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APPLIED ISSUES

Are alien fish a reliable indicator of river health?

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SUMMARY

1. The ability of many introduced fish species to thrive in degraded aquatic habitats and their potential to impact on aquatic ecosystem structure and function suggest that introduced fish may represent both a symptom and a cause of decline in river health and the integrity of native aquatic communities.
2. The varying sensitivities of many commonly introduced fish species to degraded stream conditions, the mechanism and reason for their introduction and the differential susceptibility of local stream habitats to invasion because of the environmental and biological characteristics of the receiving water body, are all confounding factors that may obscure the interpretation of patterns of introduced fish species distribution and abundance and therefore their reliability as indicators of river health.
3. In the present study, we address the question of whether alien fish (i.e. those species introduced from other countries) are a reliable indicator of the health of streams and rivers in south-eastern Queensland, Australia. We examine the relationships of alien fish species distributions and indices of abundance and biomass with the natural environmental features, the biotic characteristics of the local native fish assemblages and indicators of anthropogenic disturbance at a large number of sites subject to varying sources and intensities of human impact.
4. Alien fish species were found to be widespread and often abundant in south-eastern Queensland rivers and streams, and the five species collected were considered to be relatively tolerant to river degradation, making them good candidate indicators of river health. Variation in alien species indices was unrelated to the size of the study sites, the sampling effort expended or natural environmental gradients. The biological resistance of the native fish fauna was not concluded to be an important factor mediating invasion success by alien species. Variation in alien fish indices was, however, strongly related to indicators of disturbance intensity describing local in-stream habitat and riparian degradation, water quality and surrounding land use, particularly the amount of urban development in the catchment.
5. Potential confounding factors that may influence the likelihood of introduction and successful establishment of an alien species and the implications of these factors for river bioassessment are discussed. We conclude that the potentially strong impact that many alien fish species can have on the biological integrity of natural aquatic ecosystems,

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together with their potential to be used as an initial basis to find out other forms of human disturbance impacts, suggest that some alien species (particularly species from the family Poeciliidae) can represent a reliable 'first cut' indicator of river health.

Keywords: disturbance, freshwater fish, introduced species, invasion resistance, river health

Introduction

Successful invasion by introduced organisms is widely regarded as being more likely in anthropogenically disturbed environments (e.g. Elton, 1958; Orians, 1986; Hobbs, 1989, 2000; Case, 1996; Moyle & Light, 1996a,b; Lozon & MacIsaac, 1997). Introduced freshwater fish, in particular, have commonly been documented to thrive in degraded aquatic habitats in many areas of the world (e.g. Moyle & Nichols, 1973; Cadwallader, 1979; Arthington, Milton & McKay, 1983; Leidy & Fiedler, 1985; Arthington, Hamlet & Bluhdorn, 1990; Gehrke *et al*., 1995; Gido & Brown, 1999; Brown, 2000; Meador, Brown & Short, 2003). Introduced fish may directly impact on native fish by predation, resource competition, interference with reproduction and/or the introduction of parasites and diseases (Meffe, 1984; Courtenay & Meffe, 1989; Arthington, 1991; Ross, 1991; Crowl, Townsend & McIntosh, 1992). They may also indirectly affect native fish by altering habitat conditions and/or ecosystem processes (e.g. productivity, food web attributes) by foraging and other activities (Taylor, Courtney & McCann, 1984; Flecker & Townsend, 1994; Roberts *et al*., 1995; Arthington & McKenzie, 1997). Introduced fish may therefore represent both a symptom and a cause of decline in river health (*sensu* Rapport, Costanza & McMichael, 1998) and the integrity of native fish communities.

The apparently strong relationship between introduced fish species and degraded stream conditions, and their potential impact on native species, has led to the frequent use of introduced fish as indicators of biological integrity and river health. The presence, richness, relative abundance and/or relative biomass of introduced species (or their complement – the relative abundance/biomass of native species) are often incorporated as component metrics in applications of the Index of Biotic Integrity (IBI) (Karr, 1981; Karr *et al*., 1986) and other river bioassessment studies (e.g. Hughes & Gammon, 1987; Crumby *et al*., 1990; Bramblett & Fausch, 1991; Minns *et al*., 1994; Lyons *et al*., 1995; Ganasan & Hughes, 1998; Hughes *et al*., 1998; Maret, 1998; Moyle & Marchetti, 1998; Moyle & Randall, 1998; Wichert & Rapport, 1998; Harris & Silveira, 1999; Belpaire *et al*., 2000; Brown, 2000; May & Brown, 2002).

The reliability of indicators of river health based on the presence, abundance and/or biomass of introduced fish species may be confounded by a number of factors, making assessment of the causes of declining river health potentially difficult, and even erroneous. The use of introduced species as an indicator of the degraded end of a disturbance gradient will only be applicable if those species comprising the index are highly tolerant of human-induced disturbances (Hughes & Oberdorf, 1998). Key attributes of species successfully invading degraded habitats are hypothesised to include broad physiological tolerances to environmental conditions, generalist resource requirements and a variety of life history attributes enabling them to persist where many native species could not (Arthington & Mitchell, 1986; Bruton, 1986; Lodge, 1993; Williamson & Fitter, 1996; Ricciardi & Rasmussen, 1998; Rosecchi, Thomas & Crivelli, 2001; Koehn, 2004). However, there are many commonly introduced fish species (e.g. salmonids) that do not possess these attributes and are not highly tolerant of the common forms of perturbation in streams and rivers such as those associated with agricultural land use and urbanisation. Indeed, all introduced species are likely to have differential tolerances to the range of stressors in streams and no species is tolerant of all stressors (Cairns, 1986; Suter, 2001). Human disturbance is therefore not a requisite for successful invasion by introduced species (Niemela & Spence, 1991; Lodge, 1993; Townsend, 1996), and particular habitats may contain introduced organisms simply because they were introduced there (e.g. intentionally for recreational fishing, as a biological control agent, or via aquarium release), or recently gained access via historically unconnected pathways (e.g. by inter-basin transfers) (Vermeij, 1991; Bunn & Arthington, 2002; Gido, Schaefer & Pigg, 2004).

Areas may be differentially susceptible to invasion, irrespective of (anthropogenic) disturbance intensity, because of the environmental characteristics (e.g. natural or artificial barriers that prevent colonisation, or habitat conditions that may or may not suit the life history requirements of the invading biota), the biological characteristics of the receiving water body or interactions between these factors (Fausch *et al.*, 2001; Byers, 2002). For example, the richness, abundance and/or composition (i.e. presence of predators and/or superior competitors) of the native biota are biological attributes widely believed to promote a degree of invasion resistance (see Baltz & Moyle, 1993; Lodge, 1993; Moyle & Light, 1996b; Levine & D'Antonio, 1999 for reviews and examples), but the universality of this concept is increasingly being questioned (e.g. Lodge, 1993; Levine & D'Antonio, 1999; Meador *et al.*, 2003; Gido *et al.*, 2004). In addition, coexistence between native and introduced species may be facilitated by natural abiotic disturbances (e.g. floods) that periodically depress populations of introduced species, but not native species that have evolved mechanisms to withstand these disturbances (e.g. Meffe, 1984; Minckley & Meffe, 1987; Pusey *et al.*, 1989; Brown & Moyle, 1997). Finally, assessments of the impacts of introduced species on local native fish fauna are potentially confounded by the impacts that human disturbances may also have on the native fish fauna.

Introduced fish may include 'exotic' or 'alien' species (terms often used to refer to species introduced from other countries) and native species or genetic stocks introduced or translocated within or beyond their natural ranges (Harris, 1995). We hereafter use the term 'alien' as we are here concerned only with this component of the introduced fish fauna as an indicator of river health (given that many Australian translocated native species are comparatively intolerant of river degradation and so would likely respond in an opposite manner to degradation). Our study area comprised numerous streams and rivers in south-eastern Queensland, Australia, where at least ten alien species from four families (Poeciliidae, Cyprinidae, Cichlidae and Cobitidae) are thought to have established self-maintaining populations (Arthington *et al.*, 1983; Kailola *et al.*, 1999; Pusey, Kennard & Arthington, 2004). We address the question of whether alien fish are a reliable indicator of the health of streams and rivers in this region by testing three null hypotheses.

(1) The distribution of alien fish species is not related to natural environmental gradients in streams.

For alien fish to be a reliable indicator of river health, it is necessary that variation along natural environmental gradients be distinguished from variation caused by human disturbance-induced change. We therefore evaluated the relationships of alien fish with catchment and local-scale environmental features in a large number of stream sites.

(2) The presence, abundance and biomass of alien fish is independent of the biotic characteristics of the local native fish community.

We evaluated the relationships of alien fish with the biotic characteristics of the local native fish fauna at our study sites. A strong inverse relationship between population characteristics of alien and native species could suggest either that alien species are impacting upon native species (a form of biological disturbance) or that sites with high native richness are less invasible. Human disturbance factors may also reduce the biological resistance of the native fish fauna, enabling invasion by alien species. We attempted to elucidate the relative importance of these factors as they can potentially confound interpretations of alien fish as an indicator of river health.

(3) The presence, abundance and biomass of alien fish is not related to indicators of anthropogenic disturbance.

We evaluated the relationships of the alien fish fauna with indicators of human disturbance, a necessary requisite for alien fish to be reliable indicators of river health.

This paper forms part of a wider study to develop an ecosystem health monitoring programme for waterways in south-eastern Queensland (Smith & Storey, 2001). The freshwater fish component of the study incorporates an evaluation of appropriate fish and habitat sampling protocols, the development of univariate and multivariate indicators of river health based on fish and an evaluation of the implications of environmental variability for biomonitoring using fish in the region. These aspects of the study will be published elsewhere.

Methods

Study area and sampling methods

The study area was confined to coastal south-eastern Queensland, Australia. The climate of the region is transitional between subtropical and temperate and the majority of rainfall and streamflow occurs in the summer months of January to March, often followed by a second minor peak in discharge between April and June (Pusey, Arthington & Read, 1993; Pusey *et al*., 2004). Prior to European settlement, the region was dominated by sclerophyll forests with substantial areas of sub-tropical rainforest and coastal 'wallum' (*Banksia* heathlands). Human land-use practices associated with extensive land clearing, cattle grazing, agricultural cropping and large urban and industrial developments, have led to substantial degradation of local riparian, in-stream habitat and water quality conditions in many streams and rivers of the region (Smith & Storey, 2001).

Forty-eight test sites in south-eastern Queensland rivers and streams were selected to reflect known gradients in anthropogenic disturbance (particularly impacts associated with catchment land use and associated local riparian and in-stream habitat degradation) and to examine whether the presence, abundance and biomass of alien fish species were related to this disturbance gradient. These sites ranged from being minimally disturbed to highly impacted (see Smith & Storey, 2001 for further description of these sites). Test sites were sampled in September and October 2000. One of the test sites sampled contained no fish and was excluded from the analyses. Seventy-two additional reference sites (least affected by human activity) were used as a basis for predicting the number of native fish species expected to occur at the test sites in the absence of anthropogenic disturbance (see the section 'Statistical Methods'). Reference sites were selected on the basis that they were minimally disturbed using criteria proposed by Hughes (1995) (e.g. undisturbed riparian vegetation, bank and channel structure in natural condition, natural hydrograph). Furthermore, reference sites were included only if they were not in close proximity to major urban areas, extractive industries (i.e. mines, quarries and sand/gravel extraction), intensive agriculture, point source pollutants) or located upstream of barriers to fish movement (e.g. dams and weirs that did not drown-out periodically or contain fish passage devices). Potential reference sites were also excluded if they contained high relative abundances of alien fish species (i.e. >20% the total number of individuals in a sample). Each reference site was sampled once between July and October over the period 1994 and 1997. Hydrological conditions during the sampling period (late winter and Spring) are typically characterised by low and stable flows (Pusey, Kennard & Arthington, 2000; Pusey *et al*., 2004). We consider that test and reference sites are valid for comparison as they encompassed the same range of relative catchment positions and stream sizes, and were sampled at a similar time of year and under similar hydrological conditions of low and stable discharge (Kennard *et al*., 2001; M. J. Kennard, unpubl. data).

Sampling was limited to river reaches that were wadeable and hence could be sampled effectively by electrofishing (i.e. generally <1.5 m maximum depth). Sites were between 70 and 80 m of stream length and usually consisted of an entire meander wavelength or riffle–run–pool sequence (Newbury & Gaboury, 1993). Fish assemblages at each site were intensively sampled using the procedures detailed in Pusey *et al.* (1998). Individual mesohabitat units (i.e. riffles, runs or pools) within each site were sampled separately and data subsequently combined for the entire site. Each mesohabitat unit was blocked upstream and downstream with weighted seine nets (11 mm stretched mesh) to prevent fish movement into or out of the study area. The site was sampled using a combination of repeated pass electrofishing (Smith-Root model 12B Backpack Electroshocker; Smith-Root, Vancouver, WA) and supplementary seine netting until few or no further fish were collected (usually four electrofishing passes and two seine hauls were required to collect all fish present). The intensive sampling regime described here has been demonstrated to provide accurate estimates of species composition and abundances at wadeable stream sites, with equivalent sampling efficiency among mesohabitat types (Pusey *et al*., 1998), and intensive sampling of a single meander wavelength is the appropriate spatial scale at which to characterise local fish assemblages in south-eastern Queensland streams and rivers (Kennard *et al*., 2001; M. J. Kennard, unpubl. data).

All fish collected were identified to the species level, counted, measured (standard length to the nearest millimetre) and native fish were returned alive to the point of capture. Alien fish were killed (using benzocaine – MS222), and not returned to the water (in accordance with the Queensland Fisheries Act, 1994). Two species, sea mullet (*Mugil cephalus*) and bony bream (*Nematalosa erebi*), were occasionally collected by electrofishing but were omitted from all analyses as these mobile, schooling species are not sampled efficiently by the methods described above (Pusey *et al.*, 1993). The weight of each fish (both native and alien species) was estimated with reference to existing relationships between body length and mass for each species (Pusey *et al.*, 2004). Fish abundance and biomass data were transformed to numerical densities (number of individuals 10 m^{-2}) and biomass densities (g 10 m^{-2}) at each site.

Catchment and local-scale physical characteristics of the study sites were estimated according to a standard protocol described in Pusey *et al.* (2004). Catchment descriptors for each site were estimated from 1 : 100 000 topographic maps using a digital planimeter or from Geographical Information System (GIS) databases. Site physical characteristics including mean wetted stream width, maximum water velocity and total water depth were calculated from a series of 40–60 point measurements located randomly throughout the site.

We characterised the potential sources and intensity of anthropogenic disturbance at each test site using a set of variables intended to reflect disturbance mechanisms operating at both large and local scales (Appendix). Catchment land use was characterised by the percentage of the catchment upstream of each site affected by land clearing, cattle grazing, agricultural cropping and urbanisation. We hypothesised that these large-scale land-use impacts would result in localised changes to water quality, riparian habitat and in-stream habitat conditions that would, in turn, influence the distribution and abundance of freshwater fish. A set of basic water chemistry variables (conductivity, turbidity, pH, total nitrogen, total phosphorus, diel range in dissolved oxygen and temperature) and several simple measures of riparian and in-stream habitat conditions (riparian vegetation cover, percentage of mud substrate, abundance of aquatic macrophytes, filamentous algae and submerged invasive terrestrial weeds) were assessed at each site to describe these potential sources of disturbance (Appendix). We recognise that many of the variables used to characterise the disturbance gradient may vary along natural environmental gradients; however, we were not able to account for this natural variation in the present study. We assumed that all disturbance variables are likely to increase in magnitude with increasing human disturbance intensity except pH (increase or decrease) and riparian cover (decrease) (Appendix). Smith & Storey (2001) provide further justification and rationale for the use of these variables to describe the disturbance gradient.

Statistical methods

Various indices were calculated to describe variation in alien fish species parameters at the test sites. These comprised the relative abundance and relative biomass of alien fishes collected at each site (expressed as a percentage of the total catch), and the total numerical density and biomass density of alien fish collected at each site. The use of a river health index based on all alien species present may be overly simplistic for river systems in which alien species with varying life history characteristics and differential tolerances to environmental stressors are included in the final index. To address this, we calculated alien fish species indices separately for the two fish families collected in the present study (Poeciliidae and Cyprinidae, see 'Results') and examined their relationships with the original indices that included all alien fish species.

We examined whether relationships existed between alien fish indices and the amount of sampling effort expended at each site (as estimated by total stream length sampled, total sampling area, total sampling volume, total fish abundance and total fish biomass) using Spearman's rank correlation. Similarly, relationships of alien fish indices with the full suite of catchment variables and local site physical characteristics were also assessed using Spearman's rank correlation. If such relationships exist, it would be difficult to separate the variation associated with human disturbance impacts from that caused by sampling effort and variation along natural environmental gradients.

Relationships of alien fish indices with the native fish species richness, abundance and biomass observed at the study sites were examined graphically using biplots and statistically using Spearman's rank correlation. We also tested the premise that local native fish assemblages with high species richness are more resistant to alien species invasion (as defined by the relative magnitude of alien species indices) by correlating the alien species indices with the number of native species expected to occur at each site in the absence of any anthropogenic stress. In this analysis, it was necessary to remove the potentially confounding effect that anthropogenic stress (caused by human disturbance factors) and the likely negative biological impact of alien species may have had upon some sites by depressing the native fish fauna, hence enabling the alien species to invade and persist. We did this by distinguishing those sites relatively free from anthropogenic stress, and with high biological integrity, from those in which the native fish fauna may have been affected by anthropogenic disturbance. We then examined the relationships between alien fish species indices and native fish species richness at each set of sites separately. The ratio of species richness observed (O) to species richness predicted (P) in the absence of stress was used to define biological integrity. Those sites with O/P ratios >0.75 contained relatively intact fish assemblages and therefore were judged to be of high biological integrity. We predicted the number of native species that should occur in the absence of stress (abiotic or biotic) using a predictive modelling approach (forward and backward stepwise multiple regression using generalised linear modelling (GLM) and Akaike's information criterion for variable selection). The model was based on relationships between native species richness and four environmental variables (site distance from the river mouth, altitude, upstream catchment area, mean site wetted width) derived from 62 least disturbed reference sites. The model was internally robust (approximate model $R^2 = 69\%$, $P < 0.001$) and could accurately predict native species richness at 10 independent validation sites foreign to the reference model (R^2 for validation site predictions = 59%, $P < 0.001$). Full details of model development and validation will be published elsewhere. We assumed that sites with O/P scores close to unity (i.e. >0.75) were also relatively unaffected by anthropogenic disturbance as O/P scores were strongly inversely related to increasing human disturbance intensity.

The relative ability of the alien species indices to accurately reflect the human disturbance gradient was also evaluated using a *post hoc* approach. Non-parametric Mann–Whitney rank tests (Mann & Whitney, 1947) were used to elucidate relationships between the disturbance variables and the presence or absence of alien species. The magnitude of individual disturbance variables at those sites where alien species were present was compared with corresponding values at sites where alien species were absent. Variation in alien species index scores at test sites were related to a suite of variables describing the source and intensity of disturbance at those sites. Bivariate relationships between alien species index scores at the test sites and the disturbance variables were established using Spearman's rank correlations to ascertain whether any simple relationships existed. Multiple regression was also used, acknowledging that the presence, abundance and biomass of alien species can potentially reflect a range of disturbance mechanisms interacting at a range of spatial scales. A principal components analysis (PCA) was used to reduce the 16 disturbance variables [$\log_{10}(x + 1)$ transformed] to a smaller number of orthogonal components, to avoid the potential problem of correlation between predictor variables in multiple regression. A similar approach has been used elsewhere (e.g. Meador *et al.*, 2003; Sloane & Norris, 2003). The PCA was based on the correlation matrix, and loadings of the original variables on each of the first five principal components were used to identify the dominant disturbance gradients in the data set. Spearman's correlation of principal component scores with catchment and local site physical characteristics was used to examine whether the disturbance gradient was confounded by variation along natural environmental gradients. Stepwise GLM was used to predict alien species index scores on the basis of the disturbance gradient principle components. The relative ability of each alien species index to reflect the disturbance gradient was determined by the strength of the relationship between index scores and the disturbance gradient components. This was assessed by comparing the amount of variance (R^2) in index scores explained by each GLM. All analyses were conducted using S-PLUS 2000 (Statistical Sciences, 1999).

Results

Characteristics of the fish fauna

Thirty-nine species of freshwater fish (defined here as those species that either breed or spend a major proportion of their life cycle in freshwater) are native to south-eastern Queensland, and at least 15 additional species, of which five species are native to Australia, have been introduced in the region (Table 1). Quantitative sampling of the fish fauna resulted in the collection of 30 species (excluding sea

Table 1 Native and introduced freshwater fish species present in south-eastern Queensland (including all coastal catchments from the Burnett River south to the border with New South Wales)

Taxon	Common name	
Neoceratodontidae		
Neoceratodus forsteri (Krefft)	Lungfish	N
Anguillidae		
Anguilla reinhardtii Steindachner	Longfinned eel	N*
A. australis Richardson	Shortfinned eel	N*
Clupeidae		
Nematalosa erebi (Günther)	Bony bream	N*
Osteoglossidae		
Scleropages leichardti Günther	Saratoga	T
Retropinnidae		
Retropinna semoni (Weber)	Australian smelt	N*
Ariidae		
Arius graeffei Kner & Steindachner	Fork-tailed catfish	N
Plotosidae		
Tandanus tandanus Mitchell	Eel-tailed catfish	N*
Neosilurus hyrtlii Steindachner	Hyrtl's tandan	N
Porochilus rendahli (Whitley)	Rendahl's catfish	N
Hemiramphidae		
Arrhamphus sclerolepis krefftii Günther	Snub-nosed garfish	N
Atherinidae		
Craterocephalus marjoriae Whitley	Marjorie's hardyhead	N*
C. stercusmuscarum fulvus Ivantsoff, Crowley & Allen	Flyspecked hardyhead	N*
Melanotaeniidae		
Melanotaenia duboulayi (Castelnau)	Duboulay's rainbowfish	N*
Rhadinocentrus ornatus Regan	Softspined sunfish	N*
Pseudomugilidae		
Pseudomugil signifer Kner	Southern blue-eye	N*
P. mellis Allen & Ivantsoff	Honey blue-eye	N*
Synbranchidae		
Ophisternon sp. (Undescribed)	Swamp eel	N*
Scorpaenidae		
Notesthes robusta (Günther)	Bullrout	N
Centropomidae		
Lates calcarifer (Bloch)	Barramundi	N
Chandidae		
Ambassis agassizii Steindachner	Olive perchlet	N*
A. marianus Günther	Estuary perchlet	N
Percichthyidae		
Maccullochella peelii mariensis Rowland	Mary River cod	N
Macquaria novemaculeata (Steindachner)	Australian bass	N*
M. ambigua (Richardson)	Golden perch	T*
Terapontidae		
Leiopotherapon unicolor (Günther)	Spangled perch	N*
Amniataba percoides (Günther)	Barred grunter	T
Bidyanus bidyanus (Mitchell)	Silver perch	T
Nannopercidae		
Nannoperca oxleyana Whitley	Oxleyan pygmy perch	N*
Kuhliidae		
Kuhlia rupestris (Lacepede)	Jungle perch	N
Apogonidae		
Glossamia aprion (Richardson)	Mouth almighty	N*
Mugilidae		
Mugil cephalus Linnaeus	Sea mullet	N*
Myxus petardi (Castelnau)	Freshwater mullet	N
Gobiidae: Eleotridinae		
Gobiomorphus australis (Krefft)	Striped gudgeon	N*
G. coxii (Krefft)	Cox's gudgeon	N*
Hypseleotris galii (Ogilby)	Firetailed gudgeon	N*
H. klunzingeri (Ogilby)	Western carp gudgeon	N*
H. compressa (Krefft)	Empire gudgeon	N*
Hypseleotris sp.4 (Undescribed)	Midgely's carp gudgeon	N
Hypseleotris sp.5 (Undescribed)	Lake's carp gudgeon	T?
Mogurnda adspersa (Castelnau)	Southern purple-spotted gudgeon	N*
Philypnodon sp. (Undescribed)	Dwarf flathead gudgeon	N*
P. grandiceps (Krefft)	Flathead gudgeon	N*
Gobiidae: Gobiinae		
Redigobius bikolanus (Herre)	Speckled goby	N
Alien species		
Cyprinidae		
Cyprinus carpio Linnaeus	European carp	A*
Carassius auratus Linnaeus	Goldfish	A*
Cobitidae		
Misgurnus anguillicaudatus Cantor	Oriental weatherloach	A
Poeciliidae		
Gambusia holbrooki (Girard)	Eastern Gambusia	A*
Xiphophorus helleri Heckel	Swordtail	A*
X. maculatus (Günther)	Platy	A*
Poecilia reticulata (Peters)	Guppy	A
P. latipinna (Le Sueur)	Sailfin molly	A
Cichlidae		
Oreochromis mossambicus (Peters)	Mozambique mouthbrooder	A
Amphilophus citrinellus (Günther)	Midas cichlid	A

Species native to the region are denoted by N, translocated native species by T (? denotes species of uncertain origin) and alien species introduced from other countries and thought to have established by A (source: Pusey *et al.*, 2004).
*Species collected during the present study.

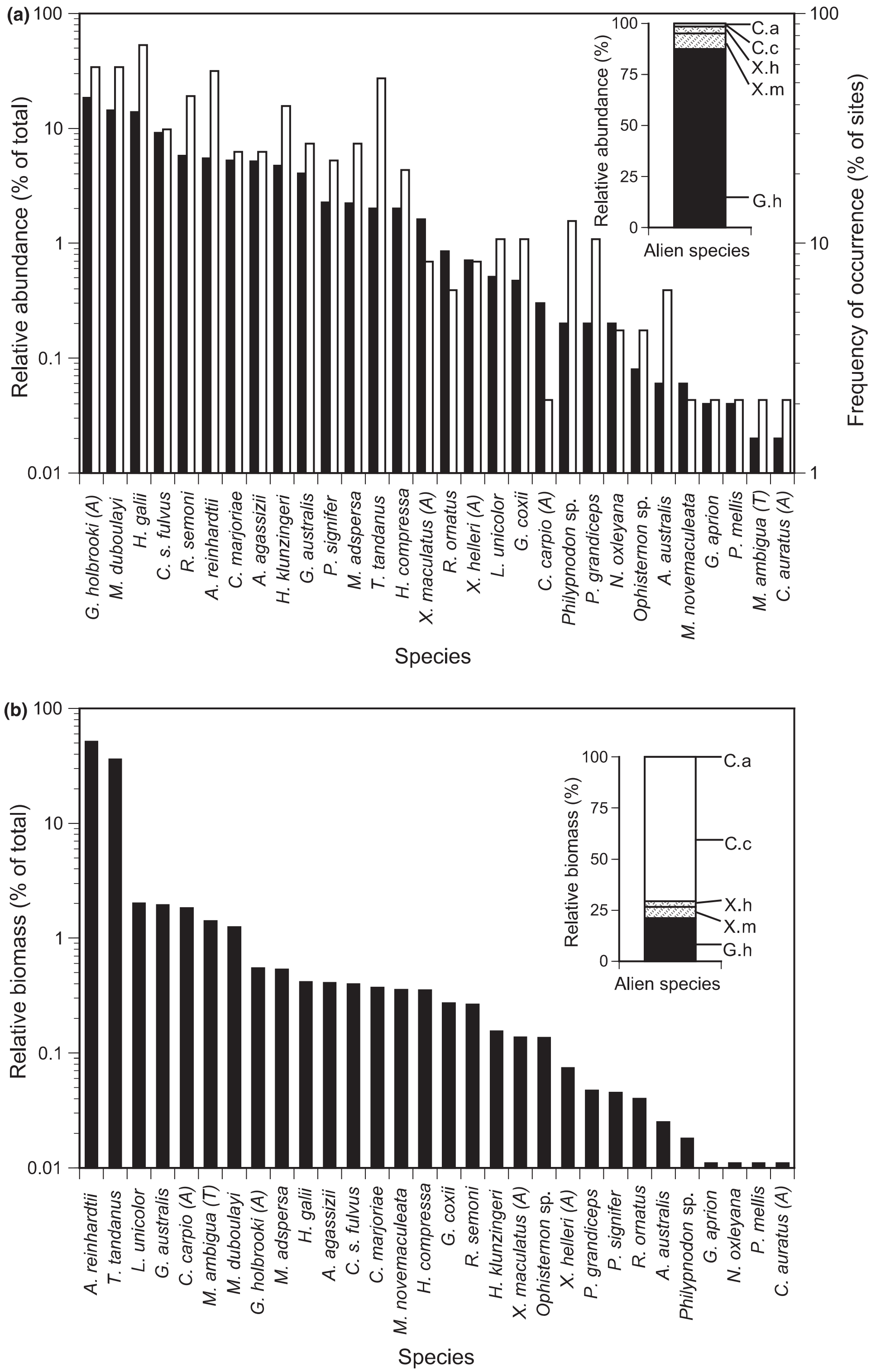

Fig. 1 Biological characteristics of the fish fauna at the study sites showing (a) relative abundance (closed bars, scale on left axis) ($n = 4943$ individuals) and frequency of occurrence (open bars, scale on right axis) ($n = 47$ sites), and (b) relative biomass (total of 69.1 kg). Alien species are denoted by 'A' and translocated native species by 'T', in parentheses. Inset histograms show the relative abundance ($n = 1041$ individuals) and relative biomass (total of 1.8 kg) of alien species only (species names are abbreviated to the first letter of the genus and species, respectively).

mullet and bony bream), 4943 individuals and 69.1 kg of fish from the 47 sites (Fig. 1). Five alien fish species from two families were collected (Family Poeciliidae: eastern *Gambusia* – *Gambusia holbrooki*, swordtail – *Xiphophorus helleri*, and platy – *X. maculatus*; Family Cyprinidae: carp – *Cyprinus carpio* and goldfish – *Carassius auratus*) (Fig. 1a), all of which are thought to be relatively tolerant to river degradation (Arthington *et al.*, 1990; Arthington & McKenzie, 1997). Poeciliids comprised over 98% of the total number of alien fish collected (total of 1041 individuals) and this family was dominated by *Gambusia holbrooki* (87% of alien fish collected). This species was also the most abundant and second most widespread of all species collected (both native and alien), forming 18.4% of the total number of fish collected and occurring at 60% of the sites (Fig. 1a). The remaining alien species collectively comprised a further 3% of the total catch and each species occurred at <10% of sites. Duboulay's rainbowfish (*Melanotaenia duboulayi*), firetailed gudgeon (*Hypseleotris galii*) and flyspecked hardyhead (*Craterocephalus stercusmuscarum fulvus*) were the most common native species, forming a further 37% of the total number of fish collected. Two native species, long-finned eel (*Anguilla reinhardtii*) and eel-tailed catfish (*Tandanus tandanus*), dominated the total catch in terms of biomass, collectively comprising over 85% of the total biomass collected (Fig. 1b). The five alien species collectively comprised only 2.5% of the total biomass, with cyprinids (mostly *C. carpio*) dominating the catch (71% of the total alien fish biomass), although this family occurred at only two sites.

Relationships of alien fish with sample effort, catchment variables and site physical characteristics

Indices of alien fish abundance (% abundance alien and total numerical density alien) and biomass (% biomass alien and total biomass density alien) were highly correlated with each other (Spearman's $r > 0.9$; Table 2). Variation in these indices was dominated by the contribution of poeciliid species (mainly *G. holbrooki*), with little influence from cyprinid species. For example, alien fish indices were highly correlated with percentage abundance of poeciliids and percentage biomass of poeciliids (Spearman's $r > 0.95$), but not percentage abundance and biomass of cyprinids (Spearman's $r < 0.29$).

Table 2 Spearman's rank correlation coefficients for relationships between alien fish species indices (abundance and biomass) and variables describing sampling effort and landscape and local scale environmental data at the 47 sites sampled. Also shown are significant rank correlations between alien fish indices and disturbance gradient variables.

	% abundance alien fish	% biomass alien fish
Alien species indices		
% biomass alien fish	0.961*	–
Total numerical density alien fish	0.966*	0.933*
Total biomass density alien fish	0.967*	0.935*
% abundance poeciliids	1.000*	0.960*
% abundance cyprinids	0.274	0.281
% biomass poeciliids	0.959*	0.996*
% biomass cyprinids	0.274	0.281
Site dimensions and sample effort		
Stream length sampled	−0.282	−0.203
Sampling area	−0.203	−0.194
Sampling volume	−0.048	−0.022
Total abundance	0.245	0.251
Total biomass	−0.167	−0.283
Catchment variables		
Upstream catchment area	0.072	0.107
Distance from stream source	0.091	0.115
Distance to river mouth	−0.276	−0.219
Altitude	−0.247	−0.221
Site physical characteristics		
Mean wetted width	0.032	0.094
Maximum depth	0.046	−0.058
Maximum velocity	−0.302	−0.361
Disturbance gradient variables		
% catchment cleared	0.447*	0.443*
% catchment cropped		0.373*
% catchment urban	0.460*	0.471*
Conductivity	0.380*	0.425*
Riparian cover	−0.435*	−0.467*
Aquatic macrophtyes	0.399*	0.458*
Submerged terrestrial vegetation	0.447*	0.404*
Mud		0.393*

*Correlations significant at $P < 0.05$ after correction for multiple comparisons using the Dunn-Sidak procedure (Quinn & Keough, 2002).

Alien fish indices were not significantly correlated ($P > 0.05$) with variables describing the size of the study site, the sampling effort expended or the total abundance or biomass of fish collected (Table 2). No significant ($P > 0.05$) relationships existed between alien fish indices and catchment variables or site physical characteristics (Table 2).

Relationships of alien fish with the native fish fauna

There were no significant relationships between the alien species relative abundance and biomass and

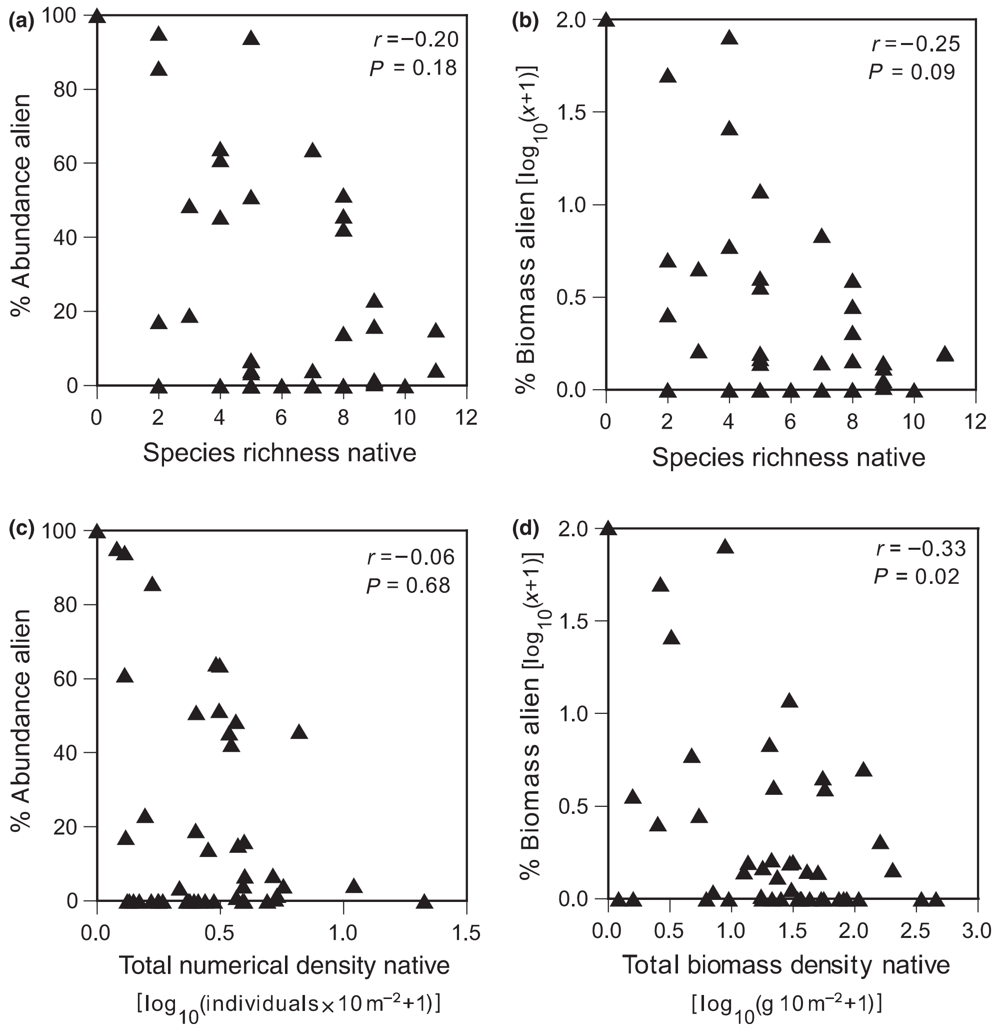

Fig. 2 Relationships of (a) alien species relative abundance and (b) alien species relative biomass with native species richness observed at the study sites. Also shown are relationships of alien species relative abundance (c) and relative biomass (d) with total densities and biomass densities of native species. Spearman's rank correlation coefficients and their significance levels for each plot are also shown. Note that some axes are plotted on a $\log_{10}(x + 1)$ scale for clarity.

the species richness, total numerical density and total biomass density of native fish observed at the study sites (Fig. 2). Similarly, no relationships were found using alien species density and biomass density data (results not shown). The wedge-shaped scatter of the data and the strongly negative slope of the upper bounds of each plot do indicate, however, that there was a decreasing relative abundance and biomass of alien fish associated with increasing species richness, numerical density and biomass density of native fish (Fig. 2). This suggests that there may be a threshold above which alien species are not able to invade or persist at certain sites, possibly because of the combined effect of high native species richness and high biological integrity, factors that may decrease the likelihood of invasion.

We attempted to remove the potentially confounding effect that anthropogenic stress (abiotic and biotic) may have had on the native fish fauna at the study sites by distinguishing those sites with high biological integrity (as defined by O/P scores) from those in which the native fish fauna may have been affected by anthropogenic disturbance. We observed only weakly negative relationships of alien fish species indices with the ratio of observed to predicted native species richness (Fig. 3a,b). Furthermore, sites with high O/P scores (and therefore considered to be of high biolo-

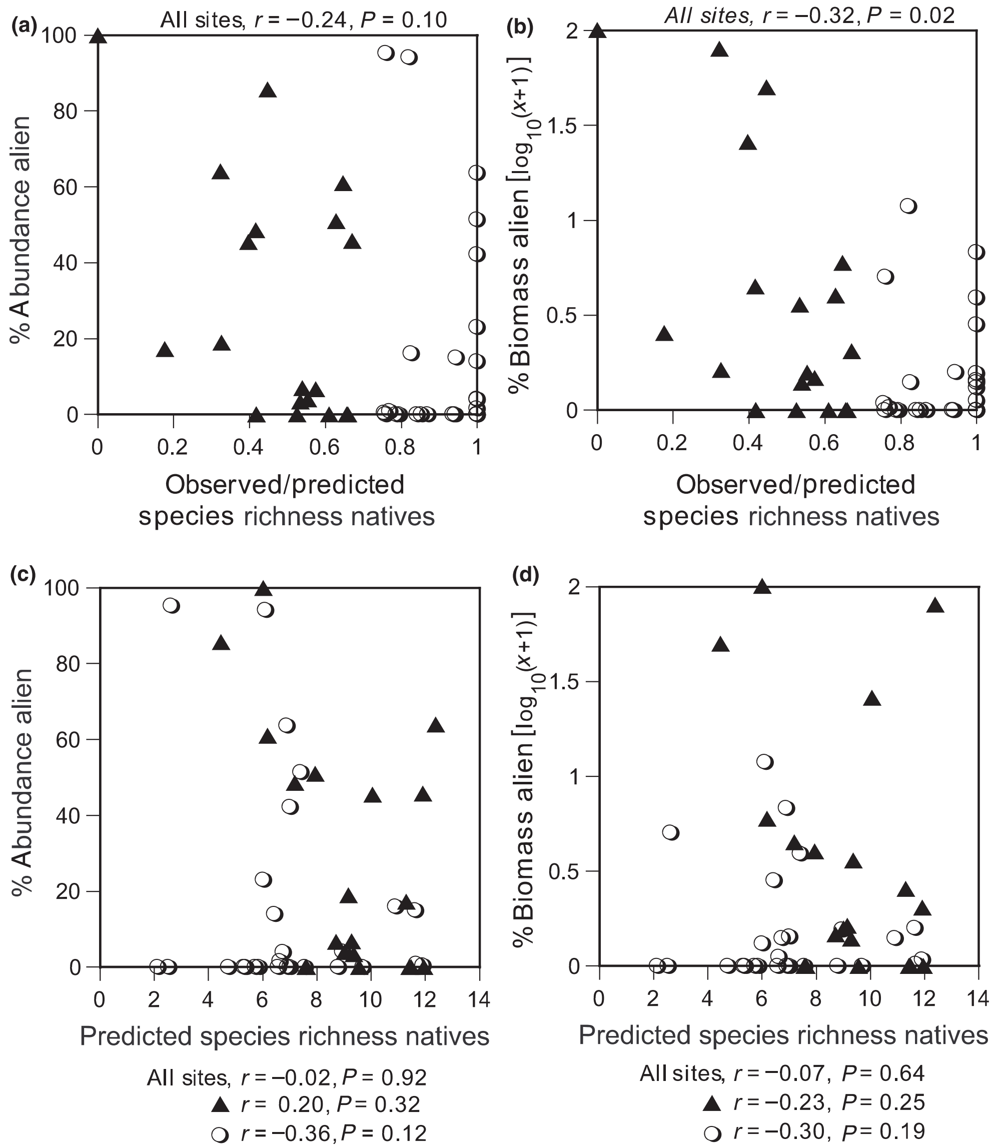

Fig. 3 Relationships of (a) alien species relative abundance and (b) alien species relative biomass with the ratio of observed to predicted native species richness at the study sites. Sites considered to be of high biological integrity (O/P scores >0.75, n = 27 sites) are denoted by open circles, and those of low biological integrity (O/P scores <0.75, n = 20 sites) by closed triangles. Also shown are relationships of alien species relative abundance (c) and relative biomass (d) with predicted native species richness. The same symbols are used for each site type. Spearman's rank correlation coefficients and their significance levels for each plot are also shown. Note that the relative biomass data are plotted on a $\log_{10}$ (x + 1) scale for clarity.

gical integrity) often also contained a high relative abundance and biomass of alien species (Fig. 3a,b). There were also no significant negative relationships ($P > 0.05$) of alien species indices with native species richness at the subset of sites considered to be of high biological integrity (native species richness O/P scores >0.75), at sites with reduced biological integrity (native species richness O/P scores <0.75) or across the entire site database (Fig. 3c,d). Sites predicted to contain a relatively high number of native species also often contained a high relative abundance and biomass of alien species (whether or not they were of high or low biological integrity). These results strongly suggest that sites with high native species richness were not less invasible, irrespective of their biotic integrity.

Relationships of alien fish with indicators of human disturbance

Sites where alien fish were present were characterised by significantly higher intensities of disturbance caused by human land-use practices (percentage of upstream catchment cleared, percentage cropped and percentage urban) than those sites without alien species (Fig. 4). These sites also had significantly wider ranges in diel dissolved oxygen concentrations, higher conductivity, lower riparian vegetation cover, muddy substrates and infestations of aquatic macrophytes (mostly alien weed species) and filamentous algae. Rank correlations between alien species indices and disturbance descriptors revealed similar patterns (Table 2). Disturbances related to land use (percentage cleared, percentage cropped, percentage urban), water chemistry (conductivity) and riparian and instream habitat degradation (riparian cover, mud, aquatic macrophytes, submerged terrestrial vegetation) were significantly correlated with the alien fish indices at the study sites (Table 2).

Principal components analysis reduced the initial 16 disturbance variables to five components that accounted for 79% of the total variation in the data (Table 3). Component 1 described a gradient of land use (clearing and grazing) and water chemistry (diel temperature range, pH and conductivity). Component 2 was associated with riparian vegetation degradation, aquatic vegetation infestations and high diel dissolved oxygen range. Component 3 reflected a nutrient gradient, component 4 was associated with muddy substrates, high turbidity and cropping in the catchment and component 5 described catchment urbanisation and infestations of submerged terrestrial vegetation. Importantly, none of the five principle components was correlated with any catchment variables or site physical characteristics (Spearman's correlations, $P > 0.05$), indicating that the disturbance gradients as summarised by the PCA was not confounded by natural environmental gradients. Multiple regression models using disturbance gradient principal components as predictors of variation in alien fish indices at test sites were highly significant ($P < 0.0001$) and could explain 76 and 57% of the variance in the relative abundance and relative biomass of alien fish, respectively (Table 4; Fig. 5). Both regression models selected three disturbance principal components (PC2, PC4 and PC5) as predic-

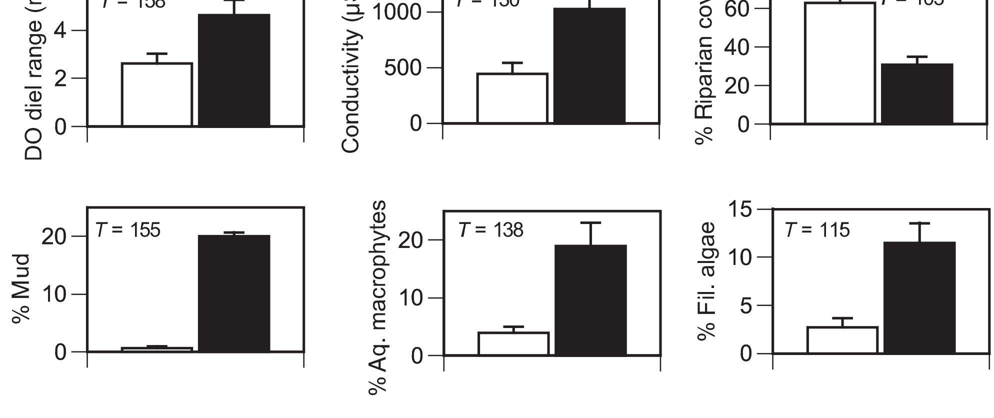

Fig. 4 Mean (±SE) values of disturbance variables significantly different at sites where alien species were present (closed bars, $n = 28$ sites) and absent (open bars, $n = 19$ sites). Mann–Whitney test statistics (T) are given for each comparison; all were significant at $P < 0.05$ after correction for multiple comparisons using the Dunn–Sidak procedure (Quinn & Keough, 2002).

Table 3 Principal components analysis of 16 disturbance variables from the 47 test sites in south-eastern Queensland

Variable	Principal component 1 (25.5%)	2 (16.6%)	3 (13.2%)	4 (12.1%)	5 (11.6%)
% catchment grazed	**0.83**	0.04	0.07	0.17	0.06
Temperature diel range	**0.70**	0.30	−0.21	−0.14	−0.26
pH	**0.69**	0.31	−0.15	0.02	−0.06
% catchment cleared	**0.68**	0.08	0.29	0.33	0.37
Conductivity	**0.57**	0.41	0.26	0.36	0.05
Aquatic macrophtyes	0.03	**0.84**	0.06	−0.06	0.19
Filamentous algae	0.18	**0.76**	−0.12	−0.06	−0.04
Dissolved oxygen diel range	0.48	**0.69**	0.01	0.14	0.10
Riparian cover	−0.42	**−0.55**	−0.06	0.18	0.04
Total nitrogen	0.04	0.01	**0.95**	0.07	−0.02
Total phosphorus	−0.06	−0.03	**0.95**	−0.02	0.05
Turbidity	0.09	−0.18	−0.15	**0.80**	0.17
Mud	0.18	0.05	0.10	**0.75**	0.06
% catchment cropped	−0.11	0.48	0.30	**0.57**	−0.29
% catchment urban	−0.17	−0.06	0.25	0.25	**0.77**
Submerged terrestrial vegetation	0.09	0.21	−0.18	−0.05	**0.76**

The percentage variation explained by each component is given in parentheses and the highest variable loadings on each principal component are shown in bold type.

tors (Table 4). These results collectively suggest that the presence and relative abundance of alien fish was strongly related to the intensity of human disturbance as measured by surrounding land use, water quality, local riparian and in-stream habitat degradation.

Discussion

This study has shown that alien fish species are widespread and often abundant in south-eastern Queensland rivers and streams. The five alien fish species collected (eastern *Gambusia*, swordtail, platy, carp and goldfish) are all thought to be relatively tolerant to river degradation (Arthington *et al.*, 1983, 1990; Arthington & McKenzie, 1997), making them good candidate indicators of river health. Our analyses revealed that variations in alien species distribution, local abundance and biomass were not related to the sizes of the study sites, the sampling effort expended or variation along natural environmental gradients. We could therefore rule out these as factors potentially confounding interpretations of alien fish as indicators of river health in the study area.

We observed no significant relationships of alien species indices with the species richness, total numerical density and biomass density of native fish present

Table 4 Summary of multiple regression models to predict variation in alien species relative abundance and biomass at the 47 test sites according to variation in the disturbance gradient principal components. For each GLM, the approximate model R^2 and the relative importance of each predictor variable fitted in the model (indicated by the percent of total variance explained) is given.

Predictor (principal component)	Disturbance gradient description	% abundance alien fish	% biomass alien fish
PC1	Catchment land use (clearing, grazing) and water quality (temperature diel range, pH, conductivity)	–	–
PC2	Riparian vegetation degradation, aquatic plant infestation, high diel DO range	19.8	19.4
PC3	High nutrients	–	–
PC4	Catchment land use (cropping), habitat degradation (muddy substrate) and high turbidity	19.6	18.5
PC5	Catchment land use (urbanisation) and habitat degradation (submerged terrestrial weeds)	36.2	19.2
GLM R^2		75.7%	57.1%

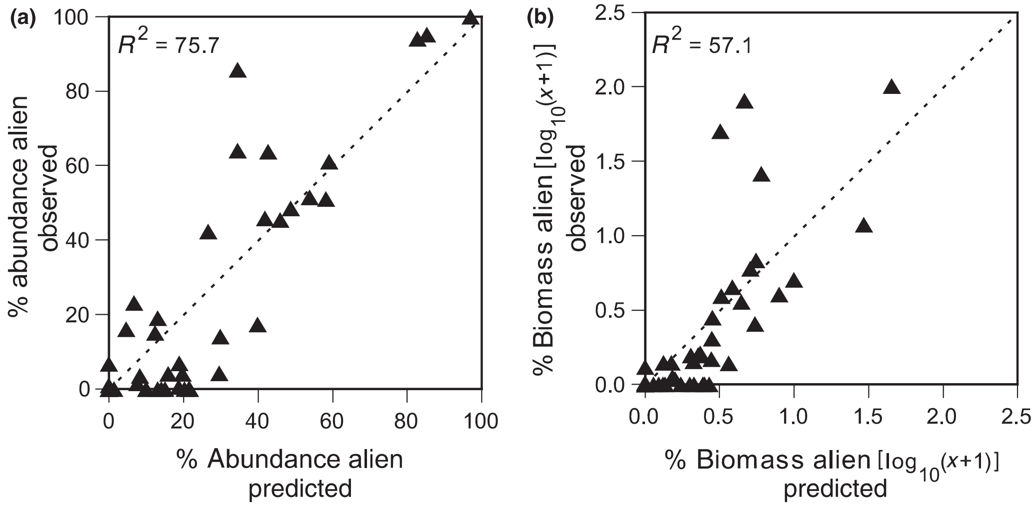

Fig. 5 Relationships between alien species relative abundance (a) and relative biomass (b) predicted by multiple regression models and the values observed at each site. The disturbance variables used as predictors for each model are given in Table 3. Dashed lines indicate hypothetical 1:1 relationships between predicted and observed values. The approximate model R^2 is given for each plot.

at the study sites. Although human disturbance factors may have reduced the biological resistance of the native fish fauna and enabled invasion by alien species, it is difficult to assess the relative importance of these potential confounding factors (i.e. the interaction between habitat degradation and reduced biotic resistance) in mediating invasion success by alien species without direct experimentation. However, the results of this study suggest that at those sites where these confounding factors were removed (i.e. the subset of sites with high biological integrity), high species richness did not confer increased invasion resistance. A similar pattern was observed at sites with reduced biotic integrity. From these data, we conclude that the biological resistance of the native fish fauna was not an important factor mediating invasion success by alien fish species, supporting the findings of Meador *et al.* (2003) and Gido *et al.* (2004) for North American streams.

Alien species were present at some undisturbed sites of high biological integrity, probably because they were introduced there or dispersed there from the original point of introduction, and were able to persist there because the environmental characteristics present suited their life history requirements. This has also been observed elsewhere; for example, populations of eastern *Gambusia* and swordtail occur in relatively undisturbed aquatic habitats within national parks and state forests in south-eastern Queensland (Arthington & Marshall, 1999; M. J. Kennard, pers. obs.). The coexistence of a diverse assemblage of native species with a high abundance and biomass of alien species at some sites may occur because insufficient time has elapsed for the negative impact of alien fish on native species to be realised. Alternatively, their coexistence may be facilitated by natural abiotic disturbances (e.g. floods and extended droughts) that periodically depress populations of alien species, but not native species that have evolved mechanisms to withstand these disturbances (e.g. Meffe, 1984; Minckley & Meffe, 1987; Pusey *et al.*, 1989; Brown & Moyle, 1997; May & Brown, 2002). The flow regimes of many south-eastern Queensland rivers and streams are highly variable and unpredictable in comparison with other Australian rivers and extremely high discharge events and extended periods of zero flow occur naturally in this region, thus constituting natural abiotic disturbances (Pusey *et al.*, 1993, 2000).

The number of introduction occasions is thought to be an important factor influencing successful establishment of fish, birds and other organisms (Ross, 1991; Case, 1996; Cassey, 2001). Alien fish species distributions, abundance and biomass data, as assessed in the present study, reveal nothing of the relative frequency of introductions but do indicate the outcome of successful species invasion. Invasion success was strongly related to the human disturbance gradient, particularly the amount of urban development in the catchment. In Australia, habitat modifications associated with the successful establishment of alien species include impoundment, diversion, channelisation and regulation of rivers; desnagging, loss of riparian vegetation, bank erosion and sedimentation; thermal and chemical pollution and the presence of introduced plants (Arthington *et al.*, 1983, 1990). Many of these disturbances were important correlates with the presence, abundance and biomass of alien fish collected during this study. We interpret these observations by suggesting that alien species are more likely to be introduced in urbanised areas, are more tolerant of associated degraded habitat conditions and possess life history attributes enabling them to persist at sites where native species could not. These conclusions remain tentative as our study was conducted over a short time span (a single sampling occasion), however we suggest that once an alien species has invaded an area and habitat conditions remain favourable, it is likely to persist there. Nevertheless, the ability of alien fish indices to reflect human disturbance to streams may be confounded by several factors. The relatively strong relationships of alien fish with proximity to urban areas, as demonstrated in the present study, may simply reflect the increased likelihood of introductions (e.g. intentional aquarium releases or accidental escapees from artificial ponds) in these areas, and may not necessarily be associated with degraded stream habitat or water quality. Conversely, river reaches may be anthropogenically disturbed but alien species are not present because they are unable to access these areas because of natural or artificial barriers, or simply because they have not been introduced there.

The use of a river health index based on all alien species present may be overly simplistic for river systems in which alien species with varying life history characteristics and differential tolerances to specific human impacts are included in the final index. For example, Maret (1998) suggested that the widespread introduction of intolerant salmonid species in central North America confounded the use of introduced species as an indicator of habitat degradation. This problem could arise in south-eastern Australian streams and rivers where salmonids have become established (Cadwallader, 1979; Arthington & Mitchell, 1986; Crowl *et al.*, 1992). In northern Australia, the alien species of poeciliids, cyprinids and cichlids present have entirely different life history requirements, reproductive styles and different tolerances to environmental stressors (see Milton & Arthington, 1983; Arthington, McKay & Milton, 1986; Arthington & Mitchell, 1986; Bruton, 1986). Although intuitively obvious, caution should be exercised when interpreting indices of river health based on alien species and reference should be made to the composition of species from which each index is derived. Nevertheless, an alien species index (particularly one based largely on poeciliids, and mainly *G. holbrooki*, such as that examined in the present study) may be a simple and effective 'first cut' indicator of river health.

The results of this study suggest that streams and rivers affected by human activity and modification are more likely to be susceptible to invasion by alien fish species. The presence of alien species can therefore be used as an indicator of degraded stream conditions and these areas can be given appropriate attention for remediation. However, the impact of alien species at degraded sites may be as much, or more, disruptive of the native fish fauna than the adverse physical and chemical conditions present, and may therefore represent a severe form of biological disturbance (Ganasan & Hughes, 1998). Although human-induced physical and chemical changes to streams can often be reversed or at least ameliorated, alien species are difficult to control and may be impossible to eradicate (Courtenay & Hensley, 1980; Courtenay & Stauffer, 1984; Ganasan & Hughes, 1998; Koehn, Brumley & Gehrke, 2000). Nevertheless, habitat restoration activities (e.g. flow restoration, introduction of woody debris or riparian vegetation rehabilitation) may help prevent the establishment of alien fish populations, assist in the management of those already present (e.g. by reducing abundances) and benefit native fish populations (Arthington *et al.*, 1990; Koehn *et al.*, 2000; Marchetti & Moyle, 2001; Brown & Ford, 2002).

Alien species are indicators of biological integrity in two fundamental respects. First, their presence represents a deviation from the historical natural condition of the fish community (i.e. the pre-introduction condition). Secondly, alien fish species have been associated with declines in, or extirpation of, native fish in a range of systems because of predation, competition and/or transmission of disease. In an analysis of 31 studies, Ross (1991) suggested that introduced fishes resulted in declines of native species in 77% of cases studied. The apparently strong impact that many alien fish species have on native fish species, together with the notion that they can also be useful as an initial basis to diagnose other forms of human disturbance impacts, suggest that some alien species can represent a reliable indicator of river health. Ultimately, indicators based on the presence, abundance and biomass of alien species have potentially broad appeal because of their practicality (i.e. relative ease of sampling, identification and analysis) and conceptual simplicity (it is easy to communicate results to managers and the wider community).

We conclude that alien fish can be a reliable indicator of river health, but with the following provisos: (1) the local fish assemblage is accurately determined with standardised sampling methods that result in equivalent levels of efficiency in collecting both native and alien species; (2) those alien species generally regarded as intolerant of degraded physical and chemical conditions (e.g. salmonids) are excluded from summary indices and (3) consideration is given to confounding factors such as the possibility that alien species may have been deliberately introduced into relatively undisturbed areas (e.g. for recreational angling, biological control or through aquarium release).

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Appendix

Variables used to quantify the source and intensity of anthropogenic disturbance at each site. Variables describe human land use, water chemistry, riparian vegetation and in-stream habitat characteristics. A description of each variable, the expected generalised response to disturbance (in parentheses) and the range of values observed at the test sites are given. Numbers in superscript refer to the methods used to measure each variable.

Variable	Description	Minimum	Maximum
Land use*			
% catchment cleared	Percentage of total catchment area cleared of native vegetation	0	90.0
% catchment grazed	Percentage of total catchment area subject to cattle grazing	0	87.0
% catchment cropped	Percentage of total catchment area subject to agricultural cropping	0	24.6
% catchment urban	Percentage of total catchment area subject to urban development	0	66.2
Water chemistry			
Conductivity (μS cm^{-1})†	Measure of total concentration of dissolved inorganic ions (increase)	91	5300
Turbidity (NTU)†	Measure of decreased ability of water to transmit light due to total suspended particulate matter (increase)	1	200
pH†	Measure of water acidity or alkalinity based on the concentration of hydrogen ions (increase or decrease)	5.2	9.1
Total nitrogen (mg L^{-1})‡	Measure of nutrient pollution (increase)	0.1	7.9
Total phosphorus (mg L^{-1})‡	Measure of nutrient pollution (increase)	0.01	7.1
Dissolved oxygen diel range (mg L^{-1})§	Range of dissolved oxygen recorded over a 24-h period (increase)	0.5	12.4
Temperature diel range (°C)§	Range of water temperature recorded over a 24-h period (increase)	0.7	9.1
Riparian vegetation¶			
Riparian cover (%)	Reach-scale estimate of percent canopy cover of the stream (decrease)	0	95.8
In-stream habitat**			
Mud (%)	Visual estimate of the percentage of stream bed covered by mud (<0.06 mm maximum particle diameter) (increase)	0	100.0
Aquatic macrophtyes (%)	Visual estimate of the percentage of stream bed covered by aquatic macrophytes (increase)	0	61.6
Filamentous algae (%)	Visual estimate of the percentage of stream bed covered by filamentous algae (increase)	0	42.4
Submerged terrestrial vegetation (%)	Visual estimate of the percentage of stream bed covered by invasive terrestrial weeds (increase)	0	33.9

*Estimated from GIS databases.
†Mean of three measurements using Greenspan sensors and DT50 data logger.
‡Single sample taken in unfiltered, detergent-washed bottle; laboratory analysis.
§Range calculated from half-hourly measurements recorded by data logger over a 24-h period.
¶Mean of three measurements using spherical densiometer.
**Mean of 40–60 individual estimates surveyed at 1-m^2 points located randomly throughout site.