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APPLIED ISSUES

Spatial and temporal impacts of a diesel fuel spill on stream invertebrates

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SUMMARY

1. We assessed the effects of a 26 500 L diesel fuel spill on the macroinvertebrate fauna of a small trout stream in central New York, U.S.A. To determine the spatial extent of the spill we sampled three locations (0.7, 5.0 and 11.8 km downstream of the spill), each containing a reference site (unaffected tributary) and an impact site (downstream of spill). Sampling was repeated four times over a 15-month period to assess temporal recovery.
2. Immediately after the spill, invertebrate density at all three locations below the spill was significantly lower than reference density. Three months after the spill, density up to 5 km below the spill was still far lower (<100 individuals per sample) than reference density (800–1200 individuals per sample). A year after the spill, density was similar between reference and impact sites, suggesting that invertebrates had recovered numerically.
3. Taxonomic richness up to 5.0 km below the spill was less than half the reference taxonomic richness and this difference persisted for at least 3 months. Some significant differences between reference and impact sites were observed after 15 months, but these differences could not be attributed to the oil spill.
4. For at least 3 months following the spill, the site immediately downstream of the spill was dominated by *Optioservus*, a petrochemical-tolerant riffle beetle. Twelve to 15 months after the spill, both the reference and impact sites near the spill were dominated numerically by the mayfly *Ephemerella*, but the degree of dominance was twice as large at the impact site.
5. We concluded that the diesel fuel spill significantly reduced the density of invertebrates (by 90%) and taxonomic richness (by 50%) at least 5.0 km downstream, but density recovered within a year. Throughout the study, however, the fauna immediately below the spill was species poor and significantly over-represented by a single dominant taxon, suggesting that 15 months was not sufficient for full community recovery from the oil spill.

Keywords: anthropogenic disturbance, biomonitoring, diesel fuel, macroinvertebrates, oil spills

Introduction

Stream biota are seriously threatened by a variety of human activities including the modification of stream channels and riparian zones, the introduction of exotic species, habitat destruction and pollution (Allan & Flecker, 1993). Despite reports of a general improvement in chemical pollution in streams, compared with the accelerating loss of stream habitat (Smith, Alexander & Wolman, 1987; Diamond, 1989; Benke, 1990), the transport of petrochemicals along stream valleys remains an environmental risk (Blumer & Sass, 1972; Bury, 1972; Cairns & Buikema, 1984).

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The extent of damage to stream fauna that has been reported following accidental oil spills is diverse and complex (Miller & Stout, 1986; Crunkilton & Duchrow, 1990). This is because effects depend on the chemical characteristics of the petrochemical, the volume spilled and the nature of the receiving water and its biota (Parker *et al*., 1976; Crunkilton & Duchrow, 1990). Clearly, high volume spills cause more damage than smaller ones (Masnik *et al*., 1976; Cushman & Goyert, 1984; Crunkilton & Duchrow, 1990). Although the effect of crude oil containing heavy insoluble compounds is generally more persistent, lighter water soluble oils that evaporate faster are also highly toxic (Blumer *et al*., 1971; Blumer & Sass, 1972; Bury, 1972; Snow, Rosenberg & Moening, 1975; Barton & Wallace, 1979b; Rosenberg, Wiens & Flannagan, 1980; Crunkilton & Duchrow, 1990). The insoluble fraction can combine with the particulate organic matter or inorganic matter on the stream bed resulting in persistently toxic effects or an increased consumption of oxygen by bacteria during decomposition (Blumer & Sass, 1972; Harrel, 1985; Crunkilton & Duchrow, 1990). However, some studies suggest that exposure to water soluble fractions of oil causes more mortality than does exposure to the products of oil degradation in sediment residues (Hoehn *et al*., 1974; Masnik *et al*., 1976).

Stream discharge also plays an important role in determining the extent of damage caused by oil spills. Smaller streams are more susceptible than larger streams (McCauley, 1966; Harrel, 1985) and spills that occur in seasons when discharge is low are more damaging when close to the vicinity of the spill (Harrel, 1985; Crunkilton & Duchrow, 1990). However, turbulent flow at the time of a spill can enhance dispersion of petrochemicals, thereby affecting the spatial extent of the immediate impact on the fauna (Pontasch & Brusven, 1988; Crunkilton & Duchrow, 1990). In contrast, scouring flows have been shown to accelerate recovery from oil spills not only by removing oil from the sediment (Guiney, Sykora & Keleti, 1987), but also by enhancing the recolonization of stream biota from upstream (Pontasch & Brusven, 1988). The season of occurrence of an oil spill also affects the rate of recovery of invertebrates by determining the availability of terrestrial stages that can recolonize streams by oviposition (Harrel, 1985; Guiney, Sykora & Keleti, 1987; Pontasch & Brusven, 1988; Crunkilton & Duchrow, 1990).

Rigorous studies of the effects of oil spills on stream biota are difficult because investigators rarely have prespill data for comparative purposes (Bury, 1972) and controlled experiments testing for such effects are unusual (Rosenberg & Wiens, 1976; Barton & Wallace, 1979a; Lock *et al*., 1981; Miller & Stout, 1986). Therefore, studies measuring the impact of accidents after they have already occurred need to be designed carefully to minimize alternative explanations for differences between impact sites and unaffected reference sites. The purpose of this study was to investigate the effects of an oil spill using a sampling scheme that enabled us to determine both the spatial and temporal extent of impacts on the invertebrate fauna of a small trout stream.

At 2:30 a.m. on 3 November 1997, three of five Conrail locomotive engines hauling 21 cars were derailed near West Danby, Tompkins County, New York, USA, spilling an estimated 26 500 L of diesel fuel into a first order reach of the Cayuga Inlet, a tributary of Cayuga Lake. A fish kill of rainbow trout (*Oncorhyncus mykiss* Walbaum), white sucker (*Catostomus commersoni* Lacepède), blacknose dace (*Rhinichthys atratulus* Agassiz) and darters (*Etheostoma* spp.) estimated at 92% of total fish abundance was reported the following day (C.C. Krueger, unpublished). Despite efforts to clean up the spill with chemical containment booms, slicks of the diesel fuel were seen floating on the surface of Cayuga Lake 16 km downstream within 24 h.

The Cayuga Inlet is one of the premier trout fishing streams in the area and holds a population of naturally breeding rainbow trout that spawn in spring. As the Inlet is one of the few tributaries to 170 km^2 Cayuga Lake where upstream migration of fish is not blocked by waterfalls, it is also an important spawning ground for Cayuga Lake brown trout (*Salmo trutta* Linnaeus) and salmon (*Salmo salar* Linnaeus). These fish were beginning their autumn run when the spill occurred. Amphibians, water birds, mink (*Mustela vison* Schreber) and other animals also use the Inlet and its riparian areas. Many of these animals ultimately depend on aquatic insects, snails and other aquatic invertebrates for food. Because of these food-web connections, an assessment of damage to the aquatic invertebrate community is crucial for gauging the magnitude of effects of this spill. To assess the recovery of the stream from this disturbance, we report impacts of the spill on the aquatic invertebrates of the Cayuga Inlet up to 15 months after the spill.

Methods

Invertebrates were sampled at sites 0.7, 5.0 and 11.8 km downstream of the spill (impact sites), and at unaffected tributaries that flow into the Inlet just upstream of each site on the main stream (Fig. 1, Table 1). These tributaries served as reference sites for gauging the impact of the spill on the main channel of Cayuga Inlet. Usage of reference sites allowed us to isolate the effects of the oil spill from other seasonal

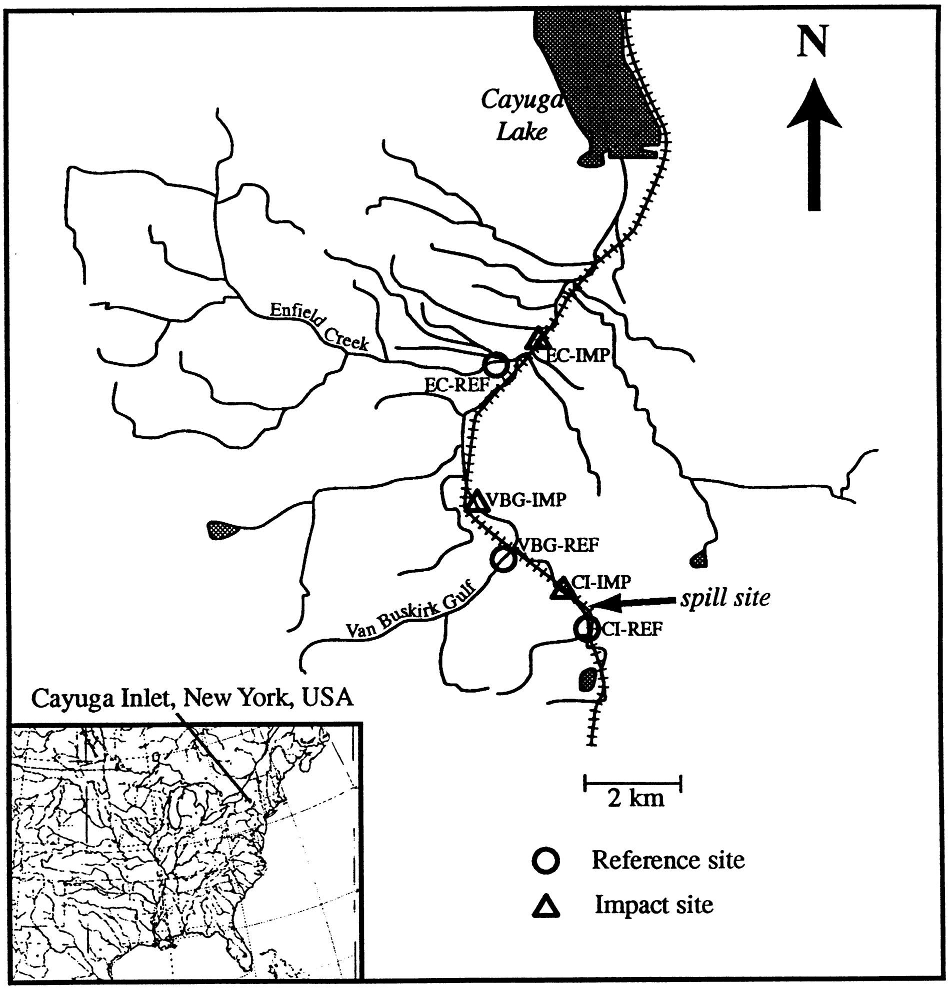

Fig. 1 Sampling locations along Cayuga Inlet, consisting of a reference site (upstream of the spill or a tributary to Cayuga Inlet) and an impact site (the Inlet itself downstream from the spill). The most-upstream Cayuga Inlet impact site (CI-IMP) is 0.7 km downstream from the spill; the Van Buskirk Gulf site (VBG-IMP) is 5.0 km downstream of the spill and Enfield Creek (EC-IMP) is 11.8 km below the spill.

Table 1 Sampling locations, dates and replication

Location	Dist. from spill (km)	Treatment	Autumn 1997 sample date	Reps	Spring 1998	Reps	Autumn 1998 sample date	Reps	Spring 1999 sample date	Reps
Cayuga Inlet (CI)	0.7	Impact	19-Nov-1997	5	3-Feb-1998	5	18-Nov-1998	6	12-Feb-1999	6
		Reference	19-Nov-1997	5	3-Feb-1998	5	18-Nov-1998	6	12-Feb-1999	6
Van Buskirk Gulf (VBG)	5.0	Impact	19-Nov-1997	6	10-Feb-1998	6	18-Nov-1998	6	12-Feb-1999	6
		Reference	19-Nov-1997	6	10-Feb-1998	6	18-Nov-1998	6	12-Feb-1999	6
Enfield Creek (EC)	11.8	Impact	29-Nov-1997	6	31-Mar-1998	6	18-Nov-1998	6	13-Feb-1999	6
		Reference	29-Nov-1997	6	31-Mar-1998	6	18-Nov-1998	6	13-Feb-1999	6

changes that occurred during the study. The tributaries were also potential sources of colonists to the damaged stream.

We sampled each pair of reference and impact sites 2 to 3 weeks, 3 to 4 months, a year and 15 months after the spill (Table 1). This sampling design enabled us to determine whether the impacts of the spill diminished over space (along 11.8 km of the Inlet) and in time (after 15 months of potential recovery). Because most aquatic invertebrates do not have aerial dispersal stages during the winter, the major source of colonists to the impact sites during the first two sampling periods would have been aquatic stages drifting in the water column from upstream.

We quantified instream habitat and basin characteristics for all six sites in the spring of 1999. Bankfull channel dimensions were estimated in the field and mean discharge was calculated at baseflow from multiple depth and current velocity readings across transects at each site. Substratum and habitat type (riffle, run or pool; after Simonson, Lyons & Kanehl, 1994) were characterized from point-estimates at regular intervals along 12 diagonal stream transects (at least 100 measurements per site). Drainage basin areas and percentage agricultural land use were obtained from U.S. Geological Survey topographical maps and aerial photographs.

We sampled benthic invertebrates using standard collecting techniques. We chose six sampling areas within a 20–30 m reach of stream at each site. To facilitate comparisons among streams we sampled primarily in riffle habitats, as pool and run habitats were not common at all sites (Table 2, Results). For each of the six samples per site, invertebrates were dislodged from the stream bottom into a standard D-frame invertebrate net (mesh size 0.8 mm) by agitating the substratum along a transect for 1 min (as in Hoehn *et al.*, 1974; Crunkilton & Duchrow, 1990). Invertebrates were separated from rocks, pebbles and leaves and preserved in 70% ethanol for later analysis. This protocol was repeated at each site during each season (6 samples $\times$ 6 sites $\times$ 4 seasons = 144 samples total).

Samples were processed in the laboratory and analysed for comparison of three different measures of aquatic invertebrate communities between impact and reference sites for each location and time period: (1) All invertebrates in each sample were counted, which gave us a relative estimate of total invertebrate density per 1 min sampling effort. (2) Taxonomic richness of each sample was also determined (total number of different taxa of invertebrates identified to the lowest taxonomic level possible, which was genus in most cases). (3) Numerical dominance of the most abundant taxon was determined by calculating the percentage of each sample comprised of the dominant taxon. Chironomids were excluded from this analysis because of the large mesh size of the nets. Voucher specimens have been permanently deposited in the Cornell University Insect Collections.

We tested for differences between the paired impact and reference sites using separate ANOVAs (treat-

Table 2 Stream habitat and basin characteristics of reference and impact sites. CI = Cayuga Inlet, VBG = Van Buskirk Gulf, EC = Enfield Creek (see Fig. 1 for locations)

Site	CI-IMP	CI-REF	VBG-IMP	VBG-REF	EC-IMP	EC-REF
Habitat (%)						
Riffle	41	48	42	63	47	46
Pool	0	9	54	28	22	4
Run	59	42	4	9	30	50
Average discharge (cm s^{-1})	0.5	0.2	1.4	0.4	3.4	1.7
Average current velocity (m s^{-1})	0.46	0.25	0.71	0.38	0.40	0.45
Substratum (%)						
<2 mm	11	5	8	3	10	11
2–16 mm	16	2	43	13	6	10
16–64 mm	50	58	31	43	43	38
64–256 mm	21	34	14	39	40	40
>256 mm	2	1	4	2	1	1
Agricultural land use (%)	7.1	21.5	47.7	42.6	32.9	26.6
Basin area (km^2)	20.2	10.9	46.6	12.0	183.3	86.6

ment = oil or no oil × three locations at increasing distances from the spill, both factors fixed) for each of the response variables (density, taxonomic richness, percentage of dominant taxon) at each season. If the treatment effect was significant, we conducted planned pairwise comparisons to determine which location had significant reference–impact differences. If location × treatment interactions were significant, we conducted planned pairwise contrasts to test whether the severity of the impact (the magnitude of the difference between reference and impact sites) at the location closest to the spill was greater than that further downstream. To normalize distributions and stabilize variances, data for density and taxonomic richness were log transformed and data for percentage dominant taxon data were arcsine transformed.

This analysis enabled us to determine whether any of the response variables differed significantly between reference and impact sites immediately after the spill, whether the magnitude of these differences diminished downstream from the spill and whether these differences declined over time. Because the oil spill 'treatment' was not randomly assigned to different streams, this statistical approach was only useful for identifying patterns of differences between reference–impact pairs. The cause of these differences could, in theory, be the oil spill or pre-existing differences among drainages. To attribute reference–impact differences to the effects of the oil spill, we made inferences obtained from the spatial pattern (asking: were reference–impact differences greater near the spill?), temporal pattern (asking did reference–impact pairs converge over time?), and physical drainage characteristics (asking were reference–impact pairs similar in other respects?). Because statistics were used in an exploratory manner to identify patterns of reference–impact differences, rather than to directly attribute causation to the oil spill, we did not adjust for multiple comparisons and rejected null hypotheses at $\alpha = 0.05$.

Results

Reference–impact pairs had comparable habitat composition (percentage riffle, run or pool), substratum and percentage agricultural land use (Table 2). Upstream sites had smaller basin areas than downstream sites (eight-fold increase in basin area from CI to EC in both impact and reference sites) (Table 2). Impact sites had greater total basin areas than reference sites, primarily because impact sites contained the catchments of their respective reference sites. Discharge and current velocity, which are typically correlated with basin area, showed the same pattern. Most sites were dominated by substratum particles of intermediate size (16–64 mm intermediate axis), and no sites had more than 11% fine particles (< 2 mm) or more than 4% large particles (> 256 mm).

Invertebrate density

At the first sampling date (Autumn 1997) total invertebrate density upstream of the spill averaged almost 1000 individuals per 1 min sample, while 0.7 km below the spill average density was only about 100 per sample (Fig. 2), suggesting an initial 90% reduction in stream invertebrates. Differences in invertebrate density between reference–impact pairs were observed as far as 11.8 km below the spill. A marginally insignificant location × treatment interaction (Table 3a) suggests that the initial severity of the impact on invertebrate density (the magnitude of the difference between reference and impact sites) was just as large 11.8 km downstream as 0.7 km downstream. We suspect that invertebrate density was generally lower at the 11.8 km location because both the reference and impact streams at this site drain relatively large catchments (Table 2) and may be subject to seasonal scouring from floods and removal of invertebrates.

Several high-flow events occurred between autumn 1997 and spring 1998, which potentially washed out some of the diesel fuel but also may have had a physical impact (scouring) on the invertebrates. Total invertebrate density actually declined from autumn 1997 to spring 1998 at the impact sites on the Inlet 0.7 and 5.0 km downstream of the spill (Fig. 2). Some of this seasonal decline may reflect natural flood events that decreased invertebrate density at the locations with larger catchments (5.0 and 11.8 km downstream from the spill). Despite these natural occurrences that could have obscured differences between reference and impact sites at the spring of 1998 sampling date, we observed virtually no recovery of the invertebrate community as far as 5.0 km downstream of the spill 3 months after it occurred. Unlike the first sampling date, there were no significant differences in

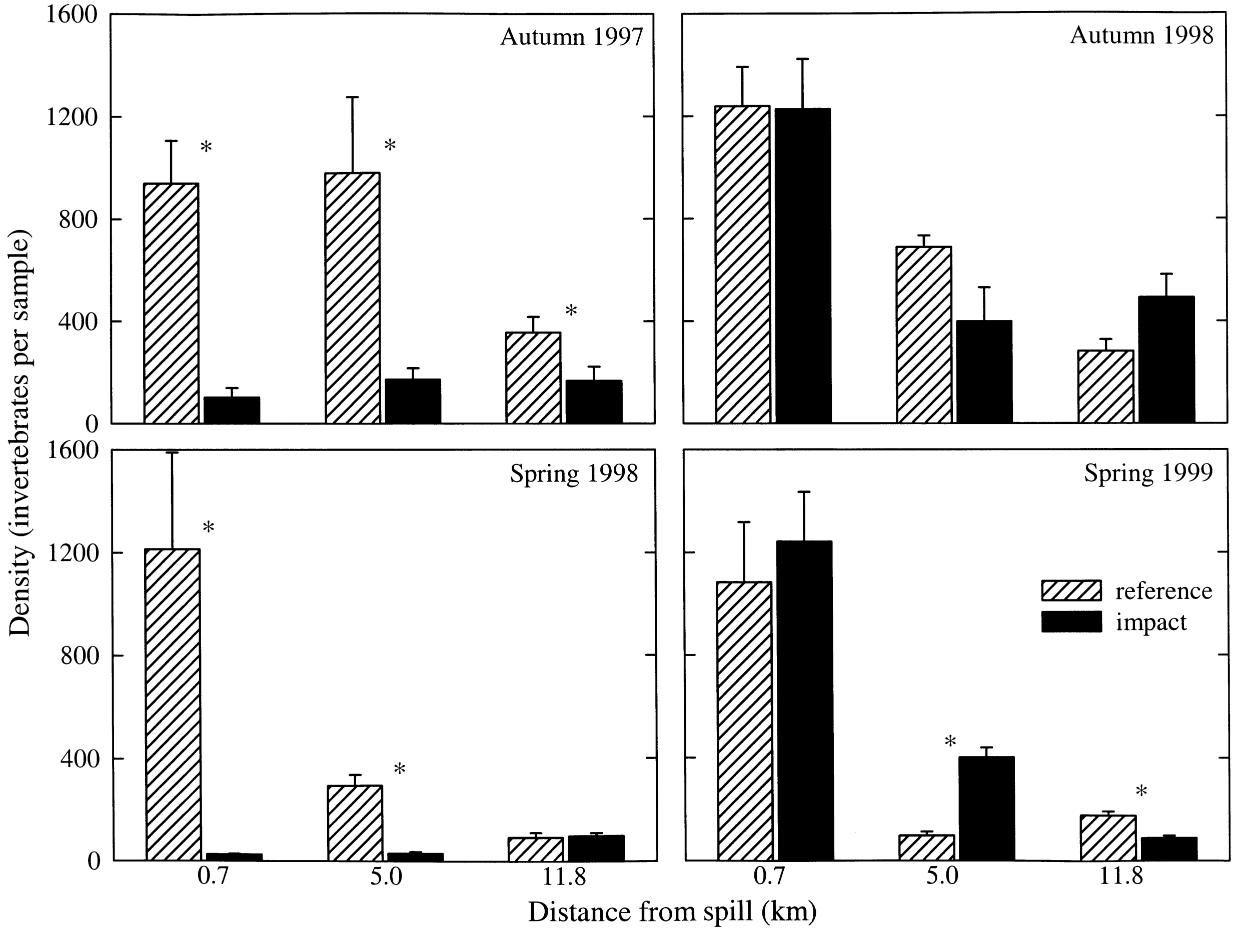

Fig. 2 Invertebrate density (mean and SE) from 1-min kick samples taken at reference and impact sites along the Cayuga Inlet during 15 months after the oil spill. Asterisks denote significant differences between reference–impact pairs.

invertebrate density between the reference and impact sites 11.8 km downstream of the spill.

A year after the spill there were no significant differences in invertebrate density between reference–impact pairs (Table 4a), not even between the reference–impact pair nearest the spill. Surprisingly, density was higher near the spill than at other locations (Fig. 2). As with the spring 1998 samples, these differences may have resulted from scour at the downstream locations with greater drainage basin areas. There was a similar pattern of downstream decline in invertebrate density in spring 1999 (Fig. 2), but at this time significant differences were apparent between reference–impact pairs (Table 4b). At the location 5.0 km below the spill, invertebrate density was significantly lower in the reference site than the impact site. This result was clearly not related to the oil spill, but because of the deterioration of the reference site from anthropogenic activity causing high turbidity and sediment loads at the 5.0 km reference site. Similarly, we attribute differences in invertebrate density between the 11.8 km reference and impact sites to natural fluctuations unrelated to the oil spill, because density did not differ between these two sites during the two previous sampling times.

Taxonomic richness

Immediately after the spill, taxonomic richness of invertebrates was also significantly lower in impact sites compared with their reference sites as far as 5.0 km downstream (Fig. 3, Table 3a). While an average of over 20 taxa was found per sample at the reference site upstream of the spill, an average of only 11 was found immediately below the spill. A similar difference occurred 5.0 km downstream.

Table 3 Year 1: Autumn 1997 (a) and Spring 1998 (b) ANOVAs for total invertebrate density (log transformed), taxonomic richness (log transformed) and percentage dominant taxon (arcsine transformed) for the three sampling locations (0.7, 5.0 and 11.8 downstream of spill) and two treatments at each location (impact and reference)

Response variable	Source	d.f.	Mean square	*F*	*P*
a. Autumn 1997					
Density	Location	2	0.505	1.01	0.376
	Treatment	1	22.979	46.09	<0.001
	Location × Trt	2	1.553	3.11	0.060
	Error	28	0.499		
Taxonomic richness	Location	2	0.178	2.67	0.087
	Treatment	1	1.340	20.97	<0.001
	Location × Trt	2	0.120	1.79	0.185
	Error	28	0.067		
Percentage dominant taxon	Location	2	0.119	6.36	0.005
	Treatment	1	0.005	0.29	0.593
	Location × Trt	2	0.085	4.52	0.020
	Error	28	0.019		
b. Spring 1998					
Density	Location	2	1.135	5.23	0.012
	Treatment	1	32.616	150.19	<0.001
	Location × Trt	2	10.534	48.51	<0.001
	Error	28	0.217		
Taxonomic richness	Location	2	0.360	4.07	0.0280
	Treatment	1	4.985	56.44	<0.001
	Location × Trt	2	1.544	17.49	<0.001
	Error	28	0.088		
Percentage dominant taxon	Location	2	1.907	57.68	<0.001
	Treatment	1	0.167	5.05	0.033
	Location × Trt	2	0.147	4.44	0.021
	Error	28	0.033		

Three months after the spill, taxonomic richness remained lower at impact versus reference sites as far as 5.0 km below the spill (Fig. 3, Table 3b). As with density, impact sites located 0.7 and 5.0 km below the spill actually showed a decrease in diversity during this time. The severity of the difference between reference and impact sites was significantly greater immediately below the spill compared with 5.0 km downstream (contrast on significant interaction, Table 3b).

No differences in taxonomic richness remained between reference–impact pairs a year after the spill (Fig. 3, Table 4a). By spring 1999, however, diversity at impact sites 0.7 and 11.8 km below the spill was significantly lower than reference values (Fig. 3, Table 4b). This pattern of declining taxonomic richness from autumn to spring parallels the overall decline in invertebrate density at all sites. As this pattern only occurred at the impact sites nearest to (0.7 km) and furthest from (11.8 km) the spill, and not at 5.0 km, we cannot attribute lower taxonomic richness at these two sites directly to the oil spill.

Percentage dominant taxon

Immediately after the spill, the percentage of individuals represented by a single taxon was similar between impact versus reference sites (Fig. 4, Table 3a). However, while all of the reference sites were dominated by larvae of various species of mayflies, the impact site immediately downstream of the spill was dominated by the riffle beetle *Optioservus*, one of the few invertebrates known to tolerate petrochemical pollution (Cairns *et al*., 1972; Barton & Wallace, 1979a; Pontasch & Brusven, 1988). Three months later, impact sites as far as 5.0 km below the spill were dominated by a single taxon significantly more than their respective reference sites (Fig. 4, Table 3b). The taxa dominating each site exhibited seasonal changes consistent with known life history patterns of stream invertebrates. For example, we observed an early spring increase in larvae of *Prosimulium*, a black fly, at the headwater reference site and an early spring increase in the mayfly *Baetis* in the

Table 4 Year 2: Autumn 1998 (a) and Spring 1999 (b) ANOVAs for total invertebrate density (log transformed), taxonomic richness (log transformed), and percentage dominant taxon (arcsine transformed) for the three sampling locations (0.7, 5.0 and 11.8 downstream of spill) and two treatments at each location (impact and reference)

Response variable	Source	d.f.	Mean square	*F*	*P*
a. Autumn 1998					
Density	Location	2	4.852	25.98	<0.001
	Treatment	1	0.048	0.26	0.615
	Location × Trt	2	1.241	6.64	0.004
	Error	30	0.187		
Taxonomic richness	Location	2	0.083	4.42	0.021
	Treatment	1	0.053	2.84	0.102
	Location × Trt	2	0.025	1.34	0.276
	Error	30	0.019		
Percentage dominant taxon	Location	2	0.085	6.81	0.004
	Treatment	1	0.698	55.94	<0.001
	Location × Trt	2	0.050	3.99	0.029
	Error	30	0.012		
b. Spring 1999					
Density	Location	2	15.498	109.90	<0.001
	Treatment	1	0.924	6.55	0.016
	Location × Trt	2	3.553	25.19	<0.001
	Error	30	0.141		
Taxonomic richness	Location	2	0.406	9.79	<0.001
	Treatment	1	0.674	16.26	<0.001
	Location × Trt	2	0.349	8.42	0.001
	Error	30	0.041		
Percentage dominant taxon	Location	2	0.124	12.79	<0.001
	Treatment	1	0.530	54.77	<0.001
	Location × Trt	2	0.079	8.19	0.002
	Error	30	0.010		

deeper-water sites. The impact site 0.7 km downstream of the spill continued to be dominated by the petrochemical-tolerant riffle beetle *Optioservus*.

A year after the spill, impact sites still had a higher percentage dominance by a single taxon than their respective reference sites, but in some cases the dominant taxon changed (Fig. 4, Table 4a). Both the reference and impact sites closest to the spill contained large numbers of early instar *Ephemerella*. *Ephemerella* dominated the fauna 0.7 km below the spill to a greater degree than immediately above it and this pattern persisted until spring 1999 (Fig. 4, Table 4b). By spring 1999 the only site that had > 50% dominance of a single taxon was the site 0.7 km downstream of the spill.

Discussion

Our survey of the invertebrate communities in sections of the Cayuga Inlet potentially affected by the diesel fuel oil spill that occurred in November 1997 indicates an immediate and severe impact (~90% reduction in density) of the stream invertebrates up to 5.0 km from the spill. Invertebrate density was also initially reduced 11.8 km downstream but this reduction was not detectable 3 months later. This immediate local reduction in the stream fauna and spatial dissipation of effect has been reported by other investigators (McCauley, 1966; Cairns *et al*., 1971; Hoehn *et al*., 1974; Harrel, 1985; Crunkilton & Duchrow, 1990). However, a severe reduction of the invertebrate fauna beyond 5.0 km of the stream is relatively extreme compared with the spatial distribution of impacts reported by other studies, with the exception of Bury (1972) who reported effects as far as 8 km downstream of a diesel fuel spill in a small California stream.

This damage was reflected in reduced numbers of taxa (compared with adjacent reference sites that were unaffected by the spill) and the predominance of an oil pollution-tolerant species of riffle beetle at the site

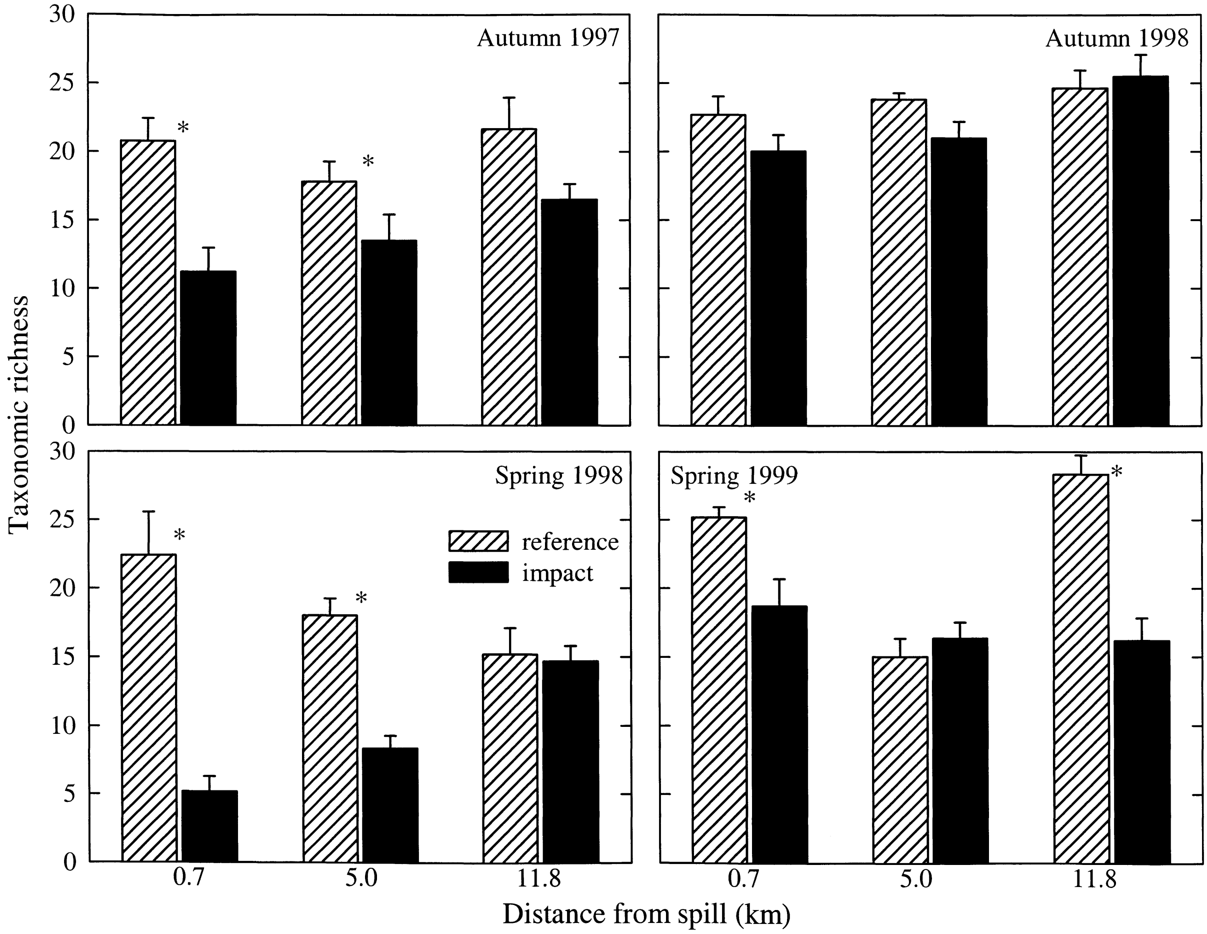

Fig. 3 Taxonomic richness (mean and SE) from 1-min kick samples taken at reference and impact sites along the Cayuga Inlet during 15 months after the oil spill. Asterisks denote significant differences between reference–impact pairs.

closest to the fuel spill. We saw few signs of recovery of the stream invertebrate community 3 months after the spill in February 1998. Invertebrate density and taxonomic richness remained significantly reduced. The oil pollution tolerant riffle beetle continued to dominate the site closest to the oil spill. Other studies of spills of similar magnitude have also reported slow recovery of numbers of invertebrates and taxonomic richness (Bury, 1972; Barton & Wallace, 1979a; Harrel, 1985; Pontasch & Brusven, 1988; Crunkilton & Duchrow, 1990).

This observation of no significant recovery of the benthic invertebrate community 3 months after the spill suggests that the stream habitat in the Cayuga Inlet was unfit for recolonization of invertebrates from the location of the spill extending downstream 5.0 km. Furthermore, the habitat had not sufficiently recovered for colonists from upstream tributaries, the only source of colonization available during that season. Other oil spills occurring during seasons when oviposition by aerial adults was unlikely produced similar delays in recovery of the stream fauna (Barton & Wallace, 1979a; Harrel, 1985).

The predominance of *Optioservus* is unusual in small trout streams and we attribute this to their tolerance of petrochemicals (Cairns *et al.*, 1971, 1972; Barton & Wallace, 1979a; Pontasch & Brusven, 1988). Many other studies have reported similar reductions in sensitive taxa such as mayflies, stoneflies and caddisflies in response to oil spills (Bugbee & Walter, 1973; Ryck & Duchrow, 1973–1974; Rosenberg & Wiens, 1976; Barton & Wallace, 1979a,b; Pontasch & Brusven, 1988; Crunkilton & Duchrow, 1990), which is generally reflected in a reduced total density and taxonomic richness. Other aquatic invertebrates, such as oligochaetes (McCauley, 1966; Barton & Wallace,

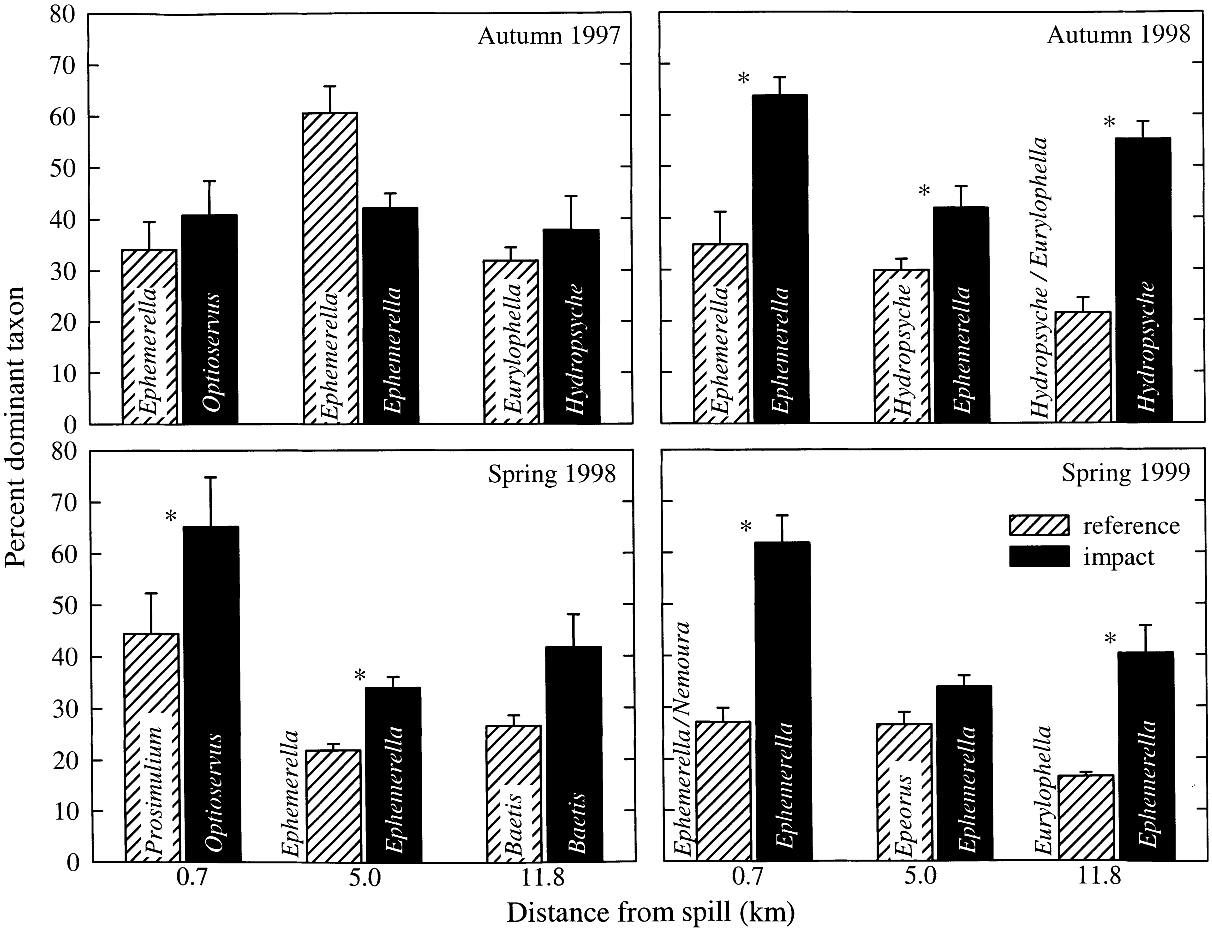

Fig. 4 Percentage dominant taxon (mean and SE) of invertebrates from 1-min kick samples at reference and impact sites along the Cayuga Inlet during 15 months after the oil spill. Asterisks denote significant differences between reference–impact pairs.

1979a; Harrel, 1985), chironomids (Bengtsson & Berggren, 1972; Ryck & Duchrow, 1973–1974; Rosenberg & Wiens, 1976; Barton & Wallace, 1979b; Crunkilton & Duchrow, 1990), leeches and nematodes (McCauley, 1966) have also been reported to tolerate petrochemical pollution. We did not observe proportionate increases in these tolerant taxa in this study, perhaps because of the large mesh size of our collecting nets.

One year after the spill, Cayuga Inlet had experienced a full season of aerial recolonization. As a result, certain taxa such as the mayfly *Ephemerella* reached high numbers even in the site located immediately below the spill. Aerial recolonization and perhaps downstream drift, appears to have returned many taxa that were absent immediately after the spill. *Ephemerella*, however, accounted for a disproportionately large fraction of the population, suggesting that other taxa, although present, remained at low densities. Because we had no prespill data, we cannot attribute this uneven distribution of individuals among taxa to effects of the oil spill. Nonetheless, this pattern of species diversity reflects persistent conditions that favoured one species, rather than a diverse community such as that of the reference site immediately above the spill site.

Although the direct toxicity of petrochemicals certainly reduces the density of stream fauna following oil spills (Cairns *et al.*, 1972; Hoehn *et al.*, 1974; Barton & Wallace, 1979a; Crunkilton & Duchrow, 1990), little is known about the importance of indirect mechanisms of impact, such as interference with respiratory membranes (Bury, 1972; Simpson, 1980; Woodward, Mehrle & Mauck, 1981, Woodward, Little & Smith, 1987), disruption of stream bottom habitat necessary for invertebrate colonization (Hoehn *et al.*,

1974) or fish spawning (Bury, 1972), and destruction of benthic food sources (Bury, 1972). Furthermore, the toxic components of oil can change over time as it weathers and is decomposed by microbes in the receiving water (Blumer & Sass, 1972; Barton & Wallace, 1979b). As dead organic matter accumulates in damaged streams, increases in biochemical oxygen demand by microbial communities can also cause lethal reductions in dissolved oxygen (Bury, 1972). Some studies have reported increases in chlorophyll *a* or algal biomass associated with oil contamination, as a result of increased primary production of oil-tolerant algae (McCauley, 1966; Rosenberg & Wiens, 1976; Lock *et al*., 1981; Cushman & Goyert, 1984; Singh & Gaur, 1989). Future studies should focus on the mechanisms by which oil has its effects, thereby increasing our understanding of factors affecting rates of recovery.

We conclude that the impact of the November 1997 diesel fuel oil spill on the stream invertebrates of the Cayuga Inlet was severe, causing damage up to 5.0 km downstream and for as long as 3 months after it occurred, although invertebrate density and taxonomic richness recovered within a year. For the duration of the study the fauna immediately below the spill was dominated by a single taxon, suggesting that 15 months was not sufficient time for full community recovery. However, we plan to continue this sampling programme to determine whether taxa that now comprise an apparently small proportion of the invertebrate community in areas affected by the oil spill will ever approach levels observed in reference sites unaffected by the spill.

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