Marine parasites as pollution indicators: an update

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SUMMARY

Eight major reviews are cited to indicate a recent knowledge explosion on the use of marine parasites as potential indicators of pollution. A literature update is given for the period 1995–2001. An analysis of the publications cited is used to provide 10 refined criteria for selecting parasites as indicator/monitor species. Previously unpublished data on *Diclidophora merlangi* and *Dictyocotyle coeliaca* confirm their value as potential indicators of hydrocarbon pollution in the North Sea. An extensive knowledge of *D. merlangi* is summarised to emphasize its potential value as an indicator species and also to encourage studies on the health status and immune responses of its host when subjected to pollutant stressors and infection with this monogenean. A discussion focuses on publications which have reported significant recent advances in this area of research and also on accompanying issues, problems and controversies. These selected publications are used to suggest species, stages in the development of species and assemblages of species worthy of further more detailed investigations into their value as indicators/monitors of pollution. It is predicted that further good progress will be made when contaminants can be accurately identified, their precise effects on both host and parasite can be measured by histochemical and biological methods and the roles of contaminants and parasites in causing disease can be assessed separately. About 100 references are cited.

Key words: Parasites, indicators, marine pollution.

INTRODUCTION

From the 1950s increasing concern about marine pollution has led to many conferences and publications (for example Ruivo *et al*. 1972; White, 1984; Salomons *et al*. 1988; GESAMP, 1990; McIntyre, 1995*a*, *b*). The methodology of detection, assessment and monitoring of pollution is diverse and includes the use of indicator species ranging from diatoms, seaweeds, free-living worms, molluscs and crustaceans to tunicates, fish, birds and mammals. The use and misuse of biological monitors was well discussed by White (1984). White argued, as had been done in previous publications, that it is unrealistic and naive to expect a single taxon of organisms simultaneously to serve as indicators for all interests and that the indicators concept is too simplistic and restrictive. It was suggested by one of us (HHW) in 1978 (see Cole, 1979) that some groups of fish parasites might be good indicators because they have a variety of life-cycle patterns with delicate developmental stages which, depending on the species, can infect most of the groups of animals previously used as indicators. If only one taxon is used, for example parasitic flatworms, a study of all stages of their life-cycles would require observations not only on other taxa serving as hosts (e.g. molluscs, arthropods, fish, birds and/or mammals) but also on bottom sediments because most helminth life-cycles involve stages, such as eggs and larvae, that are in contact with the sea bottom. Thus the fact that sediments alone can be used as indicators (White, 1984 p. 326) supports the use of free-living stages of parasites especially if they are closely associated with sediments.

The last twenty years have seen a knowledge explosion on the use of marine parasites as potential monitors, as is evident from Møller (1987), Khan & Thulin (1991), Vethaak & Rheinallt (1992), Williams & Jones (1994), MacKenzie *et al*. (1995), Overstreet (1997), MacKenzie (1999) and Hemmingsen & MacKenzie (2001). Since around 1995 about 50 publications have appeared on the subject. Williams & Jones (1994 p. 34) listed over 30 genera of helminths then thought to be of potential value as pollution indicators, whilst MacKenzie *et al*. (1995) focused on various kinds of marine pollution and their potential effects on parasite transmission stages, including those of the monogeneans *Diclidophora merlangi* on *Merlangius merlangus* and *Dictyocotyle coeliaca* in *Raja radiata* and *R. naevus*. MacKenzie (1999) reiterated some of these aspects. Our view in 1995 was based on extensive unpublished observations and data on these two monogeneans. Not unexpectedly, recent publications on marine parasites as indicators of pollution include views which are sceptical about their use, those which accept their potential value but emphasise the need for caution in interpreting results (e.g. MacKenzie *et al*. 1995), and papers with few if any reservations on parasites as bioindicators. It is now tempting to join the last category for reasons that we hope will become apparent in the conclusions

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Table 1. Recently reported effects of pollution on marine hosts and/or parasites

Type of pollution and parasite(s)	Host(s)	Effect(s)	Locality	Reference
Hydrocarbons				
Perkinsus marinus (Protozoa)	*Crassostrea virginica* (Mollusca)	Increased susceptibility to infection with exposure to pollutants	Chesapeake Bay, USA	Chu & Hale (1994)
Trichodina sp. (Protozoa) *Gyrodactylus* sp. (Monogenea) Gastrointestinal digeneans	*Hippoglossoides platessoides* (Pisces)	Significant differences in prevalences and abundances of infection between polluted and reference sites	St. Lawrence estuary, Quebec	Marcogliese, Nagler & Cyr (1998)
Bucephalus-like digenean	*Bathymodiolus* sp. (Mollusca)	Unusually high prevalences (>70%)	Gulf of Mexico	Powell *et al*. (1999)
Gyrodactylus sp.	*Ammodytes hexapterus* (Pisces)	Increased abundance of infection with increased exposure to pollutants	Alaska	Moles & Wade (2001)
Heavy metals				
Many helminths	Fish hosts	Parasites accumulate heavy metals at orders of magnitude greater than those in host tissues or in the environment	Worldwide	Sures, Siddall & Taraschewski (1999)
Cryptocotyle lingua (Digenea) *Probopyrus pandalicola* (Isopoda)	*Littorina littorea* (Mollusca)	Horizontal swimming rate and longevity of cercariae significantly reduced in polluted environment	Ireland	Cross, Irwin & Fitzpatrick (2001)
Eustrongylides sp. (Nematoda)	*Palaeomonetes pugio* (Crustacea) *Fundulus heteroclitus* (Pisces)	Uptake of mercury lower in parasites than in hosts. Uptake also lower in unparasitized hosts	New Jersey	Bergey, Weis & Weis (2002)
Thermal				
Aquatic parasites in general	Aquatic hosts in general	Predicts responses of various parasites to long-term climatic change	Worldwide	Marcogliese (2001)
Pulp and Paper Mill Effluents				
Glugea stephani (Protozoa) *Cryptocotyle lingua* (Digenea) *Echinorhynchus gadi* (Acanthocephala) Anisakid nematode larvae	*Pseudopleuronectes americanus* (Pisces)	Differences in parasitic infection between clean and polluted sites suggested host immuno-suppression due to pollutants	Newfoundland	Barker, Khan & Hooper (1994)
Trichodina spp. (Protozoa)	*Myoxocephalus scorpius*, *M. octodecemspinosus* (Pisces)	Intensities of infection significantly higher at polluted sites	Newfoundland	Khan *et al*. (1994)
Echinorhynchus gadi *Cryptobia* sp. (Protozoa)	*P. americanus*	Significantly lower abundance of infection at polluted site	Newfoundland	Khan & Payne (1997)

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Mariculture				
Three larval digeneans	*Paralichthys* spp. (Pisces) *Littorina saxatilis*, *L. obtusata*	Higher parasitaemias at polluted site	Chile	George-Nascimento *et al.* (2000)
Monogenea and gut helminths	*Siganus rivulatus* (Pisces)	Poorest and least diverse parasite communities found near fish farms	Red Sea and Eastern Mediterranean Sea	Diamant *et al.* (1999)
Eutrophication				
Protozoan and metazoan parasites	Many spp. of fish and molluscs	Changes over a 40 year period related to increasing eutrophication	Baltic Sea	Reimer (1995)
Metazoan parasite faunas	Gobiidae, 4 spp. (Pisces)	Differences in parasite communities between sites related to different levels of oxygen saturation	Baltic Sea	Zander & Kesting (1996)
Trichodina spp.	*Platichthys flesus* (Pisces)	Seasonal changes in prevalence of infection suggested to be linked to changes in bacterial biomass	Baltic Sea	Palm & Dobberstein (1999)
Metazoan parasite faunas	Fish, crustaceans and molluscs	Impoverishment of parasite faunas over an 18 year period due to increasing eutrophication	Baltic Sea	Kesting & Zander (2000)
Other and mixed pollutants				
Gastrointestinal helminths	*H. platessoides*, *Limanda limanda* (Pisces)	No evidence of effects of sewage sludge on levels	Scottish coastal waters	Siddall, Pike & McVicar (1994)
Various parasites	Molluscs, crustaceans	Infections with different parasites increase or decrease with increasing organic pollution. Industrial waste depresses the formation and functioning of host/parasite systems	Baltic Sea	Machkevsky & Gaevskaya (1997)
Entire parasite fauna	*Bairdiella chrysura* (Pisces)	Different taxonomic groups of parasites responded differently to different types of pollution	Florida, USA	Landsberg *et al.* (1998)
Ceratomyxa acadiensis (Protozoa) *Steringophorus furciger*, *Cryptocotyle lingua* (Digenea)	*P. americanus*	Significant differences in prevalences and abundances of infection between polluted and reference sites	Newfoundland	Khan (1998*a*, *b*, 1999)
Echinorhynchus gadi (Acanthocephala) *Perkinsus marinus*	*Crassostrea virginica* (Mollusca)	Highest levels of infection related to reduced water flow, low dissolved oxygen and high sedimentation rates	North Carolina, USA	Lenihan *et al.* (1999)
Actinomyces sp. (Fungi)	*Palaemon elegans* (Crustacea)	Prevalences and intensities of infection significantly higher where domestic sewage is discharged in area	Black Sea	Tkachuk & Mordvinova (1999)

Table 1. (*cont.*)

Type of pollution and parasite(s)	Host(s)	Effect(s)	Locality	Reference
Entire parasite fauna	*P. flesus*	Most polluted location had lowest species diversity and highest intensity of *Trichodina* sp.	Eastern North Sea	Broeg *et al.* (1999)
Ligula pavlovskii (Cestoda)	*Neogobius fluviatilis* (Pisces)	Lack of benthos food in estuaries polluted by industrial, domestic and agricultural waste resulted in increased feeding by gobies on planktonic crustaceans, leading to increased infection	Black Sea	Kvach (2001)

of this paper, especially the encouraging trend in a direction we suggested in 1995: the use of parasites together with 'a combined monitoring approach including the analysis of sediment contamination, infaunal community composition and laboratory bioassays'.

Our aims in this paper are to: (1.) update literature on different types of pollution; (2.) update and refine criteria for selecting parasites as monitors; (3.) present unpublished data on *Diclidophora merlangi* and *Dictyocotyle coeliaca* as an aid to further work on their use as biomonitors; (4.) discuss problems and controversies in this area of research; and (5.) suggest species that have potential for use as indicators if used in combination with other approaches to biomonitoring.

LITERATURE UPDATE

Papers published since 1995 have focused on the effects of hydrocarbons, heavy metals, climate and temperature (thermal), pulp and paper mill effluents, eutrophication and its various causes, including aquaculture, and various combinations of these types of pollution. These, in relation to the parasite/host systems studied, together with locality and references, are given in Table 1.

REFINED CRITERIA FOR SELECTING HOST/PARASITE SYSTEMS AS BIOMONITORS

Some of the authors referred to in our literature update clearly indicated a need (1.) to select well known parasite/host systems in well known study areas; (2.) to combine their use as biomonitors with other methods of investigating pollution; (3.) to verify results in the laboratory; and (4.) for a better knowledge of the effects of pollutants on fish health and immune responses.

Advances in our knowledge in these areas are encouraging and call for a need to update and refine criteria previously used in selecting suitable host-parasite systems. To this end we suggest the following criteria of which we would consider 1 to 8 to be essential requirements, while 9 and 10 are preferable if achievable: (1.) The ecology of the study area should be well known from research over a long period. (2.) Both host and parasite should be readily available for study throughout the year and over a number of years using cost-effective methods. (3.) Host and parasite should be readily identifiable without the aid of time-consuming methods. (4.) Problems regarding possible sampling of different host and parasite populations should be taken into consideration. (5.) The ecology and life-cycles of both host and parasite should be well known. (6.) There should be consistency in the use of ecological terms, for example those in Bush *et al.* (1997). (7.) The pollutant(s) should be identifiable and their

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Table 2. Published information on the biology of *Diclidophora merlangi*

Reference	Summary of information
Dawes (1947)	Taxonomic history from 1832. Name and taxonomic characters beyond dispute since 1943. Distribution: North Sea (75% prevalence in whiting in 1908, up to 6/fish), English Channel, Irish Sea and Mediterranean (where Cerfontaine collected 100 specimens in 1895).
Llewellyn (1954)	8 species of polyopisthocotylean monogeneans studied, including *D. merlangi*, feed mainly on the blood of their hosts. Blood is probably haemolysed fairly rapidly and then absorbed by amoeboid digestion.
Llewellyn (1956)	16 diclidophorean species strictly specific to one host species. One species/host. 44 of 507 (8·7%) whiting infected at Plymouth.
Llewellyn (1958)	Structure of adhesive organ and adhesive mechanism of *D. merlangi* to gills of host described.
Halton & Jennings (1965)	*D. merlangi* feeds mainly on blood and has high levels of alkaline phosphatase.
Halton, Dermott & Morris (1968)	Haematin, an indigestible breakdown product of haemoglobin, found in gut of *D. merlangi* due to reverse pinocytosis.
Llewellyn & Tully (1969)	Distinctive features of 12 spp. of monogeneans, including *D. merlangi*, described.
Arme & Walkey (1970)	Food of monogeneans and serum antibodies possibly of importance in host specificity. Larvae of monogeneans attracted by specific host chemoattractants.
Morris & Halton (1971)	Ultrastructure of the tegument of *D. merlangi* described.
Arme & Halton (1972)	Numbers present can be estimated by naked eye examination. Prevalences of 43–59% recorded over an 18 month period within 100 miles of Portavogie, Northern Ireland. Earlier observations that first gill arch is favoured site of attachment confirmed. Distribution on gills influenced by complex of factors involving parasite/parasite interactions and/or responses to other stimuli.
Llewellyn (1972)	Fish hosts of monogeneans swim up to 300 times faster than the infective larvae. For infection to take place fish are probably stationary on the sea bed in the vicinity of sites where parasite eggs have been laid.
Halton (1974)	Absorption of haemoglobin in the gut of *D. merlangi* takes place in pigmented haematin cells. Process of absorption described.
Halton, Morris & Hardcastle (1974)	Three distinct groups of glands described opening into buccal cavity, prepharynx and oesophagus of *D. merlangi*.
Halton (1975)	Ultrastructural and cytochemical changes accompanying intacellular digestion and cellular defecation in the haematin cell of *D. merlangi* described.
Halton & Morris (1975)	Ultrastructure of the anterior alimentary tract of *D. merlangi* described.
Macdonald (1975)	Prevalence on whiting in the English Channel 1–5% from 1971 to 1973, 60% off northeast Scotland in 1973–1974. Oncomiracidia in *D. merlangi* eggs fail to develop at temperatures below 8 °C. Hatching experiments revealed no evidence of different hatching times at different times of the year. Oncomiracidia swim actively for 12–15 h at 13 °C, 9 h at 18 °C; cilia lost at 24 h and death occurs within 30 h of hatching. Host biology and other aspects of the life cycle of the parasite discussed. A key reference for experimental work.
Macdonald & Caley (1975)	Description of reproduction in *D. merlangi*. 165 of 310 whiting 25–28 cm long from inshore waters of northeast Scotland had one *D. merlangi* and 60 had two.
Halton (1976)	EM and section autoradiography used to find evidence of sloughing and renewal of haematin (digestive) cells in the gut of *D. merlangi*. Sloughing occurs only rarely and renewal takes place at a very low rate.
Halton & Hardcastle (1976)	Spermatogenesis in *D. merlangi* described.
Halton (1979)	Surface topography of *D. merlangi* revealed by SEM.
Smyth & Halton (1983)	Descriptions of morphology and physiology of the Monogenea, including about 50 entries in the index on *D. merlangi*.
Llewellyn, Green & Kearn (1984)	Long-term variations in prevalence of *D. merlangi* on whiting off Plymouth: 10% in the 1950s to <1% in the 1970s.
Maule *et al.* (1989*a*)	Pancreatic polypeptide immunoreactivity identified, quantified and characterized.
Maule *et al.* (1989*b*)	Tachykinin immunoreactivity quantified and chemically characterized in extracts of parasite and host.
Maule *et al.* (1990*a*)	Distribution of serotoninergic and peptidergic components in the nervous system mapped.
Maule *et al.* (1990*b*)	Involvement of a peptididergic cell population in egg-forming sequence inferred from its strategic location.
Halton *et al.* (1991)	Secretions of pancreatic polypeptide-immunoreactive cells may serve to regulate ootype motility and thereby help coordinate egg production.
Maule *et al.* (1992)	Localisation and distribution of neuropeptide F-immunoreactivity investigated.
Rubec & Dronen (1994)	Review of genus *Diclidophora*.
Brownlee *et al.* (1995)	Localisation and distribution of SALMFamide(S1)-immunoreactivity in the nervous system determined.

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Table 2. (*cont.*)

Reference	Summary of information
Johnston *et al.* (1995)	Comparison with 3 turbellarian species of localization, quantification and characterization of neuropeptide F- and FMRamide-immunoreactive peptides.
Smart *et al.* (1995)	Distribution of molecules related to the *Diploptera punctata* allatostatins within the nervous system suggests that they function as neurotransmitters/ neuromodulators with roles in locomotion, feeding, reproduction and sensory perception.
Williams & MacKenzie (1995)	Prevalence data from 73 samples of whiting taken from 1990 to 1995 throughout the North Sea indicated increase in infection levels over about past 25 years.
Mair *et al.* (1997)	Comparative analysis of the distribution of bradykinin-, GYIRFamide- and neuropeptide F-like immunoreactivites.
Moneypenny *et al.* (1997)	Actions of FMRFamine-related peptides on motility *in vitro* examined for the first time.
Halton *et al.* (1998)	Neuromusculature described in detail. Function discussed with respect to adhesion, alimentation and reproduction.
Mair *et al.* (1998)	Recent advances in flatworm muscle research reviewed, with several references to *D. merlangi*.

possible effects on both host and parasite considered relative to those of almost 30 biotic and abiotic factors. (8.) Selection should focus on host/parasite systems with large geographical and ecological ranges but also where populations might be restricted in their migrations within this range. Sampling should occur where conditions are thought to be optimal for host and parasite as well as near the limits of the parasite's geographical range. (9.) Wherever possible the indicator parasite(s) should be used in conjunction with one or more of about 50 other techniques used for monitoring the biological effects of pollution. (10.) Host/parasite systems for which it might be possible to investigate the complex interactions between pollutant, immune response and parasites when interpreting results, should be selected.

DICLIDOPHORA MERLANGI AND *DICTYOCOTYLE COELIACA* AS POTENTIAL INDICATORS OF POLLUTION IN THE NORTH SEA AND ADJACENT WATERS

During the period 1990–1995 the present authors investigated the potential of the gill parasitic monogenean *Diclidophora merlangi* as an indicator of marine pollution, with particular reference to hydrocarbon pollution associated with the oil industry in the North Sea. This parasite was selected for investigation for the following reasons. (1.) Its biology and ecology are relatively well known. (2.) Previous workers have provided data on its distribution and prevalence in British waters (Llewellyn, 1956; Smith, 1969; Shotter, 1972, 1973*a*, *b*; Pilcher, Whitfield & Riley, 1989; Lang, 1990). (3.) It is relatively easily seen and highly host-specific to whiting *Merlangius merlangus* L, which are themselves abundant and easy to sample.

Important references on *D. merlangi* are listed in chronological order in Table 2. This table summarises the main observations on this species and shows that it is amongst the best known of all marine polyopisthocotylean monogeneans.

The aim of our study was to test the hypothesis that some forms of pollution, particularly hydrocarbon, are associated with increased infection by ectoparasites. We did this by comparing our data on *D. merlangi* with those of the earlier workers referred to above, and then comparing levels of infection on whiting collected from areas of oil and gas production in the North Sea with those from areas unaffected by these activities. Smith (1969) presented data from whiting collected in 1963–1964 at four stations in the central North Sea close to some sampled by us in 1991. The mean intensities of infection in our samples were significantly higher than Smith's, suggesting that levels of infection in the North Sea had increased considerably in the intervening three decades. Results from two sets of samples taken during research vessel cruises in May 1990 and in June–July 1991 showed that prevalences and mean intensities of *D. merlangi* tended to be higher on whiting caught at stations close to oil installations than at other stations (Figs. 1, 2). Later sampling in 1993 and 1995 failed to show such clear-cut differences, but these discrepancies may be due to a number of biotic and abiotic factors, including the fact that the whiting is a migratory species, so different populations may have been sampled in different years and seasons. Nevertheless, we believe that this particular host/parasite relationship is worth investigating further as an indicator of pollution, particularly hydrocarbon, in the northeast Atlantic. Both host and parasite are suitable for experimental work.

The prevalence of another monogenean, *Dictyocotyle coeliaca*, in the North Sea, appears to have changed over the last 35 years or so. Williams (1965) recorded a prevalence of 59·2% in a sample of 76

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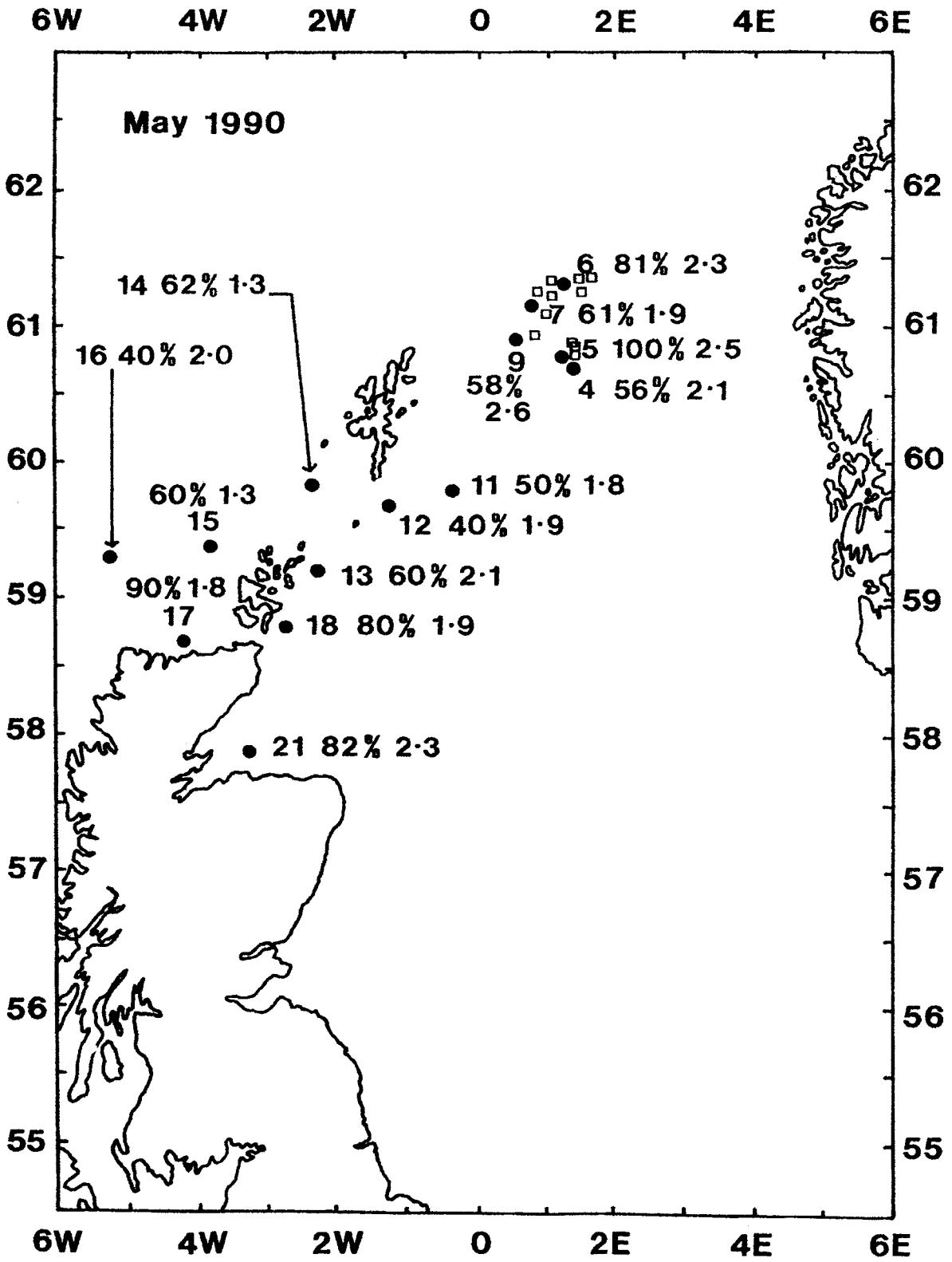


Fig. 1. Map of northern North Sea showing 21 positions (solid circles) of *Merlangius merlangus* samples taken in May 1990 with percentage prevalences and mean intensities of *Diclidophora merlangi* infection, and sites of major oil and gas installations (open squares).

North Sea *Raja radiata*. In 1990–91, however, the prevalence was 89·3% in a sample of 28 rays. It is premature to suggest that this is a real change associated with hydrocarbon pollution. Problems in investigating a migratory host species might be alleviated if a suitable sedentary benthic fish was studied in the same locality. Williams (1961) referred to evidence that various species of *Raja* do not show extensive migratory movements. Two species of this genus are often caught in sufficiently large

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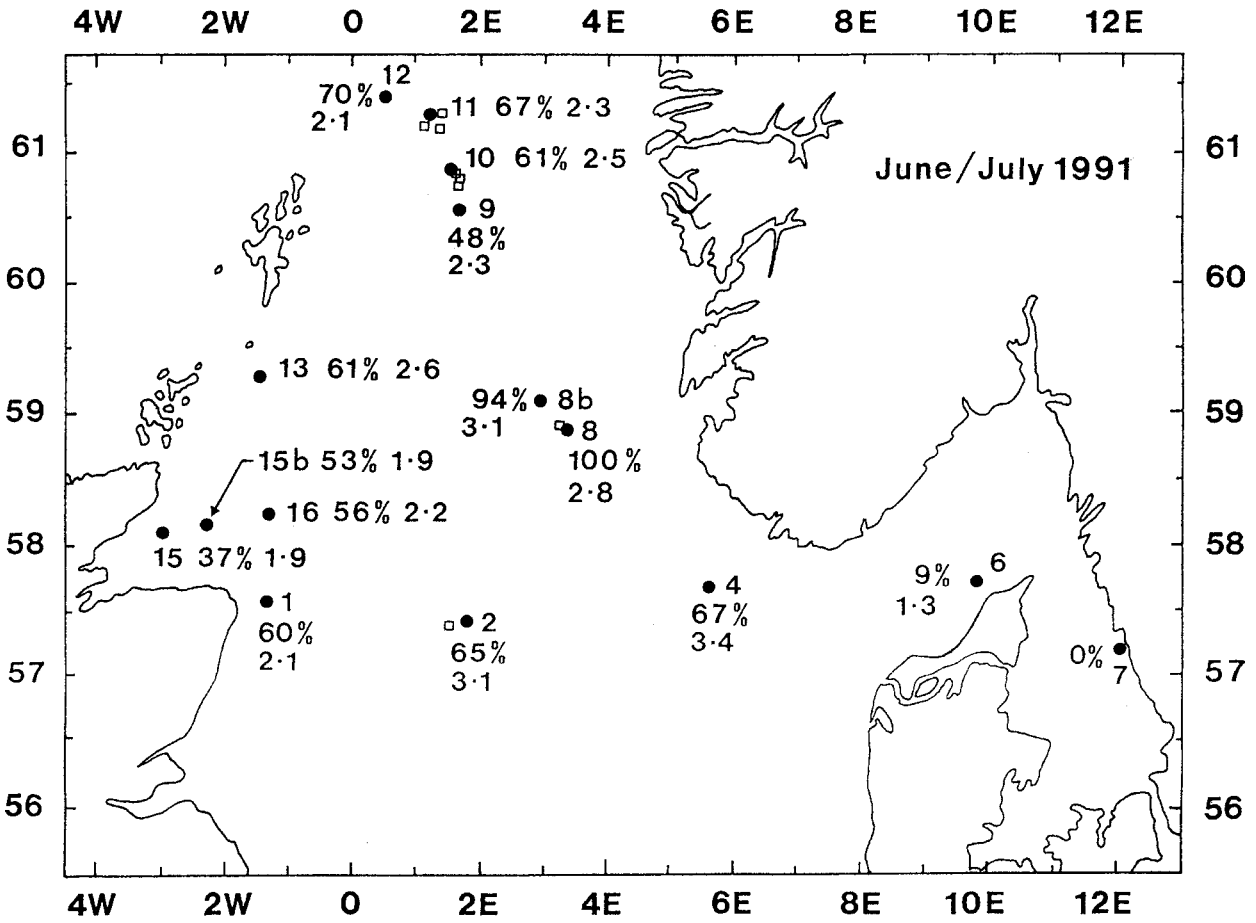


Fig. 2. As Figure 1 for samples taken in June–July 1991.

numbers on North Sea research cruises sampling for *Merlangius merlangus*. Further monitoring of *R. radiata* and *R. naevus* for the presence of *Dictyocotyle coeliaca* and *Calicotyle kroyeri* could, therefore, be easily achieved at little extra cost and effort. These monogeneans are conspicuous, easily identified and their hosts can be successfully maintained in aquaria for experimental work, especially the responses of oncomiracidia to chemicals in the environment. Focusing on these monogeneans and on *Diclidophora* as indicator species may obviate criticisms of using a pelagic migratory fish only for pollution studies.

DISCUSSION

As indicated in our aims and objectives, research on marine parasites as pollution indicators is fraught with problems and issues. Amongst the main problems are (1.) difficulties in defining what constitutes pollution and its main causes, and (2.) understanding the relationship between a parasite species and its environment which is affected by almost 30 biotic and abiotic factors (Williams & Jones, 1994). There are however, clear indications in recent publications that some of these problems are being slowly resolved. A main issue is a division between a minority of fish parasitologists, for example Kennedy (1997) and Elston *et al.* (1997), who are sceptical about the use of fish parasites in this research, and a substantial majority who are in favour although many advocate caution in doing so. A comment on the minority view is appropriate before discussing how some of the main problems are being resolved. Kennedy (1997) was of the view that until we know the precise causal relationship between fish parasites and pollution their use has no clear advantages over free-living organisms as indicators of pollution. He listed 8 problems and difficulties in using them as indicators of environmental change. It is evident, however that six of these problems do not apply in our choice of *D. merlangi* as an indicator. Chubb (1997), anticipating publications by Yeomans, Chubb & Sweeting (1997) and Yeomans *et al.* (1999), questioned Kennedy's view that it is unlikely that parasites will provide easy options for monitoring environmental change. Chubb's work and that of his colleagues present convincing field and experimental results that indicate a clear link between water-borne bacterial numbers (in an organic pollution gradient) and increased intensity of trichodinid infestations. Elston *et al.* (1997), in discussing research results funded by the Exxon Corporation, found no trends in the health and condition of herring *Clupea pallasi* that could reasonably be attributed to the Exxon

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Valdez oil spill in 1989 in Prince William Sound, Alaska. They were sceptical about the use of condition factor, disease and indices of liver function as indicators of pollution exposure. They believed that such claims are invalid unless other factors unrelated to pollutant exposure are considered, for example age and reproductive stage of the herring, spawning behaviour and location and date of capture. The results of Moles & Wade (2001), however, do not support those of Elston *et al*. (1997). They stated that the link between hydrocarbon-induced immunosuppression and gill parasites, although often theorised, had never been tested. They maintained Pacific sand lance, *Ammodytes hexapterus*, for five weeks in a holding tank with a 3 cm layer of sand sediment before exposing them to crude oil at a level corresponding approximately to the concentrations of hydrocarbons in the shallow subtidal (10–30 m) following the Exxon Valdez oil spill. The effects of the oiled sediment on blood phagocytic function and parasite abundance were determined. This was the first laboratory study to note increases in a species of *Gyrodactylus* on the gills of a fish maintained on sediments at a low concentration of crude oil. They suggested that the fish were immunologically compromised due to the stress of exposure to oiled sediments. Higher levels of exposure not only resulted in lower non-specific immune responses but were also correlated to an increase in prevalence of gill monogeneans. Conversely when the immune response was elevated both prevalence and abundance of the parasite infections were reduced. Immune based biomarkers are useful measures of environmental quality. The stress associated with exposure to polycyclic aromatic hydrocarbons (PAH) can both stimulate and suppress phagocytic activity, depending on concentrations. The prevalence and abundance of gill parasites appears to be correlated with phagocytic activity and may provide a field estimate of animal health.

In returning to a discussion of the problems referred to above we can now claim to have a better understanding of the general nature of pollution and its causes. McIntyre (1995*a*) pointed out that monitoring aimed at selected problems of marine pollution began around 1920 and from then until the 1940s focused mainly on problems arising from discharges of oil from ships. From the late 1940s to the 1950s fallout from radionuclides could be detected in all the world's oceans. Persistent residues from pesticides also affected fish-eating birds during this period on a global basis. The 'Minimata' disease in Japan in the 1950s was eventually traced to mercury-rich factory effluents and this drew attention to the dangers of heavy metals at sea. The Torrey Canyon disaster in 1967 diverted attention away from operational discharges of oil and focused on spills from large tankers. McIntyre (1995*a*) lists contaminants to include metals, nutrients, radionuclides, oil, synthetic organic compounds, plastics, sediments, carbon dioxide and other radiatively active gases, and a great diversity of municipal and industrial wastes. Seventy-seven per cent of contaminants originate from land and reach the sea waterborne or airborne. Only 12% are derived from shipping.

In referring to the report of the North Sea Task Force (1993), McIntyre (1995*b*) gives an excellent reason for supporting studies in the North Sea. This report was put together over several years by scientists from the eight countries surrounding the North Sea. Offshore the main polluting inputs, apart from atmospheric deposition, are from shipping and hydrocarbon extraction and there is little contamination in the northern and central parts. Shallow coastal zones, however, are very heavily polluted with many contaminants. McIntyre concluded that although in most situations pollution effects would be the results of multiple exposures to a variety of contaminants, the best measure of the integrated impact is through biological effect studies. The North Sea Task Force report firmly recommends fish disease surveys as one of four approaches in studying pollution effects although all carry difficulties in interpretation. Although the diseases referred to did not include metazoan parasites, we consider our decision to examine whiting and its specific *Diclidophora* parasite to be vindicated in the report.

We are also pleased that the suggestion in MacKenzie *et al*. (1995) and MacKenzie (1999) that the transmission stages of parasites, particularly helminths, could provide a good early warning system for marine pollution has received practical support from the results of Cross, Irwin & Fitzpatrick (2001). Their study clearly indicated that pollution-induced reductions in cercarial quality of the common inshore digenean *Cryptocotyle lingua* seemed capable of producing transmission failure. They also commented that cercariae in general could be excellent indicators. This study investigated the effects of heavy metal pollution, but again it is important to note that other types of pollution can have the opposite effect. Barker, Khan & Hooper (1994) found significantly higher levels of *C. lingua* infection in winter flounder from a site contaminated by pulp and paper mill effluent than in those from their reference site.

Lafferty (1997) gave an admirable review of the use of parasites to assess environmental quality and its complexity. He briefly discussed eight approaches to environmental assessment. A table summarised the nine main causes of change in aquatic environments: heavy metals, acid precipitation, sewage-sludge, industrial effluent, crude oil, pulp-mill effluent, thermal effluent, eutrophication and unspecified human 'disturbance'. Their effects on parasites have been studied on Digenea, Acanthocephala, Cestoda, Monogenea, Nematoda, Ciliophora and 'other groups'. Lafferty correctly drew attention to the need to fill many important gaps in

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our knowledge before conclusions can be drawn on the use of parasites as pollution indicators and advocated further research on the cercariae and miracidia of digeneans, ciliated protozoans and the presence or absence of digeneans in fish as promising areas for further research. A most important step towards further progress would be to adopt better study designs widely used in environmental impact assessment. With increased knowledge and improvements in methodology Lafferty believed environmental parasitology would contribute substantially to future impact assessment.

Lafferty & Kuris (1999) reiterated this view and drew attention to many examples of the interaction between parasites and other stressors in aquatic environments. They emphasized the importance of considering the full range of potentially interacting components of a system because the various direct and indirect effects that can impinge on a parasite's complex life cycle can make the effect of a stressor quite complex. Complexities aside, they believed that parasites can and do interact with other stressors. Recognizing these complexities fish parasitologists, as stated by McVicar (1997), appear to have pursued one or more types of study focusing on (1.) a known contaminant, (2.) a known source of pollution, and/or (3.) disease as the end point of pollution. Progress, often based only on field work, has been made on the effects of a single contaminant or a known source of pollution, as is evident from many examples given in our table updating recent literature on parasites and pollution. In assessing this progress careful consideration should be given to Hoole (1997) who stated that there is no definitive study correlating a pollutant with change in the immune status of fish and subsequent susceptibility to parasitic infection. There are, however, studies which have noted changes in several immune parameters. Hoole reviewed the variable effects of pollutants on innate immunity, antibody levels and leucocyte activity, migration and numbers and emphasized that pollutants affect the dynamics of parasite infections in fish in (1.) having toxic effects on the parasite and its free-living stages, (2.) reducing numbers of invertebrate hosts, and (3.) altering the susceptibility of fish to parasite infection. He concluded that there is evidence that pollution does affect several immune mechanisms which are stimulated by parasites. These immune parameters can be increased in fish exposed to chronic levels of some pollutants thereby possibly increasing host resistance to parasites. In contrast, the suppressive effects of pollutants on the fish immune system is also well documented and he cites his work on increase in apoptosis in pronephric cells of *Cyprinus carpio* exposed to cadmium. The interactions between pollutant, immune response and parasite are, therefore, very complex. More work is required on fish helminths to clarify: (1.) immune evasion strategies, for example inhibition of leucocyte adherence; (2.) evasion/tolerance of reactive oxygen intermediates; (3.) evasion of antibodies; (4.) proteinase inhibitor production; and (5.) masking host proteins.

Attempts are being made by a number of workers to consider one or more of the problems we have already discussed. Amongst those who have reported encouraging results are Khan (1998*a*, *b*, 1999), Khan *et al.* (1994), Broeg *et al.* (1999), Diamant *et al.* (1999), George-Nascimento *et al.* (2000) and Overstreet (1999). These authors used data in addition to those from parasite studies, such as chemical analysis of the water together with biochemical and histochemical studies of host tissues. A recommendation of the ICES Advisory Committee on the Marine Environment was pursued by Broeg *et al.* (1999), i.e. tests on the activity of CYPIA-dependent monoxygenase ethoxyresoruffin O-decthylase (EROD) on the integrity of lysosomal membranes in hepatocytes as an indicator of non-specific acute and chronic toxic effects. The neutral lipid content in the liver was used as a marker for pathologically induced fat accumulation and lysosomal stability/macrophage aggregate activity was tested for measuring immunosuppression. Using flounder, *Platichthys flesus*, and its parasite assemblage of 33 species in four locations of the German Bight, Broeg *et al.* concluded that use of a combination of bioindicators for pollution monitoring, including EROD activity, lysosomal membrane stability and parasite diversity, facilitates the interpretation of results against a background of natural and seasonal variation and provides valuable information about the stress level of individual fish. *Trichodina* sp. best reflected the pollution gradient with highest infection intensity in the most polluted location, the Elbe estuary. A significant result from residue analysis of DDT and PCBs in flounder muscle was that the pollution pattern was different for every site and season sampled in the North Sea. No location was 'unpolluted'.

A similar approach was adopted by Diamant *et al.* (1999) in a study of 22 species of heteroxenous and monoxenous parasites of *Siganus rivulatus* in the Red Sea and the Mediterranean. The Mediterranean data yielded a very low species richness value due to the absence of heteroxenous species. Mean values of EROD activity in Mediterranean fish were almost double those from the Red Sea and were therefore a good measure of exposure to contaminants. Lysosomal stability values were even more discernible for the two localities. Using acid phosphatase, the mean destabilisation time in fish from the Mediterranean was 8 minutes compared with 18 minutes for Red Sea fish. These results clearly indicated liver cell damage in the Mediterranean fish and was a good measure of the basic effects of the contaminants on the liver of *S. rivulatus*. This is a comparison of species richness in two localities showing high values

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in an ecologically stable habitat and low values for polluted areas near cage mariculture activities. These were validated by biochemical and histochemical results. It was concluded that changes in parasitological parameters are sensible tools for detecting environmental changes due to pollution.

Towards concluding this discussion of recent progress in marine pollution studies, we draw attention to difficulties in interpreting results in three areas of research, namely the effects of (1.) climate and temperature changes, (2.) pollutants on the community ecology of parasites, and (3.) a mixture of pollutants especially in areas where little basic work has been done on parasite taxonomy and much less on the ecology of host-parasite systems. A reminder of the complexity of the effects of temperature and climate changes was given by Attrill & Power (2002). They drew attention to the long-term influence of climate on our seas and thus on marine fish stocks. These authors found that nine of the 15 species of fish investigated demonstrated a significant variation between population abundance and the North Atlantic Oscillation Index (NAOI), but no significant relationship between gadoids, including whiting *M. merlangus*, and this index. Marcogliese (2001) drew attention to notable consequences of climate change for abiotic and biotic aspects of the environment and to the enormous literature on this subject. He then explored the potential response of parasites of aquatic animals to climate change. Kesting & Zander (2000) and Landsberg *et al.* (1998) are good examples of interesting results obtained from community ecology studies and of investigations of the different effects of various pollutants.

From 1992 to 1994 Kesting & Zander (2000) examined 1245 fish of five species, 2850 gammarids of four species, 18 980 copepods of four species, and 1610 snails of three species in the Schlei Fjord of the Baltic Sea. Their main aims were to gain knowledge of the metazoan parasite communities of brackish water with varying degrees of salinity and to compare the results with other studies in the same area from 1977 to 1994, since it was known that a considerable increase in eutrophication had taken place during this 17 year period. They found that 21 host species were known in the study area in 1991 but only 14 were present in 1994. Similarly from 1991 to 1994 there was a reduction in the number of parasite species from 18 to 8. It is suggested that two stressors may be related to these changes: low and changing salinity and, more importantly, eutrophication with high oxygen deficiency following pollution with nitrogen and phosphate as a result of farming activities.

An important contribution was made by Landsberg *et al.* (1998). They evaluated the influence of parasite assemblages on the health of fish and also changes in parasite diversity, prevalence, richness and abundance in response to environmental stressors. Three categories of environmental parameters were considered: (1.) external abiotic (2.) external biotic and (3.) condition of individual fish using organosomatic indices of the spleen and liver. Their aim was to develop a cost-effective index for monitoring and assessing estuarine health. Twenty silver perch, *Berdiella chrysura*, were taken from each of the 19 sites off the coast of Florida and 18 461 parasites representing 44 taxa were found. Nine of the taxa were present at every site and 22 of the most abundant taxa comprised 99·16% of the individuals found. The species diversity ranged from 1·48 to 3·36. Data on the prevalence of parasite groups by site and apparent response of these to environmental stressors were subjected to a rigorous statistical analysis using various methods. The results were used to construct a parasite index with a point score by site. This index was based on changes in the prevalence of parasitic groups and also in three ecological parasite measures (species diversity, parasite species richness and mean number of taxa per fish) in response to particular environmental stressors. Scores of 59 and 109 were recorded for the healthiest and unhealthiest site respectively. A relationship was found between particular stressors and parasites, namely (1.) temperature and monogeneans, (2.) contaminants and nematodes, (3.) low dissolved oxygen and protozoans and (4.) salinity together with a mixture of metal and organic contaminants and crustaceans. They concluded that parasites of fish are useful biomarkers and appear to be more sensitive to environmental stressors than are the fish themselves.

Finally in these complex areas of research, Marcogliese, Nagler & Cyr (1998) reported notable results. They exposed American plaice, *Hippoglossoides platessoides*, to high levels of polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) in contaminated sediments. The fish were infected with 18 helminth species, four myxozoans and one protozoan. Significant results were obtained from *Trichodina* sp., *Gyrodactylus* sp. and gastrointestinal digeneans. There was a greater abundance of *Gyrodactylus* and a decrease in *Trichodina* in exposed fish. An intriguing result was obtained with gastrointestinal digeneans in that, contrary to other studies, no change was observed.

CONCLUSIONS

In the last decade there has been an accumulation of published evidence supporting the use of trichodinids as indicators of excessive eutrophication, gyrodactylids to detect hydrocarbons in marine sediments, and adult acanthocephalans and adult tapeworms for determining high levels of heavy metals. Considerable progress has also been made when parasite studies have been related to chemical analyses of water and to biochemical and histochemical

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research on host tissues. This approach facilitates the interpretation of data against a background of other complex factors, including the effects of pollutants as stressors which might affect parasite populations. Stressors may cause either increased or decreased intensity of infection depending on the nature of the pollutant and/or the complexity of the host parasite system under investigation. Such effects on the dynamics of host-parasite systems and disease are important complex factors which can only be safely interpreted by specialists in community ecology. There is, however, evidence that disease as the end-point of pollution is a good biomarker. Further work is required on the variable effects of pollutants on fish immune responses and their consequential effects on parasite populations. Marine parasites are as valuable and perhaps have fewer drawbacks than free-living animals as indicators of pollution (see Marcogliese & Cone, 1997). Direct and/or indirect effects of some parasites on the organs and tissues of fish caught in polluted waters are often clearly visible to the naked eye, for example distinctly anaemic as opposed to bright red gills, obvious variations in liver colour (light pink to dark red) or gall bladder colour (from a light yellowish green to a dark brown). Such differences (although they disappear on fixation and preservation) are often an indication of the presence or absence of a parasite species and are in themselves good initial field indicators of pollution worthy of more detailed laboratory deductive methods of examination. There are good reasons for pursuing further research on the monogenean *D. merlangi* as an indicator and monitor of hydrocarbon pollution in selected areas of the North Sea. We reaffirm that other species named in MacKenzie *et al.* (1995) are good potential indicators and/or monitors of pollution. Other papers cited in this review provide clear evidence that considerable progress has been made since 1995 from studies of *Trichodina* spp., myxosporeans, haematozoa, digenean cercariae, gastrointestinal helminths and the entire parasite assemblages of some fish species.

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