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An Ghníomhaireacht um Chaomhnú Comhshaoil

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IMPLANT: The Impact of Plant Nutrients on Primary Productivity in Running Waters: Evaluating the Risk to Stream Ecological Status

STRIVE

Environmental Protection Agency Programme

2007-2013

SSTI Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Environmental Protection Agency

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EPA STRIVE Programme 2007–2013

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The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The main threat to surface water quality in Ireland and much of Western Europe is eutrophication, due to the excessive inputs of agricultural- and municipal-derived plant nutrients. Such nutrients have widespread ecological effects, notably the increased growth of aquatic plants and algae. Under the terms of the European Union Water Framework Directive (WFD), participating nations, including Ireland, must achieve good water status for all surface waters by 2015. Some 30% of Irish running waters currently fail to meet this objective, largely due to eutrophication, and require significant efforts to bring them to the required standard. Although the quantitative relationships between nutrient levels, primary producers and their consumers are reasonably well established for standing waters, scientific understanding of these links in running waters is weaker, due to their greater environmental complexity. The aims of this study were to investigate the relationships between plant nutrients, primary producers and their invertebrate consumers in running waters and to identify the main factors that affect this relationship.

The study had two phases:

1. A descriptive phase where the standing stock of algae and invertebrates in Munster streams across nutrient and riparian shade gradients was investigated; and

2. A second phase which experimentally tested the roles of the various factors that drive the growth of benthic algae in a single nutrient-impacted stream – the Owennagearagh Stream, a tributary of the River Lee in County Cork.

The levels of algae on natural stones in the study streams showed little consistent response to either phosphorus or nitrogen nutrient enrichment, contrary to expectations that eutrophication would be associated with high algal biomass. Benthic algal densities were uniformly low in oligotrophic streams, but also low in the most nutrient-rich streams. In streams of intermediate nutrient levels, algal biomass showed great variation. Benthic algal abundance was, however, negatively related to the biomass of invertebrate grazers, principally nymphs of the common and abundant stream mayfly *Baetis rhodani.* There was also an inconsistent response of benthic algae to riparian shade. For much of the year, there was no significant increase in algal biomass in open parts of streams; however, it was markedly higher in open stream sections in May, a month of high incident light prior to stream riparian canopy closure. At this time, grazing invertebrates, chiefly *Baetis rhodani* and the stream limpet *Ancylus fluviatilis*, were also more abundant in these open sections, suggesting a strong ability of these grazers to migrate towards stream patches of high food abundance. Together, these findings indicate that large invertebrate grazer populations may be able to mitigate the enhanced algal productivity associated with elevated nutrients and higher light levels.

Subsequent experiments in the Owennagearagh confirmed the patterns revealed by the descriptive study. These experiments were performed in stream stretches of strongly contrasting nutrient levels, upstream and downstream of a waste-water treatment plant discharge, where concentrations of plant nutrients and other more toxic chemicals, such as ammonia, were elevated. Using novel experimental techniques to exclude highly mobile invertebrate grazers from benthic substrate, the ability of small-bodied invertebrate grazers, notably *Baetis rhodani*, to exert sufficient grazing pressure to effectively control the colonisation and growth of the nuisance ‘blanket weed’ *Cladophora glomerata*, even in severely impacted stretches downstream of the discharge, was demonstrated conclusively. In fact, *Baetis* nymphs were much more abundant in the nutrient-rich stream sections downstream of the discharge, showing that populations of these grazers were able to track increases in the productivity of *Cladophora* at local scales. This experiment also revealed the strong impact that dense riparian shade can have on the growth and productivity of benthic algae, although

such shade did not lower the maximum biomass that algae could attain on substrata.

During the experimental study, a very marked small-scale pattern was observed in algal growth on stones in the stream. Contrary to expectations, stones in slower-flowing parts of the stream had greater densities of *Cladophora* filaments than stones in faster-flowing habitats. Investigations revealed that stream hydraulic forces only indirectly caused these patterns, which were instead again generated by differences in invertebrate grazing pressure. Lower velocities allowed higher deposition of benthic organic matter, leading to low benthic and interstitial oxygen levels, which discouraged invertebrate grazers and shifted the algal–grazer balance in favour of *Cladophora*.

Hydraulic stress, however, was shown to play a very major role in the third experiment in the Owennagearagh Stream. In this experiment, the densities of grazers on benthic substrata were experimentally manipulated over 3 months in the summer of 2009, a period characterised by frequent spate episodes due to heavy rainfall. As for the previous experiment, it was found that grazing invertebrates were successful at controlling the colonisation and growth of *Cladophora* for much of the time. However, there were several occasions when *Cladophora* was able to 'escape' from grazing pressure, after the mass emergence of *Baetis* mayfly adults from the stream in early summer and following periods of 2–3 weeks of low discharge. *Cladophora* was shown to attain a considerable degree of grazer invulnerability, such that the grazers were no longer able to control its biomass accumulation on substrata. Subsequent spate events removed this accumulated *Cladophora*, thus 'resetting' the system and re-establishing grazer dominance.

An important finding of the study was the weak correspondence between the nutrient concentrations in the study streams and the widely used biotic indices (the Irish Quality Rating (Q-value) and the UK (Biological Monitoring Working Party) BMWP systems). Critically, Q4-rated streams (indicating 'good' ecological status) were found across a wide range of nutrient levels, either indicating that nutrient levels have little impact on stream ecological status or that the Q-value system performs poorly at distinguishing between nutrient-enriched and nutrient-poor streams. The study also found that changes in the elemental composition (carbon/nitrogen/phosphorus ratio) of stream biota tended to track those of their environment. This suggests that the shifts in invertebrate communities typically seen in eutrophic streams may not simply reflect dominance by 'pollution-tolerant' species, but may be a result of intrinsic, elemental requirements of both algae and their consumers. Nutrient-rich taxa most likely require nutrient-rich resources. All of the study streams remained generally well oxygenated (likely a function of the relatively high gradient and cool temperatures facilitating high dissolved oxygen levels), such that sensitive 'pollution-intolerant' invertebrate taxa remained abundant, even in streams with high nutrient loadings. This study's findings indicate that further research and development of biotic scoring systems for running waters in Ireland is needed to make them more sensitive to nutrient enrichment, rather than organic pollution.

This study has highlighted the importance of the balance between the dominant factors governing algal growth rates – nutrient enrichment and light – and the dominant factors controlling algal accrual – grazing pressure and hydraulic disturbance. Together, grazing pressure and hydraulic stress have the potential to prevent the excessive growth of nuisance filamentous algae, even in streams with high nutrient loadings. Very high nutrient levels will, however, tend to increase the likelihood of such algae to escape grazing pressure during periods of low flow and low grazing pressure, and attain nuisance levels. Equally, in systems with permanently reduced hydraulic stress and low grazing pressure (for example, those found in highly engineered channels), excessive algal growth is likely to occur at lower nutrient loadings than in systems with stronger controlling factors.

1 Introduction

1.1 Background

Under the European Union (EU) Water Framework Directive (WFD), Ireland must achieve good surface water quality, implement bio-assessment monitoring and develop sustainable use of its river basins. In this regard, the WFD emphasises the need to understand stream ecosystem processes. Primary productivity is one of the major processes in freshwater systems. However, excessive algal growth can potentially lead to low levels of night-time dissolved oxygen (DO) and this is a major factor associated with the degradation of eutrophic streams and rivers (Carpenter et al., 1998; McGarrigle, 1998; Miltner and Rankin, 1998; Smith et al., 1999; Dodds and Welch, 2000). The death and decay of algae and macrophytes can cause further deoxygenation due to the high aerobic respiration of heterotrophic microbes. Oxygen concentrations below critical threshold levels, due to night-time respiration, can have serious ecological consequences, including fish kills. Filamentous benthic algae, particularly the macroalga *Cladophora glomerata*, can also trap fine sediment within the benthic substrate, leading to substrate cementation, with negative consequences for organisms associated with clean, coarse gravel. This has been shown to negatively impact, among other aspects of stream ecology, on salmonid spawning (Crisp, 2000). Inputs of nitrogen and particularly phosphorus into watercourses are the chief causes of eutrophication of rivers and streams in most developed countries (Carpenter et al., 1998; Smith et al., 1999).

Trends from 1971 to 2000 show a strong decline in the numbers of unpolluted rivers in Ireland, and a concomitant increase in the numbers of slightly and moderately polluted rivers (EPA, 2004). This increase in the number of polluted rivers is attributed to increased phosphorus inflow from diffuse agricultural sources (Bowman and Clabby, 1998), and nutrient inflows from industrial and urban point sources. The long-term over-application of phosphorus on farmland has resulted in stores of soil phosphorus that may take many decades to decrease to levels compatible with unpolluted rivers. There is a clear and pressing need to understand how such a disturbance will impact on the functioning of stream ecosystems and how measures can be implemented to minimise the risk of ecosystem degradation. The development of credible nutrient guidelines and management strategies for rivers is highlighted in the WFD. To ensure acceptable river water quality, concentrations of key nutrients must remain below threshold levels, which have been estimated for some countries and regions (McGarrigle, 1998; Dodds and Welch, 2000). However, these levels are likely to change between systems as a result of interactions with other nutrients as well as complex physical and biological factors. Indeed, streams in regions of different geology and land use often respond quite differently to inputs of nitrogen or phosphorus (Klotz, 1985). It will also become increasingly important to be able to measure the environmental benefits accruing from reductions in nutrient fluxes against the economic costs of implementing nutrient management strategies. For this to be achieved, the ecological factors underpinning the variable responses of stream ecosystems to nutrients must be understood.

Typically, algal growth in freshwater systems is highly regulated by terrestrial nutrient input (Wallace et al., 1997) and therefore responds to localised point or diffuse sources. There is strong evidence that eutrophication increases primary productivity and reduces species diversity. Yet, the relationship between nutrient concentrations – mainly phosphorus and nitrogen – and ecological responses is only poorly understood in lotic ecosystems compared with lentic systems (McGarrigle, 1998; Smith et al., 1999; Edwards and Chambers, 2002). Generally, algal accrual is tightly controlled by a suite of growth requirements (i.e. bottom–up control mechanisms) and external forces that limit the realised growth through effective removal (top–down control mechanisms). Phosphorus has been considered to be the main limiting nutrient in many flowing waters (McGarrigle, 1998). In other streams and rivers, it was found that nitrogen and phosphorus act together in controlling primary productivity (Dodds and Welch, 2000). Previous field experiments have aimed to establish the 'breakpoints' of nutrient levels at which algal abundance suddenly increases (Dodds et al., 2002).

Seasonally abundant algal growths and, in extreme cases, stream-wide algal infestations occur as a result of nutrient enrichment. These episodes of algal blooms can have deleterious consequences associated with clogging of water extraction machinery, disruption of recreational activities (e.g. fishing), unpleasant odours created when large algal mats begin to decay, and the harmful effects on aquatic life through deoxygenation of both the water column and interstitial spaces. Filamentous algae, particularly *Cladophora glomerata* (L. Kütz), are considered to be nuisance algae due to their tolerance of high nutrient concentrations and excessive growths or 'blooms' associated with eutrophic systems (Whitton, 1970; Bolas and Lund, 1974). Despite its eutrophic pervasiveness, *Cladophora glomerata* is also found in oligotrophic systems at much lower densities, where the term nuisance is not applicable. Observed increases in abundance associated with nutrient enrichment has led to the incorporation of *Cladophora* in biotic indices (Marker and Bolas, 1984; Toner et al., 2005) and its presence is assumed to reflect ecological degradation, e.g. the Irish Quality Rating (Q-value) biotic score system (Kelly-Quinn et al., 2002).

Several explanations have been put forward to account for the observed lack of predictability between stream nutrient concentrations and the response of river biota. These include hydraulic disturbance (Biggs et al., 2000; Coroi et al., 2005), water chemistry (Dodds and Welch, 2000), grazing (Kjeldsen, 1996) and particularly shade (Kjeldsen et al., 1996; Davies-Colley and Quinn, 1998). These growth-determining factors are thought to increase or decrease the risk of a given river developing excessive algal growth and associated ecosystem degradation.

The relationship between light and primary productivity is complex. It initially comprises a positive link between relatively low light intensities and biomass production, followed by a plateau, and, at very high light intensities, a decrease in primary productivity (Hill, 1996). Shading reduces the solar light intensity that is available at the stream level. For example, up to 95% of incident solar radiation can be blocked by a full riparian canopy that covers a narrow stream (Hill, 1996), and this has consequences for primary productivity. It has been argued that light constraints can be exploited to moderate nutrient-enrichment-mediated increases in algal productivity (Hill and Knight, 1988; Winterbourn, 1990; Taulbee et al., 2005).

Many 'eutrophication-tolerant' invertebrate species are categorised as grazing invertebrates, i.e. those which feed on algae. Their responses to nutrient enrichment differ depending on the previous state of their environment. Grazer growth rates can increase rapidly if these organisms were previously food limited (Rosemond et al., 1993). Grazer density can also increase either through migration of individuals attracted by the enhanced food availability (Elwood et al., 1981) or else through improved recruitment (Peterson et al., 1993). The resulting increase in grazing pressure is usually quite rapid in temperate streams, ranging from weeks to months (Rosemond et al., 1993) or years, for Arctic streams (Peterson et al., 1993). In systems where algae and/or grazers are not limited by physico–chemical factors, such as low pH, heavy riparian shade or hydraulic stress, moderate nutrient enrichment in streams would therefore be expected to translate into higher secondary production rather than higher periphytic biomass. Such a pattern has been found in field surveys (Bourassa and Cattaneo, 1998).

Although herbivory has been shown to play an important role in controlling algal biomass in lotic systems (Lamberti and Resh, 1983; Steinman, 1991; Rosemond et al., 1993; Harrison and Hildrew, 1998; Brown et al., 2000; Opsahl et al., 2003), the relationships between grazing and environmental factors, such as flow rates, irradiance and stoichiometry, remain largely unknown. Water velocity and associated shear stress are recognised as important controllers of the colonisation, distribution, persistence, composition and metabolism of algae in lotic systems (Biggs and Thomsen, 1995; Biggs and Stokseth, 1996; Dodds and Biggs, 2002; Opsahl et al., 2003). All forms of aquatic algal assemblages are highly regulated by flood episodes, where filaments are torn off through hydraulic shear stress (Okada and Watanabe, 2005). Low-profile adnate algae in the form of biofilms are more resistant to medium flow regimes than filamentous algae, e.g. *Cladophora*. Yet post-spate filamentous algal regrowth is more rapid due to basal filament refugia and strong 'hold-fast' attachment (Benenati et al., 2000). The periodicity of flood events is an integral mechanism determining the ultimate degree of algal colonisation. Systems with frequent flood events benefit due to regular substrate cleansing. These flood events not only govern algal communities but also deplete invertebrate (grazer) communities which ultimately can affect top–down control efficiency.

This study focused on the ecological status of streams in south-west Ireland, highlighting the importance of the balance between the dominant factors governing algal growth rates – nutrient enrichment and light – and the dominant factors controlling algal accrual – grazing pressure and hydraulic disturbance.

1.2 Objectives and Aims

1.2.1 Objectives

- To quantify the relationship between nutrient levels and primary producers, and the potential influence of variables (including nutrient stoichiometry, water chemistry, hydraulic disturbance, riparian shade and benthic macroinvertebrate grazing) on this relationship, through a large-scale, multi-stream study in south-west Ireland.
- To determine the impact of riparian canopy shade on the relationship between nutrients, autotrophs and invertebrate consumers through a smaller-scale, more intensive study of a limited number of streams in south-west Ireland.
- To determine more precisely the processes underpinning the observed patterns in plant nutrients, primary and secondary producers and any controlling effects of shade and hydraulic action in a series of manipulative field experiments in a single study stream in County Cork.

1.2.2 Aims

- Identification of those environmental factors that mitigate the ecological impact of eutrophication of streams in the Munster area.
- Establishment of quantitative relationships between nutrients, light (shade), primary producers and invertebrate grazers.
- Development of a user-friendly classification system that identifies stream types which are most at risk from eutrophication.
- Development of guidelines to improve management of stream ecosystems, and to decrease risk of stream degradation.

2 Material and Methods

2.1 Field Sites

Two sets of streams were chosen for descriptive studies. A first set (Fig. 2.1a) of 32 streams was chosen to represent a wide range of nutrient concentrations characteristic of the streams in south-west Ireland. A second, smaller set of six streams was selected for the study on the interactive effects of nutrients and riparian canopy shade. Within a single 300-m stretch in each of these streams, the Delahinagh, Ell, Bride, Adabullane, Shournagh and Gortnalour (Fig 2.1b), 10 distinct patches were identified that present a gradient of riparian canopy density (canopy openness).

Following this descriptive phase, manipulative experiments were performed in a single stream in County Cork – the Owennagearagh (Fig. 2.1b), which possessed contingent reaches of strongly contrasting nutrient status and high populations of grazers and filamentous algae. This stream was chosen to allow comparisons of grazing invertebrate communities and their effects on the colonisation and growth of filamentous algae at stream reaches above and below a waste-water treatment plant (WWTP) discharge pipe, which constantly released high levels of phosphate and ammonium, enriching the study reaches downstream.

2.2 Field Methods

2.2.1 *Physico–chemical measurements*

Width and depth were measured for all stream patches. Water velocity was determined for each stream patch using an electromagnetic flow meter. Altitude, slope and catchment land uses were calculated using online mapping facilities. For the smaller-scale descriptive study and the single manipulative study, measurements of DO and water depth were taken using in situ data-logging equipment. For the single stream study only, stream-bed substrate samples were taken using a sediment surber sampler and sediment organic matter (measured as ash-free dry mass (AFDM)) was calculated. Stream-bed redox potential (Eh) in this stream was measured using a hand-held meter.

The riparian canopy openness for all study sites was quantified using hemispherical photographs. These were taken using a tripod-mounted digital camera fitted with a fisheye lens. Digital hemispherical images were uploaded onto a computer and percentage canopy openness was quantified using Gap Light Analyser (GLA) software.

2.2.2 *Algae and diatom sampling*

For the multi-stream field surveys, epilithic biofilm was collected from randomly selected stones from each site. Biofilm and any associated epilithic invertebrates were scraped and brushed from the stones in situ and stored in sample bottles kept on ice. Biofilm was subsequently quantified in the laboratory (see Section 2.3).

For the single-stream (Owennagearagh) survey, filamentous algal cover (primarily *Cladophora*) on natural stones was quantified in the field by scoring stones for presence/absence of the algae. Stones were categorised as either low-profile stones (i.e. those protruding less than 20 mm from the stream bed) or high-profile stones (i.e. those protruding more than 80 mm from the stream bed).

As part of an experiment into the effects of grazing invertebrates on benthic algae, *Cladophora* was also quantified on artificial substrata, by scoring for presence/absence on individual 1-cm^2 sectors of a 100-cm^2 tile surface. Tile surface algae were then collected in sample bottles for laboratory analysis.

2.2.3 *Benthic macroinvertebrates*

For all the investigations, stream benthic macroinvertebrate assemblages were sampled at each of the selected sites using a 25 cm × 25 cm 1-mm mesh surber sampler.

The numbers of grazers colonising tile surfaces in the grazer exclusion experiment in the Owennagearagh Stream were determined using a glass-bottomed

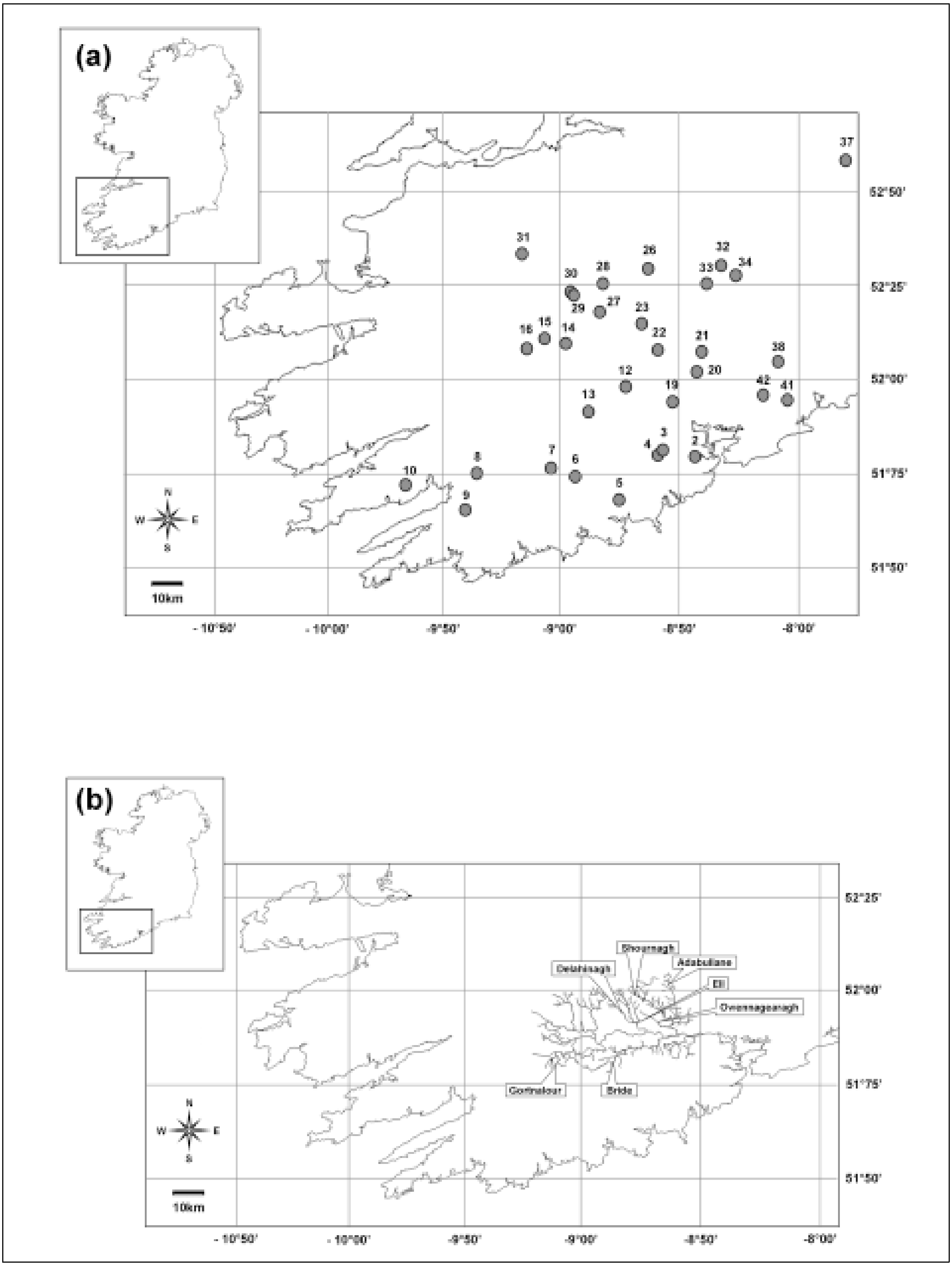

Figure 2.1. Maps showing the locations of the study sites for (a) the large-scale, multi-stream study, and (b) both the small-scale multi-stream study and experimental studies on a single system.

viewing box submerged beneath the stream surface. This reduced light reflection and ripples from the water surface. Only the four most abundant grazers were recorded. Invertebrates that were not classified as grazers were not quantified.

2.2.4 Grazer exclusion

In two separate investigations into the potential impact of grazers in the Owennagearagh Stream, grazing invertebrates were excluded from benthic substrata in two ways.

1. The first method used colonisation tiles that were artificially raised above the level of the stream bed. Tiles were tied securely to bricks placed on the stream bed, thus raising them some 8 cm above the stream bed, effectively reducing the density of benthic grazers.

2. The second method involved the application of electric fields around colonisation tiles that were placed on the stream bed. High-voltage electrical pulses (8.6 kV) were applied using a bank-side electric fence unit to unglazed ceramic tiles held in grids (Fig. 2.2). Each grid was securely fixed to the stream bed using steel bars and positioned to ensure that the base of the grid was flush with the stream bed, thus allowing invertebrate migration. This treatment effectively excluded almost all invertebrates and allowed 'ungrazed' algal growth to be compared with that on similar grids and tiles with no electric treatment.

2.3 Laboratory Methods

Stream water was analysed in the laboratory for alkalinity, nitrate, nitrite, total oxidised nitrogen (TON), ammonium, total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), calcium and chloride. Conductivity was measured in the field using a hand-held meter.

Invertebrates from the surber samples were identified to family level using a stereomicroscope. Invertebrate abundance, species diversity, species richness, Q-value score and average score per taxon (ASPT) were calculated for each surber sample from each site. Invertebrates were also categorised according to their dominant feeding category (Tachet et al., 2000).

To quantify algal biomass on stone or tile surfaces, periphyton collected and frozen in the field was gently thawed and the resulting suspension was filtered through 1.2-µm glass-fibre filters. Half of the filtrate was then frozen for later chlorophyll extraction while the second half was oven-dried at 60°C until constant weight, then weighed and combusted in a furnace oven at 450°C for 8 h to determine AFDM. Chlorophyll *a* was extracted in 90% acetone overnight at 4°C and measured by spectrophotometry at standard wavelengths – 750 nm for turbidity, 664 nm for chlorophyll *a*, 647 nm for chlorophyll *b* and 630 nm for chlorophyll *c* (Lorenzen, 1967).

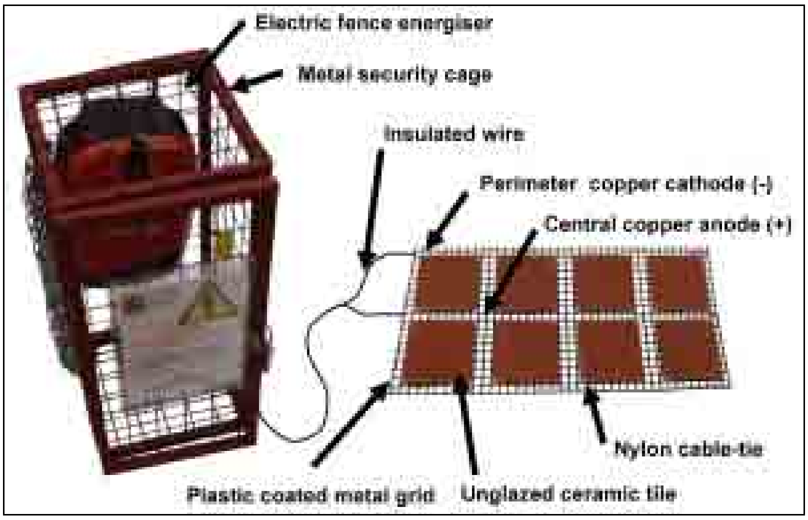

Figure 2.2. Equipment used for high-voltage invertebrate exclusion experiment.

3 Results: Large-Scale Multi-Stream Study

3.1 Physico–Chemical Variables

Nutrient concentrations differed considerably among the selected set of 32 streams. TN ranged from 0.28 to 10.02 mg N/l and TP from 0.004 to 0.22 mg P/l, with one stream displaying a TP value of 0.55 mg P/l in the spring. Annual mean values for TN and TP ranged from 0.4 to 8.8 mg N/l, and from 0.005 to 0.148 mg P/l, respectively. TN was significantly related to TP and marginally related to seasons. Higher TP concentrations were observed in summer and autumn than in spring and higher TN concentrations were observed in autumn than in the other two seasons. The nutrient status of the streams, however, remained remarkably consistent over the year: streams that contained low concentrations of nutrients in summer contained low concentrations of nutrients in the other two sampling seasons and streams that contained high concentrations of nutrients in summer contained high concentrations in the other two sampling seasons. Among the other chemical determinants, only calcium concentrations varied statistically among the seasons, with lower calcium concentrations in autumn than in summer.

3.2 Periphyton Biomass and Diatoms vs Nutrients

Periphytic chlorophyll *a* levels varied considerably between streams and seasons. The lowest levels of chlorophyll *a* were found in summer (mean ± SE: 9.2 ± 1.5 µg chlorophyll *a*/cm^2), intermediate levels in autumn (15.2 ± 2.2 µg chlorophyll *a*/cm^2), and the highest levels were found in spring (25.8 ± 5.5 µg chlorophyll *a*/cm^2). Surprisingly, there was little clear relationship between periphytic chlorophyll *a* levels and either TN or TP (Fig. 3.1). Chlorophyll *a* levels

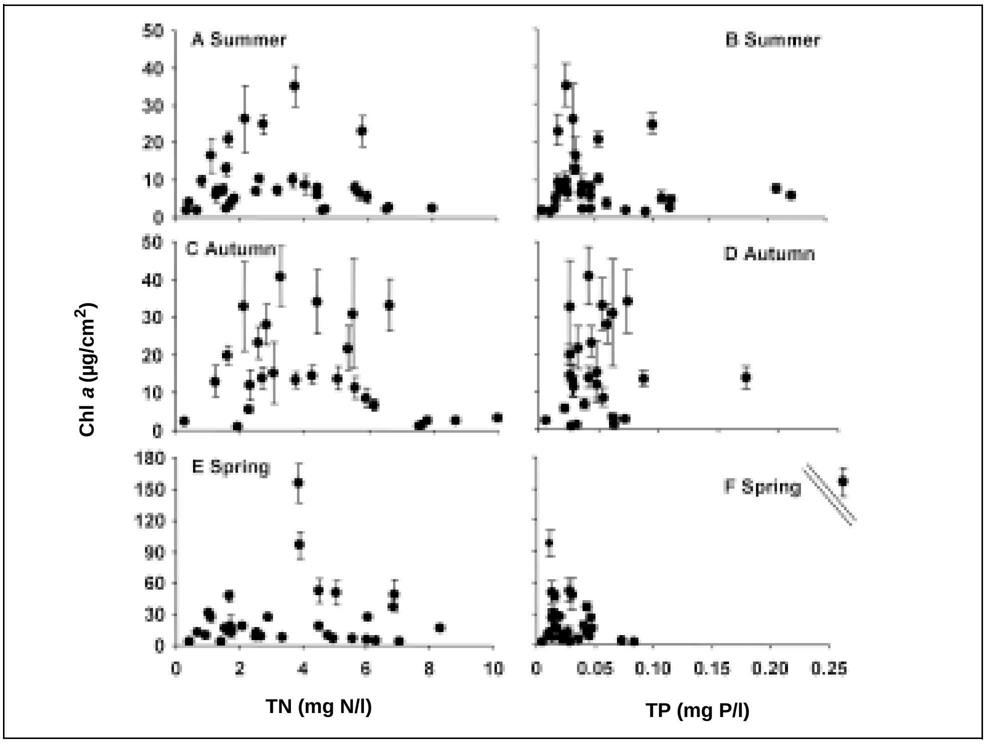

Figure 3.1. Chlorophyll *a* (Chl *a*) as a function of total nitrogen (TN) (A, C and E) and total phosphorus (TP) (B, D and F) for each of three sampling seasons: summer (A and B), autumn (C and D) and spring (E and F). Values represent the means for the eight replicate stones ±1 SE.

were always low at both low and high nutrient concentrations, but highly variable at intermediate nutrient concentrations (Fig. 3.1).

3.3 Autotrophic Biomass (Chlorophyll *a*) and Grazers

The total biomass of invertebrates varied between seasons. Summer densities ranged between 0.10 and 4.48 g/m^2 (mean = 1.00 g/m^2). Autumn densities ranged between 0.04 and 1.88 g/m^2 (mean = 0.50 g/m^2). Spring densities ranged between 0.13 and 4.98 g/m^2 (mean = 1.40 g/m^2). Although changes in community structures were observed seasonally, most of the common families were present in all seasons. Further analysis showed that total grazer biomass per stream increased with increasing total nitrogen concentrations (Fig. 3.2). Chlorophyll *a* levels were inversely related both to the density of nymphs of the common mayfly family Baetidae and that of a suite of 'slow moving' grazers (the cased caddis Glossosomatidae and Goeridae, and the gastropods Ancylidae, Hydrobiidae, Lymnaeidae, Neritidae and Physidae) (Fig. 3.3). No other variables (i.e. the other invertebrate families, seasons or chemical and environmental variables) were significantly linked to chlorophyll *a* levels.

3.4 Biological Indices of Water Quality

There was a rather narrow range of values for both the Irish Q-value system (summer values ranged from 3 to 4) and the Biological Monitoring Working Party (BMWP)/ASPT scores across study streams, indicating that streams were of good to intermediate ecological status (Fig. 3.4). Correlations between biotic indices and TN were significant in the case of the Q-value ($r = -0.46$, $p < 0.01$) but not for the ASPT score ($r = -0.27$, $p > 0.1$). Low nutrient concentrations were systematically associated with relatively high Q-values and ASPT scores, while high nutrient concentrations were associated with both good and intermediate

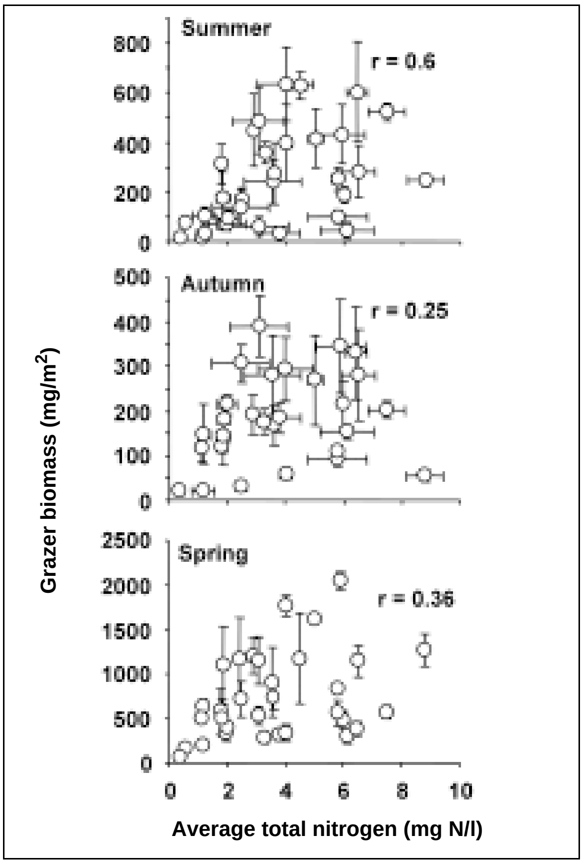

Figure 3.2. Relationship between total grazer biomass and total nitrogen. Data shown for summer, autumn and spring.

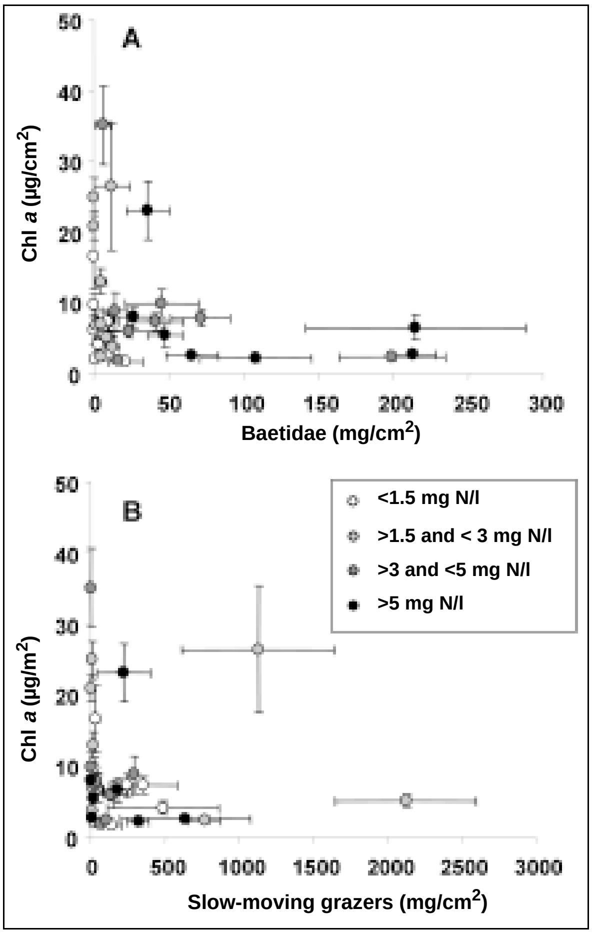

Figure 3.3. Relationships between chlorophyll *a* and Baetidae (A), and between chlorophyll *a* and slow-moving grazers (B). Slow-moving invertebrate grazers include the cased caddis Glossosomatidae and Goeridae and the gastropods Ancylidae, Hydrobiidae, Lymnaeidae, Neritidae and Physidae. Categories are of total nitrogen (arbitrary cut-offs)

water qualities (Fig. 3.4A and B). However, neither metric was able to characterise accurately the nutrient status of individual streams. High chlorophyll *a* levels were not related to Q-values (Fig. 3.4C) but always with ASPT values below 6.5 (Fig. 3.4D). It should be noted, however, that twice as many streams that had ASPT scores below 6.5 also displayed low chlorophyll *a* levels (Fig. 3.4D).

3.5 Discussion

Across the 32 streams of the study, there was a large range in both TN (0.28–10.02 mg N/l) and TP (0.004–0.22 mg P/l). Despite this, there was no clear relationship between nutrients and periphytic chlorophyll *a* or AFDM. These nutrients are essential for the growth of primary producers, and, consistently, low levels of periphytic chlorophyll *a* were found in nutrient-poor streams. However, increased nutrient concentrations were not necessarily associated with increased chlorophyll *a* levels or AFDM accumulation. Interestingly, the streams that exhibited the highest chlorophyll *a* levels had intermediate nutrient concentrations. Thus, the findings show that even the streams with the highest nutrient concentrations did not exhibit excessive algal growth. Analysis of diatom communities also reflected this weak link between benthic algae and plant nutrients. The Trophic Diatom Index (TDI) – a biotic index that has been shown to reflect nutrient status of running waters in the UK (Kelly and Whitton, 1995) – responded poorly to nitrogen and phosphorus nutrient enrichment across the study streams, although the diatom community did reflect

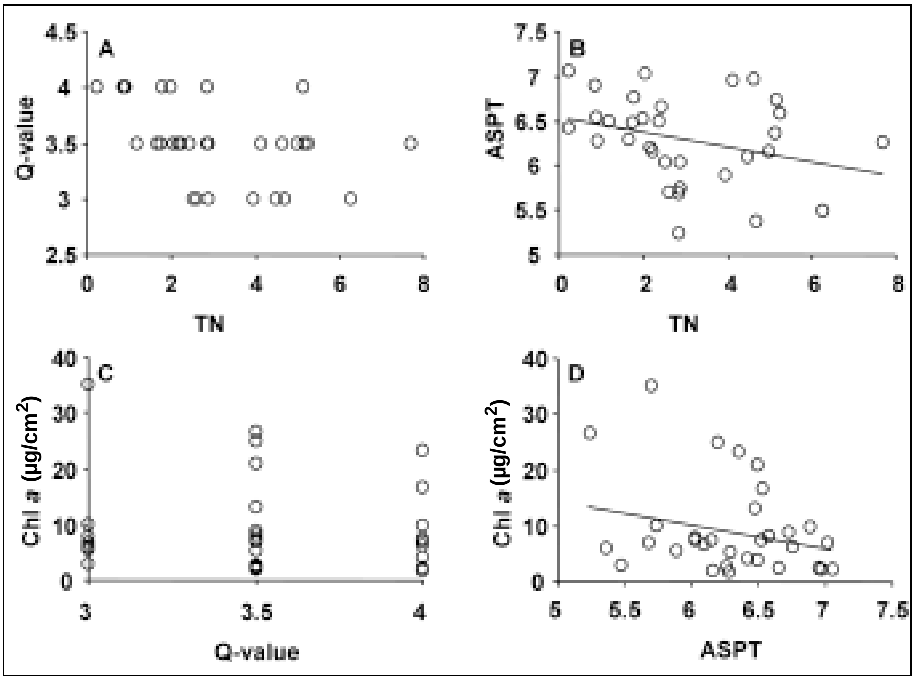

Figure 3.4. Relationship between (A) total nitrogen and Q-value, (B) total nitrogen (TN) and average score per taxon (ASPT), (C) Q-value and chlorophyll *a* (Chl *a*) and (D) ASPT and chlorophyll *a*. Lines represent the best fit for a correlation.

changes in catchment land use. Within this study, therefore, the TDI did not prove to be a useful tool for identifying streams experiencing nutrient enrichment. Periphytic algal biomass did, however, show a strong negative relationship with invertebrate algal grazers, particularly with the mayfly *Baetis rhodani*, suggesting that grazing pressure is a strong top–down force controlling the standing stock of benthic algae in streams. Few previous studies have empirically demonstrated such an effect, particularly for these small-bodied grazing invertebrates.

The results from this study show the following:

- Current biotic indices do not effectively indicate those streams experiencing nutrient enrichment;
- Algal standing stock is not a good proxy for estimating the nutrient status of a stream; and
- Nutrient enrichment facilitates invertebrate community shifts towards a greater mobile grazer component which are associated with reduced standing stock of algae. This suggests that in nutrient-rich systems algae are controlled by the grazing invertebrate community.

4 Results: Small-Scale Multi-Stream Study

4.1 Stream Physico–Chemical Variables

4.1.1 Nutrients

The six streams used in the study were chosen along a nutrient gradient of nitrogen (nitrate) and phosphorus (SRP) (Fig. 4.1). Variation in SRP concentrations was proportional to the magnitude of concentration, i.e. the Gortnalour had the lowest SRP and the smallest variation. Nitrate concentrations were generally well correlated with phosphorus concentrations, although the Bride had a higher phosphorus/nitrogen ratio than the other streams (Fig. 4.1).

4.1.2 Dissolved oxygen concentrations

DO saturation exhibited marked diurnal fluctuations, with supersaturation occurring under high light levels while the lowest DO levels were measured at night. The largest variation in DO occurred in the most nutrient-rich streams. Despite these differences, the lowest DO level (found in the nutrient-rich Delahinagh) was 88%, which can be assumed to impose relatively minor detrimental effects on stream biota.

4.1.3 Riparian canopy openness

For all the six streams, a wide range of sites of varying riparian canopy cover was identified. Medium canopied patches (30–60% cover) were difficult to find in some streams, particularly in the summer months (May to August) due to the structure of the riparian canopy. Canopy openness for pre-selected patches exhibited seasonal variation where openness increased during the winter months for sites dominated by deciduous species.

4.2 Periphyton Biomass

As for the larger-scale study (Chapter 3), periphyton chlorophyll *a* concentration was highly variable across both nutrient and shade gradients. This study's predictions that increases in both nutrient concentrations and light availability would cause consistent increases in algal biomass were not supported. Mean values of chlorophyll *a* in May were considerably higher than for the other sample occasions. December and February samples contained the lowest chlorophyll *a* concentrations which is most likely due to high stream discharges (scouring) and low growth rates associated with these

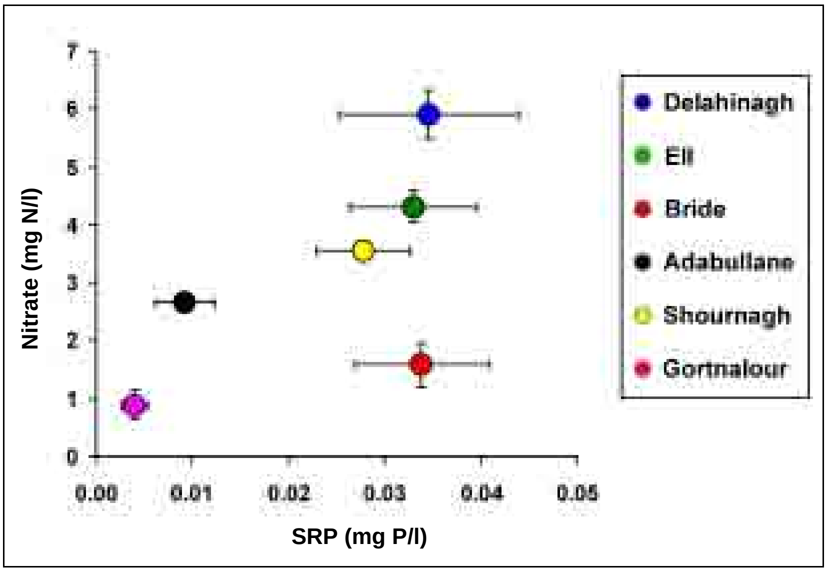

Figure 4.1. Mean (±1 SE) soluble reactive phosphorus (SRP) and nitrate concentrations for the six streams.

winter months. As above, AFDM was positively correlated with chlorophyll *a*. The lowest monthly mean AFDM values were obtained in the August sampling session (2.99 ± 0.23 mg/cm^2) and the highest were recorded in May (6.47 ± 0.40 mg/cm^2). As with the chlorophyll *a* data, a linear relationship was not observed for AFDM along nutrient or shade gradients.

4.3 Benthic Macroinvertebrates

ASPT, but not taxon richness, differed significantly between the streams, with the differences apparently being nutrient mediated. Microphyte grazing invertebrates and detritivores were found to be more abundant in open patches of the streams in May. The link between abundance and light was strongest for the mayfly *Baetis rhodani* and the river limpet *Ancylus fluviatilis* (Fig. 4.2). For *Baetis* the positive correlation was strongest in the nutrient-rich streams and the trend weakened with reduced nutrient concentrations (Fig. 4.2). This relationship between invertebrates and light did not persist in the other four sampling occasions.

4.4 Discussion

It is well documented that both nutrient enrichment (Dodds and Welch, 2000) and increases in irradiance (Hill and Harvey, 1990; Steinman, 1992; Hill et al., 1995) facilitate higher primary productivity in lotic environments, usually accompanied by higher standing stock of benthic algae. This study's results, however, have shown little relationship between algal standing stock and either the nutrient status or riparian canopy density of a stream. In spring, grazing invertebrates were, however, shown to increase in abundance in open patches and this result was most apparent in the nutrient-rich streams. The open areas seemed to attract grazing invertebrates from the whole stream reach, leaving depauperate grazing populations in shaded patches (Feminella et al., 1989). The higher growth of algae in open patches may therefore have been matched by a higher grazing pressure, such that there was little overall consistent difference in algal biomass across shade gradients. These results again confirm the potential importance of grazing invertebrates in controlling the growth of algae both between streams, as in the larger-scale study, and also within streams, i.e. between patches differing in light supply. Increased grazing pressure within a stream may come from increased reproduction or reduced mortality of grazing invertebrate populations, leading to a long-term increase in population density, or from increased immigration or reduced emigration from a patch, leading to short-term population shifts.

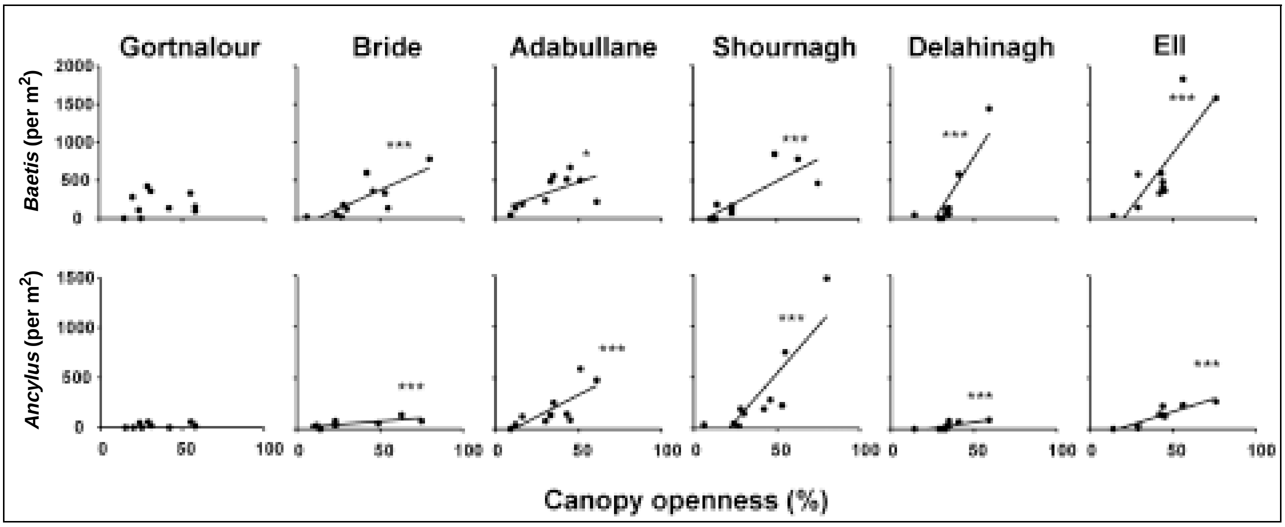

Figure 4.2. *Baetis* and *Ancylus* abundance along a gradient of canopy openness for the study streams, May 2007. Significance levels of Pearson's product moment correlation coefficient shown where applicable, ***p < 0.001, **p < 0.01, *p < 0.05. Streams on left-hand side are nutrient poor, streams on right are nutrient rich.

4.4.1 Summary

- Algal standing stock was not influenced by nutrient enrichment or riparian shade.

- Grazing invertebrates were more abundant in open sections of nutrient-rich streams in spring.

- Similar levels of algae were found in low light, low grazer, as in high light, high grazer, habitats.

- Grazing invertebrates were shown to play an important role in controlling benthic algae at smaller, between-patch scales.

5 Results: Experimental Studies on a Single System – the Owennagearagh

5.1 Field Survey

5.1.1 Spatial variation in Cladophora

The investigation of the small-scale spatial patchiness of *Cladophora* cover within a river showed that filaments were more abundant in nutrient-enriched sites downstream of the WWTP discharge as well as in open, sunlit patches. Greater *Cladophora* cover was also found in patches of slow-flowing water rather than faster-flowing water (Fig. 5.1). Epilithic (stone-surface) *Cladophora* colonised both high- and low-profile stones at all three sites; however, colonisation of low-profile stones only occurred in slow-flowing patches – filaments were absent from low-profile stones in fast-flowing water (Fig. 5.2). The *Cladophora* patterns on natural stones were matched by growth patterns on experimental substrata, where colonisation tiles were either placed at stream-bed level or raised some 8 cm above the bed by being securely tied to bricks. Algal biomass and *Cladophora* filaments were significantly more abundant on raised tiles.

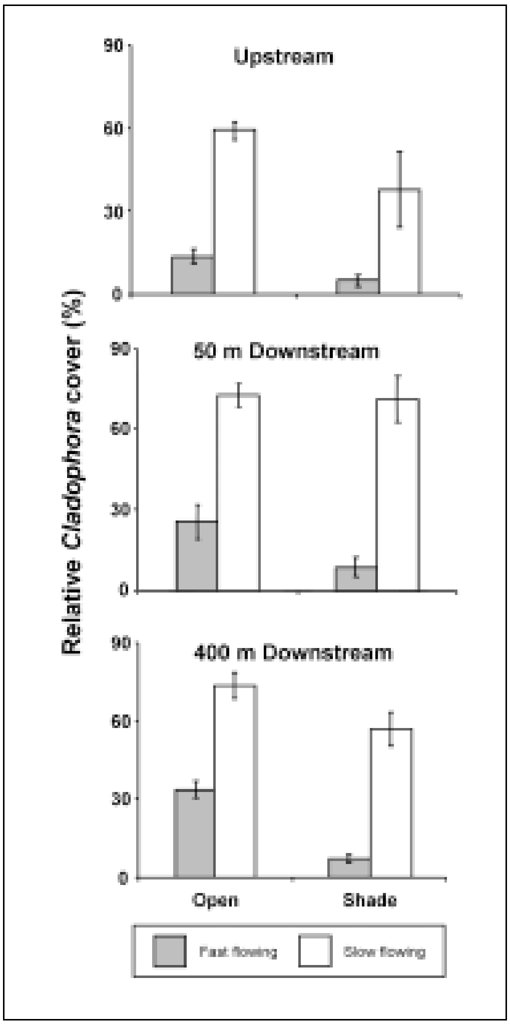

Figure 5.1. Mean (±1 SE) relative *Cladophora glomerata* cover for patches of different flow and shade conditions at the upstream, 50-m downstream and 400-m downstream sites.

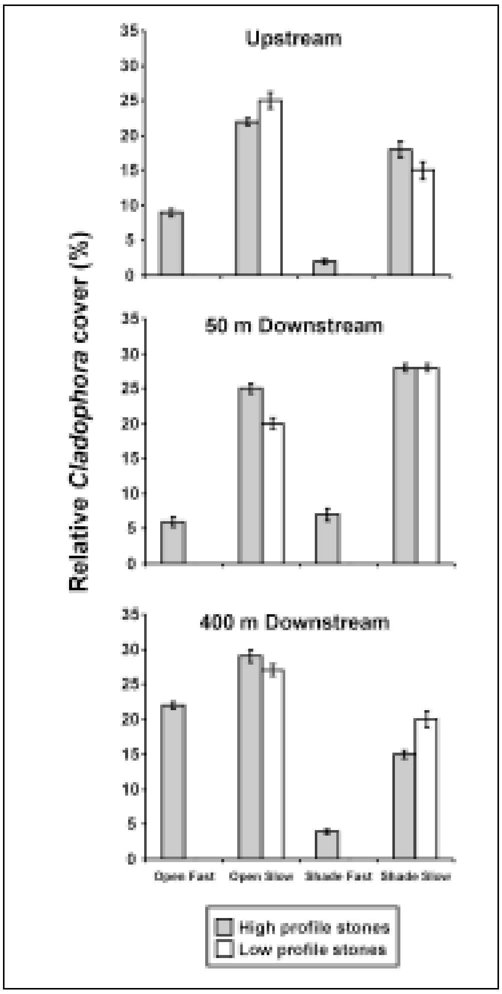

Figure 5.2. Mean (± 1 SE) relative abundance of *Cladophora* colonising high- and low-profile stones for the upstream, 50-m downstream and 400-m downstream sites.

5.1.2 Benthic organic matter and redox potential

Slow-flowing stream patches at all three sites accumulated a much greater biomass of benthic organic sediment than fast-flowing patches, which were virtually sediment-free. Redox potentials, a measure of the oxygen concentrations, were significantly higher in fast-flowing patches at all three sites.

5.1.3 Benthic macroinvertebrates

There were striking patterns in the spatial distribution of the dominant grazer taxa (*Agapetus, Ancylus* and *Baetis*). Grazing invertebrates were more abundant both in open patches (a likely function of increased algal growth) and also in fast-flowing patches (a likely function of the lower benthic organic sediment and higher oxygen content). All grazers were also greatly more abundant on lower-profile stones, in all three sites.

5.2 Grazer Exclusion Experiment Using Electric Fields

Two experiments were performed using electric fields to exclude grazing invertebrates. The first experiment, conducted in summer 2008, revealed that the algivorous mayfly *Baetis rhodani* was able to control the colonisation and growth of *Cladophora* filaments downstream of a WWTP discharge pipe. Further, the density of *Baetis* was much greater downstream of the discharge pipe, showing that *Baetis* population density can respond to localised, small-scale increases in nutrient loading and primary productivity. Following the success of this experiment at revealing the potential role of grazers in controlling nuisance algae, another experiment was performed in summer 2009, investigating the interactive roles of grazing pressure, nutrient loading and hydraulic disturbance in controlling benthic algal biomass. The results of this second experiment are described below.

5.2.1 Surbers

Bi-weekly monitoring of the abundances of grazing invertebrates at the three sites showed that larval densities of the grazing caddisfly *Agapetus* and the mayfly *Baetis* were markedly reduced following emergence of adults after Week 4 of the experiment. Numbers of larvae in the benthos rose rapidly shortly afterwards. Despite rapid increases in their abundance, the biomass of the small-bodied early instar *Baetis* remained low for the remainder of the experiment.

5.2.2 Tile surface invertebrates

Tiles subjected to the electric fields consistently had fewer grazers than the control tiles, indicating that the high-voltage fields were an extremely effective method of reducing the presence of grazing invertebrates (Fig. 5.3). The ephemeral emergences of invertebrates, as seen in the surber samples, were also observed on the tile surfaces.

5.2.3 Tile surface algae

Grazer-excluded tiles consistently accrued more algae than their grazed counterparts (Fig. 5.4). Periods of high flow and associated hydraulic shear stress at Weeks 3, 7 and 10 were also extremely effective at reducing the abundance of *Cladophora* on tiles. The greatest accrual of *Cladophora* was recorded on sample date 9 (3 July). The preceding 2-week growth period was characterised by low flow and low *Baetis* biomass. Grazer-excluded tiles at the 400-m downstream site achieved the greatest growths of *Cladophora* followed by the 50-m downstream and then the upstream site.

5.3 Discussion

The investigation of the small-scale patchiness of algae and grazers in the Owennagearagh revealed the strong role played by grazing invertebrates in controlling *Cladophora*. The grazer–algal interaction was, however, mediated by flow conditions. Low-velocity patches of the stream bed accumulated higher densities of organic matter, had lower DO levels, and this was associated with low-grazing invertebrate densities. As a result, these low-flow patches accumulated high densities of filamentous algae. Grazers were also less abundant on taller substrata, leading to higher algal abundance on these stones. These results thus show both the strong role played by grazers in controlling algae in streams, and the risk of high growth of filamentous algae should grazer abundance be locally reduced.

The effectiveness of grazing invertebrates in controlling algal growth was observed clearly during the experiment using high-voltage electrical fields, as grazed tiles typically remained free from excessive algal growth. Only during a period of low-grazing invertebrate biomass and low flow did the grazed tiles accrue substantial amounts of filamentous algae. The high colonisation and growth of *Cladophora* on tiles accessible to grazers during such periods indicate the high risk of algal 'escape' from grazers in nutrient-enriched streams, subject to high bottom–up pressure, potentially leading to high biomass of grazer-invulnerable nuisance algae. Hydraulic disturbance, in the form of spate flows, was shown to re-establish the dominance of grazers. Over longer periods of time with constant low flows, such as might be found in drier summers, algal escape might thus be expected to occur more frequently.

Filamentous algal taxa are more susceptible to hydraulic regimes than non-filamentous forms (Biggs and Thomsen, 1995; Francoeur and Biggs, 2006) and are more readily removed through shear stress. The abundance of filamentous algae is therefore likely to be more temporally variable compared with that of adnate species. This study's results show that hydraulic shear stress and scour, especially those associated with flood events, acted as a strong non-trophic top–down controlling mechanism that effectively removed *Cladophora* biomass. The abundance of *Cladophora* is therefore determined by the stability of its habitat's hydrological regime and the species will mostly persist in stable, low-flow conditions. The Owennagearagh is characterised by 'flashy' hydrological patterns, which have been shown to remove and 'reset' grazer–periphyton interactions, allowing grazer supremacy to re-establish. Combined

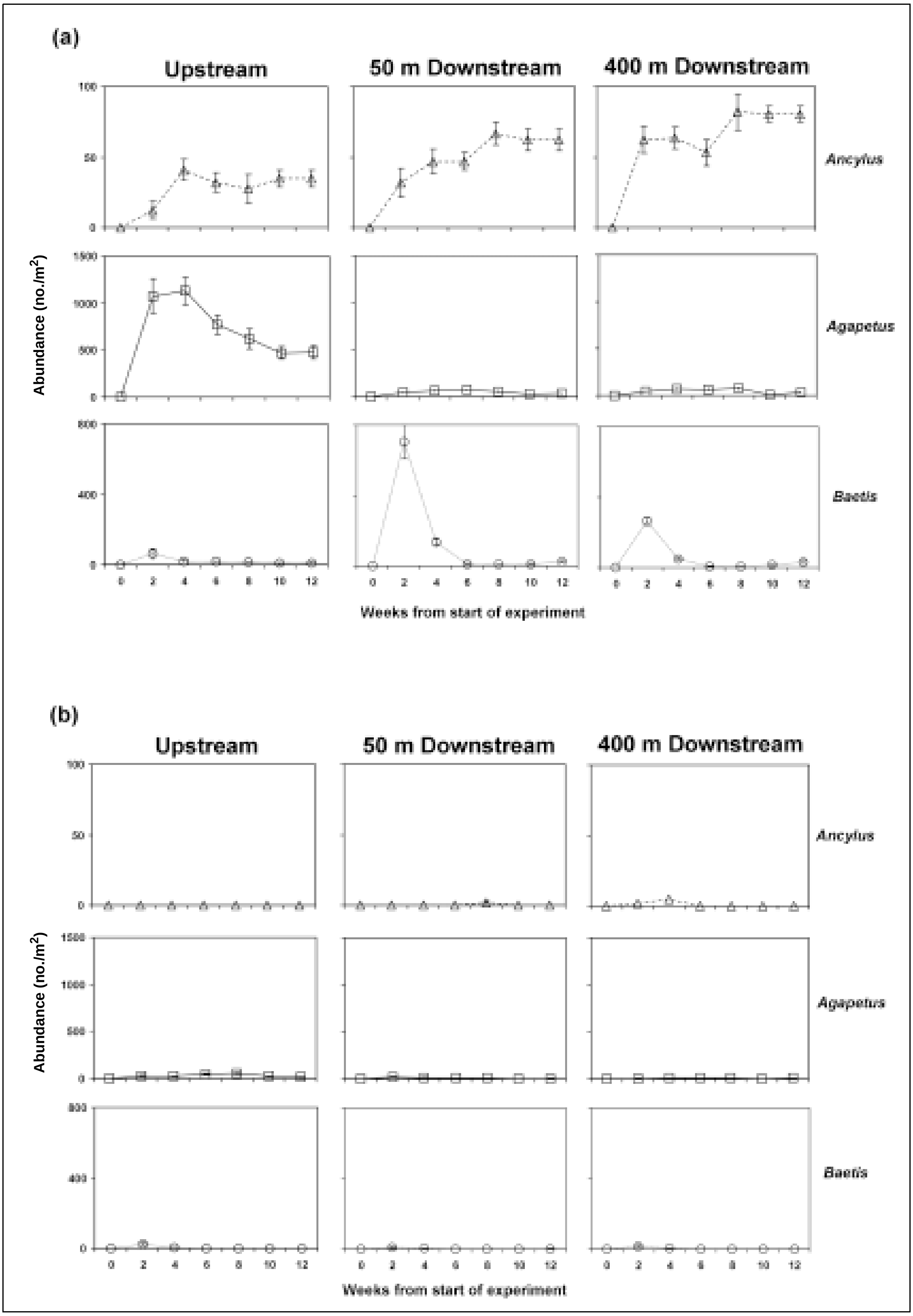

Figure 5.3. Data from colonisation tiles. Bi-weekly mean (± 1 SE) abundances of major grazing invertebrates (*Ancylus, Agapetus and Baetis*) for (a) grazed and (b) grazer-excluded tiles from the upstream, 50-m downstream and 400-m downstream sites.

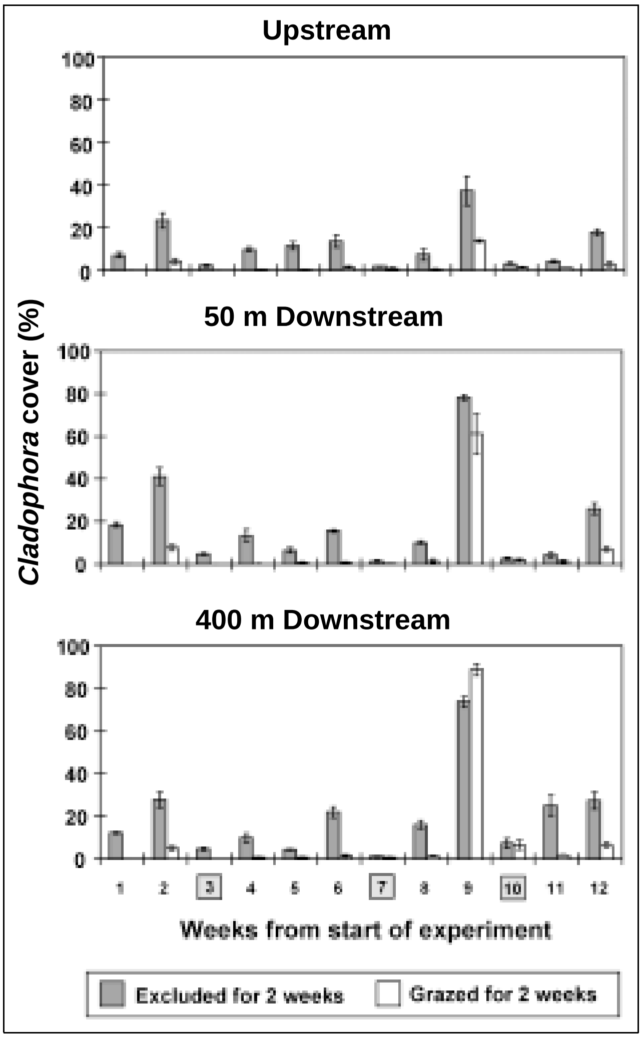

Figure 5.4. Mean (± 1 SE) weekly *Cladophora* percentage cover for new tiles added every 2 weeks and exposed to grazed and grazer-excluded treatments; weeks experiencing spate episodes (depth >40 cm) are indicated by shaded boxes. Data shown for the upstream, 50-m downstream and 400-m downstream sites.

biotic and abiotic pressures meant that, for the majority of the experiment, grazed tiles remained free from filamentous algae. Algal 'escape' was only observed when imbalances occurred between top–down (scour and grazing effects) and bottom–up (nutrient enrichment) controlling mechanisms.

5.3.1 Summary

- Grazing invertebrates play an important role in controlling the growth of nuisance algae in streams subjected to high nutrient loading.
- Natural stream architecture and micro-habitat conditions dictate grazer accessibility to and the suitability of particular substrata.
- Benthic habitats with low grazer abundances can experience algal dominance and can suffer from nuisance algal growths.
- Hydraulic shear stress and scour act as a strong top–down control mechanism on algal growth and persistence.

6 Discussion and Conclusions

This study has shown that stream benthic algae are controlled by a suite of forces, including:

- Nutrient levels;
- Canopy shade;
- Hydraulic action; and
- Grazing pressure from small-bodied algivorous benthic macroinvertebrates.

Disturbances to these various top–down and bottom–up processes governing the equilibrium between algal accumulation and loss may result in reduced ecological status through the excessive growth of nuisance filamentous algae.

Nutrient enrichment can influence the alga–grazer link in several ways:

1. Increased nutrient concentrations facilitate higher primary productivity;
2. The elemental composition (nitrogen/phosphorus/carbon) of primary producers changes; and
3. Invertebrate communities become dominated by ‘pollution-tolerant’ species.

The combined effects of these changes can shift the equilibrium between primary and secondary producers. Low-nutrient streams have weak algal growth potential, such that the food base of the invertebrate community is largely detritus based. These systems also have low populations of grazing invertebrates. Nutrient-enriched systems have greater algal productivity and support higher grazer populations as a result. These streams can retain ecosystem integrity (i.e. lack of excessive growths of benthic filamentous algae), despite elevated nutrient levels, provided that the alga–grazer equilibrium is maintained.

A meta-analysis of published literature showed that stream invertebrate elemental stoichiometry reflected environmental nutrient levels, with taxa containing high nitrogen/carbon or phosphorus/carbon ratios found in more nutrient-rich environments, and taxa with low nitrogen/carbon or phosphorus/carbon ratios found in more nutrient-poor environments. The shift in invertebrate communities generally seen when streams suffer eutrophication is commonly thought to be a function of invertebrate tolerance to changing environmental conditions, particularly reduced oxygen levels. The findings of this study shed new light on the mechanisms underlying nutrient-mediated changes in stream communities and suggest that nutrients may drive community change directly, rather than indirectly.

In a large-scale, multi-stream study of the standing biomass of epilithic primary producers and benthic macroinvertebrate communities across a trophic gradient, this study has shown that there was little clear relationship between nutrient enrichment and algal biomass, although diatom community composition did show some relationship to water chemistry. Grazing macroinvertebrates (notably the common mayfly species *Baetis rhodani*) increased in abundance along a nutrient gradient and their abundance was in turn inversely related to standing biomass of benthic algae, implying top–down control of algal biomass by these small-bodied mayfly nymphs. This study thus revealed that increasing nutrient supplies in streams did not result in a simple increase in the standing crop of benthic algae, but rather in an increase in the number of primary consumers. This pattern of strong potential top–down control was also seen in a series of smaller-scale investigations into the role of riparian shade and nutrient supply in stream ecosystems. In a small-scale study of six streams of contrasting plant nutrient concentrations, grazing invertebrates were found to be more abundant in stream stretches with low overhead riparian canopy cover, indicating a greater overall primary and secondary productivity of these habitats. However, accumulation of algal biomass in open habitats was no greater in nutrient-rich streams than in nutrient-poor streams, indicating the effectiveness of grazing invertebrates at mitigating the increased bottom–up force on algal growth from nutrient enrichment. These two studies, at different scales, have shown that accumulated levels of chlorophyll *a* are a poor proxy of stream nutrient status, and that increased primary production in some nutrient-enriched Irish streams may be effectively transferred to higher trophic levels through the grazing food chain.

Although there is widespread concern about the impact of nutrients on primary production in streams, most attention has focused on the abundance of nuisance algae, rather than on biofilms themselves. The filamentous alga *Cladophora glomerata* is widely reported as a nuisance alga in nutrient-enriched streams. In a series of small-scale experimental investigations in a single nutrient-enriched stream, it was shown that *Cladophora* can be strongly controlled by top–down grazing pressure, demonstrating that invertebrate grazers can perform a valuable 'ecosystem engineering' role by reducing the ability of *Cladophora* to 'blanket' the bed of streams and thereby maintain the ecological integrity of streams.

In the Owennagearagh, *Cladophora* was found to have a very patchy distribution within the stream, with densest growth of the alga in slow-flowing patches of stream bed containing high organic matter and low benthic oxygen levels. *Cladophora* was also found to grow more densely on tall stones projecting above the stream bed, rather than on flatter stones that are more accessible to invertebrate grazers. This fragmented local distribution was linked to the low abundance of grazing invertebrates in *Cladophora*-rich habitats, rather than any physical factors. The colonisation and growth of *Cladophora* was then investigated in manipulation studies whereby grazing invertebrates were excluded from artificial benthic substrata using electric fields. These studies showed that *Cladophora* grows rapidly on substrata in the absence of grazing invertebrates. In the presence of grazers, however, *Cladophora* failed to establish on substrata, even downstream of a sewage input, in an area of considerable nutrient enrichment. The grazer that appeared to be implicated most in *Cladophora* control was the abundant and common mayfly *Baetis rhodani*. This is the first time that such a critical ecosystem role has been attributed to this species, most published studies having shown that control of filamentous algae in streams is associated with large-bodied taxa such as cased caddis, snails and crayfish.

Growth of *Cladophora* can occur in habitats with high grazer populations – so-called algal 'escapes'. This phenomenon was further investigated in a second grazer-exclusion experiment, where the growth potential of *Cladophora* was tested during periods of fluctuating grazer pressure and hydraulic stress. Over the course of this experiment, grazing densities of *Baetis* nymphs decreased substantially due to the emergence of the adult stages in early summer and there occurred several short periods of relatively low flow. *Cladophora* was able to establish during these low-flow periods, even on substrata that were not grazer excluded. Accumulated *Cladophora* biomass did, however, not persist and was decreased following subsequent spates.

These results highlight the importance of stream habitat integrity in supporting a high population of grazing invertebrates, which was shown to perform a critical ecosystem service of controlling potentially nuisance algae. These taxa, predominantly mayflies and caddisflies in this study, are sensitive to changes in habitat conditions and water quality and are generally considered to prefer relatively silt-free stony substrata and high oxygen concentrations. Although patches of silty, low-oxygen conditions with few grazers developed at a local scale in this study stream, grazer abundance was generally high throughout, even in the nutrient-enriched stretch downstream of a WWTP discharge pipe. Water column DO levels remained high in the study streams, likely due to cool summer temperatures and high flows during the study period.

The multi-stream study of algal biomass across a nutrient gradient showed that nuisance algal growths were rare in the study catchments. In the locations where they occurred, however, it was clear that imbalances in grazer–alga interactions were the likely causes. The prevalence of grazer control in study streams can be attributed to both the relatively high gradient of many streams and the pluvio-cool summer climate of the region (high precipitation and low temperatures), which minimise lotic deoxygenation and benthic sedimentation. It should be noted that these studies were conducted in years of high rainfall and relatively low summer temperatures, which would have shifted the producer–consumer equilibrium towards algal grazers. In summers of lower rainfall, the equilibrium may be expected to shift towards algal growth, leading to a greater prevalence of nuisance algal growth in streams.

Despite this study's findings that grazers can perform a stronger-than-expected role in preventing the growth of filamentous algae in streams, nutrient enrichment remains a threat to the ecological status of streams in Ireland.

7 Management Recommendations

It has been shown that nutrient enrichment, at the moderate levels encountered in the study, is only weakly correlated with declines in stream ecological status. Nutrient enrichment may only be an issue for stream ecological status in this study region under very high nutrient loadings or where primary consumer populations are impaired, allowing excessive algal growth. Benthic macroinvertebrates, particularly the widespread and abundant mayfly *Baetis rhodani*, have been shown to be potentially highly effective controlling agents of both epilithic biofilm and benthic filamentous algae, including the 'blanket weed' *Cladophora glomerata*. These invertebrates thus provide valuable ecosystem 'goods and services' by preventing excessive algal growth and facilitating the transfer of matter and energy from primary producers to secondary consumers. This study's results have shown that small-bodied grazers exert a strong top–down control of nuisance algae in nutrient-enriched systems. It has also been shown, however, that temporal perturbations in grazer pressure can result in high filamentous algal accumulation and can potentially lead to a rapid change to a grazer-resistant state of excessive algal growth. The implications of these findings are that factors that result in anthropogenically mediated declines of grazer populations, such as organic and inorganic pollution and excessive siltation, are likely to increase the risk of excessive algal growth, particularly in streams with high nutrient loading. Such impacts are also likely to be magnified during periods of low flow, when hydraulic stress is insufficient to 'reset' a system dominated by grazer-resistant algae to one dominated by grazers.

Riparian shade was found to strongly reduce benthic algal colonisation and productivity, but not necessarily realised periphytic biomass. The higher potential algal growth rate in open, unshaded stretches is likely to lead to greater risk of algal 'escape' from controlling factors and excessive and undesirable growths. Encouraging the growth of dense riparian trees along streams may be considered in nutrient-rich stretches, but would also likely reduce secondary and tertiary productivity, which may be undesirable. Clearly, a balance must be struck between reduced primary, secondary and, particularly, tertiary productivity in streams with high nutrient loadings.

Although a comprehensive water quality monitoring programme is currently in place in the Irish Republic, a better understanding of the links between nutrient enrichment and biotic and abiotic responses in streams will facilitate a more appropriate and accurate monitoring programme. Existing biomonitoring of individual streams using macroinvertebrates is a weak tool for detecting moderate to high nutrient enrichment. In this study, streams of 'good' ecological status (Q4) were found across a wide nutrient gradient. Streams at the higher end of nutrient enrichment are, however, more at risk of ecological deterioration and need to be identified for more intensive monitoring. The impact of nutrient-enriched waters on downstream habitats (particularly nutrient-sensitive estuaries) should also be taken into greater consideration when determining ecological status. For example, a Q4 stream of good ecological status may nonetheless supply poor-quality water (in terms of its nutrient loading) to an estuary. It is a recommendation of this study that further research is undertaken on developing more refined biomonitoring approaches that can distinguish between streams of different nutrient status, so as to identify waterbodies that need more advanced nutrient management strategies. Unlike many other biomonitoring systems in Europe, the Irish Q-value system explicitly downgrades a waterbody when certain biota are present or numerous (as opposed to simply giving such biota low biotic scores). For example, excessive numbers of *Baetis rhodani* or moderate to excessive densities of *Cladophora* would in themselves reduce the Q-value of a given system. The results of this study have shown that both of these organisms respond clearly to nutrient enrichment and in fact high numbers of *Baetis* may be the most obvious (or even the only) biological indication of high nutrient levels. Thus, the findings confirm and stress the importance of measuring the abundance (both relative and absolute) of both organisms when determining the Q-value, as is currently practised.

This study has shown clearly that different streams show contrasting biological responses to nutrient enrichment. Accurate prediction of the realised effect of nutrient inputs on the biology of a given stream may therefore not be possible either between or within ecoregions, but the potential impacts may be gauged. The relative risk of nutrient enrichment to the ecological status of a given stream will depend on:

1. Its sensitivity;
2. Its level of existing impairment; and
3. Its ability to mitigate nutrient inputs.

Sensitivity can be divided into biological, economic and legislative sensitivities. A particular river system may contain rare or sensitive species, such as the freshwater pearl mussel (*Margaritifera margaritifera)*, sensitive habitats, such as fish spawning sites, or may debouch into sensitive habitats, particularly estuarine or coastal habitats. Secondly, river systems may possess economic sensitivity to eutrophication in terms of drinking water sources, tourism and recreation. Thirdly, a river may have legislative sensitivity, in that it may have regional, national or international statutory protection, a good example being the Munster Blackwater, which is under severe pressure from eutrophication.

The risk of eutrophication may also depend on the level of existing impairment from a variety of factors, including:

- The degree of anthropogenic channel alteration;
- The naturalness of the river;
- Urbanisation; and
- Numbers and densities of alien species.

A highly altered river, with little natural instream or riparian habitat and with high populations of non-native species could therefore be seen to be less at risk of further degradation, because of its existing poor ecological status.

Lastly, several factors may mitigate the impact of nutrient enrichment in a given waterbody. As this study has shown, these include:

- High levels of calcium (which would bind and precipitate phosphorus, so lowering its biological impact);
- Hydraulic disturbance and dense riparian shade (which would prevent the expression of high primary productivity and so reduce the impact of plant nutrients); and
- High grazing pressure, which although not greatly lowering primary productivity, would potentially protect the stream from excessively high standing stock of nuisance algae.

In this way, river systems may be divided into risk categories, depending on their potential sensitivity to existing or further eutrophication. Such an approach may aid the targeting of management procedures to reduce nutrient inputs into streams.

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Acronyms

AFDM	Ash-free dry mass
ASPT	Average score per taxon
BMWP	Biological Monitoring Working Party
Eh	Redox potential
EU	European Union
GLA	Gap Light Analyser
SRP	Soluble reactive phosphorus
TDI	Trophic Diatom Index
TN	Total nitrogen
TON	Total oxidised nitrogen
TP	Total phosphorus
WFD	Water Framework Directive
WWTP	Waste-water treatment plant

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.
- Scardadh dramhuisce

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

National Development Plan 2007 - 2013

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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SSTI Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government