were both visited by him early in his career. Both were ruins, conveying a sense of brooding melancholy that was popular at the time. His famous painting of Durham Cathedral, overlooking the River Wear further downstream, on the other hand, has a sense of grandeur mingled with this reverence for the past. High Force, the waterfall on the upper Tees, by contrast with these, fed a taste for the sublime: the experience of a natural power that directly threatens one's sense of self-preservation.

Look at a painting by Claude Lorrain (c. 1604 – 1682) who epitomised an earlier school of landscape painting, and you will see an idealised landscape, not necessarily one that exists anywhere outside the artist's imagination, but one which conveys a sense of calm, order and tranquility. Look at a landscape by Turner and you may be able to identify an actual place, even locate the precise spot where Turner must have sat. Equally, you can walk beside the River Wear or River Tees close to the locations he painted and wonder why Turner had not chosen this or that location as a subject. If Lorrain imagined a landscape, then Turner selected a viewpoint from amongst the many that he passed. A landscape is, in other words, the result of an interplay between artist and his environment. Or, more pragmatically, between an artist, his environment and his perceptions of what his customers expected a landscape painting to convey. An ideal landscape, an idyllic landscape: both are human constructions – a view of a world altered by man, but a view that has been, in turn, filtered and selected to match certain aesthetic premises.

In my study in Durham there is a copy of the Water Framework Directive: seventy-three pages of Eurospeak that has slipped, almost unnoticed by the majority of the British public, into our legislation (as is the case, it must be admitted, for most European Union laws) yet which has created the context for my professional life over the past decade. It is also why, as I look across Weardale, I am thinking about Turner and Claude Lorrain.

The purpose of the Water Framework Directive is to govern the way that water is managed across the European Union. It recognises that, in a small, densely-populated continent that extends from the Arctic Circle to the semi-arid regions of the Mediterranean, clean water is a scarce resource that needs to be managed carefully. If those

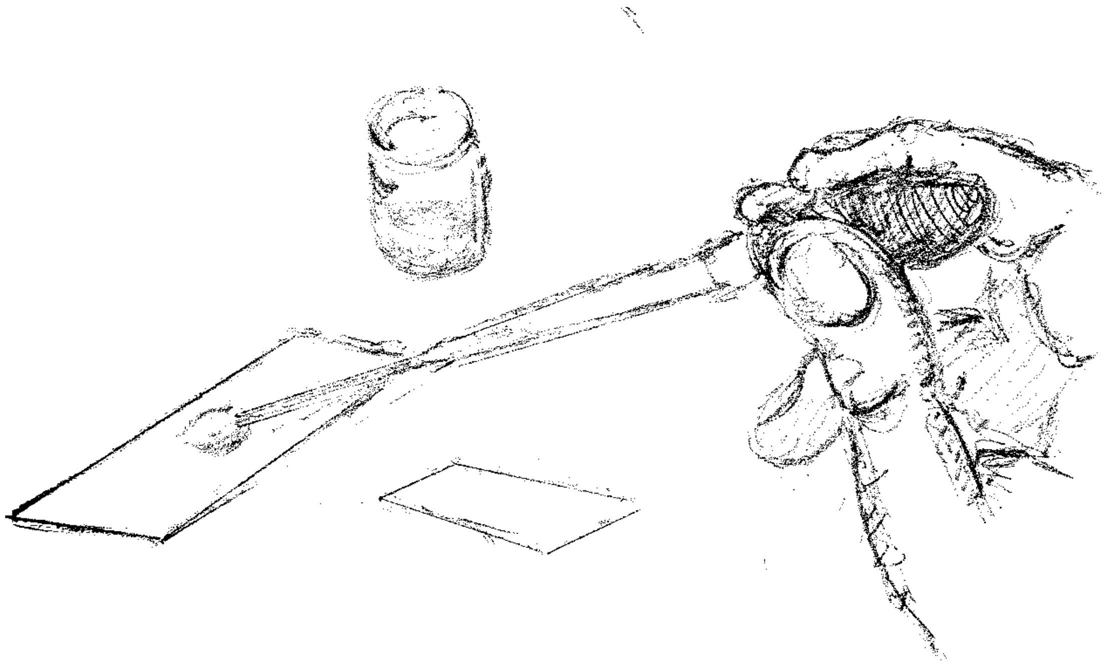

Fig. 9. Making a wet mount: transferring a drop of sample from a vial to a glass microscope slide.

who use rivers as a conduit for their waste matter, or who pump water from a river for irrigation or as a coolant for their industries were allowed to continue unregulated, those who live downstream and who want to purify it and pipe it into homes for drinking, or those who want to canoe on it, swim in it or fish in it might find that these activities are compromised. So, to fall back on a rather tired cliché, the Water Framework Directive aims to create a level playing field across the European Union. It does this not by setting out regulations on how we use water but, instead, by setting some basic rules about the plants and animals that you should expect to find in a river or lake. The presence of a healthy ecosystem, in other words, indicates that we must be managing the river or lake reasonably well, just as a singing canary told the miners that the air was safe to breathe or a food taster told the king that no one had poisoned his food. The European Union, in other words, lets you do what you like with a river – pump industrial effluent in, pump out water for irrigation or whatever – so long as the ecology conforms to the Water Framework Directive's prescription.

And here is the link to Turner: the Water Framework Directive's prescription is that a river should conform to an "ideal". Turner looked for an ideal landscape; modern ecologists are striving, instead, for the perfect lake or river (or, for that matter, estuary or coastal water). The formal term that the Water Framework Directive uses is "ecological status", which it defines as:

> … an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters. (Article 2, clause 21)

In practical terms, this is assessed as the difference between what we see in a river or lake when we visit it or take a sample, and what we would expect to see if there was little or no human impact on that water body. The Water Framework Directive defines five classes of ecological status: high, good, moderate, poor and bad. Of these, high and good are deemed to be acceptable; however, if the ecological status of a water body is moderate, poor or bad, it will need to be brought back to at least good ecological status. High ecological status corresponds, more or less, to the ideal state, whilst good ecological status is defined as a state where the ecology deviates

> … only slightly from [that] associated with the surface water body type under undisturbed conditions." (Annex V, Table 1.2)

All of this sounds a reasonable, if somewhat idealistic at the level of a broad principle. What the Directive has asked us to do is to find the point at which the hand of man overrules the hand of nature in forming the freshwater world. Yet it leaves us with a number of problems. How do we define what we mean by a river or lake with little or no human impact? What, exactly, do we mean by a "slight" change in the ecology? To what extent is this ideal state something that can be defined and measured in an objective fashion? How do we tell the difference between changes caused by man and those that occur naturally in rivers? Is this ideal not, like Turner and Lorrain's paintings, at least partly defined by our expectations? And, finally, how do we achieve this goal of all water bodies having no more than a slight change in their ecology in a way that allows modern society to continue to function?

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Compare and contrast: if the River Wear at Wolsingham represents a stream in something close to its natural state, then perhaps this journey should now continue to a river where the hand of man is much more evident? I have travelled about thirty kilometres north from Wolsingham and am standing beside the Causey Burn which flows east then north across County Durham, becomes the River Team and finally joins the River Tyne near Gateshead. Rising some twenty-five metres above the stream is a stone-built single-spanned bridge, stretching from one side of the narrow gorge to the other. This is Causey Arch and it is the oldest railway bridge in the world, dating from 1726 and introducing us to some of the industrial features that have shaped this part of the world and which continue to exert an influence on the rivers and streams of the area.

Causey Arch carried a waggonway – a predecessor of the railways - across the valley in which Causey Burn runs. Scrambling up a steep footpath and crossing the arch, I found myself looking at a replica of one of these wagons, which were filled with coal and hauled by horses from the pits to the staithes beside the Tyne where it was loaded onto colliers for the journey by sea to London. But my journey does not concern coal; at least, not directly. Causey Arch gives us some context for the stream that flows along the valley bottom: it speaks of the long history of mining, taking us back to the earliest days of the Industrial Revolution, and explaining reasons why people settled in this part of County Durham

This is now a tranquil wooded valley, traversed by footpaths and busy with walkers and climbers at weekends. Close to the river, however, an odour of decay lingers. Appearances are deceptive: in the six kilometres between me and the source of Causey Burn, the river receives effluent from the sewage works serving the north side of the town of Stanley and the village of Tanfield Lea. There are also two industrial estates and a pipe which discharges water pumped out of the abandoned mines as well as sundry other minor sources of pollution. All this into a river less than a quarter of the size of the River Wear at Wolsingham. It is a good place to see what a polluted river looks like.

Leaning down to pick up a stone, I can see that, unlike the smooth, slippery surface that most of the cobbles at Wolsingham presented, this one has a tangled mat of fine, bright-green filaments, mixed with a quantity of fine silt. If I rub a few of these filaments between my thumb and forefinger, and look at it through my handlens, I can see each filament to be somewhat finer than a human hair and to be sparingly branched along its length. This is a filamentous green alga whose scientific name is *Cladophora glomerata* but which is more commonly known to anglers and others with an interest in the aquatic world, as "blanket weed".

On my first visit in 1983 there was no *Cladophora* at all. The only plants I saw there were aquatic mosses forming beard-like fringes on the more stable stones. Water managers usually regard *Cladophora glomerata* to be a nuisance as well as being a sign of polluted water so its absence in 1983 and presence now would seem, at first glance, to indicate that the burn at Causey Arch had deteriorated in quality.

Cladophora glomerata is an extraordinarily successful plant in freshwaters across the globe, especially where man has inadvertently fertilised the water, either with sewage or agricultural runoff. It does, however, have an Achilles' heel: one type of pollution which it cannot tolerate is heavy metals and the presence of a battery factory two kilometres upstream from where I am standing was enough, thanks to the zinc-rich effluent that it produced, to keep *Cladophora* out of this part of Causey Burn. Closure of the battery factory in 1996 ended the zinc pollution and, thereafter, *Cladophora* was able to thrive again in the river. Studying – and managing – pollution is often like peeling away the layers of an onion – remove one pressure on the environment simply means that another, previously masked, now comes to the fore. Even after the battery factory closed, Causey Burn was still a small stream draining a densely-populated area of west Durham. The sewage works at East Tanfield continued to pour in treated effluent and the burn was still a long way from being the idyll that the Water Framework Directive expects our rivers to be.

The filaments of *Cladophora*, which seem so fine and fragile when removed from the water and viewed with the naked eye are, viewed under the microscope, about a twentieth of a millimetre across: several times larger, in other words, than the *Achnanthidium* and *Gomphonema* cells that we saw in the River Wear. Gardeners know that plants respond to fertilisers differently, and *Cladophora* is one of those plants that likes to live in nutrient-rich water. The effluent from a sewage works is really a very dilute manure, but one that is constantly replenished, so there is no shortage of nutrients here. And as *Cladophora* grows over the more stable substrates, so the algae which we found in our near-natural stream at Wolsingham – species adapted to living without this constant supply of dilute fertiliser – now find themselves shaded by a dense canopy of *Cladophora* filaments.

They respond in one of two ways: as we saw in the spring sample from the Wear, many diatoms are motile and are able to exploit this property to move through the dense matrix of *Cladophora* filaments plus silt particles that they trap and the network of bacterial and fungal filaments that also grows here. However, when you look closely under the

Fig. 10. Top: The River Team at Causey Arch; middle left: close-up, showing the river bed smothered with blanket weed (*Cladophora glomerata*); middle right: a single cobble from the River Team, showing the *Cladophora* filaments; middle left: a view of *Cladophora* filaments under the microscope; bottom: a schematic view of *Cladophora* on a stone in Causey Burn, showing intertwined filaments of *Microspora amoena*, epiphytic diatoms (*Cocconeis placentula* and *Rhoicosphenia abbreviata*) and cyanobacteria (*Chamaesiphon incrustans*) plus, moving through the matrix of filaments and organic and inorganic particles, motile cells of the diatoms *Craticula, Navicula* and *Nitzschia.*

microscope, you will see that the *Cladophora* filaments are themselves covered with algal cells: many are diatoms, mostly with a low, limpet-like profile, belonging to a species called *Cocconeis placentula*, but there are also some very short filaments – just a few cells long – of a Cyanobacterium called *Chamaesiphon incrustans*. A few genera of algae seem to be particularly well-adapted to living this piggy-back existence: these are the epiphytes of the subaquatic world, comparable to mistletoe and ivy in terrestrial forests.

Not all the stones here are covered with *Cladophora*. Few of those smaller than a fist have any at all and, when I take a sample and view it under the microscope, I can see that they are covered with *Cocconeis placentula*, the limpet-like diatom that, in the previous paragraph. was an epiphyte on *Cladophora*. I soon see why this species is so abundant: scanning across the slide, I see another small invertebrate larva grazing on the algae. This is the larva of another type of midge, *Simulium*. The adults are the black flies which swarm on river banks on summer evenings and which (unlike the adult chironomids) bite humans.

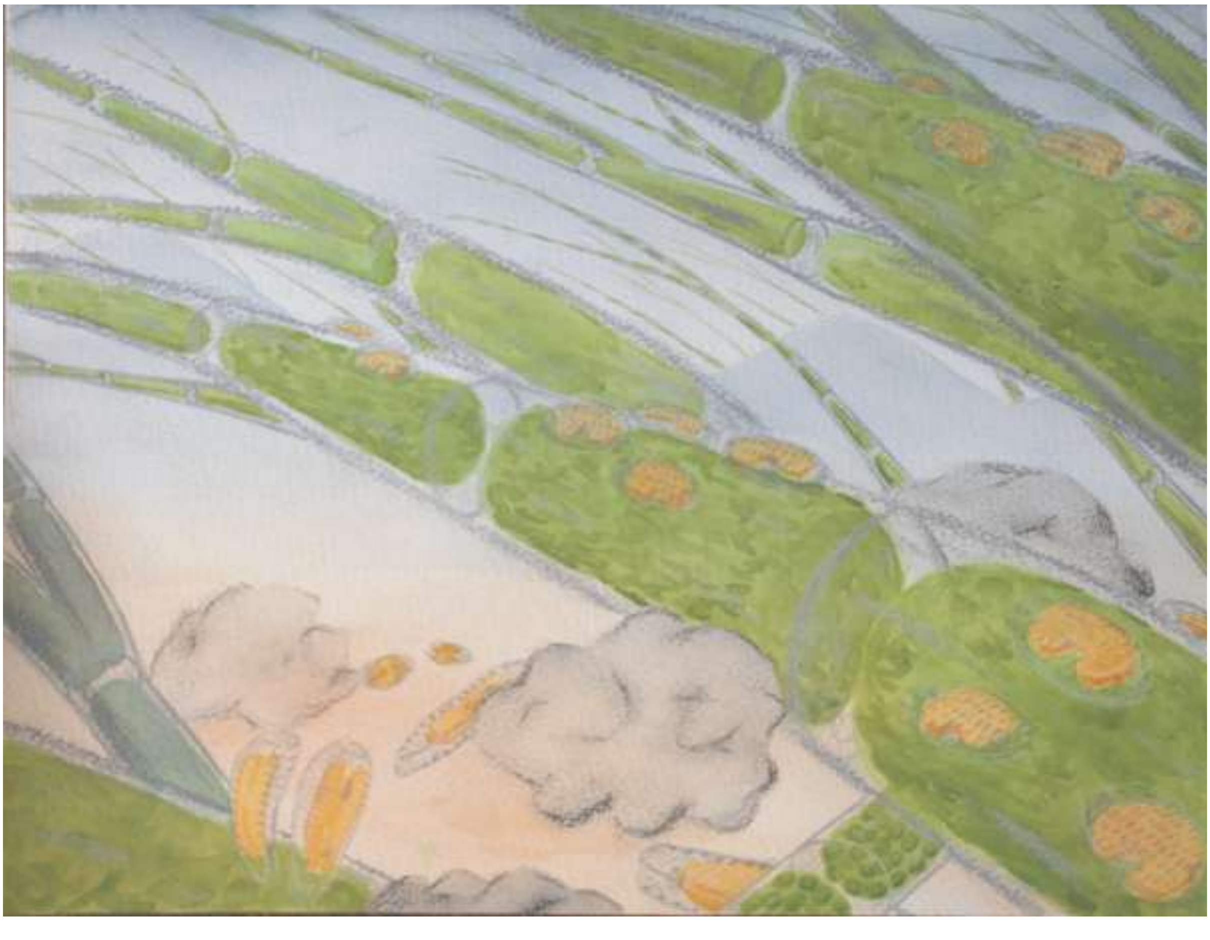

Fig. 11. The underwater landscape of the River Team. Filaments of *Cladophora glomerata* dominate this view. These, in turn, are colonised by smaller algae – prostrate, elliptical cells of *Cocconeis placentula* and upright, curved cells of *Rhoicosphenia abbreviata*. The tangle of filaments also traps sediment particles and motile diatoms such as *Nitzschia palea* move through the dense tangle of algal filaments and organic and inorganic particles in search of light.

They lay eggs on the river bank from which the larvae hatch. Unlike the chironomid larvae, simulidae are sessile, spinning a web on a submerged surface, then attaching themselves to this using a ring of tiny hooks at the ends of their abdomen. They then feed by sifting the water using comb-like mouth parts and capturing particles which may either be decayed organic matter or tiny algae. On the day I was examining the surface of stones from the River Team, one *Simulium* was bent over double as it busily used these combs to find sustenance amongst the bottom-dwelling algae. The low, streamlined growth form of *Cocconeis placentula* made it resistant to this grazing.

Modern science seems to have an in-built tendency to reductionism. We focus on one group of organisms and, as we try to isolate one or a few of the many variables that can affect these, we inadvertently ignore other factors. As a biologist interested in how pollution affects streams and rivers, it is tempting to interpret the differences between the Wear at Wolsingham and the Team at Causey in terms of the chemical environment: the low nutrient concentrations at the former favoured *Achnanthidium minutissimum*; higher concentrations of nutrients at Causey favour *Cocconeis placentula*. But the truth is always more complicated. Different grazers have subtly different effects on the algae, the establishment of *Cladophora* changes the environment on the larger stones, turning the open "pastures" I described at Wolsingham into dense, shaded "forests", and forcing the other algae to adapt. And then there are the smaller stones – less stable, more likely to be turned during a spate – which are never stable enough for *Cladophora* to establish, where different algae are able to thrive. It is this patchiness, this heterogeneity, that ensures that the ecology, even of quite polluted rivers, is so diverse. And, through this diversity, there is resilience, because there will always be a few individuals able to thrive in response to a change in conditions, whether natural or man-made. So I can visit the Team, the Wear or any other river, over and over again and never find the exactly the same group of organisms twice. Rivers are, in short, predictably unpredictable, and unpicking the reasons why I find a particular set of organisms at any particular time and place is part of their fascination.

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The word "pollution" has become so ubiquitous in our age as a word describing environmental damage that it is easy to forget its long ancestry which predates modern concerns. An edition of the Shorter Oxford Dictionary from the 1930s defines the verb "pollute" as follows:

> ***1.*** To render ceremonially or morally impure; to profane, desecrate, to sully, corrupt.
> **2.** To make physically impure, foul or filthy; to dirty, stain, taint, befoul.

"Pollution" from our post-industrial vantage, is usually expressed as something that can be measured, yet the casual walker beside a polluted river or stream will often have an innate sense that something is "wrong". It is often expressed as a musty, disagreeable smell (in the case of sewage pollution) or choking green algae, in the case of some other types of pollution. It is this intuitive "sense" that something is not right that aligns most closely with the definition of pollution in its broad sense as defined here. In theology and anthropology, this sense that something is "wrong" relates to something sacred that has been upset or desecrated or whose purity has been violated. There are, for example, 52 references to "pollution" in King James' Version of the Bible, mostly from the Old Testament and mainly relating to the manner in which sacrifices were presented to God. In the book of Numbers, for example, God is speaking to the Israelites before they enter the Promised Land:

> "Do not pollute the land where you are. Bloodshed pollutes the land, and atonement cannot be made for the land on which blood has been shed, except by the blood of the one who shed it." Numbers 35: 33

Definitions of ritual pollution can extend to include contact with the "impure" – a sense that an Orthodox Jew or high caste Hindu would still recognise. Similarly, Muslims subject themselves to a ritual wash before praying as a symbol of cleansing away the dirt of the physical world to prepare themselves for their encounter with God.

The Oxford English Dictionary's first record of the verb "pollute" being applied to water is attributed to Florence Nightingale in 1860. It is significant that this happened at the height of Victoria's reign when, on the one hand, Britain is presiding over the largest empire the world has ever seen whilst at home millions still lived in overcrowded and squalid conditions. Three cholera epidemics had ravaged the country over the past 30 years: the first had killed 31 thousand people out of a total population of about 16.3 million in Great Britain. 20 years earlier, Charles Dickens had described Oliver Twist's introduction to London's slums:

> "A dirtier or more wretched place he had never seen. The street was very narrow and muddy, and the air was impregnated with filthy odours. There were a good many small shops; but the only stock in trade appeared to be heaps of children, who, even at that time of night, were crawling in and out at the doors, or screaming from the inside. The sole places that seemed to prosper amid the general blight of the

> place, were the public houses; and in them, the lowest orders of Irish were wrangling with might and main."

The evolution of the meaning of the term "pollution" is not difficult to discern in this passage where the filthy disease-bearing odours – the *miasmas* of the ancients – are intermingled with the loose morals – akin to the older idea of pollution as something that is morally impure or profane. What is perhaps significant is that the plight of the poor, urban slum-dweller was finally – thanks to social reformers such as Florence Nightingale and Dickens – receiving serious attention.

The London to which they were directing their attention was growing at a phenomenal rate. Already a city of over a million people at the start of the nineteenth century, it had doubled by 1850 and would double again before the end of the century. Much of this growth was due to immigration from the countryside as the Enclosure Acts and the Corn Laws reduced the numbers employed in agriculture. So high was the death rate in cities that urban populations could not replace themselves by reproduction alone and were sustained by the constant flow of immigrants from the surrounding countryside. The sheer bulk of excrement that was produced by this population was approximately doubled by the animal population: not just the horses which pulled coaches, carts and cabs, but also domestic fowl, cattle and pigs whose protein supplemented an otherwise meagre and unhealthy diet.

Much of this excrement found its way, eventually, via open drains and sewers, to the Thames and its cumulative effect was sufficient to wipe out the salmon fishery that once flourished in the river between Putney Bridge and Greenwich. Even eels, the hardiest and most resistant of fish, were reported to be dying due to the lack of oxygen in the water.

The idea that disease was caused by *miasmas*, literally "bad air", had survived since the days of Hippocrates and Galen, largely due to the lack of a credible alternative. Air became poisoned by emanations from rotting animal and plant material, the soil and standing water. As a predictive framework, *miasmas* work reasonably well: the idea of *miasmas* has its root in Mediterranean regions where malaria (which also means "bad air" but from a Latin, rather than Greek, root) was endemic. Areas with stagnant water were ideal for mosquitoes to lay their eggs. In temperate regions, it was the heaps of rotting excrement and manure which were especially responsible for the *miasmas*, but low lying areas beside rivers such as the Thames were also noticeably moister and danker than higher ground such as Hampstead. Low-lying areas encouraged the accumulation of excrement and polluted waters, decreased the opportunities for collecting drinking water from fresh-flowing streams and increased the risk of wells becoming contaminated by sewage.

It is only when viewed with the benefit of hindsight that *miasmas* appear hopelessly naïve largely because no-one was able to find a causative link between *miasmas* and the diseases that they were supposed to cause. What was it in the composition of the air around *miasmas* that was responsible for the diseases? It was this that propelled a generation of

Fig. 12. Lowering a coverslip onto a slide.

chemists, including Joseph Priestley and Antoine-Laurent Lavoissier, into studies which led to the discovery of the major constituents of air during the late eighteenth and nineteenth centuries. The disease-causing agents, however, remained elusive.

One of those wondering about the causes of cholera was a medical doctor called Arthur Hill Hassall (1817-1894). He was, like many Victorians of his class and time, a polymath: whilst he pursued his medical training in Dublin, he also explored the coast of Ireland and made himself an expert on a group of marine invertebrates then called "zoophytes" but which we now know as sea anemones, corals and other animals that resemble plants. Back in London, he practised as a physician for a few years and then took himself off to Kew Gardens to train as a botanist and slowly taught himself about freshwater algae. His hunch that the key to understanding the causes of cholera lay in the water Londoners drank led him to sample the reservoirs and rivers that the water companies used to supply the city with drinking water. Hassall, peering down his microscope saw a myriad of strange organisms and thought he had solved the mystery.

He published his findings in *The Lancet*, describing the organisms he found in each sample and accompanying these with diagrams, each in a circular frame, as if to simulate the view down the microscope, and crammed with the bizarre (and, to the Victorian sensibility, appalling) organisms he had found. There are several recognisable algae in these pictures, along with protozoans and nematode worms. Hassall had made an important step forward in that he had ascribed the cause of cholera to biology rather than chemistry, but the algae and protozoans that he had drawn were not, themselves, the cause. That would have to wait until 1885, when Robert Koch first discovered the bacterium responsible. Hassall had, quite simply, got it wrong: but, in the process, he had kick-started the study of algae in Britain. His plates, too, played a role in establishing the link between drinking water and disease in the eyes of the general public: his drawings were even waved around in a parliamentary debate to emphasis the poor state of London's drinking water.

Hassall was one of a group of reformers concerned with public health in the middle of the nineteenth century who managed to establish the link between drinking water and disease. His mistake in pointing to the algae as possible disease-causing organisms was understandable: his microscope was extremely crude by modern standards: optical technology was less advanced and he relied on daylight rather than high intensity bulbs to illuminate his specimens and, more pertinently, the bacterium responsible for cholera is an order of magnitude smaller than even the smallest algae that he found. His error, made in good faith, is not uncommon in ecology. We make observations and then try to derive plausible explanations. But the worlds we deal with are so complicated that alternative explanations for the phenomena we observe are usually available (even if, as in Hassall's case, he could not see them). The process is known as "weak inference": it is not that our conclusions are necessarily wrong, but nor do we have assurance that they are right. This leaves ecologists vulnerable to criticism by others, often with their own vested interests to promote.

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If Hassall and his colleagues were beginning to understand the effects of pollution on rivers in the middle of the nineteenth century, then why are there still so many streams similar to the River Team all over the UK? I was pondering this question as I stood beside the River Skerne, about thirty kilometres south from Causey Arch. Until a few years ago, everyone saw the River Skerne every time they looked at a five pound note, because these used to bear a picture of Stevenson's Locomotion crossing the Skerne Bridge on the Stockton and Darlington Railway. We are a few kilometres above that point, and just a kilometre or so below Newton Aycliffe sewage works.

There are two parts to the answer: the first is that one outcome of the work of Hassall and his colleagues is that we no longer drink untreated water from rivers or lakes. The second part of the answer is stream ecosystems are efficient natural waste disposal units. If a leaf falls into the stream from an overhanging branch, there are invertebrates that will shred this up and eat it. The leaf will pass through their digestive systems and what is not absorbed by their bodies will pass out as what freshwater biologists coyly refer to as "fine particulate organic matter" or "FPOM". More invertebrates – small shrimps, aquatic relatives of the woodlouse and midge larvae especially – will eat this FPOM and break it down further. Bacteria will, in turn, use the tiny molecules that result as their energy supply and, eventually, the leaf tissues will be reduced to carbon dioxide and water. The stream ecosystem is, to use a domestic analogy, a very dilute compost heap.

If you have a compost heap, you'll know that it is a good way of getting rid of potato peelings and other vegetable trimmings, as well as garden waste. Our waste becomes, in turn, food for earthworms and wood lice as well as for bacteria and fungi. Keen gardeners will also tell you that piling on too many grass clippings in one go will mean that the bugs that break down the waste to make compost will use up all the oxygen and will produce an anerobic, smelly mess, rather than the fine, crumbly compost you expected. Some experts suggest you turn the contents of a compost heap from time to time in order to make sure that even the deeply-buried organisms get occasional gasps of fresh air.

The same principles apply to rivers: the leaves and other vegetation that fall in naturally are gradually broken down, partly by invertebrate animals (earthworms in the compost heap, invertebrate larvae in the stream) and partly by bacteria and fungi. The whole system is delicately-balanced – as oxygen is used up by these microorganisms, so it is replenished partly by natural diffusion into the water from the air and partly by the plants and algae that live in the stream. As the material is broken down, so the nutrients that they contained are released for the plants and algae to absorb to fuel their own growth.

Knowing this we can start to understand sewage from an ecological perspective. It is no more than concentrated FPOM. It swamps the natural capacity of the bacteria, fungi and invertebrates in the water to break it down and, in the process, uses up the oxygen. It is, in other words, "fast food" for streams – no longer does the stream receive a balanced diet, rich in leaves (equivalent to "roughage" in our own diets) and so those invertebrates that are adapted to shredding and eating are edged out by the myriads of invertebrates which feast on the FPOM.

In the mid-nineteenth century when Hassell was working, British rivers were in a parlous state. The problem was not just that people were moving to cities but also that mains sewers were replacing the traditional "night soil" collectors, who took human waste to the countryside for use as fertiliser. The sheer quantity of sewage dumped in the Thames created a significant problem for navigation, quite apart from the fears associated with miasmas.

At about the same time as Robert Koch was discovering that bacteria such as that which caused cholera were the "enemy" of the water reformers, other biologists – notably William Dibdin (1850 – 1925) – were discovering that they were also our "friends", by breaking down the enormous quantities of raw sewage dumped into the River Thames at the time. Dibdin's Big Idea was to recreate, on an area by the Thames at Barking, the conditions that these bugs liked, but in a concentrated form – the first sewage works – in order to let them break the sewage down for us. It focussed all the natural processes which broke down organic matter in rivers into a single site creating, in effect, an enormous aquatic compost or manure heap. And this, in essence, is what happens at the sewage works at Newton Aycliffe, just upstream from where I am standing. However, the process is never 100% successful. Traditionally, the water industry assumed that the natural capacity of the river itself would finish off the job for them. The stretches of rivers immediately downstream from sewage works were, therefore, dominated by animals feeding on the FPOM, and have high numbers of bacteria and fungi. All this activity needs oxygen, so one of the standard measures of the scale of organic pollution in rivers is,

Fig. 13. Top left: The River Skerne at Coatham Mundeville; centre right: a tuft of *Vaucheria* from the Skerne; centre left: the view down the microscope; bottom: the arrangement of *Vaucheria* mat of entangled filaments, mostly growing vertically, to create a microscopic "forest" on and around which other algae are growing. We can see the inorganic particles (a.) which are trapped within the *Vaucheria* mat as they are washed downstream. Two types of epiphyte can be seen. There is *Cocconeis placentula* (b. – seen both from above and in profile) which lies flat on the surface, like a limpet, and also *Rhoicosphenia abbreviata* (c. – seen from the front and the side) which grows vertically from the surface. Motile diatoms belonging to the genus *Navicula* (d. – from above; one seen from the side is just to the right) move in and around the vertical filaments around which chains of cells of the diatom *Melosira varians* (e.) are entangled.

The filaments of *Vaucheria* are about a tenth of a millimetre across, but I've exaggerated the scale of the diatoms to make the diagram clearer. The Cocconeis (b.) is about a hundredth of a millimetre across in reality. ➔


b.
c.
d.
e.
a.

simply, to measure this "biological oxygen demand". We would expect it to be high close to the source, but a few kilometres downstream this process of breakdown should be complete and the river should, in theory, have recovered.

Standards have improved, and water companies now are expected to manage their sewage works to a much higher standard than before privatisation but, still, as I look into the Skerne at Coatham Mundeville, I can see tell-tale signs of a sewage works a few kilometres upstream. There is an old water industry adage that "the solution to pollution is dilution", and a stream such as the Skerne simply does not have enough water in it to dilute the effluents from a medium-size town such as Newton Aycliffe adequately. The alternative is to improve the sewage works, but that will increase the utility bills for local residents. And, standing on the narrow bridge over the Skerne at Coatham Mundeville, rather than, like me, in the river itself, they might wonder if this was worthwhile.

The view from this bridge is a typical pastoral British landscape – gentle limestone hills rising in the distance and willow trees overhanging the stream. Perhaps, like at the River Team, there is sometimes a slight odour of decay hanging over the water, but the overall impression is something approaching the rural idyll we examined earlier.

Just as at the River Team, impressions change when I take a closer look and, once again, the river bed is covered with bright green tufts of algae. From a distance, they might be confused with the *Cladophora* I saw at Causey, but closer inspection shows these to have a felty texture, and that the filaments, rather than trail in the water, are actually growing vertically. This growth form makes them natural sediment traps and I need to rinse the sample I collected for some time under the tap before I am left with a handful of bright green felt which I can then tease apart and put under my microscope. The differences between this and *Cladophora* are now slightly more apparent: the filaments are wider and do not appear to be divided into distinct cells. Rather, they have the appearance of a sausage skin, about a tenth of a millimetre in diameter, the interior of which are lined with tiny, bright green chloroplasts. On the outside, there was a scattering of attached single-celled algae on which some midge larvae were grazing, along with various organic and inorganic particles.

So there are some differences between *Cladophora* and *Vaucheria* but, from a visual inspection alone, enough similarities for them to be regarded as relatives for a long time. I have a copy of George West and Felix Fritsch's freshwater algal Flora published in 1927, and this includes *Vaucheria* with the green algae (technically known as "Chlorophyta"). The most recent Flora, on the other hand, puts *Vaucheria* into a separate group: the Xanthophyta. West and Fritsch lived in an age where the classification of algae was based mostly on direct observation. The modern algal scientist has a much bigger toolkit, including biochemical analyses which reveal that the photosynthetic pigments of *Vaucheria* are quite different to those of *Cladophora* and that, rather than accumulate the products of photosynthesis as starch (as the green algae and all higher plants do), *Vaucheria* and the other Xanthophyta store these as a different compound, called chrysolmainarin. Colour, in other words, is an unreliable barometer of affinities within the freshwater algae, in the same way that you would not classify a whale as a fish just because it possessed fins. If you were trying to name a plant you had found in a terrestrial habitat, you would find that the books tend to focus their attention on the flowers. Trying to name a plant you found in a woodland from just the leaves is not easy and, in effect, all our *Vaucheria* is offering us is these vegetative parts – the equivalent of the leaves. Unfortunately, many freshwater algae rarely form reproductive organs – the equivalent of a higher plant's flower- which makes it hard to tell different species apart. Just focussing on what we can see with a microscope also hides a number of clues to their affinities – deeply technical stuff but, to cut to the chase, these link *Vaucheria* and its relatives to the diatoms and, perhaps surprisingly, the wracks and kelps of our seashores, rather than to green algae such as *Cladophora*.

I went back to the River Skerne a few weeks later to collect another sample and most of the *Vaucheria* had disappeared, with *Cladophora* more evident. Thinking back, I also remember times when the River Team had been coated with felt carpets of *Vaucheria*, rather than the usual *Cladophora*. My best bet is that the habit of *Vaucheria* was well suited to the long period of warm, dry weather that had preceded my first visit. The growth form of *Vaucheria* is even suited to short periods out of the water: the densely-packed filaments act as wicks to conduct the water from the base of the tuft up to the growing tips. However, heavy rain in the period between the two visits had washed it away, and the more firmly-attached growth form of *Cladophora* had taken over. This is mostly speculation. There is much that we still do not know, even about relatively common freshwater algae.

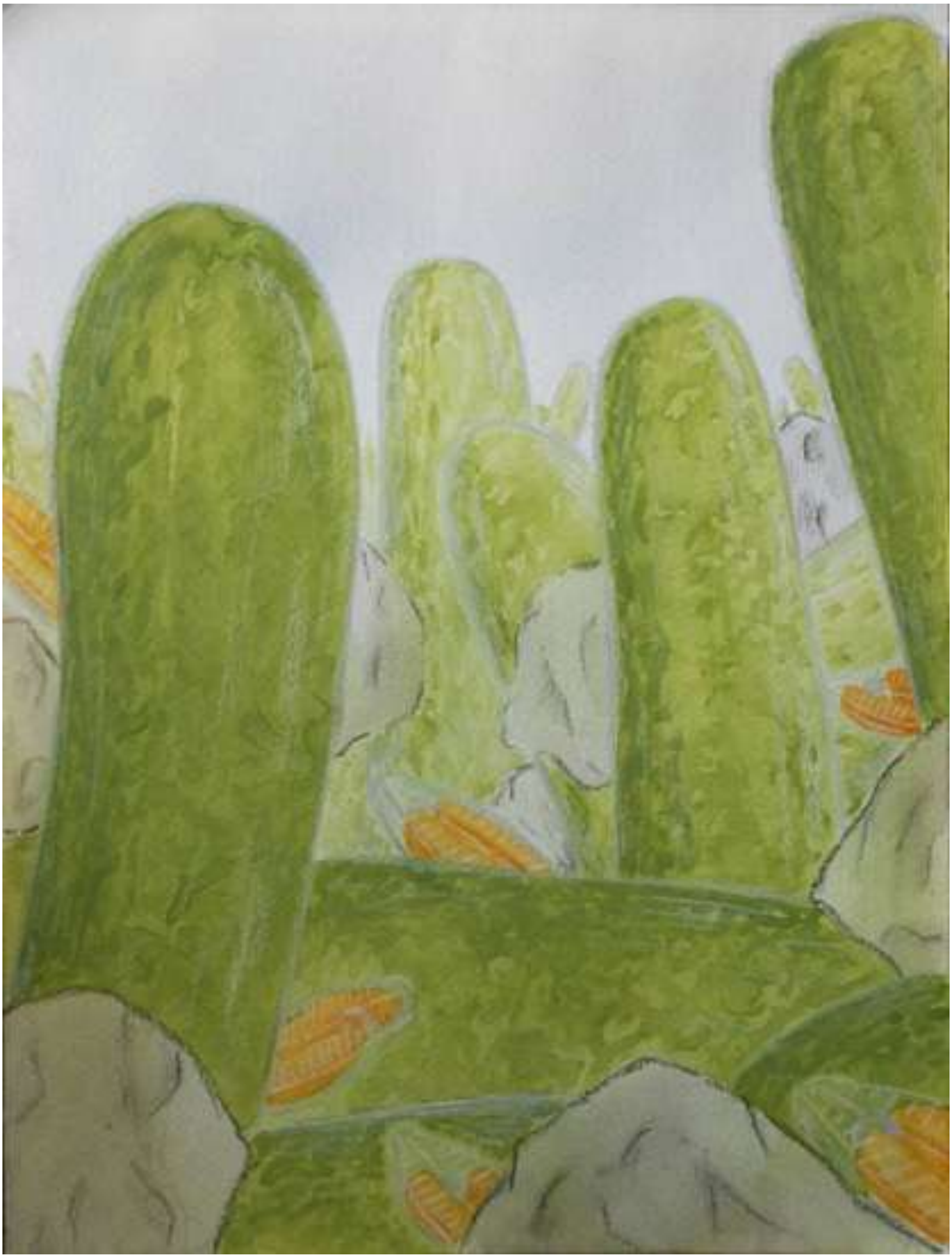

Fig. 14. Inside a *Vaucheria* "forest" from the River Skerne at Coatham Mundeville.

- 10 -

So why have I called this book "Of Microscopes and Monsters"? "Microscopes" should be self-explanatory, but how do "monsters" fit in? A few years ago, a Dutch colleague wrote a paper and, as I had done some of the analyses that supported the work, he included me as a co-author. He sent me a proof to check before publication but, as it was written in Dutch, I could not be of much help. What I did notice, as I scanned through the text, however, was repeated use of the word "monster". In English, this has a very particular meaning – huge, often imaginary and usually ferocious beasts, far removed from the microscopic algae I thought we had written about. "Monster" in Dutch, I was told, meant "sample". Intrigued by this, I went to my Shorter Oxford Dictionary and looked up the etymology of the word. "Monster", I learnt, is a Middle English word derived from the Latin "monstrum", meaning a divine portent or warning. The idea behind this was that strange apparitions – malformed animals, misshapen births – were sent as warnings of an impending catastrophe of some sort. And so the link to the Dutch word for "sample" became much clearer: in fact, our word "monitor" also shares a similar derivation. The samples environmental scientists collect give us insights about the state of a river or lake and these, in turn, help us to predict - prophesy, if we stay with the apocalyptic theme – what might happen if we don't do something. We want to know, for example, if there is a risk that fish are likely to die due to lack of oxygen on a warm summer evening, or that swimmers or canoeists are likely to get skin rashes after swimming in a lake. Arthur Hill Hassall clearly saw algae as "monsters", albeit on a microscopic scale; The bizarre appearance of the algae and other life that he depicted, along with his suspicion that these were responsible for cholera, certainly fitted both senses of the word.

We need a short diversion at this point, in order to understand how water pollution is measured in the UK. During the early part of my career, the environment was a minority concern. Ecologists, by and large, knew about the major environmental challenges but there was little political will to invest in practical solutions. During the late 1980s this started to change: in the UK, the unexpected success of the Green Party in the 1989 elections for the European Parliament signalled a rise in public interest. A year later, the establishment of the National Rivers Authority (NRA), a by-product of water privatisation, signalled a greater willingness on the part of Government to tackle the challenges that the aquatic environment presented.

There were biologists in the water industry before this point, but they were bit-players in a world where engineers and chemists generally ran the show. At this point, biologists could, for the most part, look at the plants and animals living in a river and assess the scale of pollution. Often, this coincided with what the chemists knew, but sometimes the biologists would find evidence of pollution in a river which the chemists thought to be free from contamination, and this would precipitate some forensic work to track down the source – perhaps a factory that emptied its tanks infrequently, and which was, consequently, missed by the chemist's monthly visit. Chemists can measure the concentration of a particular substance to the nearest part per billion but only if they had set out to look for that substance and it was in the water at the time they took their sample. The plants and animals that live in the river, however, are exposed to all the contamination in a river, including the substances the chemicals did not suspect they needed to measure, all the time, not just on the day that they collect their sample.

Biologists in the water industry gradually became aware of the potential of using ecology to assess the state of the river from the 1960s onwards. However, the biology, at this time, was essentially descriptive and most effective when applied on a local scale. The new legislation created a national body for water management, and therefore a need to make nationwide comparisons, and also to start to develop an ability to predict as well as just to describe. In other words, the pre-1989 biologist could use the invertebrates present in a river to rank the biology of that river on a scale, roughly 1-10, where "1" is bad and "10" is excellent quality. If a biologist collected a sample from above and below a sewage works, he might find the upstream sample scored 6 and the downstream sample scored 4. He might conclude that the sewage works was causing some pollution although, in the pre-NRA days, he would have worked for the organisation that had responsibility for both managing the sewage works and enforcing the legislation. Not surprisingly, many UK rivers were in a poor state.

However, the biologists who used these simple indices all over the country also realised that rivers apparently free from pollution were not all giving the same result. A chalk stream in southern England, for example, consistently had more diverse invertebrate faunas and higher scores than even an unpolluted stream draining the Pennines. Another facet of the same problem was that the invertebrates found in the headwaters of any river are not necessarily the same as those found in the reaches close to the tidal limit. This means that a biologist could not make a direct comparison between index values calculated from two samples even if from the same river without knowing more about the locations they were collected from. This is not a problem when the biologist was concerned primarily with the effect of a single source of pollution on a river because he or she could evaluate the results downstream **relative** to those upstream. But suppose the upstream site is, itself, polluted? How much better could that site be? There are, in other words, benefits from converting our relative estimates of biological quality into **absolute** measures of the condition of river ecology. Or, to put it another way, to find a way of quantifying the "ideal" state described in chapter 6.

This was a question that occupied the minds of a group of scientists based in the Dorset laboratory of the Freshwater Biological Association (FBA) during the mid-1980s. Up until this point I have tried to describe stream ecology in qualitative terms, in order to help you to visualise the worlds that I am describing. However, the FBA team had the advantage not just of having some highly experienced invertebrate ecologists working on the problem, but also, in Ralph Clarke, a talented statistician. He was able to take the various observations that his ecologist colleagues made about the sites they were sampling – easily measured properties such as the altitude, width, depth and stream hardness – and use these to predict the value of indices if there was no pollution present at that site. If you divide the value of the index you calculate after analysis of a sample from the site you are studying by the "expected" value, based on Clarke's predictions, you get a ratio. If the observed sample is the same as the prediction, your ratio (called an "Ecological Quality Ratio" or EQR) is one. If it is lower than one then this is an indication that your invertebrates are not as healthy as you should expect, and you can start to hunt for possible reasons. Clarke and his colleagues had, inadvertently, laid the foundation stone for the Water Framework Directive which would come into force a decade later.

The next challenge, however, is to work out how to get from the present "observed" state to the ideal or "expected" state. Almost any change in the quality of a river requires either building new treatment facilities or changing treatment processes, with implications for capital investment programs or running costs. Sewage works were, by the early 1990s, managed by private companies and the price they charged their customers was a politically-sensitive subject. Decisions on how to manage a river had direct effects on people's water bills, particularly as both regulator and water companies were overcoming a long period of underinvestment.

Water quality did improve in the early 1990s as a result of the stronger legislation. However, as we saw in the River Team, managing pollution is like peeling away the layers of an onion, and the improvements to sewage treatment revealed other, hitherto hidden, problem. The high concentrations of phosphorus and other nutrients in rivers was not addressed by this legislation. Back in chapter 3 we saw bubbles of oxygen on stones caused by the algae busy converting the sun's energy to carbohydrates. This photosynthesis only occurs, however, during daylight hours. During warm summer nights, on the other hand, the prolific plant growth that results from abundant nutrients can suck so much of the oxygen out of the water that fish can, in effect, suffocate. There was no willingness to address this on a broad scale as the capital investment needed to build the plant to remove phosphorus was huge. However, in 1991, a new piece of legislation, the Urban Wastewater Treatment Directive (UWWTD), came out of Brussels, creating the imperative for the NRA to tackle this issue. Unfortunately, the invertebrate-based methods for assessing river ecology, in which the NRA had invested so much money, were not very good at detecting these effects.

And so I inadvertently stumbled into this scene: a Fellowship at the University of Durham that seemed at one point to be going nowhere now had a focus: maybe there would be ways of using the algae in rivers to help us understand the scale of risk that excessive nutrients presented to a river? The French had already devised some methods for using diatoms to evaluate water quality but in a fairly general manner. I looked at their methods and started to tweak them in ways that focussed particularly on nutrients. The outcome was an index which the NRA (which evolved into the Environment Agency in 1995) and sister agencies in Scotland and Northern Ireland could use. When my Fellowship ended, I bought myself a second-hand microscope and continued the work as a freelance consultant.

The Water Framework Directive, in effect, requires all Member States in the EU to perform what amounts to a regular "MoT" test on water bodies – a checklist of the properties of a river that should be inspected, and some guidance on what constitutes an acceptable state, as we saw in chapter 7. So all the EU members had to find ways of measuring the different components of aquatic ecosystems in ways that are relevant to their circumstances. In the case of UK rivers, we had a foundation, not just for the invertebrates and diatoms but also for the larger plants of rivers. No longer was the biology a subsidiary tool for water management: it now played a central role in decision-making in the aquatic environment. The next step, for all of us, was to work out exactly what that natural state of any river should be.

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That Causey Burn and the River Skerne are polluted is incontrovertible. The question that this observation prompts is "what do we mean by "unpolluted"?" What are the properties we are looking for that define a clean river? I have made the comparison here between these sites and the River Wear at Wolsingham, but how do I actually know that the Wear, itself, is clean?

For the first half of my career, rivers were defined as "clean" or "polluted" in terms of whether or not we could measure any pollutants in their water. The preferred state was, obviously, "unpolluted", yet this is a negative property – "good" as defined by an absence of undesirable properties. I had mused on these topics a few years earlier whilst sitting in a hospital whilst my father recovered from a heart attack. At the entrance to each ward there was a handwash conspicuously placed on the wall for staff and visitors to use. More handwashes were placed at strategic locations around the ward and available, and legions of auxiliary staff seemed to be constantly swabbing and wiping every surface. But the cleaning alone did not make him better; there is, in other words, more to "health" than "cleanliness". If "clean" is defined by an absence, then "health" implies a positive - a body that is fit enough to live a normal life.

From the 1990s onwards, momentum developed amongst ecologists to apply similar phraseology to the environment. The roots of this thinking came from the work of James Lovelock, whose Gaia theory suggested that earth should be treated as a super-organism, with the different components interacting to provide the same kind of control over global processes as a body can exert over its component parts. Pollution, to take this metaphor a little further, was a kind of "sickness". The metaphor is seductively simple but someone living on a crowded island such as Britain as the twentieth century slipped into the twenty-first could be forgiven for wondering about exactly what a "healthy" ecosystem would have looked like.

One of the surprises of the Water Framework Directive was that it had told us that "healthy" coincided with "undisturbed" conditions yet gave very few details on how to define "undisturbed" beyond some vague statements about "… no, or only very minor, anthropogenic alterations ..". Yet this undisturbed state was the reference against which all water bodies – marine and freshwater – had to be measured. The search for "reference conditions" has become one of the major intellectual challenges of the last decade, if only because so much of Europe has been settled and exploited by man for so long. The answer is to define how healthy a river or lake is by reference to those water bodies that we already know to be healthy, just as a doctor has a pre-determined idea of what a healthy body should look like and how it should perform. Yet this, in turn, begs another question, and one that is much harder to answer: where do we find these healthy rivers or lakes on this crowded island? And that, in turn, takes us to the remotest corners, where the human footprint is barely discernible, in order to sample the diversity of life that these contain. This information would then allow us to form a view of the properties to which all rivers and lakes should aspire.

I had tried to articulate these ideas to my father whilst we were visiting whisky distilleries on Islay after he had recovered from his heart attack. I had taken the opportunity of being in a remote corner of the country to visit Loch Lossit, which my colleagues and I had decided was a good candidate for a near-pristine "reference" lake. As he is a non-scientist, I searched for a suitable metaphor and finally told him that I was engaged in the search for the perfect lake.

This implies, in turn, a different sort of journey: if we are to use a near-pristine lake such as Loch Lossit as a benchmark for lakes elsewhere in the country, we are also making a journey backwards in time (because, we are suggesting, Loch Lossit represents a condition that many other lakes had once enjoyed) and a journey forward in time (because, if appropriate measures were taken, these impacted lakes could once again attain this state). This restoration is, in fact, also a requirement of the Directive although it is unlikely to be cheap. It will involve tighter controls on how sewage works are managed, for example, which may result in higher water bills. It may mean closer regulation of farmers and industry, which will affect their costs and, in turn, the prices we pay for their goods. So there is a further challenge in the Water Framework Directive - implied rather than spelt out – to explain to the wider world exactly what we mean by "ecological health", why a river has failed to meet the required standards and what benefits will accrue to a community from the expenditure required to nurse that river back to health.

Reflecting back now, the genesis of this book lay in that pilgrimage to Islay: My career had slipped, more by accident than design, into an obscure academic backwater which meant that I knew a lot about a group of organisms that most people barely, if ever noticed. Over the years, a series of twists and turns in environmental politics had meant that this backwater, this group of organisms – and my own work on them – were going to have an effect on everyone's pockets.

Fig. 15. Examining a specimen under the microscope.

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And so I came to Wastwater. Under the shadows of Scafell Pike and Great Gable, Wastwater is one of the most remote lakes in England. The only habitation in the catchment are a small hamlet, Wasdale Head, two kilometres to the northeast of the lake, a couple of campsites and a few scattered farms. Applying the criterion of the perfect lake from the previous chapter – a lake where the human footprint is barely discernable – Wastwater seems like an ideal candidate. In which case, we could reason, documenting the plants and animals that live here would give us a benchmark against which other lakes could be compared? This, we have found, is true up to a point but if you were standing beside one of the Norfolk Broads, you might wonder if the lakes that develop in the flat landscapes of East Anglia should really be judged against lakes such as Wastwater, where the geology is so different. Comparisons should, in other words, be restricted to lakes of a similar nature. Even within the Lake District, for example, Windermere cannot be compared directly with Wastwater: the hard rocks that make up Scafell Pike and the other mountains in this part of the Lake District are less easily eroded meaning that the Wastwater contains fewer dissolved minerals than that of Windermere.

A second reason for visiting near-pristine lakes such as Wastwater is that we can study how the various plants and animals interact with each other, and then use this to develop ideas about how natural lake ecosystems actually work. Rather than just make interminable lists of species and describe the patterns that we find, we can start to evaluate lakes in terms of the processes that are happening. You might learn to recognise a right back in a football team by his appearance or by the number on the back of his shirt, but you will have only a very superficial understanding of football unless you also know how a right back interacts with the goalkeeper and other defenders to stop the opposition scoring, and with the midfield players to push the ball upfield in order to create the opportunities needed to win the game. So it is with ecology: we have met *Achnanthidium minutissimum* already in our clean rivers, but how does this diatom interact with the other algae, as well as with the invertebrates that eat it, and does this tell us about the steps necessary to restore polluted ecosystems to a healthy state?

There is nothing wrong with describing the patterns that exist in ecology. The problem comes when we try to ascribe causes to these patterns. We can find relationships between the patterns and the environment, but noting that there is a relationship between two variables is not the same as saying that one is affecting the other. Both may be responding to a third, unmeasured, variable. And, to further complicate matters, the relationships that ecologists do find are often very noisy, and we are, again, faced with the problem of "weak inference" mentioned earlier.

I had come to Wastwater because a colleague, Lydia King, had chosen it as a location for an experiment during her PhD studies. She was grappling with the same issues that I described above. She had established that there were relationships between the types of algae that she found in lakes in the Lake District and the amount of nutrients that they contained. She also saw that the types of algae she found depended upon how acid or alkaline the water was. But the water chemistry only explained a part of the variation in the algae and now she wanted to find out about the variation that was not explained by this. In particular, she wanted to know how much of the variation was due to the way that the algae interacted with each other.

Her experiment resembles a very famous ecological experiment which was started in the middle of the nineteenth century at Rothamstead agricultural research station in Hertfordshire. A large field, called Broadbalk, was divided into plots which were then treated with different combinations of artificial fertilsers and farmyard manure, in order to see which gave the highest yields of cereals. In 1882, after the experiment had been running for about forty years, a strip of land at one end of the field was left unharvested in order to see what happened. This area was, itself, divided into two: half was left completely untouched, allowing weeds to overtake the wheat. Later, shrubs such as hawthorn and, eventually, trees, invaded and this part of the experiment is now a mature woodland with ash, sycamore and hawthorn. The other half was also left untouched except that woody plants were pulled up before they were allowed to establish. This developed in a different way, with plants typical of open ground. The experiment is a good example of how the vegetation of a site can change naturally at a site over time – ecologists call this "succession", as the different species jostle for the resources such as nutrients and sunlight. The "winners" in a natural temperate landscape such as Britain are usually trees and the deciduous forest such as that we now see at Broadbalk Wilderness is termed the "climax" vegetation.

From my point of view – trying to understand how the environment shapes the ecology – work such as this introduces time as another variable that we need to study. Except, when we are dealing with microscopic algae, we need to think not in decades or centuries but weeks. Lydia's experiment involved putting clay pots into the shallows at the edge of Wastwater and then watched how the algal communities changed over the course of six weeks. She also examined small parts of the pots at extremely high magnifications using a scanning electron microscope and the resulting pictures, along with her data, provided the basis for the paintings in Figs 16 and 17 which show that the changes very similar to those we saw over one hundred years at the Broadbalk Wilderness are happening over the course of a few weeks in Wastwater.

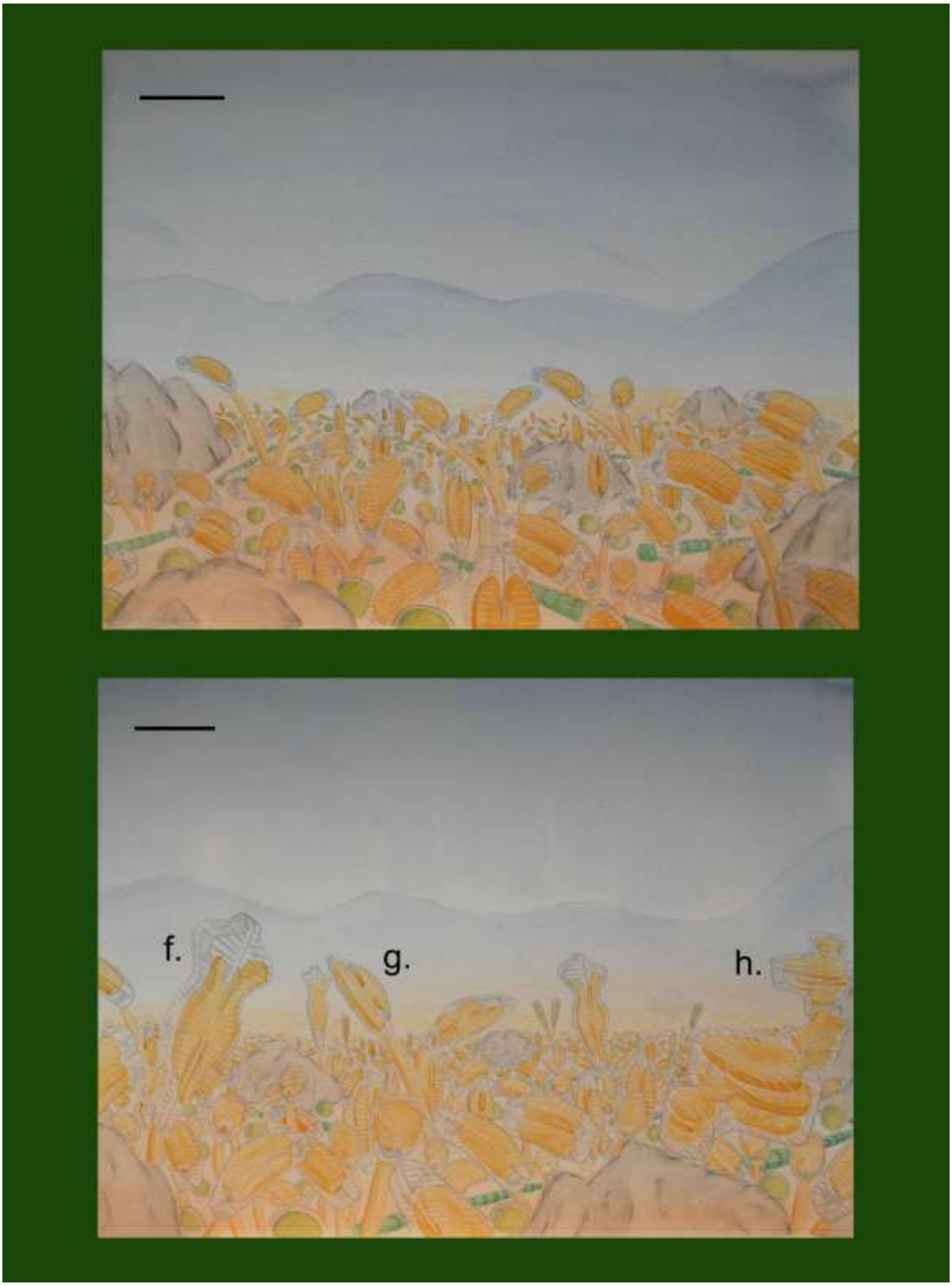
Fig. 16. Upper image: the author sampling from Wastwater in 2007 (photo: Ed Kelly); lower image: The microbial world of the littoral zone of Wastwater after two weeks of colonisation. Key: a. unidentified small unicellular blue-green alga; b. unidentified small unicellular green alga; c. thin filament of *Phormidium*; d. *Achnanthidium minutissimum*; e. *Gomphonema parvulum*. Scale bar: 10 µm (foreground).


e.
a.
b.
d.
c.

The first diorama (Fig. 16 – lower image) shows the surface of the plant pot after being submerged in Wastwater for two weeks. You could think of this as a patch of waste ground that was, at the start of the experiment, bare of vegetation. If we watched this patch over a number of weeks, we would notice some plants appearing: scattered stalks of grass, perhaps some rosebay willow herb, dock or plantains. A gardener might dismiss these as "weeds", although this term has no ecological meaning, usually referring just to a plant that is growing in the wrong place. Ecologists prefer to think of these as "pioneers": plants adapted to colonising new habitats, growing quickly (which might mean producing lots of seeds in a short space of time or producing rhizomes or runners) and covering the ground. This same process has taken place on Lydia's plant pot in Wastwater: the "weeds" in this case are scattered thin filaments of the blue-green alga *Phormidium,* the diatoms *Achnanthidium minutissimum* and *Gomphonema parvulum* plus a number of spherical green and blue-green cells that she couldn't identify. Such is the scale that we are working at that this open landscape still contains about 92000 cells per square centimetre.

When she came back a week later, much of the empty space had been infilled; there were now about 300,000 cells per square centimetre (Fig. 17, upper image). These mostly belonged to the same species that she had found the week before. The difference is that they are now rubbing up against each other and this has some important consequences. All plants need light and nutrients to grow and algae are no exceptions. Sunlight provides the energy for photosynthesis but now, at week three, the density of algae is such that there is a chance that some of the light will be intercepted by a neighbouring cell. The total amount of sunlight that filters through the water to the pot surface is already much lower than that available at the lake surface; now it has to be shared out between many more cells. At this point, properties such as fast growth rates that helped our pioneers to colonise the plant pot become less relevant, and it is algae that are better adapted to capturing the limited light that will survive. So when Lydia came back to Wastwater after six weeks, she saw a very different community of algae on her pots (Fig. 17, lower image). There was still a lot of *Achnanthidium minutissimum*, but rising above these was another species of *Gomphonema*; one which has an elegant art deco shape but which, more importantly for our story, grows on a long stalk. There is also a diatom whose cells are shaped like an orange-segment; this is *Cymbella affinis* and this, too, grows on a long-stalk, the better to grow above the *Achnanthidium* and other pioneers. The equivalent on the patch of wasteland that we had been following would be invasion by shrubs such as hawthorn and blackthorn, although this would happen two or three years after the first pioneers had arrived, not six weeks as Lydia had observed for the algae. She also found a diatom called *Tabellaria flocculosa* which forms filaments. These often start out loosely-attached to the substratum but more often break free and become entangled around the other algae. In our "wasteland" analogy, these would be the brambles.

Fig. 17. Upper image: the microbial world of the littoral zone of Wastwater after three weeks of colonisation. The composition is similar to that in Fig. 3 but with a higher density of cells. Scale bar: 10 µm (foreground); lower image: the microbial world of the littoral zone of Wastwater after five weeks of colonisation. Key: f. *Gomphonema acuminatum*; g. *Cymbella affinis*; h. *Tabellaria flocculosa*. Scale bar: 10 µm (foreground).


f.
g.
h.

The experiment finished shortly after this, terminated when the apparatus was overturned. Whether by a wave or by vandalism, Lydia will never know but this event is, itself, a metaphor for the harsh world in which benthic algae have to survive. In real life, the many cobbles in the littoral zone will be rolled by wave action or, as we saw in the River Wear, invertebrate grazers could have removed much of the "shrubbery", leaving a "pasture" composed of the tough, fast-growing species such as *Achnanthidium minutissimum* to dominate samples. The "successions" we see in the microscopic world not only take place much more quickly than those in the macro world, but they also rarely have a stable "climax": just a brief pause before the next onslaught from the physical, chemical and biological processes that shape their existence.

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You might be thinking that somewhere in this story, I have started to confuse space and time. If I travel to a remote location, I argued for both Loch Lossit and Wastwater, I could find lakes in which human impacts were hard to measure. Such lakes were "living fossils" indicating how lakes in the far past might have appeared, and how lakes currently impacted by human activities could, once again, appear.

When Einstein grappled with the relationship between space and time, he sought the solution in elegant equations. In our case, we need something less abstract, more tangible, to make sense of these inter-relationships: we need a window into the past. We've already learnt that diatoms have glass-like cell walls and it is through these that we will now peer back into history.

A lake such as Wastwater has an enormous number of diatoms living attached to surfaces in the shallower water at the margins and suspended in the water – as plankton – throughout its area. It is not always a clear distinction – some of the attached algae may be dislodged by wave action and become temporary members of the plankton and some of the plankton will settle and become entangled with the benthic life. Over the course of a year many will die and sink through the water to settle on the bottom sediments. The next year, the pattern will repeat itself, with that year's algae coming to rest on top of those from the previous year. The soft-bodied algae will decay, but the glass-like cell walls of diatoms are resistant to this and will remain intact and, largely, in the same position as where they originally settled. Over time, a deep layer of soft mud, rich in organic matter from the decaying plants and animals will accumulate, along with a liberal scattering of diatoms and other decay-resistant bodies, such as pollen grains.

The mud at the bottom of Wastwater will have been gradually accumulating since the end of the last ice age, about 12,000 years ago and, roughly from the middle of the 20th century, scientists have realised that the distribution of diatoms and pollen grains throughout the layers of the sediment may tell us something about how the vegetation around the lake, and the conditions within the lake have changed. They take a boat to the middle of the lake, assemble what looks to the layman like a miniature oil rig and force the end into the mud to collect a core of sediment for analysis back in the laboratory. It is not just from lakes that these cores can be collected, but peat bogs too, and over the last half century or so, a huge number of cores have been collected from all around the UK, allowing us to build up a picture of how the British landscape has changed.

We are going to follow the changes in the pollen grains collected from a bog in Upper Teesdale, in the Pennines, as this is an area that ecologists have studied in great detail. And we will look first at the pollen grains, as these give us an idea of way the broader landscape has changed, and helps to create a context through which we can interpret changes in lakes and rivers.

The trained eye can distinguish the pollen grains from different types of plant. Grass pollen is one of the most basic types: more or less spherical grains with a single pore, out of which a tiny tube grows when it lands on a stigma, in order to fertilise the egg. Other types of pollen grain are, broadly speaking, variants on this basic form – sometimes oval rather than round, with two, three, four or more pores and with various types of knobs and spikes on the outside. The pollen of pine is particularly distinctive: the basic round grain has two large ears attached, so that it looks like the head of Mickey Mouse. These act as sails, helping to blow it enormous distances. Ironically, pollen analysis is possibly the only area of botany where mistaking a buttercup and an oak tree is a risk: it takes some practice to be able to differentiate between their pollen grains. However, if you are patient enough to meticulously name and count the pollen grains found at different depths in the peat you can build up a picture of the vegetation that had cloaked the area around the core site at different stages in the past.

A pollen analyst may find fifty or more different types of pollen in a core but, fortunately, there is a convention in studies such as this, to present a summary of the data, by grouping all the pollen that belonged to "trees", all that belonged to "shrubs" and all that belonged to non-woody plants ("herbs"), so you don't have to be an expert botanist in order to follow these changes (Fig. 18). In order to interpret this, imagine the width of the graph as representing all the pollen grains counted (100%) and the depth representing the depth of the core, which in turn relates to a particular age (I've written the age rather than the depth on the graph, to make it easier to interpret). Gazing across the treeless landscape that is characteristic of the Pennine fells today, it is a little surprising to see that about a quarter of the pollen found at the surface of this core is tree pollen – mostly birch, oak and alder. These light grains must have blown here from elsewhere but their presence in such numbers suggests we need to approach this graph with a measure of caution. In fact, pollen analysts get used to phenomena such as this and check the pollen representation in surface layers of sediments where they know what the modern flora looks like. For them, there is no contradiction between a treeless landscape and a recent pollen deposit where twenty five percent of the pollen comes from trees.

Further down the core, however, at a depth corresponding to about 6000 years ago, tree pollen constituted about half the total pollen at this site. A more detailed breakdown of the types of pollen shows that, at this time, there was a lot more pine, along with oak and alder in Upper Teesdale. From about 5000 years ago the number of grains of heather pollen start to increase: the explanation being that the climate cooled slightly and got wetter at this time, and this led to the soil becoming waterlogged and less favourable for trees. So the bogs and moors that we see today started to appear at about this time instead. From here to the top of the core, the tree cover gradually declines. The topmost layers – from about 2570 years ago onwards – show a more rapid decline, probably associated with Bronze Age farmers clearing the woodland that remained for farming, but the decline had actually started much earlier.

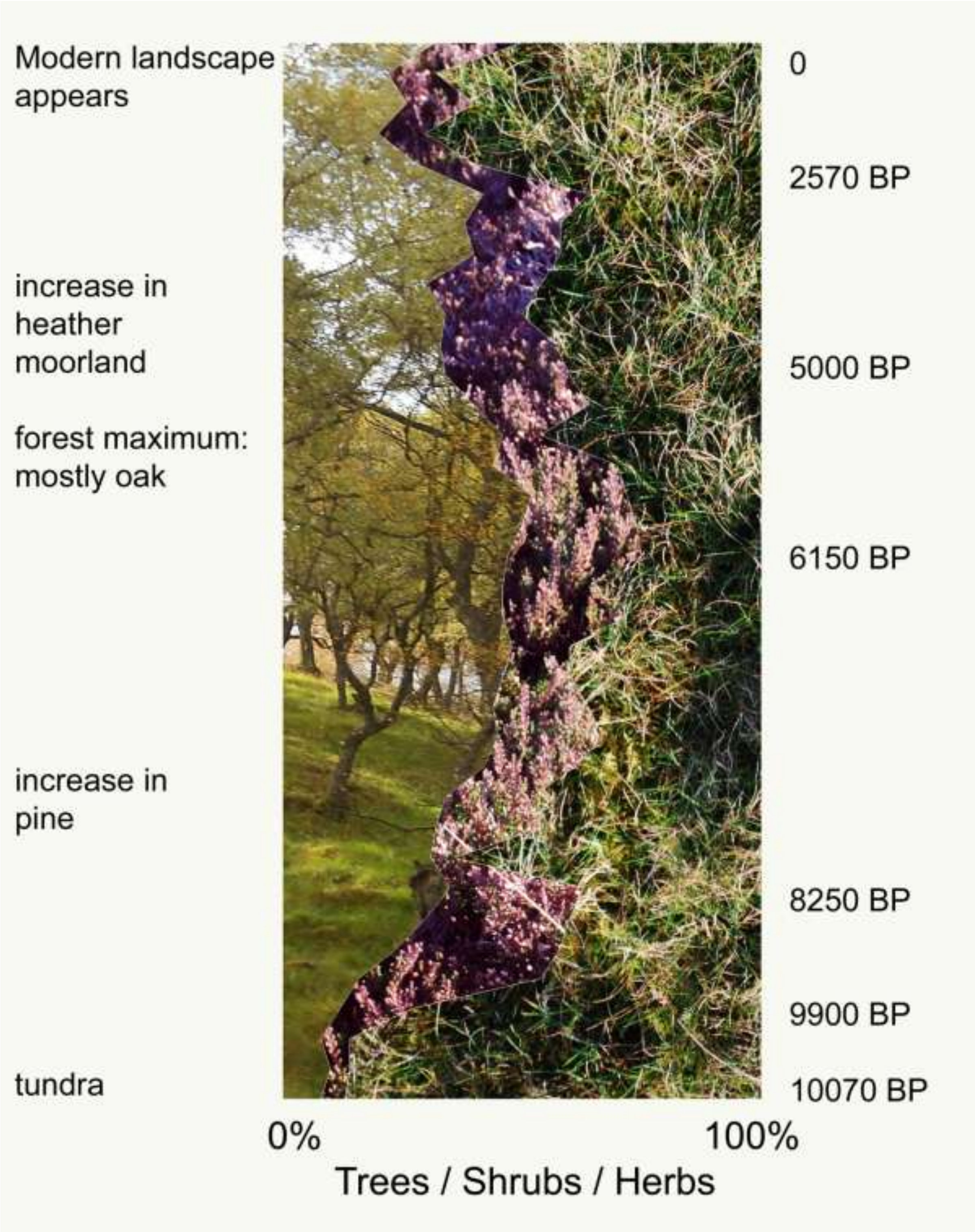

Fig. 18. The summary pollen diagram from Red Moss, Upper Teesdale.

Moving down the core is like taking a particularly long hike, starting in Upper Teesdale but descending down the valley to the natural deciduous woodlands which can still be found in some parts of northern England and Scotland. As you move further down the core, so you need, in your imagination, to leap over the North Sea to the pine forests of Scandinavia, then keep walking northwards. As you reach about 8250 years ago, so you are getting to the northern limits of the pine forests, where there are fewer trees and more low shrubs, grasses and herbs. You are approaching the Arctic Circle and are standing in the tundra which covered much of Britain at the time when it was just emerging from the Ice Age. The oldest peat in this core is about 10000 years old and most of the width of the graph – over 80% - is taken up by herbs, mostly grasses and sedges. The wind blowing from Cross Fell now seems much, much cooler. Time, perhaps, to return to the modern day?

Our journey through the core has shown us that the landscape at Upper Teesdale – an environment whose recent changes we have already seen – is one where the hand of man extends back almost 3000 years, and that natural environmental change continued for even longer before that. Travel to the Mediterranean and man's influence on vegetation extends back almost twice as far - some 5500 years. Yet, both figures pale into insignificance beside the scale of natural environmental change, as Europe warmed up, and then cooled slightly, after the Ice Age. Having set out to find the perfect lake or river, I find that my target is going to be elusive, not just because the British landscape is so altered but also because the whole idea of "natural" is not a static concept. Even if we just look at the 2750 years during which we can see human influences in Upper Teesdale, we are faced with tantalising questions: how, for example, did man influence the River Tees and its tributaries back in those early days? Was it friend or foe to him? And, most tantalising of all; should we worry? To what extent should the idealism embodied in the Water Framework Directive be leavened by pragmatism? If we can swim in it, fish in it and (after treatment) drink it …. if there is enough water for businesses situated along the river to use, if regulations are in place to stop them polluting it … shouldn't we be content?

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I have travelled 150 km west from upper Teesdale to look at another lake – a loch, actually, as I am now in Scotland – in order to try to answer these questions. It was a long drive, out along the Solway coast to Newton Stewart, then northwards along progressively narrower roads into mountainous scenery. I parked my car at the eastern end of Loch Trool, where the road finally gave way to a track, winding down the hillside into a glorious forested landscape. I followed this track on foot for a couple of kilometres, then struck off, following a small burn up the hillside, struggling through knee-high grass and soft boggy ground and scrambling over granite boulders. A herd of highland cattle lifted their heads at one point to contemplate this rare invader into their territory before returning their attention to the grass. Finally, the land flattened out and I was looking across a small loch, no more than a few hectares in size, nestled underneath a granite escarpment. This is Round Loch of Glenhead and, if we apply the principle that the further we go from human habitation, the more likely we are to find a lake in pristine condition, this, even more so than Wastwater, ought to be a prime candidate for The Perfect Lake?

Pushing through the heather that surrounds the lake, I found myself standing on a small beach, composed of fine white sand: almost pure quartz, the end-product of the erosion of the granite hills around me. I waded out into the shallow water at the lake margin and looked around. There were almost none of the cobble-sized stones that I found in Wastwater or on the beds of many of the streams that I visited, which meant that I was going to have to re-think my sampling strategy. On the other hand, once the water was about twenty centimetres deep, stems of aquatic plants – an aquatic *Lobelia* and a quillwort - started to appear, rising vertically out of the water. The submerged portions were surrounded by a dark brown translucent cloud, but as soon as I scooped it out of the water, it collapsed into an amorphous slimy gunk.

Later, staring down my microscope at a sample of this gunk, I could see a rich mixture of algae. There were long filaments of a green alga called *Mougeotia* – cells whose chloroplasts were flat plates, which could rotate round the central axis of the cell in order to catch as much light as possible. Tangled around this were much thinner filaments of a blue-green alga called *Lyngbya* –a close relative of the *Phormidium* which we met in the River Wear, and chains of *Tabellaria*, albeit a different species to the one we met in Wastwater. Within this tangled web, there were other algae: *Merismopeodia*, an ordered array of blue-green cells within a mucilaginous matrix; elegant vase-shaped cells of *Dinobryon* and, creeping through this tangle, diatoms. One was a species of *Navicula* but there were also larger boat-shaped cells – some almost a tenth of a millimetre long – of a type known as *Frustulia*. And, to complete this submerged melange, there were trapped particles of peat, washed in from the catchment, and responsible for the dark brown colour of the gunk. Attached to the plant stems, I saw several cells of small, asymmetrical diatoms belonging to a genus called *Eunotia,* along with needle-shaped cells of another genus, *Peronia.*

These algae are very different to those that we have seen at the other locations we have studied. Even where we see genera that we recognise – such as *Navicula* – the species is different. The reasons for these differences were unpicked in a piece of scientific detective work during the 1980s. In brief, it turns out that the water in Round Loch of Glenhead is very weakly acidic, conditions which many of the algae we have met hitherto are unable to tolerate.

Interest in Round Loch of Glenhead and other acidic lochs in Galloway grew in the early 1980s, as concern mounted that these lakes, along with others in Scandinavia and beyond, were not naturally acid but had become more acid in recent years. Lakes in Scandinavia which had supported, in living memory, trout fisheries, no longer could support trout, and the finger was pointed at industrial areas of north-west Europe, and particularly coal-fired power stations, which pumped gases out of their chimneys which were converted in the upper atmosphere into dilute sulphuric and nitric acid. This was blown across Europe and finally deposited, hundreds of kilometres from the factories as "acid rain".

The implication of a theory such as this is that the companies that operate power stations needed to invest in expensive equipment to remove the noxious gases from their chimneys before they were released. Either their profits were reduced or (more likely) their customers paid more for energy. But, in the early 1980s, this was just a theory and the power companies were not prepared to spend their money or their customer's money on a theory unless there was a more convincing linkage between their exhaust gases and the acidification of lakes. Strong evidence that Round Loch of Glenhead was, once, less acidic than it was in the 1980s would help but such a remote loch is visited rarely, and there were too few measurements of the water chemistry for any trends to be apparent. Two scientists from University College London, Roger Flower and Rick Battarbee now came onto the scene. Both were geographers by training, with an interest in lakes and in palaeoecology. They took cores from Round Loch and analysed samples from different depths in order to see which diatoms were preserved. They also sent off samples to specialist laboratories who used radioisotopes to date each of the layers of the core.

Fig. 19. Top: Round Loch of Glenhead; centre left: the algal community smothering stems of *Lobelia* in the littoral of the Round Loch; bottom left: the view down the microscope; bottom right: schematic view of the community smothering aquatic plants in Round Loch; the green alga *Mougeotia* (a), the diatom *Tabellaria* (b) and a narrow filamentous cyanobacterium, *Lyngbya* (c) form a tangle of filaments within which peat particles (d) are trapped and other algae such as *Frustulia krammeri* (e) and *Navicula leptostriata* (f) move around. Some algae are attached directly to the plants: *Peronia fibula* (g), *Eunotia implicata* (h) and *E. bilunaris* (i). Other algae such as the Cyanobacterium *Merismopedia* (j) also live amidst the tangled filaments. Scale bar (bottom right): 10 micrometres (1/100th of a millimetre). ➔


a.
j.
g.
e.
f.
h.
c.
b.
i.
d.

What their analyses reveal is a period of very rapid change in the upper layers of the sediments, starting from the middle of the 19th century. The diatoms at depths below about 20 centimetres suggested water here was naturally more acidic than that of Wastwater – there is less *Achnanthidium minutissimum*, for example, and more *Eunotia*. Flower and Battarbee grouped the diatoms into those that thrived in near-neutral conditions and those that preferred acidic water. In 1850, about a third of all the diatoms they found fell into the first category but by the surface layers this had dropped to about 20 per cent and the acid-loving diatoms now constituted the remainder.

Throughout the 1980s, their research continued. They visited lakes in the UK and beyond and saw that the picture seen in Round Loch of Glenhead was repeated in many other regions. Broadly speaking, the softer the water in the lake, and the closer it was to major industrial centres (especially if downwind), the more acid the water had become in recent years. The crucial evidence, however, was that by using diatoms, Roger Flower, Rick Battarbee and their colleagues had been able to show that these lakes and lochs, in their natural state, were not so acid, and should have been able to support trout fisheries. There was, in other words, a link between the activities of factories and power stations in industrial regions and the livelihoods of people many hundreds of kilometres downwind. As a result, legislation was passed requiring power stations and other major industrial plants to install equipment that removed the noxious gases before they were released.

This story has a happy ending, of sorts. The work by University College continued after the legislation was passed, mostly funded by the Department of Food and Rural Affairs, and Flower and Battarbee have recorded a gradual increase in pH in Round Loch of Glenhead and other acidified lochs, and a gradual shift in the diatoms back towards those that prefer near-neutral (if still slightly acid) conditions. But the diatoms we see now are not exactly the same as those they found in their cores from pre-industrial periods. Rick Battarbee has mused that the fall in sulphur dioxide – the major exhaust gas from power stations – has been more dramatic than that of nitrous oxides – which comes from vehicle emissions which have proved harder to reduce. There is evidence that nitrogen is naturally scarce in many of our upland lochs and lakes so the modern lochs are, in effect, more nutrient rich than in their pre-industrial days. Maybe the rich growths of *Mougeotia* around the Lobelia and quillwort stems is a consequence of this and maybe the *Navicula* which is now common in the lake is able to use this matrix of filaments to move around. But there is still much that we do not know.

What we do know, as a result of these studies, is that simply travelling to remote places is no guarantee that we will find a lake in pristine condition. The answer is to combine the search for remote, pristine lakes with studies of their sediments. However, it takes months to build up the detailed picture of changes in lake sediments that I describe for Round Loch of Glenhead and when the Water Framework Directive arrived, UK regulators needed data from many lakes very quickly. The University College team had, by this time, grown and extended their interest in lake sediments beyond acidification. Having established that the major changes occurred over the past 150 years or so, and knowing that lake sediments accumulate very slowly, they took short cores – just a metre or

Fig. 20. The microscopic world around a quillwort stem from Round Loch of Glenhead, July 2011. Filaments of *Mougeotia* and *Lyngbya* are entangled with chains of the diatom *Tabellaria quadrisepatata*, within which particles of peat are trapped. *Peronia fibula* (top) and *Eunotia bilunaris* (bottom) are attached to the plant stem and *Navicula leptostriata* moves through the algal matrix.

so in length – from many Scottish lochs and just looked at the surface layer – representing the present day – and the bottom of the core, which they assumed to represent a point before the industrial era. If a lake was in a pristine state, they reasoned, the diatoms in the two samples would be very similar; the more different they were, the greater the impact. Some of the deeper, naturally nutrient-poor Scottish lochs, such as Loch Rannoch, did appear to have changed very little over the time represented by the core but over two-thirds of the lakes did show changes – particularly amongst the shallow lakes, and all suggesting increases in the quantities of nutrients available for the algae.

And the situation gets worse when you move south to England, and away from the remote mountainous regions where the soils are too thin to support intensive agriculture. Indeed, when you start searching for pristine examples of lakes in hard water areas, very few pass all the tests – there is too much human activity – intensive agriculture and settlement – in their catchments to be sure that they are pristine. The Norfolk Broads are the best documented example: there are photographs, taken in Victorian times, showing Broads with rich and diverse assemblages of aquatic plants, which have now largely disappeared, replaced by "pea soups" of suspended algae. Accurately calibrating our assessments of lake ecology becomes very difficult when there are almost no pristine lakes to act as a benchmark.

The window into the past that lake sediments give us has been invaluable but what about rivers? Palaeoecology depends upon conditions which allow the gradual, undisturbed accumulation of sediment and the constant flow of rivers, and the regular powerful spates meant that there was little chance for sediment to accumulate for so long. How can we find similar windows into the past? Again, the diatoms spring to mind as likely candidates for this task but we need to find a situation where the diatoms living at a site in the distant past have been preserved without any risk of disturbance.

The answer to this conundrum lies, appropriately, in the backrooms of Britain's regional museums. Earlier generations of natural historians were assiduous collectors and cataloguers of Britain's plants and animals and many of their collections were donated, either in their own lifetime or on their death, to museums. Such collections represent an alternative window into the past. In some cases, earlier generations of microscopists donated collections of microscope slides so that the diatoms can be re-examined by modern scientists, but such collections are few and far between. An alternative resource is the large collections of pressed plants that museums have accumulated. The submerged aquatic plants in these collections would have been colonised by diatoms and other algae as they grew and, in many cases, we can carefully take samples from the preserved specimens (the curators were mostly happy for us to do this, so long as we did not take too much, and did not use particularly valuable specimens) and then prepare and analyse these in the same way that we would for a modern sample. In our case, we had a good idea of what we thought the natural diatom assemblage would have looked like, from studies on our remote "reference sites" and the herbarium samples allowed us to test this idea – to see if we could bridge the gap between space and time. We limited ourselves to samples collected before the Second World War (a useful baseline, as this represents the point when agriculture had to become more productive in order to feed a population largely cut-off from overseas food supplies). The earliest specimen in our study dated from 1855. Generally, we found, our initial ideas about the biology of near-natural rivers were confirmed by these historical samples, much to our collective relief. *Achnanthidium minutissimum*, for example, which we saw in the Wear at Wolsingham and at other clean sites, tended to be more abundant in the older samples and there were more cells of *Nitzschia* species in the samples we collected for this study. It is a far from perfect approach, but this is real ecology in action. It is often ragged at the edges, and trying to see a biological signal in the face of a highly variable environment and alternative, and often highly plausible, explanations, can be tough. The best we can hope for is, like Hansel and Gretel, that there will be one or two white stones to mark our way forward.

The work on diatoms preserved in lake sediments, pollen in peat bogs and on the museum specimens all enshrine a much older principle: walking backwards into the future. For Cardinal Newman, this was an essential part of a person's spiritual journey: everyone needs to reflect on and learn from their experiences, and the experiences of others, if they are not to repeat their mistakes. Newman's near contemporaries John Ruskin and William Morris saw this in much more tangible terms. You will find hundreds of twee parodies of the Arts and Craft Movement in National Trust gift shops up and down the country without ever realising Morris's true intentions. On the cusp of the age of mass production, he wanted to restore the dignity and individuality of the work of older generations of artisans. Progress always comes at a cost and part of this cost lies in what we forget. Later generations have little idea of what has been forgotten: we end up re-learning from scratch. And so it is with these studies: the diatoms and pollen offer us a glimpse at what freshwaters might have been like in an earlier, more idyllic age. These glimpses into our biological past become, in effect, an act of collective remembrance.

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There is a liberal scattering of the gothic script indicating archaeological sites across the Ordnance Survey map covering my next location. Stonehenge is only 25 kilometres to the east, which means that my search for the historical state of this particular river is complicated by at least 4000 years of human activity in the area. I am in Wiltshire, standing beside the River Wylye in a quintessential English village nestling in chalk downland. This is a landscape deeply rooted in the English imagination; Thomas Hardy wrote his novels nearby, and if we cross the hills to north of where I stand, we reach the valley where Kenneth Grahame found inspiration to write Wind in the Willows.

In many ways, this is the Perfect River. The water is crystal-clear, I can see decent-sized trout darting between the patches of water crowfoot and there is even a swan floating serenely a few metres downstream from where I am standing. Yet that is not enough, as we have seen. The Perfect River, or the Perfect Lake, cannot be just a human construct, an idyll, a romanticised notion; it has to be rooted in reality. That is what we were trying to do when we searched for lakes and streams where the hand of man was barely discernable, what we were striving for when looking at cores of lake sediments or sorting through Victorian museum specimens. And that is what I cannot do here in Wiltshire, an idyllic landscape without a doubt, but one where the hand of man is evident all around me.

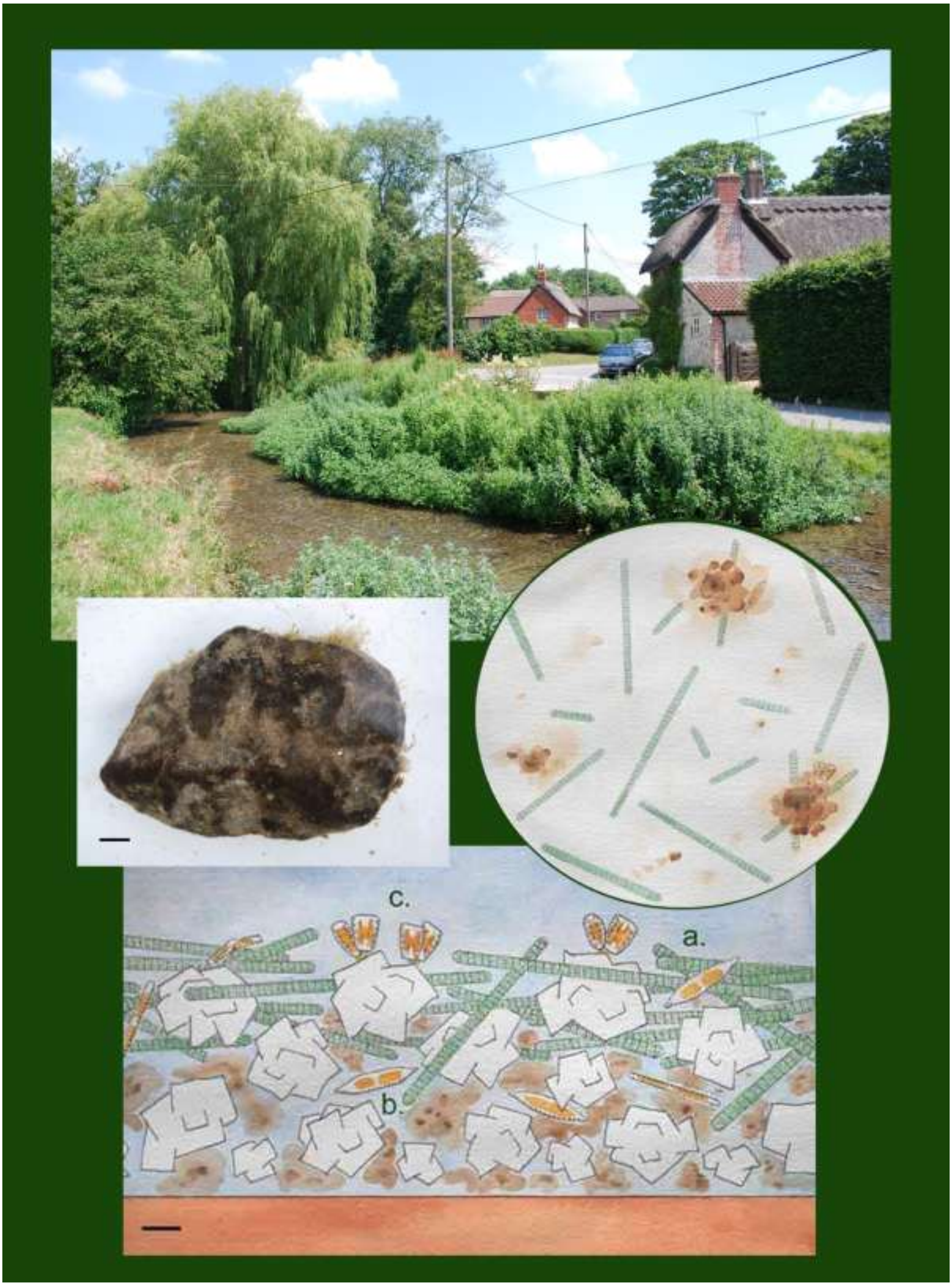
The Wylye is very different to the rivers I've talked about before. Both the Wear and Causey Burn (and the Coquet, which follows) have their sources in the Pennine uplands, where high rainfall and steep relief combine to make the rivers "flashy": rainwater rushes off from the fells into tributary streams which merge to create huge torrents which pass downstream over the course of a couple of days before the waters sink back to their usual levels. Here, in the chalk landscapes of southern England, the rock is soft and permeable; the rainwater soaks in and forms underground reservoirs, called "aquifers". In the few places where the aquifer reaches the surface the water bubbles out as a spring and these, in turn, are the sources of the chalk streams so beloved by trout fishermen. Unlike the rain-fed rivers of the Pennines that I knew fairly well, the flow of chalk streams is very stable, fed by this steady underground water supply.

A couple of years ago, a colleague had mused aloud to me that the properties of chalk streams that we so admire were mostly the result of man's modifications of the landscape – in particular the removal of the natural tree cover which allowed water crowfoot to thrive. Chalk streams, in other words, rank alongside hay meadows and heather moorlands as the most glorious manifestations of man's management of nature on our islands.

The Wylye is several metres wide here, despite being just a couple of kilometres from the source, but the water is shallow and I can wade across it very easily. The substratum is composed mostly of gravel and pebbles, the latter made mostly of flint, interspersed with just a few larger cobbles. On the May morning when I visited, it is the latter than interested me: not just because of their relative size but also because of their dark coloration. Under the microscope, these dark patches revealed themselves to be composed almost entirely of unbranched filaments of the Cyanobacterium *Phormidium flavosum*. There were some diatoms present (mostly motile *Nitzschias* along with an attached diatom called *Staurosirella pinnata*) but these comprised less than ten percent of the total Combining the field and microscopic observations allows us to build up a picture of how the biofilm is composed (Fig. 15). The stability of the cobbles, relative to the pebbles and gravel that predominate on the river bed is an ideal environment for algae to grow. However, this means that an organism that stays in one place is likely to be shaded out by those that arrive later. The intertwined filaments of *Phormidium* stretch and twist to capture as much of the light as possible, and the diatoms that live within the mat also have to be motile if they are to stay in the upper surface where there is enough light for photosynthesis. Sand and silt particles become trapped in the mat of filaments and, themselves provide a substrate for sessile diatoms. One, in particular, *Staurosirella pinnata*, is common in this sample. A sand grain is pure quartz through which light can penetrate. So long as the diatom is able to stay attached when the sand grain is rolled by the current, it can still get some light for photosynthesis even when the grain is overturned.

Reflecting on the natural history of microscopic organisms in chalk streams was not the primary purpose of my visit on this May morning. I had come to collect samples as part of a study in which we were using the Wylye as a test case to work out how the ecological ideals of the Water Framework Directive translate into the ultimate reality of a charge on your utility bill. For the first two or three years of our work on the Directive, we had busied ourselves translating its technical requirements into a language that ecologists working for the Environment Agency and their Scottish and Irish counterparts could understand. We had searched for examples of the Perfect River around the country and had found ways of relating the actual biology of rivers to what these Perfect Rivers told us to expect. We had worked closely with ecologists in the Environment Agency and SEPA, discussed the outcomes with them and they had agreed with out conclusions. At the end, we had published our results in a well-regarded scientific journal and I felt personally satisfied with a job well done.

Fig. 21. Top: the River Wylye at Kingston Deverill, photographed on 4 July 2011; centre left: a close-up of a single cobble from the stream collected on 10 May 2011. The tufts at the top of the picture are diatom growths – probably *Diatoma*. Scale bar: 1 cm; centre right: the view down the microscope (400 x magnification); bottom: schematic representation of the organisation of the algae present. Key: a. *Phormidium flavosum*; b. *Nitzschia* sp.; c. *Staurosirella pinnata*. Scale bar: 10 µm (1/100th of a millimetre) ➔


c.
a.
b.

The problem came when the results of assessments from around the country started to be collated. Many, many rivers were failing to achieve the standards that the Water Framework Directive required, and in many cases it was the algae that were causing the failures. Looking at the stringent requirements in the Directive and at what I knew about the state of the UK's rivers, this was no great surprise but, seen from the perspective of an Environment Agency policy maker, this was a catastrophe. First of all, the pre-WFD "view" of river quality in England and Wales was that about 80 per cent of rivers were of good quality. The new map of ecological status suggested that only about 20 per cent of rivers achieved the required status. Second, they now were tasked with getting all these failing rivers back to good status, which meant, amongst other things, imposing tighter limits on the water companies that discharged sewage into our rivers. We were sent back to look again at our results and working out just how tight these new limits needed to be.

The circuitous route I will take to these limits starts with the ingredients for a Victoria Sponge cake: 125 grams of self-raising flour, 125 grams of butter, 125 grams of sugar and three eggs. If you have these ingredients plus an oven, you can make a Victoria sponge. If you have all these ingredients except you are missing one egg, you can't. Even if you have a kilogram each of flour, butter and sugar, you still cannot make a cake. The lack of egg limits your capability to make a cake. The same applies to plants: the potential to create new biomass is only as great as the nutrient that is in shortest supply, relative to the rest. This, then, is the "limiting factor" and, for many freshwaters, it is often phosphorus that limits growth. Plants need only tiny amounts of phosphorus – about one percent of their total dry mass – but the quantities available in pristine water are even tinier. The Wylye, as we have seen, is underlain by chalk geology; chalk is almost pure calcium carbonate with just the faintest traces of phosphorus. The vegetation in the land surrounding the Wylye contains a small amount of phosphorus and a few leaves and other organic debris will occasionally make their way into the river. That is all that the algae, water crowfoot and other aquatic plants have to grow in the natural state.

If it is phosphorus that is limiting plant growth in a stream, then the effect of adding phosphorus will be to unlock the potential for all the other "ingredients" which could not be used to be built into new plant tissue. However, during this process the species that had adapted to carefully scavenge and horde the tiny quantities that are found in a natural stream will be pushed out of the way by more competitive, "weedy" species, just as nettles spring up on fertile patches of waste land. The resulting shift in both types of algae and plant and their quantities is a microscopic and subaquatic equivalent of the forest of briar roses that sprung up around Sleeping Beauty's castle. During the daytime, these will be photosynthesising, and producing oxygen as a by-product. However, at night-time, the photosynthesis will stop and the respiration of these plants and algae will suck oxygen from the water, making it difficult, particularly in the summer, for trout and salmon to survive. The coating of algae which can grow up on the fine gravels makes it harder for the trout to find spawning sites. There will also be less oxygen in the water percolating through the surface layers of the sediments which the trout eggs and fry need to survive.

In trying to get from our results to the limits that the Environment Agency needed to impose we faced a number of problems. The first was that, outside of a few academic scientists, few people knew what a diatom was, which made using it as the basis for potentially expensive regulatory limits problematic. We had been too busy talking to each other about the technicalities of using diatoms and it was only when our ecologist colleagues in the Environment Agency started to discuss limits with their colleagues involved in policy and regulation that the dearth of ecological understanding in the middle and upper strata of management started to become clear. The second problem was a classical ecological conundrum in that we had observed an association between biology and the environment, but that this is not necessarily the same as proving a causal relationship. This, combined with the third problem, that we really had quite small datasets with which to work, gave enough room for detractors to get to work deconstructing our work. We had come up with some numbers that were consistent with what the literature told us but which were eye-wateringly low compared to what the water companies routinely achieved. The next stages involved some scenes straight out of *Yes, Minister*, in which statistical wonks took the numbers and found reasons to almost double them so that the final limit for lowland chalk rivers such as the Wylye was 120 micrograms of phosphorus per litre (about one part per ten million). No-one seemed particularly happy with the outcome: my colleagues and I felt that our data had been misused ("policy-led evidence", as one colleague wryly put it), other aquatic ecologists felt that 120 micrograms per litre was far too much phosphorus for a lowland river (we agreed!) whilst the water companies even this doctored limit was ridiculously low.

All of which, in a roundabout way, brought me to the banks of the River Wylye on this May morning. I was working on a project, along with a team of environmental scientists from other consultancies and universities trying to work out whether or not this value of 120 micrograms per litre was actually realistic. Except that "realistic" itself, is as problematic a phrase as "ideal". As ever, with environmental regulation, someone has to pay the bill and "realistic" represents some kind of balance between what people are prepared to accept as a charge on their utility bills balanced against genuine and well-substantiated losses and changes to the UK's biodiversity. I'm circling around what has become a preoccupation over the past year or so: does anyone – should anyone – really care about changes to a group of microscopic organisms that most people cannot see and which even the experts do not fully understand? We are losing organisms that most people didn't know we ever had. Should we care?

Fig. 22. The "landscape" of a submerged cobble in the River Wylye at Kingston Deverill in May 2011.

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So why should we care? Let's go right back to the start when I told you that there were almost 5000 species of algae recorded from Britain and Ireland. There are, in other words, about eighteen times more species of algae than birds yet the Royal Society for the Preservation of Birds is the largest conservation charity in Europe, with over a million members. It is, perhaps, over-simplistic to distil this to numbers: birds are advanced, warm-blooded creatures with well-developed familial and social structures that make it easy for us to anthropomorphise them. Algae lack these advantages.

Ornithological charities argue that to conserve a bird such as a woodpecker, we need to conserve the habitat – the forest – in which it lives and, therefore, every other organism that lives in the forest is also conserved. The birds are, in other words, "flagship species" that hold public attention and act as goodwill ambassadors for the small and largely overlooked plants and animals that also populate forests. This is a "top-down" argument, focussing on the charismatic components of the forest ecosystem. But another way of approaching the topic is to say that ecosystems are defined by processes rather than by organisms. Your car engine will not function without a carburettor but it is the reactions that happen inside the carburettor that makes the car move. Woodpeckers need trees but trees, in turn, depend upon a whole suite of organisms - insects, worms and fungi, for example – that break down leaf litter, release the nutrients that it contains and help in its subsequent uptake by the tree again. The decline in numbers of birds of prey in the 1950s and 60s was caused by high concentrations of pesticides in their bodies. All the smaller animals that they eaten had accumulated pesticides from the food they had eaten, and this was then passed on up the food chain. It is a good example of how conservation of the charismatic species depended upon understanding the whole ecosystem: the "verbs" as well as the "nouns".

The same argument applies to lakes and rivers: appearance of salmon in a river is often cited in the press as a sign that that river is much cleaner now than it was in the past. And salmon are good examples of "flagship species" that are indicating that those responsible for river basin management are getting things right. Once again, however, the "top down" argument needs to be complemented by a "bottom-up" understanding of just what conditions a salmon needs. Although salmon are definitely on the increase in British rivers, there is evidence from Ireland that even the tiniest amount of enrichment can lead to excessive algal growth. The paradox is that giving the fish more food – by increasing the number of invertebrate grazers – is actually to the salmon's detriment. Salmon, so the Irish researchers argued, were adapted to efficiently foraging for food when it was scarce but the energy they spent in searching for food made them less efficient than trout when food was no longer scarce. Southern English chalk streams such as the Wylye have also seen drops in the numbers of salmon and trout in recent years: a syndrome known as "chalk stream malaise". The reason is not fully understood but algal growth due to excessive nutrients is suspected to be one of several possible factors Once again, protecting the big, charismatic species cannot be achieved unless we also understand the biology of the small, easily-overlooked species that form the base of the food chain.

If one argument for wanting to know about the diversity of freshwater algae is the need to get a better overall understanding of freshwater ecosystems then another is because of the insights algae gives us into evolutionary processes. For eighty percent of the earth's history algae – many remarkably similar to modern blue-green algae – were the only organisms that inhabited our planet and it is from algae that all other plants evolved. Moreover, because they are short-lived and often reproduce much more rapidly than more advanced organisms, they are extremely useful as a means of getting insights into evolutionary processes. And the microscopic world has a breath-taking amount of diversity.

Again, let's start with the familiar. Humans are mammals and, as such, share an evolutionary heritage with all other mammals, from chimpanzees through to the duck-billed platypus. This flowering plants is, biologically speaking, a similar level of organisation, so the difference between the simplest (a magnolia tree, for example) and a highly complex flowering plant such as an orchid can be compared – very roughly – to the difference between yourself and a duck-billed platypus. Stir in the conifers, ferns, mosses and liverworts and you have a grouping that corresponds, again very approximately, to the difference between us and other backboned organisms (birds, reptiles, amphibians, fish). In the 19th century, the plant kingdom was divided into two: the ferns, conifers and flowering plants formed one natural grouping, united by the possession of a vascular system – internal plumbing that conducted water from the roots to the leaves and, in turn, dispersed the products of photosynthesis from the leaves to the rest of the plant. The other grouping was the "thallophyta", which included the algae along with fungi, mosses and liverworts. It was really "real plants" and "the rest", with "thallophyta" being a catch-all category for the inconspicuous and microscopic organisms overlooked by most botanists. The study of algae emerged as a distinct sub-discipline within botany in the late 17th century, a discipline limited by the capabilities of microscopes available at the time. The first comprehensive account of the freshwater algae of Britain and Ireland was published in 1845 by Arthur Hill Hassall, who we have already met. Leafing through this book now, we see that the broad classification of algal groups was already much as we have encountered so far in this book: the green algae, the blue-green algae, the diatoms, and others. What has happened in the century and a half since the publication of Hassall's book is that biologists have used the technology available to them to understand how all these groups relate to one another. And what has emerged is that the differences, in evolutionary terms, between groups of algae is greater than the difference between humans and the most primitive fish. To push our "animal" metaphor a little further, the algae, therefore, correspond to everything else in the animal world: all the insects, spiders, worms, slugs and snails and everything else that creeps or crawls upon the earth. They do not just constitute four fifths of the number of species recorded from Britain and Ireland, they also constitute at least four fifths of the evolutionary diversity and a single, all-embracing term such as "algae" suddenly seems to be hopelessly constricting.

Seventy-seven years elapsed after Hassall's book appeared before the next guide to freshwater algae of Britain was written by George West and Felix Eugen Fritsch. Making use of advances in optics in the meantime, they were able to describe many more algae than Hassall although, as we saw in chapter 9, their work was still limited by reliance on what they could see as they peered down their microscopes. Nonetheless, where Hassall described eight species of *Navicula*, the small boat-shaped diatoms we've met in several of our samples, West and Fritsch now found 22 separate species. Meanwhile, in Germany, another scientist, Frederich Hustedt was writing the diatom section of an ambitious project called the *Süsswasser Flora von Mitteleuropa* (Freshwater Flora of Central Europe), which included descriptions and illustrations of 109 species of *Navicula*.

This leap in numbers came about partly from better optics and partly because Hustedt was a specialist in diatoms whereas West and Fritsch were generalists, interested in all algal groups. But it was also because Hustedt had decided, by peering at the silica cell walls of diatoms, that many of the genera described by earlier microscopists were sufficiently similar to *Navicula* that they could all be merged together. Hustedt's Flora was the standard work for diatom taxonomy for the next fifty years; more species of *Navicula* were added to his list of 109, but the broad framework remained intact. One of these species was "*Navicula pupula*", somewhat smaller than *Navicula lanceolata*, which we met earlier, and squatter, with more rounded ends. It lived on the mud at the bottom of lakes, ponds and, to a lesser extent, rivers. Both Hustedt and subsequent workers noticed that there were a number of distinct "varieties" of *Navicula pupula* (much as modern gardeners recognise varieties of roses, for example), each differing slightly in outline and size.

The story now takes an unexpected twist, because an Edinburgh-based scientist called David Mann argued that Hustedt had been wrong to call this species *Navicula pupula*, and its original name of *Sellaphora pupula*, assigned by a Russian botanist called Mereschkowsky in 1902 should be re-instated. He then started to grow *Sellaphora pupula* (as we must now call it) in the laboratory and made some surprising discoveries. There is a lay understanding of the term "species" which suggests a group of organisms which share common properties – they would tend to look and behave the same way. However, biologists have a very precise understanding that goes beyond appearances: members of a species must be capable of interbreeding and producing viable offspring. Studying this in algae is not very easy so many workers tend to assume that a difference in appearance, if consistent and, especially, if the characters don't overlap with those of other species, is sufficient grounds on which to describe a species. The term, "variety" presumes that, despite slight differences in appearance, they can still interbreed with other varieties of the same species. What David Mann discovered in his laboratory in Edinburgh was that the half-dozen or so described varieties of *Sellaphora pupula* were not capable of mating with other varieties, and so should be considered to be separate species. And, taking the work yet further, there were forms barely distinguishable with the light microscope which also failed to mate with other forms. At the latest count, there are approximately 38 separate species within the complex that Merrschkowksy and Hustedt had described living in the UK alone.

At their worst, diatomists can appear, even to fellow biologists, as obsessives, lost in fine detail and losing the bigger picture. But scaling up the work on *Sellaphora pupula*, and similar work on other groups of diatoms, and the number of diatom species escalates upwards from the 10,000 or so that have been described so far to 100,000 or more. The biologist J.B.S. Haldane's famous quotation, when asked if anything could be concluded about the creator from the study of creation, "an inordinate fondness for beetles" " could, just as well be applied to diatoms. Remember, too, the huge contribution that algae make to global productivity: approximately half of all the productivity on the planet – and diatoms probably account for half of this and, in the process, they are soaking up some of the greenhouse gases that are implicated in climate change. We are blundering around, trying to limit the extent of climate change, but barely understanding how the engine that drives our planet actually works.

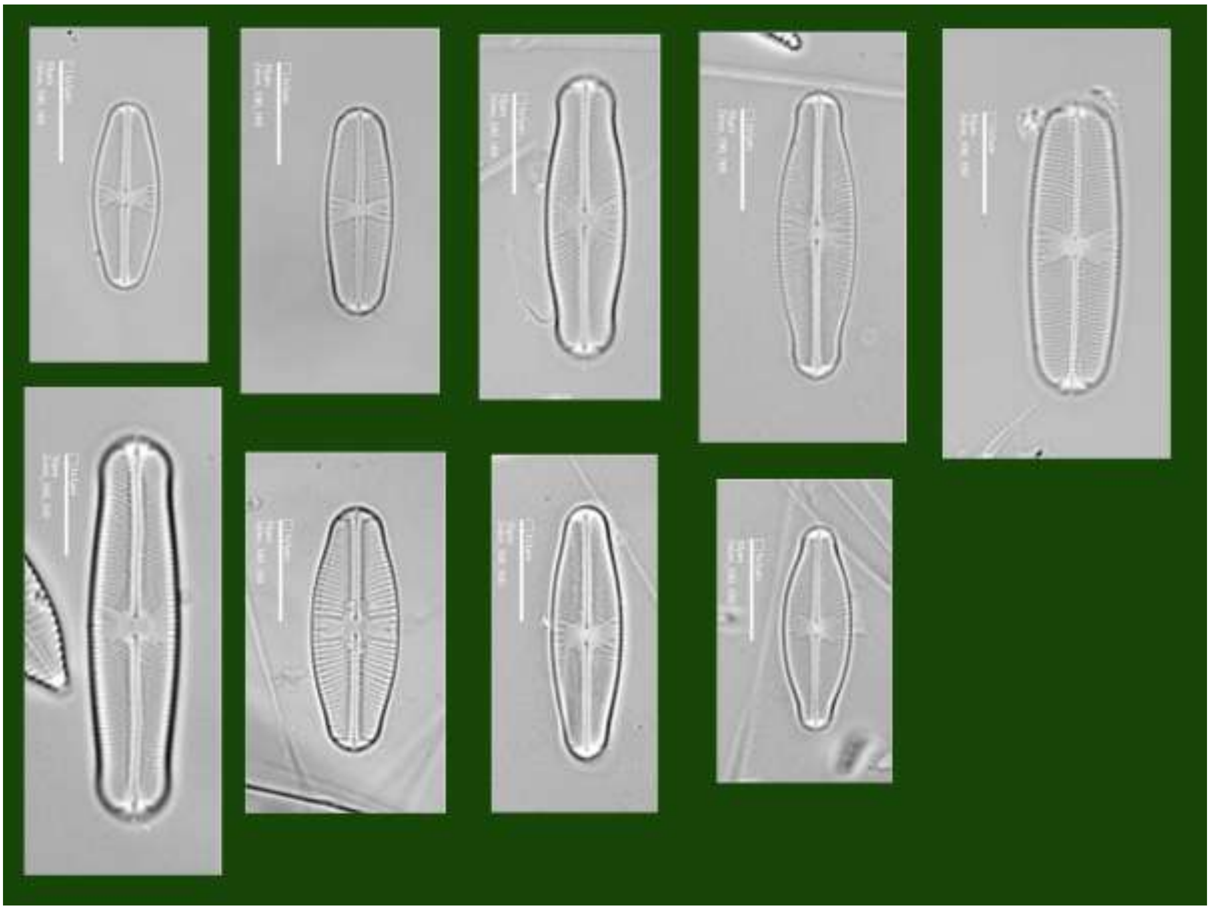

Fig. 23. The diversity of freshwater diatoms. Each image shows a valve (half a cell wall) that would have been classified as "*Sellaphora pupula*" in most 20th century diatom Floras but which has subsequently been shown to be a genetically-distinct species in its own right. Images are from the ADIAC database (http://rbg-web2.rbge.org.uk/ADIAC/db/instruct.htm)

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The red flag marking the edge of Otterburn Ranges in Northumberland hung limply on the day I visited: the absence of wind was a rare treat at this point in the Pennines, 390 metres above sea level and just one and a half kilometres from the Scottish border. The Pennine Way wound down from the hillside in front of me before turning sharply and heading along a track towards the remains of a Roman fort. Kirk Yetholm, the northern terminus of the Pennine Way is just 25 km further on. Hadrian's Wall is some 50 kilometres south, mostly sheltered by the Tyne valley. This location, Chew Street, must have been a particularly bleak posting for a legionary.

The River Coquet here is only about a metre across. It tumbles off the volcanic rocks that underlie this part of the Pennines – the Cheviots – as an alternating sequence of rocky riffles and slower-flowing pools, gradually increasing in size as its slope decreases and it meanders through one of the most beautiful and unspoilt valleys in northern England before joining the North Sea at Amble. There is just one small market town, Rothbury, about 30 km downstream from where I stand and, otherwise, just small villages, hamlets and farmland. So many walkers visiting this region have been surprised to see what looks like raw sewage floating down the river at certain times of the year. The complaints to the Environment Agency are so regular that they no longer need to send anyone out to investigate. They know what it is.

Crouching down beside a tiny tributary stream, only half a metre or so across, I can see the culprit almost straight away Lifting out one of the larger stones from the stream bed, I see tufts of what look like soggy brown cotton wool. There are points further downstream when these growths almost blanket the river bed in the summer, and you can easily imagine that some of these, sheared from their substrate during a spate, could be mistaken for raw sewage as they drifted down.

If you have read this far, you have probably guessed by now that it is an alga, though this is not immediately obvious under the microscope. What I can see is a series of almost colourless, sometimes branched stalks criss-crossing my field of view. Just occasionally, I can see a diatom which, at just over a tenth of a millmetre long, is huge by the standards of the diatoms we have met so far. The whole entity is 90 per cent or more stalk, pushing the cells themselves – which belong to a species called *Didymosphenia geminata* – up towards the sunlight, although the story is, inevitably, rather more complicated than it first seems.

Take a closer look at the stone in Fig. 16. There are a number of discrete clumps of *Didymosphenia*, but also, if you look closely, some tiny limpet-like snails, just a couple of millimetres across. These belong to a family called the Ancylidae, and they move across the rock surface grazing on the algae that they find. So there are, actually, two distinct types of algal community on this rock: a tightly-grazed "pasture", similar to that which we saw in the River Wear at Wolsingham, interspersed with occasional "copses" of *Didymosphenia* whose stalks are smothered with epiphytes – many, many tiny cells of *Achnanthidium minutissimum* plus long, needle-like cells belonging to at least two species of another genus called *Synedra*.

There has been enormous interest in *Didymosphenia geminata* over the past decade because it has appeared in parts of the world where it had not previously been recorded and, in these places – most notably New Zealand and parts of western USA and Canada – it has behaved like an invasive species, spreading rapidly and growing prolifically to such an extent that it threatens the lucrative sports fisheries in some regions. A few people have wondered if *Didymosphenia* has been in these places for a long time but has only just been noticed. However, it is such a large and distinctive alga that it is unlikely to have been overlooked by biologists in the past. It is also possible that a few cells arrived in these places on the boots or equipment of anglers, found its new environment to be very conducive and then spread rapidly.

The question everyone asked was why so much algae in such an apparently pristine environment? We have already noted that algae thrive in polluted rivers due to the nutrients found in sewage. Yet here, in the upper Coquet, we have copious growths of algae yet no obvious sources of fertiliser. What is happening?

It is, if you remember, phosphorus which is the nutrient that is most likely to limit algal growth in freshwaters. The chemistry of phosphorus is complicated and measurement is made more difficult because, in unpolluted environments, the quantities are so small that extremely sensitive equipment is needed. But even if you have this sensitive equipment, the quantities in nature vary from day to day, so a sample collected on one day might not yield the same result as one collected two days later. This is especially true in areas such as the Pennines where there is much peat. The phosphorus content of peat is small but if it is all washed out at the same time (after a storm, for example), then the concentration in the river might be high for a brief period before dropping back to its normal concentrations. Also, just to complicate matters further, this extra phosphorus is often still bound into tiny fragments of peat, rather than dissolved in the water.

Fig. 24. Top left: River Coquet at Chew Street, June 2011; Top right: close up of a stone (about 20 cm across) showing *Didymosphenia* growths; centre left: the view down the microscope (400x magnification); cenre right: schematic view through part of a *Didymosphenia* colony; a) *Didymosphenia geminata*; b) *Achnanthidium minutissimum* epiphytic on the *Didymosphenia* stalks; c) *Synedra ulna* and d) *Synedra rumpens* growing on the stalks; bottom left: schematic view of the entire *Didymosphenia* colony. ➔


a.
b.
c.
d.
e.

The trick to survival in these apparently inhospitable environments is, therefore, to find a way of tapping into this extra phosphorus supply on those occasions when it is available. And one solution, that seems now to be quite widespread amongst algae, is to exude an enzyme, called phosphatase, which digests the phosphorus from the peat and other organic particles and so releases the nutrient for the alga to absorb. In the case of *Didymosphenia*, it seems that the stalk is more than just a means of pushing the cell up towards the light, as it seems to play an important role in this enzyme activity as well.

Phosphorus accounts for less than one per cent of the mass of a typical plant cell because despite its essential role in nucleic acids and in energy transfer and storage inside the cell, the actual quantities needed for this are very low.. Moreover, in the case of *Didymosphenia*, most of the biomass lies in the stalk, which is made from phosphorus-free polysaccharide. The profusion of phosphatase within the *Didymosphenia* colony will also mean that any phosphorus in a dead cell can be quickly reabsorbed into living cells, so the colony as a whole can survive on what seems like extremely low concentrations of phosphorus.

The Ancylidae snails raise another question: in the River Wear we saw the effect that grazing invertebrate organisms can have on the microscopic flora. Here we seem to have profuse growths of algae living alongside grazers. What is going on? On previous visits I had sampled the algae that lived in the areas between the *Didymosphenia* colonies and these looked very like the communities we saw in the River Wear in the summer – a shortly-cropped "turf" of *Achnanthidium*, so the snails were obviously doing their job. What may happen is that the *Didymosphenia* starts to grow here in early Spring, before the water is warm enough for the grazers to be active, and the robust stalks are simply too large for most of the invertebrates to manipulate into their mouths. In the samples I was looking at, I saw a few midge larvae were creeping along the stalks and eating the smaller diatoms, but dwarfed by the *Didymosphenia* itself.

There has been enormous interest in *Didymosphenia* over the past decade, as people try to understand why it is spreading and disrupting fisheries. It has even joined *Cladophora* in being one of the few freshwater algae to earn a non-technical name: "Didymo" or, in some regions, "rock snot". But we still seem to know relatively little about it. Like much in ecology, there is probably a narrow "window of opportunity" when a number of factors come into alignment: a stable substratum without too many scouring spates, a supply of nutrients, but in a form that the algae we normally associate with enriched conditions cannot access, and a means of getting ahead of the grazers for long enough to accumulate sufficient biomass. The authorities in the regions where it is spreading are enlisting the support of anglers and other water users, asking them to clean and disinfect their equipment to prevent the movement of *Didymosphenia* to catchments where it has not yet been found. But, as is the case with many invasive species, it is very hard to imagine how anyone can find a way of manipulating conditions in order to return these streams to their pre-Didymo condition.

Fig. 25. A view through a *Didymosphenia geminata* colony, showing the stalks smothered with the diatoms *Achnanthidium minutissimum* (on short stalks) and *Synedra* spp.

"Enormous" is a relative phrase. For someone such as myself, *Didymosphenia* is a huge diatom but I smile wryly when I find myself using this adjective, and pinch myself to remember that it is only a tenth of a millimetre long. But then I see photographs of streams in New Zealand where people are lifting up mats of *Didymosphenia* as large as a sheep's fleece, and wonder if these superlatives are, indeed, justified. Perhaps *Didymosphenia* crystallises some of my fascinations with the algae: simultaneously beautiful, tiny and yet with measurable impacts on the way we live our lives?

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I have structured this book as a travelogue, taking you to different streams and lakes, and then trying to explain which algae live in these places, and a little about their natural history. My intention has been to point out how much of the biodiversity in Britain is hidden from view but one inevitable consequence is that you are probably reeling from a long list of unfamiliar names that lack the immediate resonances that a common name of a land plant – "oak", "buttercup" or "stinging nettle" - might evoke. So, in this chapter, I am going to reshuffle the pack of names I've talked about and present, instead, an overview of the algae world.

I have already explained that "algae" is a term that embraces a huge amount of the world's biodiversity. The latest Flora of British and Irish freshwater algae, published in 2011, describes 15 separate "phyla" of algae – a phylum is the term for a high-level grouping of organisms – to give you some idea, humans share a single phylum with not just birds, frogs, snakes and fish, but also sea squirts. Not all these phyla necessarily contain large numbers of species but they are regarded as representing evolutionarily distinct lineages of organisms.

The **diatoms**, or **Bacillariophyta**, are probably the largest of these phyla, with about 2500 representatives recorded from British and Irish freshwaters and many more yet to be described. You rarely find a sample from an aquatic habitat that does not contain some diatoms. We saw how some are attached to surfaces: *Didymosphenia* and some *Gomphonemas* form "bushes", *Achnanthidium minutissimum* grows on short stalks whilst *Cocconeis placentula* has a low, limpet-like growth form. Other diatoms, such as *Navicula* and *Nitzschia*, are able to move around. There are also many types of diatoms that grow suspended in lakes as part of the plankton, as well as many genera that are confined to marine and brackish habitats and which we have not encountered at all in this book.

Diatoms illustrate many of the challenges that those who study algae face. Superficially, they do not resemble plants - they are not green, for example, and many move around whereas we expect plants to be sessile. In fact, it was not until 1844 that diatoms were regarded as "plants" rather than "animals". Now, many scientists regard the diatoms, and many other groups of algae, as neither "plants" nor "animals" but as a separate group, the Protoctista, or "first established life", alongside protozoans and some primitive fungi.

Although I said earlier that colour is an unreliable barometer of affinities within freshwater algae, the yellow-brown colour of diatoms does hint at their relationship with the wracks and kelps of our seashore who, in turn, belong to a phylum called the **Phaeophyta**, or **brown algae**. There are about 200 species of brown algae around our shores, but just three species have been recorded from freshwaters.

In the River Skerne we met *Vaucheria*, which belongs to a group called the **Xanthophyta** or **yellow-green algae**, which are also related to the diatoms. A total of 27 genera and about 80 species of Xanthophyta have been recorded from Britain and Ireland, not just from freshwaters but also from damp soil. A few species have also been recorded from marine and brackish environments.

The **Chrysophyta**, or **golden algae**, are also distantly related to the diatoms and Xanthophyta, but we have not met them in the samples I've described. I did see some colonies of a genus called *Dinobryon* in Round Loch of Glenhead, but they never made it to my illustrations. *Dinobryon*, and a few other species, are common in lake plankton and another group of species are common smothering stones in streams in the depths of winter. 54 genera and 250 species of Chrysophyta have been recorded from Britain and Ireland, all from freshwaters.

At several of the sites, we have met **green algae** or **Chlorophyta**: *Ulothrix zonata* in the Wear at Wolsingham, *Cladophora glomerata* in the River Team and *Mougeotia* in Round Loch of Glenhead. In the next chapter we will also meet *Stigeoclonium tenue*. All of these are filamentous, but other green algae are microscopic single cells, form colonies composed of a number of cells or, in a few cases, have structures that are several centimetres across. The latter includes some seaweeds – the sea lettuce, *Ulva lactuca*, for example, and also the stoneworts. In total, there are almost 300 genera and over 2700 species of green algae and they are the only group that approach the diatoms in terms of the number of species.

The green algae are the group that look most like the plants with which we see all around us. They mostly share the same bright green colour and also store their food reserves as starch, as do land plants. There are exceptions to the general rule that they are bright green: an alga called *Haematococcus* forms bright red crusts inside bird baths and another, *Trenteopolia*, forms vivid orange patches on walls and tree trunks. Underneath these bright colours, the algae contain the same green pigments as other plants: the red and orange pigments are carotenoids which protect these algae, which live in habitats that are exposed to the full force of the sun, just as we would use sun screen. Indeed, compounds produced by algae such as these have been investigated as possible sources of sun screens in the future.

About half of all the species of green algae belong to a group called the desmids, which we have not encountered on these journeys. Perhaps if I had spent more time around Round Loch of Glenhead I would have found plenty of desmids, as these are often associated with peat bogs and soft water. They have a characteristic structure: each is a single cell, but divided into two compartments, each a mirror-image of its partner and containing a single chloroplast. There is a beauty which derives from this symmetry and, like the diatoms, there is a myriad of variations on a few basic themes.

Fig. 26. The variety of freshwater algae (clockwise from top left): diatoms (*Encyonema*) in a mucilage tube (photo: Chris Carter); the freshwater brown alga *Heribaudiella* in a stream in Norway (photo: Susanne Schneider); *Haematococcus*, the "bird bath alga"; the chrysophyte *Hydrurus foetidus* from a stream in Germany; an assortment of desmids (*Micrasterias*) (photo: Chris Carter); the Xanthophyta *Tribonema* on a pond in Norfolk (photo: Geoff Phillips) ➔


25 µm

The other group of algae that we have met at several sites is the **blue-green algae**, or **Cyanobacteria**. We met filaments of *Phormidium* in the Rivers Wear and Wylye, thin filmanets of *Lyngbya* at Round Loch of Glenhead, along with colonies of *Merismopedia*. There were also a number of unnamed cells in the early samples from Wastwater. These samples have just touched on a little of the diversity of cyanobactieria in Britain and Ireland. They are common constituents of the plankton, particularly in the summer and particularly in nutrient-rich lakes. Most algae have a density greater than that of water and naturally sink into the deep, dark depths. It is the weak convection currents in the water that bring them back to the lighter upper layers where they can photosynthesise. A few algae have tiny whip-like flagellae that can propel them through the water and help them to maintain their position but the cyanobacteria have another way of staying in the upper layers: they produce gas-filled vacuoles which act as microscopic life jackets, and make the algae sufficiently buoyant that they float upwards, rather than sinking down. A second trick of the cyanobacteria is their capacity to produce toxins (see chapter 5) which, in their natural state, deter grazers but which can lead to lakes being closed to water sports during warm summers. There are about 80 genera of cyanobacteria and about 350 species, mostly from freshwaters.

Two other groups are important in freshwaters but have not been encountered in this book. The first of these are the **red algae**, or **Rhodophyta**. There are a few filaments of *Auodinella violaceum*, a species of Rhodophyta, on the left hand side of Fig. 6 but it was not a major part of the flora of this stream. These, like the Chrysophytes and some diatoms, are at their most prolific in the winter and early spring, particularly in clean and fast-flowing rivers. The Rhodophyta form a large and diverse group of seaweeds, with 425 species recorded from our coasts, but only 12 genera and 24 species have been recorded from freshwaters. One of the most conspicuous is *Hildenbrandia rivulare*, which forms red crusts on rocks in rivers where the water is hard and not too polluted but not all are red. *Lemanea*, whose filaments are common in Pennine rivers, and *Batrachospermum,* which bears a superficial resemblance to frog spawn, are usually a dull olive-green colour.

The **Euglenophyta** is a group which can occasionally be quite common. The surface of ponds can turn bright red during warm summers due to growths of *Euglena*. Like the green algae, the red colour is due to the production of pigments which protect the cell from the damaging effect of bright sunlight. As is the case with the diatoms, many of the Euglenophyta test our understanding of what we mean by "plant" or "animal": members of the genus *Euglena* are single cells which are capable of movement (thanks to a flagellum) yet also contain chlorophyll, making them capable of photosynthesis. However, they are also capable of absorbing simple compounds directly from the environment, cutting out their reliance on sunlight. They have, in other words, a mixture of "plant" and "animal" properties that makes neat categorisation impossible.

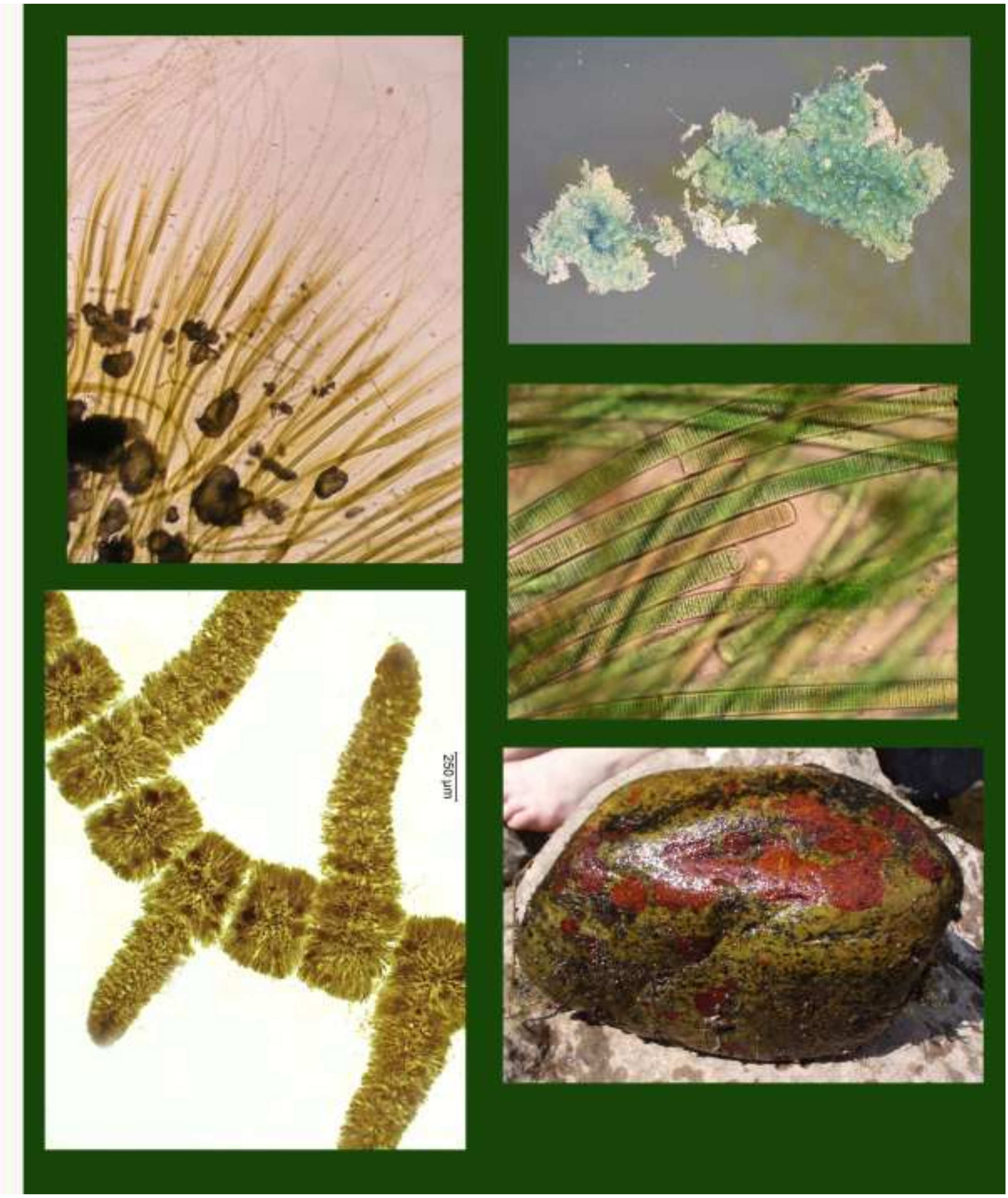

Fig. 27. The variety of freshwater algae (continued) (clockwise from top left): The cyanobacterium *Rivularia* from a stream in Upper Teesdale; a mat of *Oscillatoria limosa* floating on the surface of Lough Erne, Enniskillen, Northern Ireland; filaments from the *Oscillatoria* mat; a boulder covered with a bright red crust of *Hildenbrandia rivulare* from a stream in Germany (photo: Lydia King); the red alga *Batrachospermum* (photo: Chris Carter).

These groups, together, account for most of the species of algae recorded from British and Irish freshwaters, although there are also a number of other smaller groups which I have not described here as well as 1873 species of lichen, each of which consists of an alga and a fungus living together in a symbiosis. Yet, compared to the more obvious organisms – flowering plants, ferns, birds, mammals, even many groups of invertebrate, we still only have a sketchy and superficial appreciation of the extent of the algal flora of these islands. Flicking through the latest freshwater algal Flora, you will see that many species have only been recorded from a single location and many are described as "probably cosmopolitan", which is academic shorthand for "I have no idea what kind of environment this species likes". I have a theory that every pond in the country has at least one species of alga that is either a new record for Britain or completely new to science. But there are simply too few scientists studying algae for us to know whether or not this is true.

One more shuffle of the pack: this time organising them by their place in evolutionary history, as best as we can know this. Our planet is thought to be about 4500 million years old: a figure so huge that it can barely be contemplated. So we will start with steps that are more easily imagined: if we assume twenty five years as the period that separates two generations, then about 21 generations separate us from the reign of Elizabeth the first, and this time span is about one fifth of the period from the present day to the Romans (2000 years). Double this period and we have the time span between us and the building of Stonehenge (4000 years). You then need to repeat this time span 16250 times in order to get back to the end of the Cretaceous period when dinosaurs were common (65 million years ago) and then multiply this eight times to get to the end of the Precambrian (542 million years ago), when the first signs of life appear in the fossil record.

Our knowledge of the history of life on earth derives largely from fossils, yet these give us only a selective view of what was living at a particular time and place. To go back to an analogy that I used earlier, fossils are composed almost entirely of the parts of organisms that do not easily compost. The soft parts of organisms rot away; the hard parts, if conditions are right (and they very often are not) are preserved. The problem is that algae have very few parts that do preserve, so the fossil record is very sparse. But there are a few well-substantiated cases of algal fossils – mostly cyanobacteria – that can be dated to the Precambrian period. These look remarkably similar to cyanobacteria which can be found living today and this raises an interesting question.

There are popular visual depictions of evolution which use a tree as a metaphor: emphasising that all organisms are derived from a common ancestor, yet have diverged, and diverged again and again, much as the branches of a tree divide and divide again.to give us the great diversity of organisms that we see all around us today. It is a neat analogy but, as the science writer Stephen Jay Gould pointed out, it is flawed in one important way. The "tree" metaphor suggests that all living organissms are a long way from their primitive origins whereas some organisms – and cyanobacteria are good examples – appear to have been here for an incredibly long time. Gould suggested that a more accurate analogy would be a low, spreading bush: it has just as many branches as a tree but the spreading has been outwards rather than upwards.

Take a cyanobacterial filament in a Precambrian ocean or lagoon as an example: the peculiar properties of water – relatively high density for its mass, high heat capacity – coupled with the availability, albeit in low quantities, of dissolved minerals – make it an ideal environment for a primitive cell to grow. At some point, these filaments must have evolved some toxins which, in turn, deterred any potential grazers and, in addition, some cyanobacteria are capable of nitrogen fixation – just as modern peas and beans are – which reduces their reliance on dissolved minerals. In other words, by the end of the Precambrian, one of the very best habitats on earth had been monopolised by a group of organisms which are still very abundant in it today. They had all they need: why evolve further?

The Creation Myth, as told by modern biology textbooks, is that organisms gradually started to move out of the oceans and onto the land at about 400 million years ago, and that these organisms were more advanced than their ocean-dwelling ancestors. The first of these, in the plant world, would have been the algae that we now see on seashores: organisms adapted to living in an environment that periodically dried out, where the range of temperatures they experienced was much wider and where the glare of the sun was no longer filtered by the water above them. But we could also view these algae as the Prodigal Sons of evolution, abandoning the relative comfort and security of the ocean for a much harsher life on land. From an evolutionary perspective, there were habitats at the edges of the oceans that were ripe for exploitation, but only if organisms could cope with the problems that even only periodic exposure created. Evolution, from here on, is largely an account of further breaking the reliance on water in order to exploit more and more of the land. But this only happens because the best habitats in the oceans had already been occupied by an extraordinarily successful group of organisms.

Of course, evolution has taken place within the algae over this period, and we will see an example of this in the next chapter. But the basic outline was sketched in a long, long time ago. Most of the rest of evolution – the seemingly never-ending procession of beautiful, sometimes bizarre organisms that parades across television screens during wildlife documentaries – are the ones that turned up late and found that all the best habitats had been grabbed already. By the algae.

- 19 -

I am East of Eden. Geographically and metaphorically. Geographically, because the area of Cumbria where I am standing lies to the east of the River Eden and there was a period, some years ago now, when the county's marketing people used the term "East of Eden" as part of a publicity campaign. Metaphorically, because East of Eden implies a place some way removed from paradise. It is the place to which Cain was exiled after he had murdered Abel, and the title of a book by John Steinbeck in which flawed humans struggle against the land and each other.

This is the Nent Valley, and the glorious Pennine landscape around me is scarred by abandoned mine workings and spoil heaps, many still bare of vegetation almost one hundred years after the end of the main period of lead mining. The lead went into church roofs, miles of pipes and, more poignantly, the ammunition which defended an empire, but the bitter legacy – the toxic pollution - of the mining remains just where they left it. This area is, indeed, some way removed from paradise.

For a river draining an area of lead mines, however, it looks surprisingly green. In fact, the river bed is smothered by a luxuriant growth of a bright green, and exceedingly slippery alga. We've met the phenomenon of algae thriving in polluted rivers before – in the Rivers Team and Skerne – but there the explanation was that the rivers were being constantly fertilised by human activities. Here, the paradox is that the alga seem to be thriving in the presence of toxic pollution.

It is not easy to get the algae onto a microscope slide – it has that slippery, elusive consistency of egg whites that makes it hard to grasp with my forceps but, eventually, I get enough onto my slide, drop on a coverslip and put it under the microscope objective.

What I see is a tangled mass of narrow filaments, mostly just under a hundredth of a millimetre in diameter, each with a single bright green chloroplast, and many bearing side branches, each gradually tapering, until it seems that the cell is too narrow to contain a chloroplast. This is a green alga – a relative of *Cladophora* – called *Stigeoclonium tenue*. Tangled in amongst this are a few short filaments of *Phormidium*, the narrow filamentous Cyanobacterium which we have seen at other sites. There are a few diatoms – mostly *Achnanthidium minutissimum*, the "grass" of the underwater pastures we saw at both Wolsingham and Wastwater – but little else.

The tangle of *Stigeoclonium* filaments that I could see under my miscroscope is yet another example of the microscopist's dilemma as *Stigeoclonium* in its natural habitat has a more complicated structure. Many of the filaments are entangled to form a mat which lies prostrate on the surface, from which other filaments rise vertically (or as vertically as the current allows). It is these erect filaments which taper off into colourless "hairs". These hairs are not present on all the filaments seen in the population from the River Nent: they develop when nutrients are scarce and, in much the same way as we saw for *Didymosphenia* in chapter 17, they release enzymes that help the alga acquire phosphorus from the water. The small sewage works at Nenthead pumps just enough nutrients into the water to make these hairs less essential than is the case in many of the streams in the surrounding area.

The story of *Stigeoclonium* and the other algae of the lead mining regions of northern England was worked out by Professor Brian Whitton and his research students at the University of Durham during the 1970s and 80s. As we have seen elsewhere, the microscopic flora of unpolluted rivers is diverse: often thirty or more species in a single sample. The heavy metals, however, make it hard for many of these to survive. It is partly the lead but there are other metals – principally zinc and cadmium - associated with the lead veins which are more soluble and so which are more readily absorbed by the plants and animals in the Nent. Once absorbed, they disrupt the cell's internal mechanisms. However, there are often a few individuals of some species which are better able to cope than the rest, in the same way that some people are less prone to heart disease than others. The algae in the River Nent are, therefore, excellent examples of the theory of natural selection in action, as the individuals that are able to cope with the metals in the Nent are those which survive and which pass on their tolerance to future generations. Some species do seem to be better able to cope than others – the algae listed in the previous paragraph crop up in many of the metal-polluted streams of the northern Pennines – and a lot of work has gone into unpicking the reasons behind this. The sliminess of the *Stigeoclonium* may be a contributory factor – the mucus acts as a barrier to the metals, and a number of algae have been shown to stop the metals getting inside the cell, though this does not work for others e – *Stigeoclonium* included. Another widespread mechanism is for the algae to produce special proteins which lock up the metals as they enter and keep them away from the delicate enzymes which govern the cellular mechanisms. What seems to happen is that there are natural variations in the number of copies of the gene which produces this protein – a variation produced by the natural low rate of mutation that occurs in all organisms. In extreme examples, a gene which acts as a "switch", turning the production of the metal-binding protein on or off, as need dictates, is deleted by a mutation, so that there is always enough of the metal-binding protein to cope with the metals to which the alga is exposed.

But why so much *Stigeoclonium*? The theory of natural selection argues that organisms are involved in a constant struggle for survival both with fellow members of their own species and with other species – those that they grow alongside, and those that would eat them. As we have seen in the previous paragraphs, there are fewer species against which they

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Fig. 28. Top left: the River Nent at Nentsberry in July 2011; top right: a single cobble from the River Nent, smothered with *Stigeoclonium*; centre right: the view down the microscope; bottom: schematic view of the algal community in situ: a) erect filaments of *Stigeoclonium* rising from the prostrate filaments smothering the rock; b) filaments of *Phormidium* entangled with the *Stigeoclonium*; c) *Achnanthidium minutissimum*. ➔

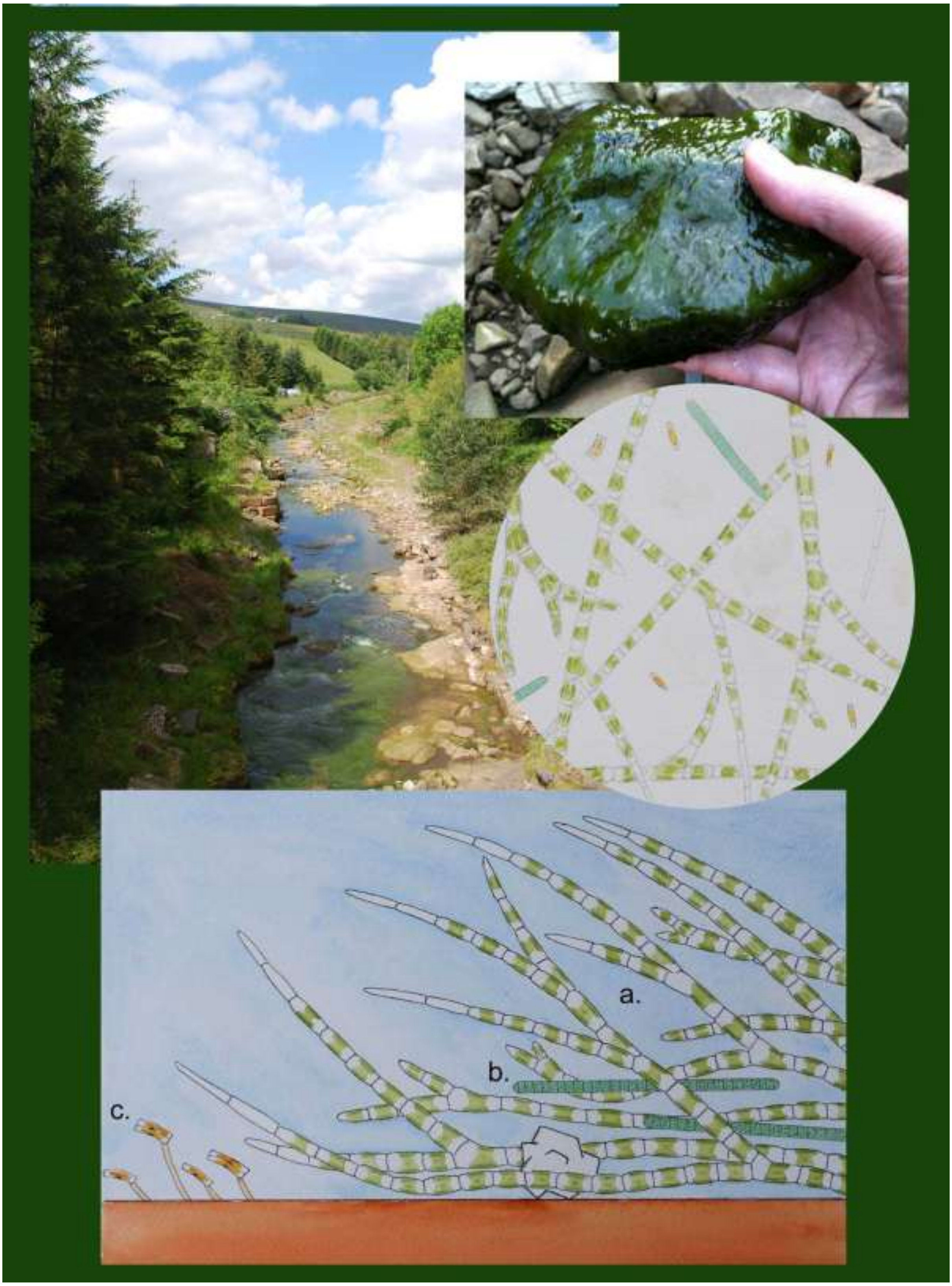
a.
b.
c.

Fig. 29. The underwater landscape of the River Nent at Nentsberry.

have to struggle for light and nutrients, so the few species that are able to survive should be capable of more prolific growth. One natural consequence, you might think, is that this, in turn, would encourage the invertebrates which graze on the algae. Remember how, in the Wear, we saw the summer population was kept cropped to a short turf by the midge larvae? Why do we not see this in the Nent too?

The answer may be that the invertebrates are less able to cope with the metals than the algae. We do not know for sure and there are probably several contributory factors. If the invertebrates which habitually graze the algae are not tolerant to the metals, then the algae will be able to grow unchecked and, simply by smothering the rock surfaces and using up the oxygen in the water, they may make it even harder for other invertebrates to survive. And so we have the apparent paradox of this luxuriant carpet of algae in a stream polluted with highly toxic metals.

And another paradox: when I was a teenager, I read and re-read Nevil Shute's novel of nuclear war *On The Beach*. The novel is set in Australia in the 1950s, shortly after a nuclear war had devastated the northern hemisphere, and the nuclear fallout was gradually drifting south. The protagonists of the novel live out their lives with the shadow of imminent death hanging over them. At one point, there is a discussion between two characters, speculating that it will be rabbits – with their prolific breeding and rapid growth – that will have the land to themselves after the humans have died out. The irony was that, at this time, before mixametosis had decimated their population, rabbits, introduced from Europe, were a major pest in Australia. Shute displays an understanding of natural selection here: you only need a few rabbits that can tolerate the post-apocalyptic environment, and then their fast-growing, fast-breeding habit, coupled with the absence of predators (larger and, therefore, slower-growing) will let them conquer the land. Push this analogy a step further: the processes we see working in the Nent will mean that there would have been prolific growths of algae in streams of Shute's post-apocalyptic world before there were rabbits grazing the banks. And, to take the analogy to its logical conclusion: algae are likely to still be here after the last human has walked the earth. They were here at the beginning of time; they will be here at the end. Compared to algae, we are mere bit-players in the history of life on earth.

- 20 -

Whenever I am in the Natural History Museum in London, I always take a few minutes to visit the gallery which contains the model of a Blue Whale. A colleague once suggested to me that this was a "small boy" thing – that the male of the species always seeks out the biggest, fastest and fiercest experiences but she was wrong. I go to see the model of the Blue Whale because it is there that I feel most humble. I am utterly dwarfed in the presence of the largest organism the world has ever seen.

Let's say the Blue Whale is about 20 metres long – so just over an order of magnitude larger than me (180 cm). I, in turn, am approximately two orders of magnitude larger than most of the insects and other bugs which crawl around our river beds whilst they are about two orders of magnitude larger than the algae on which many of them feed, and which we have been exploring. The smallest algae are more than three orders of magnitude smaller than the bugs so, very roughly, six orders of magnitude separate the largest whales from the smallest algae. You would need to lay two million cells of *Achnanthidium minutissimum* end-to-end to match the length of a Blue Whale.

Yet, as I have already said, there are about 5000 known species of algae in Britain and Ireland, representing about four fifths of all the plant diversity on these islands. Each has a story to tell. Just as a gardener can tell you which plants like fertiliser and which don't, which like bright sunlight and which like shade, which are perennial, which annual, which like acid conditions and which like lime, so each species of alga has its own preferences. Most, it must be admitted, are still little more than names in a book, and their ecology is barely known.

I have a fondness for the Psalms. Many are achingly beautiful. All touch themes that are as relevant today as when they were written 2500 years ago. My favourites are the ones in which David, if it was he who was the author, sits on a dark hillside and contemplates the night sky. If this is what a man writes staring up at the cosmos with his naked eyes writes, what would he have written, had he had a telescope? And what would he have written if he had been able to stare down a microscope? To see worlds which were simultaneously ubiquitous, extraordinary and yet barely known?

The heavens declare the glory of God,
the skies proclaim the work of his hands.
Day after day they pour forth speech;
night after night they display knowledge.
There is no speech or language
where their voice is not heard.
Their voice goes out into all the earth,
their words to the end of the world.

Psalm 19, v. 1-4

Maybe David Attenborough is the modern-day successor to David, the biblical psalmist? Perhaps his series – *Life On Earth, Life in the Undergrowth, The Blue Planet* and all the rest - are modern, secular responses to the experiences which inspired the Psalms? Maybe. The awe in a world that one David attributed to God, the latter David attributes to evolution. We understand creation to be a more dynamic entity than our forebears could ever contemplate and, as such, King David's God-as-a- noun becomes modern David's god-as-a-verb: As scientists, we strive for objectivity in our professional writings yet most biologists I have met still admit to awe when contemplating nature and, in this, there is, perhaps, a vestigial spirituality which the psalmists would recognise? Even Darwin occasionally lapsed into psalmody:

> It is interesting to contemplate a tangled bank, clothed with many plants of many kinds, with birds singing on bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other and dependent upon each other in so complex a manner, have all been produced by laws acting around us. These laws, taken in the largest sense, being Growth with Reproduction; Inheritance, which is almost implied by reproduction; Variability from the indirect and direct action of the conditions of life, and from use and disuse; a Ratio of Increase so high as to lead to a Struggle for Life, and as a consequence to Natural Selection, entailing Divergence of Character and the Extinction of less-improved forms. Thus, from the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely the production of the higher animals, directly follows. There is grandeur in this view of life, with its several powers, having been originally breathed by the Creator into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and wonderful have been and are being evolved.

All of this begs a response from us. If the Blue Whale is the largest organism that has ever lived on this planet then our species, *Homo sapiens*, is, undoubtedly, the most powerful. For every high profile extinction which we read about in the newspapers, there will be hundreds of other species – particularly the insignificant and microscopic – which will disappear without being noticed and, in many cases, without ever being described. They take with them their secrets and their stories. Already there are algae which are widely used in the food and pharmaceutical industries, and as sources of fuel. Who knows what benefits mankind is losing as each of these uncatalogued species is lost? But the arguments are not just utilitarian: algae are key constituents in the engine room of Planet Earth and knowing that this inconspicuous and largely overlooked part of global biodiversity is structured and functioning properly is a reassurance that we, temporary stewards of this planet, are fulfilling our own obligations. However, to be sure of this, we need to know more about them. And knowing more about them means studying and contemplating them as we try to unpick their stories. And staring down a microscope at a diverse *mélange* of intricately-sculpted organisms each a fiftieth of a millimetre long feeds my own sense of awe and, with it, my own sense of humility, as I recognise how little I know and how much less I understand.

> We do not own the world, and its riches are not ours to dispose of at will. Show a loving consideration for all creatures, and seek to maintain the beauty and variety of

the world. Work to ensure that our increasing power over nature is used responsibly, with reverence for life. Rejoice in the splendour of God's continuing creation.

Notes

The opening quotation is from Ralph Waldo Emerson's *Nature* (1836)

- 1 -

Let us start with the familiar…
The number of freshwater algae is from Whitton *et al.* (1998) and seaweeds from Juliet Brodie (pers. comm.); flowering plants: Rose (1981), mosses and liverworts: Smith (1978; 1990); ferns: Merryweather and Hill (1992); number of algae species: Anderson (1992); Mann and Droop (1996).

The superlatives continue….
The density of algae in Windermere is from Reynolds (1984) and the estimate of the number of algae in the River Wear is a rough calculation of my own, assuming 500 individuals per square millimetre, an average width of 10 metres and a distance of 25 kilometres to the source. The estimate of the proportion of total productivity contributed by algae is from Field et al. (1998).

The journeys described in this book… .
Details of Anton van Leuwenhoek's life are given in Ford (1991). Van Leuwenhoek also makes a fictional appearance in Tracey Chevalier's *The Girl With A Pearl Earring*. (2000).

Were van Leuwenhoek to walk into….
The first reconstruction of dinosaurs in their natural habitat was by Henry de la Beche (1796-1855) in 1830. The early history of these reconstructions is discussed in Rudwick (1993).

- 2 -

Wolsingham is on Ordnance Survey Outdoor Leisure (1:25000) map OL31 (North Pennines: Weardale and Teesdale). Wolsingham bridge is at NZ 073 368.

Journeys have to start somewhere …
There have been a number of scientific studies of the River Wear over the years. These include: water chemistry: Neal *et al.* (1998); algae: Holmes and Whitton (1981); Kelly (2002); larger plants (macrophytes): Whitton *et al.* (1998); invertebrates: Gibbins *et al.* (2000); fish: Gibbins and Heslop (2000). All contain references to earlier studies on the river.

I mentioned in the previous section ….
It is difficult to find good estimates of the costs of implementation of the Water Framework Directive. A regulatory impact assessment by DEFRA (www.defra.gov.uk/corporate/consult/river-basin/) contains estimates ranging from about £900 million to £2400 million pounds per year which, assuming that these costs are passed on to consumers, works out at increases between about £40 and £110 per household. A House of Lords European Union Committee report *An Indispensable*

Resource: EU Freshwater Policy (http://www.publications.parliament.uk/pa/ld201012/ldselect/ldeucom/296/29605.htm) reports a DEFRA estimate of £27 billion over the next twenty years explicitly in relation to the costs of removing pharmaceutical residues from sewage discharges. Calculations assume a population of 61 million people, with an average of 2.36 people per household.

A new phrase has entered …..
The OECD defines ecosystem services as: "the provision of ecosystem inputs, the assimilative capacity of the environment and the provision of biodiversity." (http://stats.oecd.org/glossary/). See also http://www.ecosystemservices.org.uk/.

Angling is a good example ….
For simplicity, I say that fish sit **close to** the top of the food chain as a reminder that fish, too, have their predators including herons, otters and, of course man.

- 3 -

In order to appreciate the beauty and diversity of the diatoms …
The standard Flora for European freshwater diatoms is the four-volumes (in German) by Krammer and Lange-Bertalot (1986-1991). Hartley *et al.* (1996) is a one-volume work on British diatoms and Kelly (2000) is an introductory guide. Cox (1996) is, at present, the only guide to identification of diatoms in their live state. Unfortunately, this is presently out of print.

There were also a few chains of green cells …..
Graham et al. (1985) describe the seasonal preferences of *Ulothrix zonata*.

Standing in the Wear at Wolsingham …
Good introductions to life in rivers are given by Giller and Malmqvist (1998) and Allan (1995). Freshwater biologists have a standard terminology for referring to the size of stones. This is the "Wentworth scale" and is summarised below:

Size category	Particle diameter (mm)	Approximate current velocity required to move particle (ms^{-1})
Boulder	>256	
Cobble	64 – 256	2
Pebble	16 – 64	1
Gravel	2 – 16	0.5
Sand	0.063 – 2	0.1
Silt	0.0039 – 0.063	
Clay	< 0.0039	

(modified from Giller & Malmqvist (1998)

A cobble, in other words, is roughly "fist" sized.

Fig. 4c is from the ADIAC database (http://rbg-web2.rbge.org.uk/ADIAC/db/instruct.htm)

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I'm not the only ecologist ….

The physics of rivers and implications for biology are explained in Giller and Malmqvist (1998) and Allan (1995). Reynolds (1984) explains viscosity in relation to algae very well.

Rivers such as the Wear ….

Rolling stones gathering no moss: see Suren and Duncan (1999)

- 5 -

One other difference …..

There is a large literature on the interactions between grazers and algae in streams, summarised by Allan (1995). Some other useful references are: Bergey (1995), Pan and Lowe (1994; 1995); Lange *et al.* (2011), Wellnitz and Ward (1998)

The other constiutents of this underwater landscape …

The early history of Cyanobacteria is given in Stewart and Rothwell (1993).

Cyanobacteria are common as part of the "plankton" … .

The death of 50 haemodiaysis patients was reported in *The Phycologist* 45 (November 1996) p. 11.

The possible role of toxins in deterring grazers is discussed in Aboal *et al.* (2002). Allan (1995) summarises the literature on the effects of grazing on stream algal communities. The comments about blue-green algal filaments being harder for chironomid larvae to manipulate are speculation, but supported by observations in Fryer (1986).

- 6 -

Idyllic is a difficult word…

The definitions are from the Concise Oxford Dictionary.

Hill (1996) describes Turner's first sketching trip to northern England and Scotland in 1797; Solkin (2009) explains the influence of Lorrain and other older painters on Turner

Andrews (1989) puts landscape art from Turner's period into a wider social context.

In my study ….

The Water Framework Directive's full title is: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. It can be downloaded from http://europa.eu/documentation/legislation/index_en.htm.

- 7 -

The Causey Burn/River Team is on Ordnance Survey Explorer (1:50000) maps 307 (Consett and Derwent Reservoir), 308 (Durham and Sunderland) and 316 (Newcastle). Causey Arch is at NZ 201 559 on map 308.

The only publication that I have been able to find on the River Team is Wehr *et al.* (1981).

***Cladophora glomerata* is an extraordinarily successful plant …**
Dodds and Gudder (1992) review the ecology of *Cladophora* and Whitton *et al.* (1989) discuss *Cladophora* in relation to heavy metal pollution.

Not all the stones ….
Simulid flies are more than just a nuisance: some forms also carry disease, including the major tropical disease Onchocerciasis. Crosskey (1990) is the standard work on blackflies whilst Welton *et al.* (1987) describe problems caused by blackflies in parts of southern England.

Giller *et al.* (1992) includes a number of useful papers on patchiness and heterogeneity in aquatic ecosystems.

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The evolution of the meaning of the term "pollution"…
Several books contributed to this section: Corbin (1996), Hamlin (1990), Karlan (1995), Luckin (1986), Porter (1997).

One of those wondering about the causes….
Gray (1983) is the only biography of Arthur Hill Hassall. Hassall (1850) reports the results of his investigations on London's water whilst Hamlin (1990) explains the impact of his work.

Hassall was one of a group of reformers
"Weak inference": see Hairston (1989).

- 9 -

The River Skerne is on Ordnance Survey Explorer (1:50000) maps 305 (Bishop Auckland) and 304 (Darlington). I was at Coatham Mundeville, NZ 291 207.

The same principles apply to rivers….
References on the history of water pollution given above also apply here. Bill Bryson's book *At Home* (2010) also discusses the evolution of sewerage as he describes the history of the domestic bathroom

At about the same time as Robert Koch….
Hamlin (1988) describes the work of Dibdin in more detail. General background on sewage treatment can be found in several textbooks, e.g. Gray (1992) and Mason (1996)

So there are some differences ….
The two algal Floras mentioned are West and Fritsch (1927) and John *et al.* (2011). Background biology of the algae is from van den Hoek *et al.* (1995).

- 10 -

So why have I called this book ….
The Dutch paper to which I refer is van Dam *et al.* (2007).

We need a short diversion at this point …   .
Rachel Carson's book *Silent Spring* (1963), highlighting the hitherto unexpected effects of pesticides on birds and other vertebrates is often cited as the starting point for the modern environmental movement. Kinnersley (1994) describes the state of the UK water industry prior to privatisation in 1989, along with an insider's account of the privatisation process and the establishment of the NRA.

The biology at this time ….
Hynes (1960) describes the earliest days of biological monitoring in rivers whilst Mason (1996) summarises the situation up to almost the present day. The earliest biotic index used in the UK was the Trent Biotic Index (Woodiwiss, 1964) which operates on a 1-15 scale but by 1989 biologists in the water authorities were using the Biological Monitoring Working Party (BMWP))system (Hawkes, 1997) which can give scores of 250 or more in particularly diverse streams. A modification of this is the Average Score Per Taxon (ASPT) which was BMWP divided by the number of families of invertebrate present. This gives values up to about seven and is generally considered to be less susceptible to seasonal variation and sampling effort (Armitage et al., 1983). The scale of natural longitudinal variation in rivers was also being explored independently at the same time, with Vannote et al. (1980)'s description of the River Continuum Concept representing an important waymark.

The next step….
The original method for assessing the "expected" state of rivers is RIVPACS ("River Invertebrate Prediction and Classification System": see Wright et al., 1989). More information on the general principles can be found in Wright *et al.* (2000) and the latest implementation (now called RICT, "River Invertebrate Classification Tool") as used by UK environmental agenices is described in detail at http://www.wfduk.org/resources%20/river-invertebrates.

Water quality did improve ….
The Urban Waste Water Treatment Directive can be found in:
http://europa.eu/legislation_summaries/environment/water_protection_management/l28008_en.htm.

And so I inadvertently stumbled into this scene ….
The French methods are summarised in Coste *et al.* (1996). The Trophic Diatom Index is described in Kelly & Whitton (1995) and the modification of this into a method suitable

for the WFD in Kelly *et al.* (2008). The method using larger aquatic plants is the Mean Trophic Rank, described in Holmes *et al.* (1999).

Over the course of about two decades …
The present UK monitoring toolkit is described at www.wfduk.org/bio_assessment.

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From the 1990s onwards …
Lovelock (1979) is the original publication on the Gaia hypothesis.

One of the surprises of the ….
There is a huge literature now on reference conditions: Stoddard *et al.* (2006) gives a very useful summary of the state of the art. Pardo *et al.* (2012) summarises the current policy in the European Union whilst Moss (2008) is a pithy critique of the implementation of the WFD in Europe.

- 12 -

Wastwater is on Ordnance Survey Explorer (1:25,000) map OL6 (The English Lakes: South-western Area). The photograph of the lake was taken from NY 151 054.

I had come to Wastwater ….
The experiment described here is from an unpublished part of Lydia's PhD; King *et al.* (2002a,b) describe variation in the algal flora across Cumbrian lakes.

Her experiment resembles a very famous ecological experiment…
More about Broadbalk and the other long-term experiments at Rothamsted can be found in Rothamsted Research (2006).

The experiment finished shortly after this….
The theoretical background to the work described here is best summarised by Biggs *et al.* (1998).

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Upper Teesdale is on Ordnance Survey Explorer (1:25000) map 31 (North Pennines: Teesdale and Weardale). The core described in detail is from Red Moss, in the vicinity of NY 811 309

We are going to follow the changes … .
Clapham (1978) is a good introduction to Upper Teesdale. The vegetation history of the area is described in Turner et al. (1973). Judy Turner also wrote a chapter summarising this work in Clapham (1978). P.W. Moore, J.A. Webb and M.E Collinson's Pollen Analysis (2nd edition, 1994, Oxford University Press) gives a general introduction to pollen analysis.

Our journey through the core …
Vegetation history in the Mediterranean is based on Kelly and Huntley (1991) and a general overview of vegetation history is given in Huntley and Webb (1988).

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Round Loch of Glenhead location is on Ordnance Survey Landranger map 77 (Newton Stewart and New Galloway) at NX 450 805. The closest parking is at Bruce's Stone, beside Loch Trool, from where it is a stiff five kilometre walk to the loch.

Interest in Round Loch of Glenhead…
The early work on acidification of lakes is summarised by Battarbee (1984). The studies on Round Loch of Glenhead are reported in Flower and Battarbee (1983) and Jones *et al.* (1989) whilst Renberg and Hellberg (1982) summarise the situation in Scandinavia.

This story has a happy ending, of sorts…
The recovery of Round Loch of Glenhead, and other Scottish lochs is described in Kernan *et al.* (2010). Maberley *et al.* (2003) gives evidence for nitrogen limitation in upland water bodies in the UK. The now-abundant *Navicula* is *N. leptostriata*.

What we do know, as a result of these studies ….
The study of 26 Scottish lochs is described in Bennion *et al.* (2004)

And the situation gets worse when you move south to England….
Historical changes in the Norfolk Broads, and recent attempts at restoration, are documented in Moss (2001).

The answer to this conundrum lies, appropriately, in the backrooms of Britain's regional museums…
The study on diatoms from herbaria is described in Yallop *et al.* (2009). Vogel *et al.* (2005) provides more information on this technique and Denys (2009) and van Dam and Mertens (1993) also demonstrate similar approaches

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The upper River Wylye is on Ordnance Survey Explorer (1:25000) Map 143 (Warminster & Trowbridge). The sample was collected from Kingston Deverill (ST 844 372).

The Wylye is very different to the rivers I've talked about before…
The biology of chalk streams and rivers is summarised in Environment Agency (2004)

The stream is several metres wide ….
A general account of algae which grow on sand grains is described by Round & Bukhatiyarova (1996); Jewson & Lowry (1993) and Jewson et al. (2006) give a detailed description of the biology of sand-dwelling diatoms in Lough Neagh, Northern Ireland.

If it is phosphorus that is limiting plant growth in a stream...
This is a very complicated subject that is hard to summarise in a few paragraphs.

Mainstone *et al.* (2000) provide a good overview of the role of phosphorus; Elser *et al.* (2007) point out that it is not just phosphorus that limits plant growth in rivers – meaning that we cannot expect to restore rivers to good ecological status unless nitrogen levels are also considered; Dodds *et al.* (1997) and Bowes *et al.* (2007) both present evidence that concentrations less than the current UK target of 120 micrograms per litre may be necessary. The results of Bowes and colleagues is particularly relevant as it describes experimental work on the River Frome, another chalk stream in south-west England.

All of which, in a roundabout way ….

The current UK standards are available from
http:// www.wfduk.org/UK_Environmental_Standards.

The good news is that, at the time of writing, a new set of phosphorus standards, based on a larger dataset and a different statistical approach are out for public consultation and can be read at http://www.wfduk.org/stakeholders/stakeholder-review-phosphorus-and-biological-standards. These numbers are, in my opinion, more ecologically realistic. although this will inevitably set even greater challenges for regulators. At least we now have a better estimation of the height of this particular Everest; the next challenge will be actually climbing it.

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So why should we care?
Information about the Royal Society for the Protection of Birds, and on the number of bird species in the UK comes from their website: www.rspb.org.uk

Ornithological charities argue…
The classic description of the decline of birds of prey due to pesticides is Rachel Carson's Silent Spring (1963).

The same argument applies to lakes and rivers…
Information on the foraging strategies of salmon and trout comes from a talk at a workshop on Ecological Responses of streams to nutrient enrichment in Cork, Ireland, in 2009, by C. Graham, S. Harrison and P. Giller.

A good summary of the state of chalk streams is given in Environment Agency (2004).

We met Arthur Hill Hassall …..
The first comprehensive guide to freshwater algae was Hassall (1850); an earlier work by Dillwyn covered marine algae too. West and Fritsch published their Flora in 1927. John et al. (2011) summarises the history of algal studies in Britain and Ireland. Hustedt (1930) is the first edition of the Süsswasser Flora; the second edition (also in German) is by Krammer and Lange-Bertalot (1986-1991). Mann (1989) argues for the re-establishment of *Sellaphora*; Mann *et al.* (2009) catalogue British species of *Sellaphora* and Poulikavoa *et al.* (2009) demonstrate that these species differ in their ecological preferences.

At their worst, diatomists can appear …..

Number of diatom species: Anderson (1992), Mann and Droop (1996). These figures are considerably higher than those cited in Mora *et al.* (2011) – the latter tried to estimate how many species from all biological domains remain to be described but their calculations fail to appreciate the impact of a fundamental shift in our understanding of species concepts, such as is taking place at present in the world of microbial ecology. The figure on diatoms representing a quarter of Earth's primary productivity is from Treguer *et al.* (1995).

The quotation by J.B.S. Haldane is from G.E. Hutchinson (1959).

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The upper Coquet is on Ordnance Survey Explorer Map 16 (The Cheviot Hills). The sample described here comes from Chew Sike (NT 794 086) about 100 metres from the confluence with the Coquet.

Take a closer look …

A note on nomenclature: the genus *Synedra* has undergone many revisions in recent years and is not used by many modern workers. Williams (2011) summarises the debate. The species on the stem of *Didymosphenia* would probably be classified as *Fragilaria rumpens* by most current workers but more work is needed to fully resolve their identity.

There has been enormous interest …..

Records of *Didymosphenia geminata* in the UK and Ireland extend back to Hassall (1852). See http://www.biosecurity.govt.nz/didymo and http://www.epa.gov/region8/water/didymosphenia/ for more information on the apparently invasive behaviour of Didymosphenia. Whitton *et al.* (2009) review the biology of *Didymosphenia*.

The trick to survival ….

See Ellwood and Whitton (2007) and Sundareshwar *et al.* (2011).

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John *et al.* (2011) is the standard Flora of freshwater algae of Britain and Ireland. Canter-Lund and Lund (1995) is an accessible and lavishly illustrated general account of British freshwater algae

Diatoms illustrate many of the challenges….

Round *et al.* (1990) give a good overview of the biology of diatoms, although there have been a number of developments since this was published. The concept of the Protoctista is still not universally accepted and almost every algal textbook presents a different classification from all the others.

These groups, together, account for ….

The standard lichen Flora of the UK is Smith *et al.* (2009).

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The River Nent is on Ordnance Survey Explorer Map 31 (North Pennines). Nentsberry is at NY 766 449.

The tangle of *Stigeoclonium* filaments ….
The biology of *Stigeoclonium* is explained in Whitton and Harding (1976), Gibson and Whitton (1987a, b) and Whitton (1988).

The story of *Stigeoclonium* ….
The tolerance of *Stigeoclonium* to zinc is described in Harding and Whitton (1976) and its ability to accumulate zinc in Kelly and Whitton (1989). Mechanisms of metal tolerance in algae include mucus production (Sorentino, 1985), exclusion (Foster, 1977) and production of metal-binding proteins (Robinson, 1989; Gupta *et al*., 1993; Turner *et al*., 1993).

The invertebrate life of the Nent is described in Armitage (1979), Armitage and Blackburn (1985) and Armitage *et al.* (2007).

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Let's say the Blue Whale is….
There are, in fact, many diatoms living on the backs of whales, though not *Achnanthidium minutissimum*. Some diatom species live exclusively in this habitat. See Denys (1997).

The quotation from the Psalms is from the New International Version of the Bible (1973, International Bible Society).

Maybe David Attenborough is ….
The quotation from Charles Darwin is from the conclusion, chapter 15 of *On The Origin of Species* (1859)

We do not own the world….
The quotation is from *Advices and Queries*, from the Yearly Meeting of the Religious Society of Friends in Britain (the Quakers).

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