River ecosystem response to bushfire disturbance: interaction with flow regulation

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Summary

Fires and river regulation are disturbances affecting many aquatic ecosystems worldwide. We examined the ecological response of rivers to the combined effects of regulation and fire. Changes in communities of benthic aquatic algae and macroinvertebrates were studied for 22 months following a wildfire through forested catchments in the Australian Capital Territory. In both the regulated (by dams) and the free-flowing rivers and streams, fire caused large changes to physical habitat for the benthic communities that overrode the effects of regulation. In unregulated streams, the benthic communities had largely recovered 22 months after the fire disturbance, but the regulated stream did not recover. It is not clear from the findings of this study if the benthic communities will recover from the fire disturbance without active restoration of stream habitat.

Keywords: benthic; disturbance; fire; flow regulation; macroinvertebrates; periphyton

Introduction

Fires, whether natural or planned, are disturbances that modify landscapes and in turn affect freshwater ecosystems. Natural disturbances are recognised as playing an important role in maintaining aquatic diversity and stream health (Resh *et al.* 1988). For a stream ecosystem, a disturbance can be defined as ‘any relatively discrete event in time that is characterised by a frequency, intensity, and severity outside a predictable range, and that disrupts ecosystem, community, or population structure and changes the resources or the physical environment’ (Resh *et al.* 1988). Typically, in a river or stream after a fire disturbance to the catchment, there are fewer individuals and taxa of aquatic macroinvertebrates than in the aquatic ecosystems of unburnt catchments (Milner 1994; Vieira *et al*. 2004). The speed and degree of recovery of populations of aquatic biota depend on the severity of the disturbance and its interaction with other underlying disturbances.

Rivers are often affected at once by both natural and human disturbances. For example, dams alter flow and sediment regimes, and therefore also influence the nature of other disturbances, such as fires. Dams trap sediment and regulate floods, artificially slowing sediment transport downstream. Meanwhile, the sediment supply from tributaries downstream of the dam is unaffected, allowing fine particles to swamp the river gravels (Petts 1988; Brookes 1994). Thus, sediment inputs into a regulated river after fire (e.g. Leitch *et al.* 1983) can become an issue where the regulated flows are insufficient to transport it. Such sediment will be detrimental to benthic communities until the fine material is flushed out of the system (Milner 1994; Vieira *et al*. 2004). Benthic communities, that is, the algae and macroinvertebrates that live on the stream-bed, can be used as biological indicators to reveal the health of a stream (Rott 1991; Rosenberg and Resh 1993).

The recovery of benthic communities in rivers exposed to both natural and human-induced disturbance generally takes longer than in natural river systems (Collier and Quinn 2003). However, the rarity of extreme fire events limits our scientific understanding of their effects on stream ecosystems because assessments are necessarily infrequent. Fire effects are further complicated in streams already stressed from an underlying disturbance such as river regulation.

Bushfires in January 2003 burnt 266 000 ha within the ACT and bordering NSW (Carey *et al*. 2003), including the Cotter River catchment that supplies the Australian Capital Territory with potable water. The objective of the study reported here was to determine the ecological effects of fire on a river that has been modified by flow regulation.

Methods

Study area

This study was conducted in two adjacent forested river catchments, the regulated Cotter River and the unregulated Goodradigbee River, which are located in the Brindabella mountain range along the eastern side of the Australian Capital Territory (ACT), Australia (Fig. 1). The Cotter River, on the eastern side, is regulated by three dams for the supply of water to the National Capital, Canberra. On the western side is the Goodradigbee River, an unregulated tributary of the Murrumbidgee River. These permeable catchments have stable soils and a long-term average annual rainfall of 930 mm, most of which falls during August–October. The Cotter River catchment covers 482 km^2 and the river is 74 km in length, flowing mostly through a steep valley. The more western Goodradigbee River catchment is 890 km^2 and the river is 75 km in length.

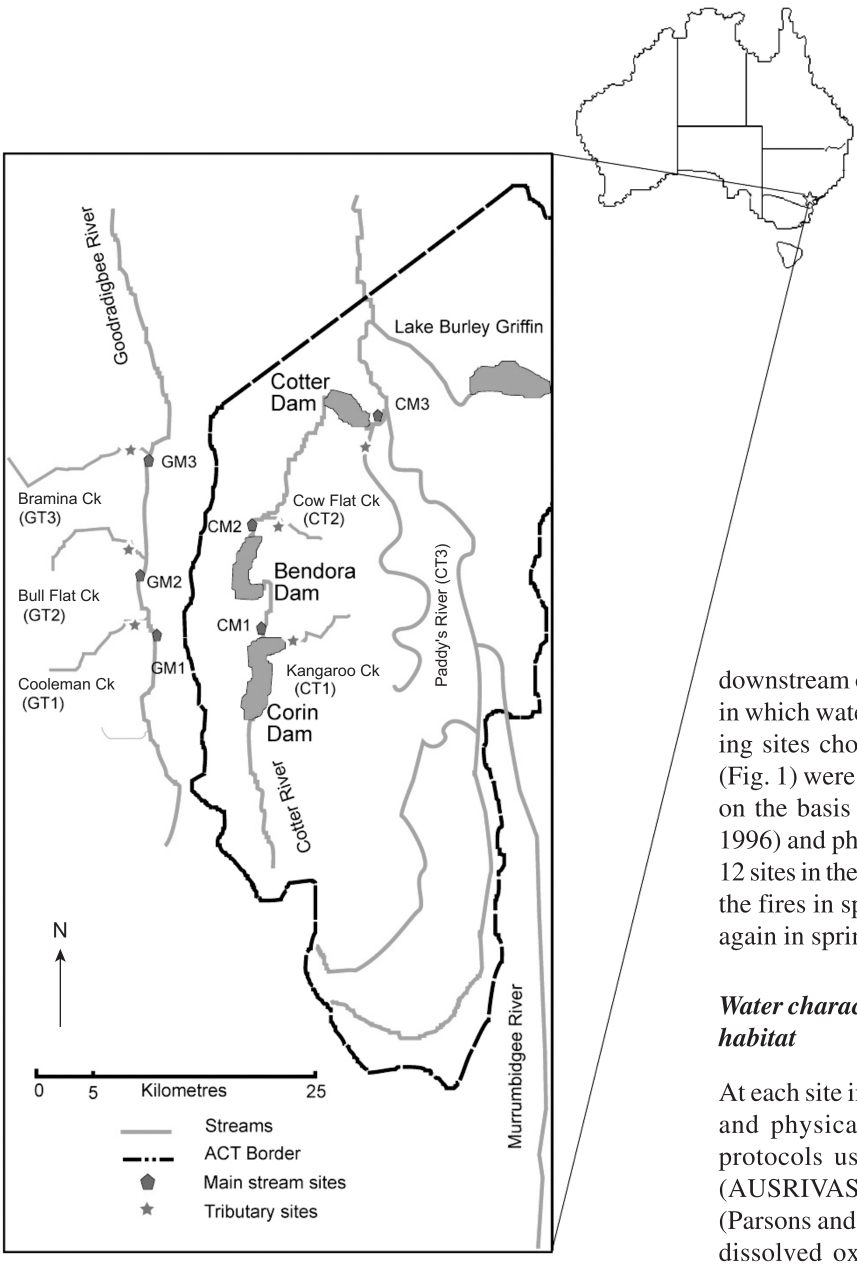


Figure 1. Location of sites sampled for macroinvertebrates in the Cotter and Goodradigbee catchments, October 2001–spring 2004

The Cotter River catchment consists mostly of granites on the ridges and slopes with Ordovician sediments (shales, sandstones and clays) closer to the Cotter River and its tributaries (Owen and Wyborn 1979). The geology and vegetation in the upper parts of the Goodradigbee and Cotter River catchments are similar. There is restricted public access to the Cotter catchment, which is mostly undeveloped and has good water quality (Hogg and Wicks 1989). Other land uses include commercial timber production (< 8% of total catchment, NCDC 1986) and low-impact recreation. The land use in the upper Goodradigbee River catchment is predominantly national park, nature reserve and some forestry. However, there is some rural grazing/cultivation along the Goodradigbee River around Brindabella station, and more in the lower part of the catchment, where forestry, both native and plantation, is also a land use (NCDC 1986).

Dry lightning storms during January 2003 along the western border of the ACT and in the Brindabella National Park to the north-west of the ACT started separate fires, which combined and burnt extensively through both the Goodradigbee and Cotter River catchments.

Study design

Water characteristics, and the composition of macroinvertebrate communities and periphyton are aspects of a river that reveal its ecological condition (e.g. Rosenberg and Resh 1993; Kutka and Richards 1996). Periphyton composition is defined as the combination of the chlorophyll-a and ash-free dry mass of organisms, primarily algae, attached to the surface of the streambed. These variables were measured in samples collected from one riffle downstream of each dam along the Cotter River and from a riffle in the nearest tributary downstream of each dam. A riffle is any shallow area of a stream in which water flows rapidly with a broken surface. Corresponding sites chosen in the Goodradigbee River and its tributaries (Fig. 1) were the best available matches to the Cotter River sites, on the basis of physical habitat variables (Parsons and Norris 1996) and physical appearance. Sampling was performed at the 12 sites in the Cotter and Goodradigbee catchments (Fig. 1) before the fires in spring 2001, again in spring 2003 after the fires and again in spring 2004 one year after the fires.

Water characteristics, benthic macroinvertebrates and physical habitat

At each site in a riffle, water characteristics, macroinvertebrates, and physical habitat variables were sampled according to protocols used in the Australian River Assessment System (AUSRIVAS) sampling and processing manual for the ACT (Parsons and Norris 1996; Coysh *et al.* 2000). Temperature, pH, dissolved oxygen, electrical conductivity and turbidity were determined in the field using a Hydrolab™ Scout sonde multiprobe. Visual estimates were made of the percentage composition of the inorganic substratum occurring in the riffle, following the key provided in the ACT AUSRIVAS Field sampling sheet (http://ausrivas.canberra.edu.au/Bioassessment/Macroinvertebrates/).

Macroinvertebrate samples were preserved in the field with 10% formalin and transferred to ethanol in the laboratory. The preserved samples were placed in a sub-sampling box comprising 100 cells (Marchant 1989) and agitated until evenly distributed. The contents of each cell were removed until approximately 200 macroinvertebrates from each sample had been identified (Parsons and Norris 1996). These were identified to family taxonomic level using keys listed by Hawking (1997), except for the chironomids, which were identified to sub-family, and worms (Oligochaeta) and mites (Acarina), which were identified to class and order respectively. Identifications were verified against a reference collection of specimens held at the Cooperative Research Centre for Freshwater Ecology, University of Canberra.

Periphyton composition

Periphyton was collected from 12 transects 1 m wide across each site, with one sample collected from each transect so that a total of 12 samples was obtained. Periphyton was removed from the upper surface of either cobbles or boulders *in situ* using a syringe sampler similar to that described by Loeb (1981). The device consists of two 60 mL syringes and a scrubbing surface of stiff nylon bristles that sweeps an area of 637 mm^2. This collected adnate (growing together) and loose forms of periphyton, as well as organic/inorganic detritus in the periphyton matrix. The detritus consisted of fine grain sediment, microbes, invertebrates and plant material. This sampler also allowed area-based quantitative assessment of periphyton. The 12 samples were randomly divided into two groups of six.

All 12 periphyton samples per site were filtered onto individual glass fibre filters. Six of them were dried at 45ºC for 24 h, weighed and placed into a furnace at 500ºC for 1 h, then weighed again. The difference of the two weights represents ash free dry mass (AFDM) and this was scaled to weight per unit area (g m^{-2}). The remaining six samples were placed into centrifuge tubes, wrapped in aluminium foil and frozen for later analysis. Chlorophyll pigments were extracted from the filters in 90% ethanol at 80ºC for 10 min. Spectrophotometric measurements (Hitachi spectrophotometer and 1 cm cuvettes) followed centrifugation. The absorbance of chlorophyll-a was measured at 664 and 750 nm. The calculation of chlorophyll-a using the Ethanol extraction method is from APHA (1985).

Data analyses

Macroinvertebrates were classified on the basis of community composition, to compare the sites downstream of dams and tributaries in the burnt Cotter River against the burnt but unregulated Goodradigbee River. Sites having similar macroinvertebrate compositions based on family-level relative abundance data (log transformed) were grouped using the Bray–Curtis distance measure, a robust measure of association for cluster analysis (Faith *et al.* 1987), and the agglomerative clustering technique with flexible Unweighted Pair-Group arithmetic Averaging (UPGMA) and $\beta = -0.1$ (Belbin and McDonald 1993). The groups were statistically analysed using PC-ORD 4.2 (McCune and Mefford 1999), and the classifications were also viewed as dendrograms to visually determine the fusion level for groups.

Differences in periphyton chlorophyll-a and AFDM between sites were determined using ANOVA, and where a significant effect was revealed the sites that were different were identified using Tukey–Kramer multiple comparison tests.

Results

Water characteristics

Spot measurements of basic water characteristics were similar at most sites before and after the fires (Table 1). A notable exception was turbidity. Immediately after the fires (spring 2003), all sites along the unregulated Goodradigbee River had higher turbidity readings than their adjacent tributaries, unlike sites along the Cotter River. Substantial turbidity readings (39 and 29 NTU) were recorded in the lower Cotter Catchment (CM3 and CT3) below the Cotter Dam in spring 2004. The variation in water temperature between sites and on sampling occasions was most likely caused by the time of day that sampling at each site was undertaken. All other spot measurements of water characteristics were similar before and after the fire at all sites.

Physical habitat

Physical characteristics of all sites were similar before the fires, the substrate being predominantly cobbles and pebbles, with the exception of the most downstream site on the Goodradigbee River (GM3, Fig. 2) where there was considerable boulder and bedrock. The percentage of sand and silt (except at GM2) increased at both regulated and unregulated sites after the fires (spring 2003). The physical characteristics of most sites in spring 2004 were similar to those pre-fire; that is, much of the silt and some sand material had been removed (Fig. 2). Sedimentation of fine material at the two most downstream sites on the Cotter River (CT3 and CM3), and an upstream tributary of the Cotter River

Table 1. Water quality characteristics of sites downstream of the dams along the Cotter River (CM1, CM2, CM3), tributaries of the Cotter River (CT1, CT2, CT3), the Goodradigbee River reference sites (GM1, GM2, GM3) and tributaries of the Goodradigbee River (GT1, GT2, GT3). N/R= measurement was not taken

Site	Water temperature (°C)			Conductivity (µS cm^{-1})			pH			Dissolved oxygen (mg L^{-1})			Dissolved oxygen (% sat)			Turbidity (NTU)		
	2001	2003	2004	2001	2003	2004	2001	2003	2004	2001	2003	2004	2001	2003	2004	2001	2003	2004
CM1	9	8	10	18	33	31	7	7	8	10	12	11	105	107	103	1	3	3
CM2	10	10	N/R	17	29	N/R	7	7	N/R	11	11	N/R	98	101	N/R	N/R	4	N/R
CM3	14	17	18	26	46	52	8	7	8	9	10	9	97	103	104	N/R	11	39
CT1	13	11	N/R	54	47	N/R	7	7	N/R	10	10	N/R	106	98	N/R	N/R	3	N/R
CT2	10	14	12	17	32	35	8	7	7	9	10	10	89	103	100	8	2	14
CT3	14	17	20	70	87	65	8	8	9	10	9	10	102	99	111	N/R	12	29
GM1	14	14	12	87	81	66	8	8	8	15	11	7	90	109	102	1	10	4
GM2	14	15	12	78	76	66	7	8	8	9	11	11	86	116	104	3	18	4
GM3	14	16	13	75	74	66	8	9	7	10	11	12	103	116	105	2	4	4
GT1	12	14	12	46	48	51	8	8	8	12	10	11	85	103	103	8	6	3
GT2	12	14	13	45	46	52	7	7	7	9	10	12	78	103	109	10	4	4
GT3	13	15	13	42	41	44	8	7	7	15	10	12	89	103	101	7	5	4

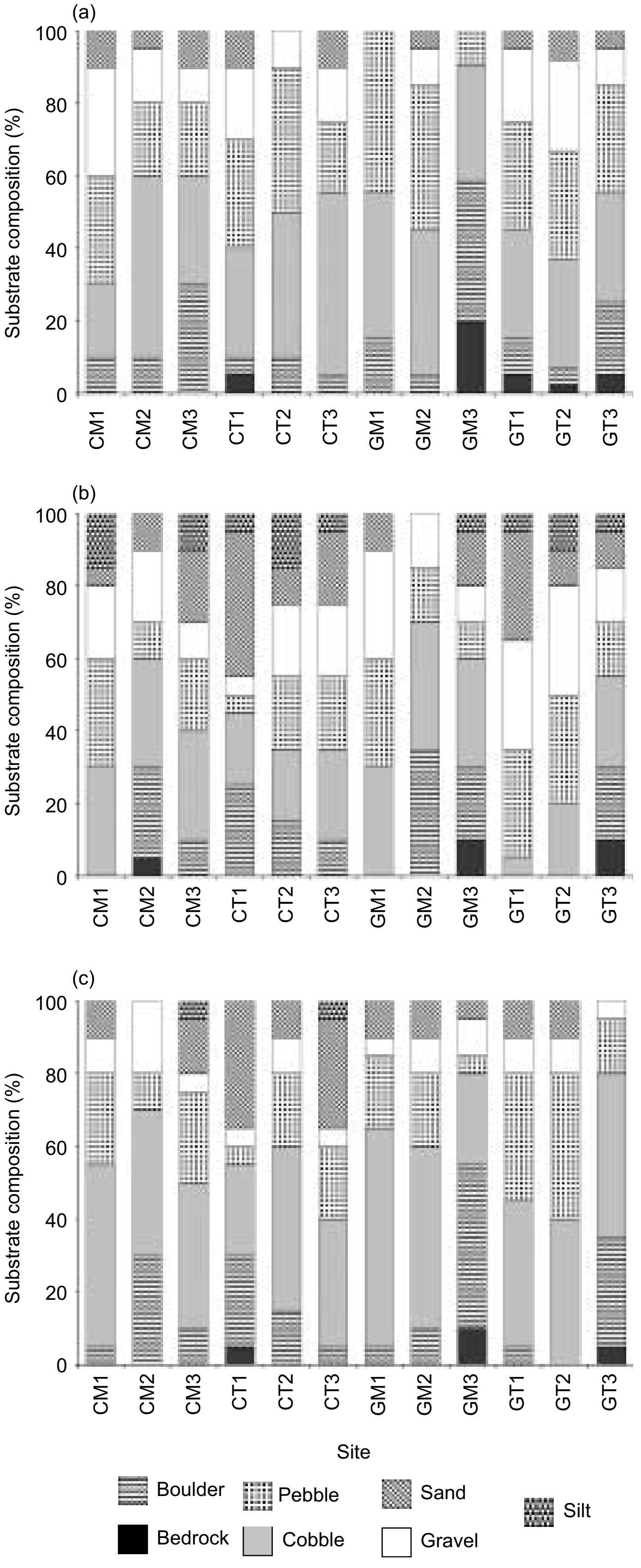


Figure 2. Relative percentage substrate composition in riffle sites downstream of the dams along the Cotter River (CM1, CM2, CM3), tributaries of the Cotter River (CT1, CT2, CT3), the Goodradigbee River reference sites (GM1, GM2, GM3) and tributaries of the Goodradigbee River (GT1, GT2, GT3) for (a) spring 2001 pre-fire, (b) spring 2003 post-fire, (c) spring 2004

(CT1) was still apparent by spring 2004, 22 months after the fire (Fig. 2).

Periphyton

Periphyton composition before the fire appears to have been influenced by the distinctive flow regimes within the two catchments. However, the differences were subsequently overridden by the impacts of the fires. Before the January 2003 fire, periphyton chlorophyll-a concentrations were significantly greater ($P < 0.0001$) at sites downstream of dams compared with the unregulated references sites (Fig. 3). However, there was no significant difference among sites in the amount of AFDM. The difference in periphyton chlorophyll-a content, but not AFDM, indicates that the composition of periphyton at sites downstream of dams was different from that at unregulated sites although the total amount of periphyton was similar at all sites. Compared with pre-fire samples, those taken in the following spring showed greater variance among sites in chlorophyll-a and AFDM, and there were no longer distinct differences between the regulated sites and the unregulated reference sites (Fig. 3). In spring 2004 AFDM and chlorophyll-a were significantly greater ($P < 0.05$, $P < 0.0001$, respectively) at the site CT3 (Paddys River), but otherwise there were no significant differences among all other sites.

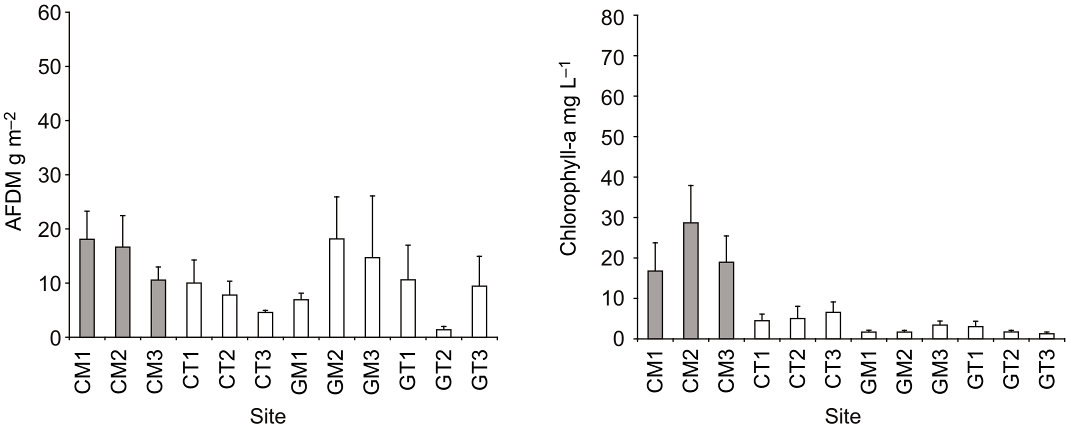
Macroinvertebrates

Spring 2001 pre-fire

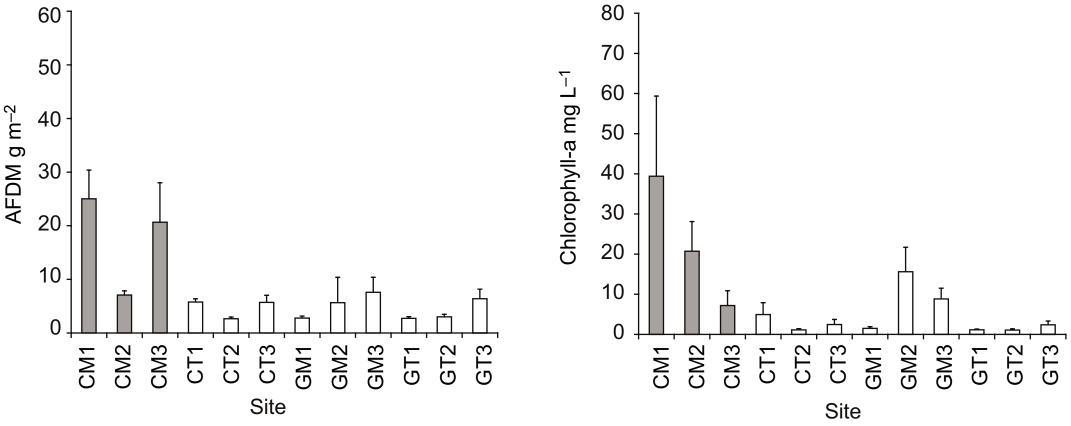
Dams and flow regulation clearly affected macroinvertebrate composition before the January 2003 fires. Fifty one taxa were identified from all sites pre-fire 2001 and were grouped into their respective Orders to simplify presentation (Fig. 4, Table 2). Some families that are more sensitive to changes in water quality and habitat than other members of their Order, including Leptophlebiidae (Ephemeroptera), and Elmidae (Coleoptera), were abundant at all sites except those downstream of dams. Taxa that are more tolerant to these changes include Ortholcladiinae (Diptera), Conoesucidae (Trichoptera), which were more abundant downstream of dams. Oligochaeta (worms), a class generally tolerant of degraded conditions, occurred at all sites, but was notable by greater relative abundance downstream of the Cotter Dam (CM3). The only taxon that was absent from sites downstream of the dams but present at all other sites was the sensitive Trichoptera taxon Glossosomatidae. However, Baetidae and Coloburiscidae (Ephemeroptera), were found at most of the reference or tributary sites and were either totally absent downstream of dams or occurred downstream of only one of the dams. The crustaceans Calanoida and Cladocera were recorded from two of the sites downstream of Bendora (CM2) and Corin (CM1) Dams.

Based on the cluster analysis of all sampling sites the three sites downstream of the Cotter River dams had a clearly different macroinvertebrate composition from all other sites (Fig. 5). The Cotter tributary sites (CT1, CT2, CT3) were more similar to the Goodradigbee River and tributary sites than they were to the sites immediately downstream of dams. The site downstream of the largest dam (CM1) contained two taxa, Physidae (Gastropoda) and Tasimiidae (Trichoptera), that were only collected from this site.

(a) Spring 2001 before the fire



(b) Spring 2003 after the fire



(c) Spring 2004

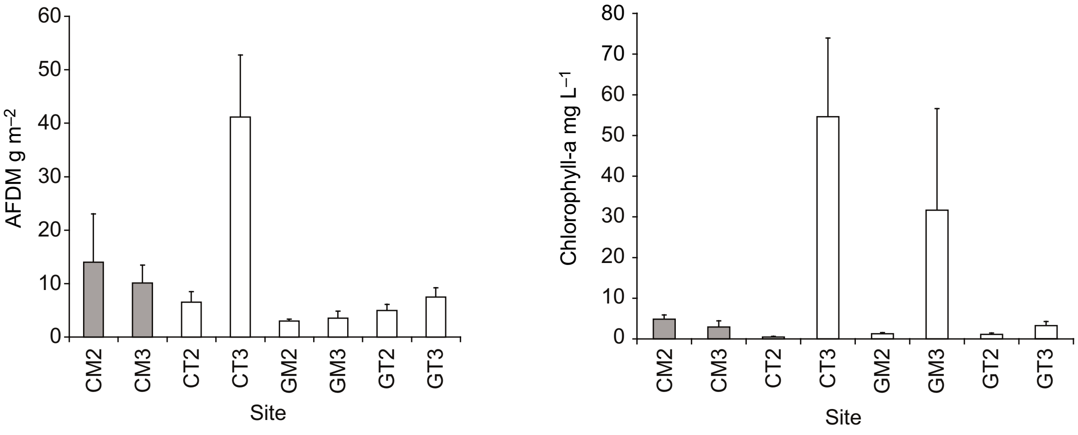


Figure 3. Chlorophyll-a and ash free dry mass (AFDM) of periphyton before (a) and after (b,c) the fire. Error bars show 1 standard error. For site code descriptions see Fig. 2. These data are unavailable for four sites in spring 2004. Shading highlights sites downstream of dams.

Table 2. Number of taxa in each sample from sites downstream of the dams along the Cotter River (CM1, CM2, CM3), tributaries of the Cotter River (CT1, CT2, CT3), the Goodradigbee River reference sites (GM1, GM2, GM3) and tributaries of the Goodradigbee River (GT1, GT2, GT3)

Year	CM1	CM2	CM3	CT1	CT2	CT3	GM1	GM2	GM3	GT1	GT2	GT3
2001	19	26	18	26	29	22	25	21	25	29	24	26
2003	17	17	10	19	11	9	21	22	14	25	24	24
2004	13	11	19	21	25	9	24	21	19	23	17	24

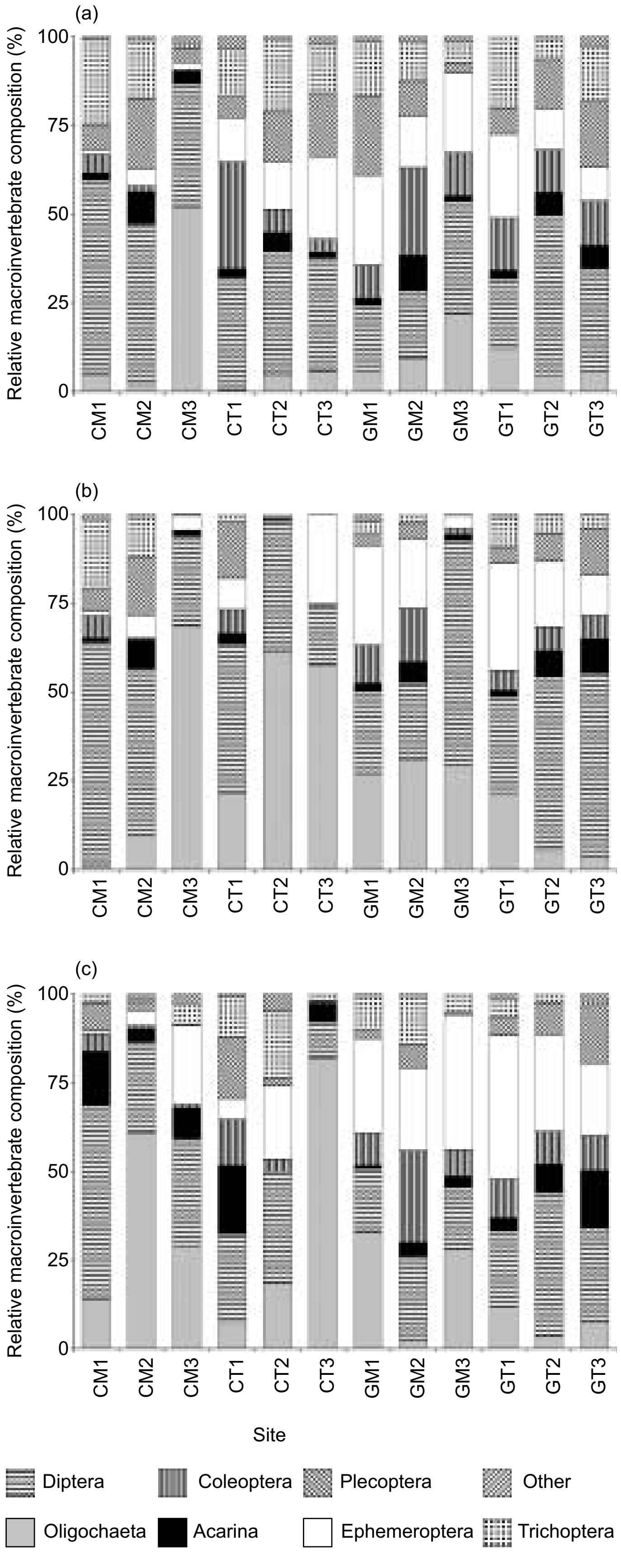


Figure 4. Relative percentage contribution of macroinvertebrate taxa to samples in (a) spring 2001 pre-fire, (b) spring 2003 post-fire, (c) spring 2004. For site code descriptions see Fig. 2.

Spring 2003

In spring 2003, 10 months after the fires, generally fewer taxa were collected at all sites but especially downstream of dams (Table 2), and both Oligochaeta and Chironomidae (Diptera) were numerically dominant at all sites (Fig. 4). However, some of the reference sites (GT2 and GT3) still contained a greater relative abundance of environmentally sensitive taxa such as Ephemeroptera and Coleoptera and more taxa (Table 2) compared with other sites. CT2, a reference site, was distinct in having more more Oligochaeta and Orthocladiinae (Diptera) than all other tributary sites in the Cotter and Goodradigbee River catchments. The two sites situated immediately below upstream dams (CM1, CM2) had clearly different macroinvertebrate composition from CM3 below the most downstream dam (Cotter Dam) in spring 2003 (Fig. 5). CM3 had a depauperate macroinvertebrate composition more similar to its nearest tributary site CT3 and the site furthest downstream in Goodradigbee River (GM3).

Spring 2004

In spring 2004, 22 months after the fires, numbers of taxa collected at unregulated sites had improved to close to pre-fire levels (Table 2). At this time all sites in the Goodradigbee River catchment were grouped together and were similar to spring 2001 pre-fire (Fig. 5). CT2 was again an outlier site containing two Trichoptera families, Philoptamidae and Tasimiidae that did not occur at any other site in either catchment. However, the numerical dominance of Oligochaeta and Chironomidae (Diptera) was less at CT2 compared with the spring 2003 sample (Figs 4 and 5) and taxa richness had increased close to the pre-fire level (Table 2). Sites downstream of Corin Dam (CM1) and Bendora Dam (CM2) grouped together (Fig. 5c), but taxa richness had decreased further compared to spring 2003 (Table 2).

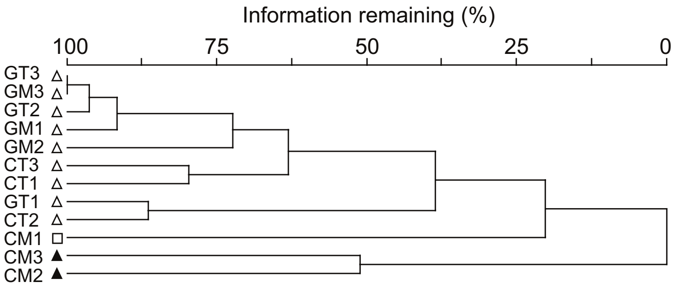
Discussion

Pre-fire benthic community structure

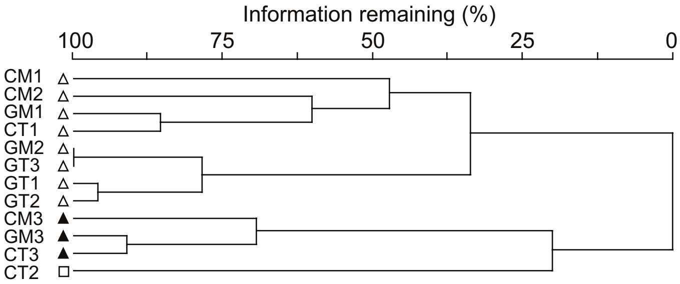
Before the 2003 fire burnt much of the Cotter and Goodradigbee Rivers' catchments there was little difference between sites in the chemical characteristics of the water (Talsma and Hallam 1982; Talsma 1983; Sloane *et al.* 1998, 1999), regardless of proximity to dams (Table 1). Given that the sites downstream of dams were physically and chemically similar to the reference and tributary sites, it would be expected that they would have similar periphyton communities (Kutka and Richards 1996; Cattaneo *et al.* 1997). Nutrient status and time since last flow disturbance have been shown to be the principal determinants of periphyton growth (Biggs 1995). Therefore, the differences in the periphyton communities between those downstream of dams and other sampling sites (Fig. 3) before the fire most likely resulted from the different flow regime, caused by river regulation.

Macroinvertebrate communities below dams often have reduced populations and displaced taxa (Weisberg *et al.* 1990; Growns and Growns 2001; Marchant and Hehir 2002). Sites downstream of dams in the Cotter River had macroinvertebrate assemblages

(a) Spring 2001 before the fire



(b) Spring 2003 after the fire



(c) Spring 2004

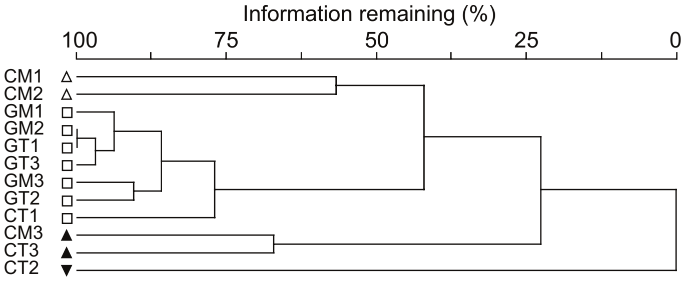


Figure 5. Classification of sites based on macroinvertebrate relative abundance ($\log_{10}$ [X+1] transformed) before (a) and after (b,c) fire in January 2003. Symbols identify groups of sites with similar family-level compositions (log transformed). For site code descriptions see Fig. 2.

distinct from those at unregulated sites (Figs 4, 5). Before the fire, macroinvertebrate taxa not abundant (Orthocladiinae and Oligochaeta) or not present (Calanoida, Cladocera and Gastropoda) at unregulated tributary and reference sites were present and more abundant at sites downstream of dams. Sensitive taxa abundant at unregulated reference and tributary sites (e.g. Leptophlebiidae and Glossosomatidae) were eliminated or present in lower numbers at sites downstream of dams in the Cotter River. Thus, the biological condition of sites below dams showed signs of stress from dams and flow regulation before the January 2003 fires.

Short to mid-term effects of fire on benthic communities

Increased nutrient concentrations, temperature and light instream are typically reported after a fire; these conditions favour algal growth (see review by Gresswell 1999). However, subsequent changes to hydrology and sediment transport associated with rainfall after the loss of terrestrial vegetation may increase the magnitude of scouring and deposition instream (Scrimgeour *et al.* 2001), which may reduce periphyton. At all sites in spring 2003 there were visible increases in finer grained material, notably silt and sand (Fig. 2). The scouring from suspended sediment associated with post-fire rainfall most likely caused the shift in periphyton communities at sites downstream of the dams, which then had less chlorophyll-a and became more similar to unregulated sites when compared with spring 2001. Thus, the effects of the fire on the periphyton community are likely to have overridden the effects of the dams and flow regulation.

Macroinvertebrate composition changes following fire have been well documented (Minshall *et al.* 1997, 2001; Papas 1998; Gresswell 1999) and may vary from little effect (e.g. Albin 1979) to marked effects on abundance and richness depending on the time since burning (e.g. Lawrence and Minshall 1994). The reduction in taxa richness and shifts in relative abundance that occurred at all sites by spring 2003, after the fire and regardless of regulation, were similar to those in the studies just mentioned. As with the periphyton, the effects of a major fire on the macroinvertebrate community overwhelmed the effects of the dams.

Fine sediments had been flushed from most of the unregulated sites by spring 2004. Two sites in the lower Cotter catchment CM3 and CT3 still had more fine sediments compared to pre fire, which is probably indicative of their position in the catchment. The lower part of the catchment is a sink for sediment, rather than a source. Fine material had become trapped in the periphyton matrix at site CT3 in the lower Cotter catchment, creating conditions unfavourable for many macroinvertebrate grazers. The consequent reduction in grazing may have allowed the increase in AFDM seen at that site (Fig. 2), similar to observations in the Makomanai River in Japan that received fine sediments from a quarry (Yamada and Nakamura 2002). Oligochaeta and chironomids were numerically dominant at CT3, which is indicative of habitat that is organically enriched (Brennan *et al.* 1978; Whitehurst and Lindsey 1990). Thus, the effects of fire on stream biota will be dependent on position in the catchment, sediment loads and particle size and post-fire rainfall, as found elsewhere (Gresswell 1999).

Flushing of fine sediment was largely complete by spring 2004 at the two upstream sites below Corin Dam (CM1) and Bendora Dam (CM2). However, areas further downstream may not have recovered as quickly as these two sites because they received more sediment from tributaries, and have more pools that may act as sinks for the finer grained material. The physical habitat at the sites CM1 and CM2 had improved by spring 2004 (Fig. 2), but their macroinvertebrate communities became further impaired in contrast to the biota at all other sites, which had largely recovered to pre-fire condition. The negative effect of the modified flow regime, combined with fire effects, had probably passed a threshold resulting in the loss of less resilient taxa previously found at sites downstream of the two dams. Therefore, the aquatic ecosystems may recover quickly from a natural disturbance such as the 2003 fire, but when combined with a human disturbance the effects may be more severe and longer lasting.

Conclusion

Fire can be a major disturbance to aquatic biota, outweighing the effects of other stressors, in this case dams and flow regulation. The effects of fire were not as severe, and recovery was faster, in the majority of unregulated tributaries and in the nearby unregulated Goodradigbee River. Thus, a natural disturbance such as fire may be more serious and longer lasting when combined with human activities such as flow regulation for water harvesting. It is not clear from this study if the benthic communities in the regulated stream will recover to pre-fire condition without active restoration.

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