Carp (Cyprinus carpio) as a powerful invader in Australian waterways

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Carp (*Cyprinus carpio*) as a powerful invader in Australian waterways

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SUMMARY

1. The invasion of carp (*Cyprinus carpio* L.) in Australia illustrates how quickly an introduced fish species can spread and dominate fish communities. This species has become the most abundant large freshwater fish in south-east Australia, now distributed over more than 1 million km^2.
2. Carp exhibit most of the traits predicted for a successful invasive fish species. In addition, degradation of aquatic environments in south-east Australia has given them a relative advantage over native species.
3. Derivation of relative measures of 13 species-specific attributes allowed a quantitative comparison between carp and abundant native fish species across five major Australian drainage divisions. In four of six geographical regions analysed, carp differed clearly from native species in their behaviour, resource use and population dynamics.
4. Climate matching was used to predict future range expansion of carp in Australia. All Australian surface waters appear to be climatically suitable for carp.
5. This assessment strongly reinforces the need for immediate management of carp in Australia to include targeted control of human-assisted dispersal, such as use of carp as bait by anglers, distribution to new locations by anglers and the use of the 'Koi' strain in the aquarium industry.
6. Given their historical spread, dispersal mechanisms and ecological requirements, the expansion of carp across most of the remainder of Australia is to be expected.

Keywords: alien species, conservation, freshwater fish, habitat modification, introduced species, invasive species, risk assessment

Introduction

The movement of species beyond their natural range has been cited as one of the most pervasive and ecologically damaging of human activities (Lodge, 1993; Wilcove *et al.*, 1998). In predicting scenarios for changes in biodiversity for 2010, Sala *et al.* (2000) concluded that biological exchange was a relatively more important threat to the biodiversity of freshwater ecosystems than to other ecosystems because of the intentional and unintentional release of organisms. The magnitude of this problem is increasing (Lodge, 1993) and the integrity of aquatic ecosystems is being challenged worldwide by invasive species (Moyle & Light, 1996). Australia has a relatively depauperate freshwater fish fauna by world standards with slightly over 200 species native (Wager & Jackson, 1993: Allen, Midgley & Allen, 2002) and currently 43 species of alien fish are recorded or established in inland fresh waters in Australia (Koehn & Mackenzie, in press). More than 16% of native species are considered to be under serious conservation threat nationally (Australian Society for Fish Biology, 2001), and detrimental interactions with alien species are considered to be a threat to 77% of these species (Jackson, Koehn & Wager, 1993).

Carp (*Cyprinus carpio* L.) are native to Eastern Europe and central Asia. Carp, which have been bred

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as an ornamental and aquaculture species (Li & Moyle, 1993; Lever, 1996), have been widely translocated, and been successful invaders in parts of Europe, Asia, Africa, North, Central and South America, Australia and Oceania (Lever, 1996; FAO, 2002). Carp is Australia's largest alien freshwater fish and now contributes more than 90% of fish biomass in many areas of south-east Australia (Harris & Gehrke, 1997). They have only invaded a small portion of the Australian continent (1 million of 7.6 million km^2) but there is the potential for future invasion of many large river systems. Like most invasive species, no risk analysis was undertaken to assess the invasion or impacts of carp prior to their introduction into Australia, and no examination has been undertaken to determine why they have become so successfully established or to predict their future spread or impacts.

Carp were first introduced to Australia on several occasions from the mid-1800s (Koehn, Brumley & Gehrke, 2000), with three different strains being recognised (Shearer & Mulley, 1978). Carp populations remained relatively contained until the introduction of the 'Boolara' strain to Gippsland in Victoria in the 1960s (Koehn *et al.*, 2000). This strain was translocated to farm dams and then spread rapidly throughout south-east Australia, particularly the Murray–Darling Basin. Carp now occupy most of this large basin (Fig. 1a) with the exception of some northern reaches, where invasion is slowed by weirs (D. Moffatt, Dept. of Natural Resources, pers. comm.), and at some higher altitudes (Driver *et al.*, 1997). Public concern (Murray–Darling Association, 1995) led to the formation of a National Carp Taskforce, a National Carp Management Strategy and the recognition of carp as a serious vertebrate pest in Australia (Braysher & Barrett, 2000; Carp Control Coordinating Group, 2000a,b).

Carp can achieve biomasses as high as 3144 kg ha^{-1} and densities of up to 1000 individuals ha^{-1} (Harris & Gehrke, 1997), and they destroy aquatic plants (Fletcher, Morison & Hume, 1985; Roberts, Chick & Thompson, 1995), increase water turbidity whilst feeding (Fletcher *et al.*, 1985; King, Robertson & Healey, 1997; Robertson, Healey & King, 1997) and thus reduce photosynthetic production and visibility for visually feeding fish.

Few alien species globally have received detailed risk assessments, and accordingly there is little predictive capability to foresee invasions, trends, potential or future impacts, let alone the development of risk management strategies to respond to possible impacts. Moreover, little attention has been paid to predicting the future impacts of introduced species that are already present (Coates & Ulaiwi, 1995). Ecological risk assessment is based on the use of knowledge to predict adverse events (Bartell, Gardner & O'Neill, 1992; Burgman, Ferson & Akçakya, 1993). Often, however, there is a lack of quantitative biological information available when management decisions need to be made (Walters & Holling, 1990; Braysher, 1993). The use of qualitative information in risk assessment is preferable to no consideration of risk at all, and the assessment in this paper uses quantitative and qualitative information, including expert opinion and a collation of information from the 'grey' literature, to provide a predictive analysis for carp.

This paper first examines the characteristics associated with carp as an invasive species, comparing them to native species, and then uses a risk analysis to provide an assessment of the probability of invasion of other areas in Australia before recommending priority management actions.

Methods

Invasive species attributes derived from Ehrlich (1976), Morton (1978, 1997), Groves & Burton (1986) and Ricciardi & Rasmussen (1998) (Table 1) were assessed for carp. Transfer vectors were documented from a variety of sources to identify pathways of introduction and dispersal and to assist in informing management options.

To compare the ecology of carp in relation to Australian fish communities, a method similar to that of Coates & Ulaiwi (1995) was used in a comparison of 13 species-specific attributes of juvenile and adult carp and dominant native fish species undertaken, for six regions across five of Australia's major river drainage divisions (divisions 1, 2, 4, 6 and 8) (Allen *et al.*, 2002; Fig. 1a; Table 2). Drainage division 1 in Fig 1a, was analysed as distinct fish faunas north and south of the Burdekin River (B. Pusey, unpubl. data). Species-specific attributes included were: maximum size (<300, 300–800 and >800 mm), depth position (benthic, midwater, surface), behaviour (solitary or schooling), diet (piscivore, omnivore, detritivore or

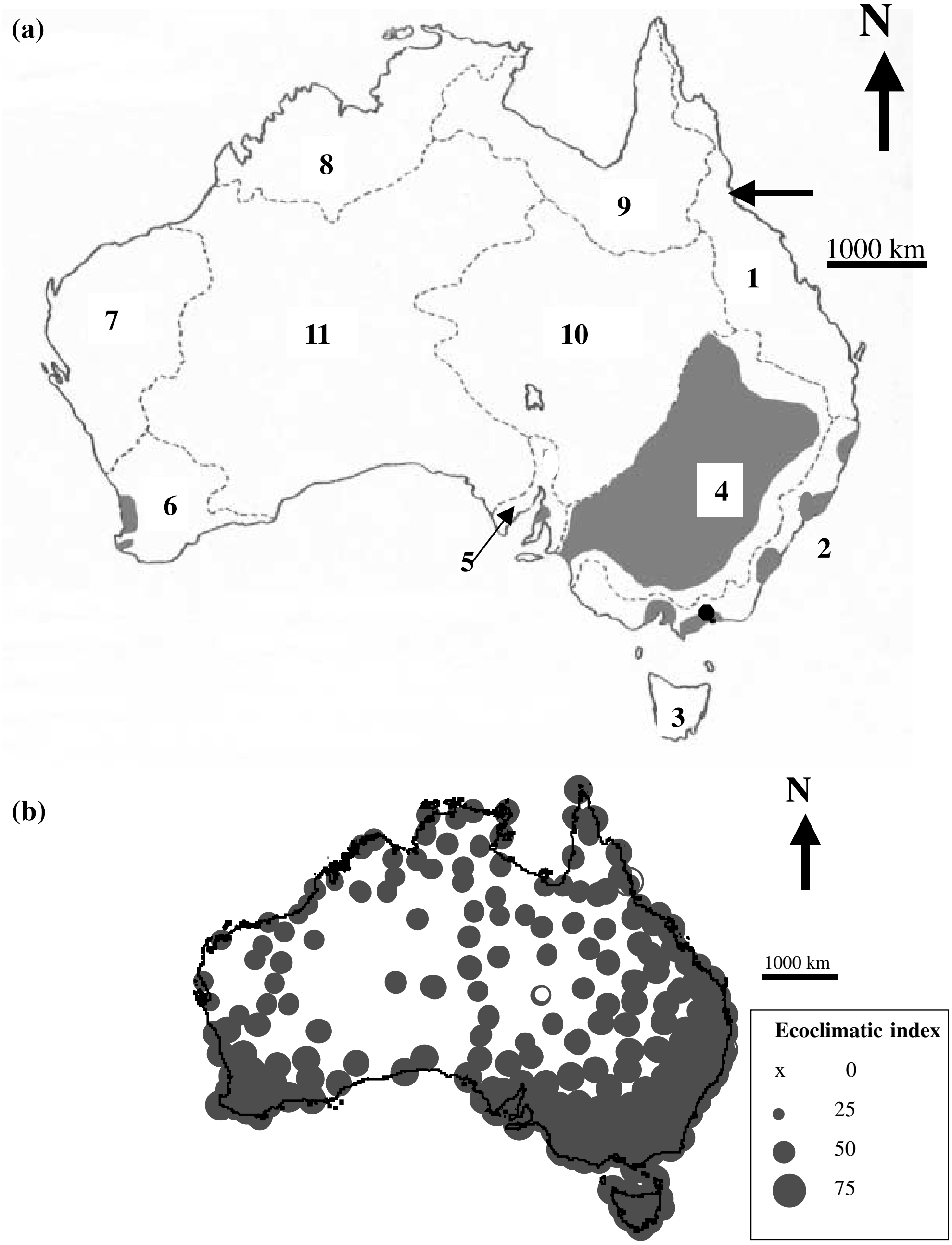

Fig. 1 (a) Distribution of carp (*Cyprinus carpio*) (shaded areas) across the major drainage divisions of the Australian continent (after Allen *et al*., 2002) 1, North-east coast (← indicates Burdekin river); 2, South-east coast; 3, Tasmania; 4, Murray–Darling Basin; 5, South Australian gulf; 6, South-west coast; 7, Indian ocean; 8, Timor sea; 9, Gulf of Carpentaria; 10, Lake Eyre/Bulloo-Bancannia; 11, Western plateau, ● indicates the original introduction site for the 'Boolarra' strain. (b) CLIMEX ecoclimatic indices showing climate matches for carp in Australia. Climatic favourableness of each location for permanent colonisation is proportional to the area of the circles.

herbivore), feeding position (benthic, midwater or surface), fecundity, environmental tolerances (e.g. water quality), habitat specificity, habitat range, movement, dispersal rates, growth rates and physical toughness (scales, spines, etc), which were all rated on a 1–3 point scale for low, medium or high. Information on these attributes was derived from Allen (1982), Cadwallader & Backhouse (1983), Merrick & Schmida (1984), Cadwallader & Lawrence (1990), Koehn & O'Connor (1990a), McDowall (1996), Allen *et al.*

Table 1 Attributes of carp as an invasive species (derived from Ehrlich, 1976; Morton, 1978, 1997; Groves & Burton, 1986; Ricciardi & Rasmussen, 1998)

Attribute	Details	References
Invasion history, wide distribution and abundance	Introduced and successfully established throughout Europe, Asia, Africa, North America, South and Central America, Australia, New Zealand, Papua New Guinea and some islands of Oceania	Lever (1996)
Wide environmental tolerances	High environmental tolerances with: temperature tolerance ranges from 2 to 40.6 °C, salinity tolerances up to about 14 ‰ (0.4 seawater salinity) and pHs from 5.0 to 10.5, oxygen levels as low as 7% saturation and generally occur in most types of freshwater habitat	Horoszewicz (1973), Ott, Heisler & Ultsch (1980), Crivelli (1981), Hellawell (1986) and Howes (1991)
High genetic variability	Three genetic strains in Australia	Shearer & Mulley (1978)
Early sexual maturity	Males at 1 year, females at 2 years	Brumley (1996)
Short generation time	2–4 years	
Rapid growth	Hatching of eggs is rapid (2 days at 25 °C) and newly hatched carp grow very rapidly	Balon (1975), Adamek (1998) and Vilizzi & Walker (1999)
High reproductive capacity	They are highly fecund broadcast spawners with egg counts as high as 2 million per female	Balon (1975); Banarescu & Coad (1991)
Broad diet	Omnivore/detritivore	Hume, Fletcher & Morison (1983)
Gregariousness	A schooling species	Cadwallader & Backhouse (1983)
Possessing natural mechanisms of dispersal	A mobile species with fish moving between schools. Dispersal can also occur with the downstream drift of larvae. Rates of transfer can be affected by conditions such as flooding	Harris (1997), Koehn & Nicol (1998) and Stuart *et al.* (2001)
Commensal with human activity	Bred as an ornamental and aquaculture species, used as bait and sought by some anglers	Li & Moyle (1993), Lever (1996) and Koehn *et al.* (2000)

(2002)), Pusey & Kennard (1996), Pusey, Arthington & Read (1998, 2000), Gehrke, Schiller & Brown (1999) and Kennard, Pusey & Arthington (2001). Non-metric multidimensional scaling (based on Euclidean distances) was then undertaken using PRIMER (Carr, 1996) as described in Clarke & Warwick (1994) to illustrate the relative similarities between species based on the selected attributes.

Native freshwater fish species richness for each region are as follows: south-east coast, 26 (Koehn & O'Connor, 1990a), Murray-Darling Basin, 35 (Cadwallader & Lawrence, 1990), south Queensland, 25 (Pusey *et al.*, 1998), north Queensland, 66 (Pusey *et al.*, 2000), Timor sea, 111 (Allen *et al.*, 2002), south-west coast, 10 (Allen, 1982).

Climate matching was conducted using CLIMEX (Sutherst *et al.*, 1999) to determine habitat areas climatically suitable for carp in Australia. Climates were matched using data from five Australian locations (Tasmania, Brisbane, Adelaide, Perth and Griffith) and nine overseas locations where carp are established (London and Liverpool in the U.K., Krakow in Poland, Wellington in New Zealand, Lae in Papua New Guinea, Sacramento in CA, U.S.A., Beijing and Chonqing in China and Tokyo in Japan). A map of ecoclimatic indices (scaled 0–100) was then produced that described the overall favourableness of climate for the persistence of carp for over 200 Australian geographic locations (Fig. 1b). Indicative absolute heat and cold stress temperatures of 5 and 35 °C (within the absolute temperature tolerances in Table 1) were used as daily minimum and maximum temperatures, as biological information was considered insufficient to formulate more exact temperature duration thresholds.

An assessment of the potential impacts of the major threats to fish in the Murray–Darling Basin (habitat destruction, water quality, harvesting, barriers, water temperature, altered flows, sedimentation, introduced species and stocking/genetics; Cadwallader, 1978; Koehn & O'Connor, 1990b) was made for carp and six large native fish species (Murray cod, trout cod, golden perch, silver perch, Macquarie perch and catfish). A simple rating for the severity of detrimental impact by each threat was made on a 1–3 point scale (Table 3).

Table 2 Native fish species and their codes used for each of the six regions for which species comparisons were undertaken (refer to Fig. 2)

Common name	Scientific name	Species code
South-west coast		
Mud minnow	*Galaxiella munda* McDowall	MM
Common galaxias	*Galaxias maculatus* (Jenyns)	CG
Western minnow	*Galaxias occidentalis* Ogilby	WM
Spotted galaxias	*Galaxias truttaceus* Valenciennes	SG
Salamanderfish	*Lepidogalaxias salamandroides* Mees	SF
Freshwater cobbler	*Tandanus bostocki* Whitley	FCB
Nightfish	*Bostockia porosa* Castelnau	NF
Western pigmy perch	*Edelia vittata* Castelnau	WPP
Balston's pigmy perch	*Nannatherina balstoni* Regan	BPP
Timor sea		
Bony herring	*Nematalosa erebi* Günther	BH
Catfish	*Tandanus* spp.	CFS
Rainbowfish	*Melanotaenia* spp.	RBWS
Sail-fin perchlet	*Ambassis agrammus* Günther	SFP
Western sooty grunter	*Hephaestus jenkinsi* Whitley	WSG
Spangled perch	*Leiopotherapon unicolor* Günther	SPE
Triangle grunter	*Syncomistes trigonicus* Vari	TG
Flat head goby	*Glossogobius giurus* Hamilton	FHG
Northern purple spotted gudgeon	*Mogurnda mogurnda* Richardson	NPSG
South-east coast		
Short-finned eel	*Anguilla australis* Richardson	SFE
Long-finned eel	*Anguilla reinhardtii* Steindachner	LFE
River Blackfish	*Gadopsis marmoratus* Richardson	RB
Common galaxias	*Galaxias maculatus* (Jenyns)	CG
Broad-finned Galaxias	*Galaxias brevipinnis* Günther	BFG
Spotted galaxias	*Galaxias truttaceus* Valenciennes	SG
Mountain Galaxias	*Galaxias olidus* Günther	MG
Tupong	*Pseudaphritis urvilli* Valenciennes	T
Southern Pygmy Perch	*Nannoperca australis* Günther	SPP
Australian Smelt	*Retropinna semoni* Weber	AS
Murray-Darling Basin		
River Blackfish	*Gadopsis marmoratus* Richardson	RB
Mountain Galaxias	*Galaxias olidus* Günther	MG
Murray Cod	*Maccullochella peelii peelii* Mitchell	MC
Trout Cod	*Maccullochella macquariensis* Cuvier	TC
Golden Perch	*Macquaria ambigua* Richardson	GP
Macquarie Perch	*Macquaria australasica* Cuvier	MP
Silver perch	*Bidyanus bidyanus* Mitchell	SP
Southern Pygmy Perch	*Nannoperca australis* Günther	SPP
Australian Smelt	*Retropinna semoni* Weber	AS
Freshwater catfish	*Tandanus tandanus* Mitchell	FC
Bony herring	*Nematalosa erebi* Günther	BH
Carp gudgeons	*Hypseleotris* spp.	CGS
North Queensland		
Goby	*Glossogobius celebius* (Valenciennes)	GO
Snakehead gudgeon	*Giurus margaritacea* (Valenciennes)	SHG
Carp gudgeon	*Hypseleotris compressa* (Krefft)	CGU
Purple spotted gudgeon	*Mogurnda adspersa* (Castelnau)	PSG
Rainbowfish	*Melanotaenia splendida splendida* (Peters)	RBW
Catfish	*Neosilurus ater* (Perugia)	CF
Freshwater catfish	*Tandanus tandanus* Mitchell	FC
Long-finned eel	*Anguilla reinhardtii* Steindachner	LFE
Blue eye	*Pseudomugil signifer* Kner	BE
Mouth almighty	*Glossamia aprion* (Richardson)	MA
Jungle perch	*Kuhlia rupestris* (Lacepede)	JP

Table 2 (*Continued*)

Common name	Scientific name	Species code
Hardyhead	*Crateocephalus strecumuscarum* (Günther)	HH
Barramundi	*Lates calcarifer* Bloch	B
Spangled perch	*Leiopotherapon unicolor* Günther	SPE
Sooty grunter	*Hephaestus fuliginosus* Macleay	SG
South Queensland		
Rainbowfish	*Melanotaenia duboulayi* (Castelnau)	RBW
Bony herring	*Nematalosa erebi* Günther	BH
Spangled perch	*Leiopotherapon unicolor* Günther	SPE
Banded grunter	*Amniataba percoides* (Günther)	BG
Freshwater catfish	*Tandanus tandanus* Mitchell	FC
Hyrtls tandan	*Neosilurus hyrtlii* Steindachner	HT
Purple spotted gudgeon	*Mogurnda adspersa* (Castelnau)	PSG
Carp gudgeon	*Hypseleotris compressa* (Krefft)	CGU
Chanda perch	*Ambassis agassizi* Steindachner	CP
Long-finned eel	*Anguilla reinhardtii* Steindachner	LFE
Grunter	*Scortum parviceps* (Macleay)	G

Table 3 Assessment of potential effects on carp and on native species from existing threats in the Murray-Darling Basin

	Species						
Threat	C	MC	TC	GP	SP	MP	CF
Habitat destruction	1	3	3	2	2	2	3
Water quality	1	2	2	3	3	2	2
Harvesting	1	3	3	2	2	2	2
Barriers	2	2	1	2	2	2	1
Water temperature	1	3	2	2	2	2	2
Altered flows	1	3	2	2	2	2	2
Sedimentation	1	2	2	2	2	2	2
Introduced species	1	2	2	1	1	2	2
Stocking/genetics	1	2	1	2	2	1	1
Total	10	22	18	16	18	17	17

Effect scores: 1, low; 2, moderate; 3, high.
C, carp; MC, Murray cod; TC, Trout cod; GP, Golden perch; SP, Silver perch; MP, Macquarie perch; CF, catfish.

Sources of information used to make these assessments included: Cadwallader (1978), Allen (1982), Cadwallader & Backhouse (1983), Merrick & Schmida (1984), Cadwallader & Lawrence (1990), Koehn & O'Connor (1990a,b), McDowall (1996) and Allen *et al.* (2002).

Results

Analysis of carp at a global scale shows that they have most of the attributes expected for a successful invasive species (Table 1): they have a well documented successful invasion history with wide distribution and abundance, wide environmental tolerances, rapid growth, high reproductive capacity, broad diet, are gregarious, possess natural mechanisms of dispersal, are commensal with human activity (attributes 1, 2, 6, 7, 8, 9, 10 and 11) and have relatively high genetic variability (three different strains introduced into Australia), early sexual maturity and short generation times (attributes 3, 4 and 5).

Two patterns emerged from the non-metric multidimensional scaling comparing the characteristics of carp to native species. In the south-west coast, Timor sea, south-coast and Murray–Darling Basin, carp showed distinct separation relative to the native species in the analyses (Fig. 2a–d). Although on the edge of MDS plots for north and south Queensland fish assemblages, carp were ecoligically closer to the other species in these cases (Fig. 2e,f).

The composite map of the climate 'Match Indices' derived using CLIMEX (Fig. 1b) indicates that climate match across Australia is almost complete and that carp could probably inhabit all climatic zones, subject to the availability of water in arid areas. Scenario testing using only maximum and minimum stress temperatures did not identify any particular areas causing major temperature stress for carp but indicated the areas most likely to do so were in north-west Australia. As CLIMEX uses air rather than water temperatures (Sutherst *et al.*, 1999), climate matching for fish has limitations. Interestingly, however, all sites provided indices of >25 for carp (Fig. 1b), indicating strong climatic matches. Gaps in this map relate to the spaces between weather recording stations rather than unsuitability of the climate.

The assessment of the potential impacts of the existing environmental threats to carp and native

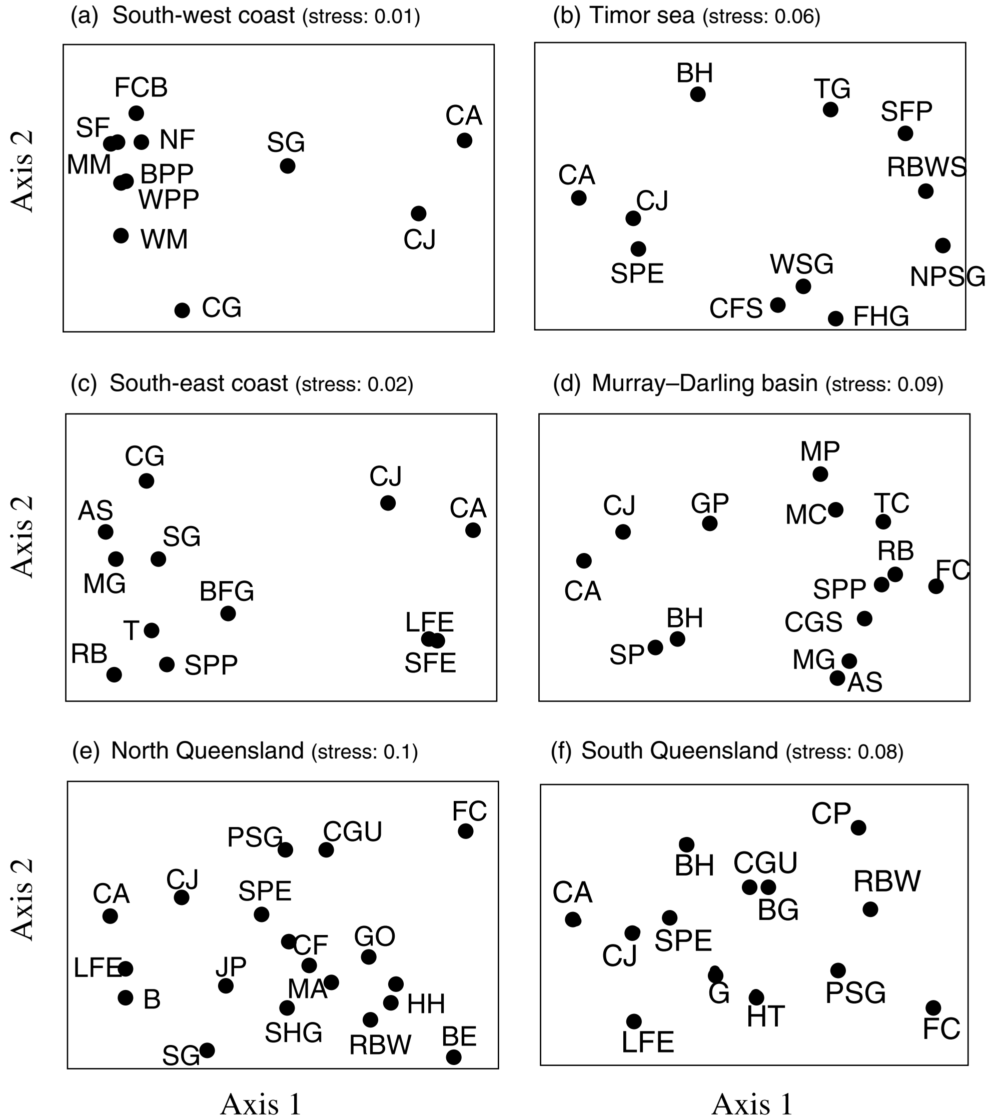

Fig. 2 The similarities between adult (CA) and juvenile carp (CJ) and native fish species (species names and codes are in Table 2) based on non-metric multi dimensional scaling of attributes for each species. (a) south-west coast; (b)Timor sea; (c)south-east coast; (d) Murray–Darling Basin; (e) north Queensland; (f) south Queensland. Euclidean distances were used as a measure of similarity between species and aspect ratios of axis 1 and 2 preserved.

species in the Murray–Darling Basin showed that carp were much less likely to be detrimentally affected (score = 10) than native species (average score = 18) (Table 3).

Discussion

Carp exhibit a range of different ecological characteristics that may allow a competitive advantage over most Australian native fish species. Carp also have several reproductive advantages including lower spawning temperatures (15–28.2 °C) (Adamek, 1998; Koehn *et al.*, 2000), hence earlier spawning times (Koehn & O'Connor, 1990a) and earlier access to resources than many native species. Carp can also take advantage of spawning areas downstream of water storages that release hypolimnetic water at temperatures too cold to permit the spawning of native species (Koehn, 2001). Hatching of carp eggs is rapid (2 days at 25 °C) and larval growth is very rapid, enabling them to quickly escape predation pressure (Adamek, 1998).

The availability of climatically suitable habitat has been found to be an important factor for predicting the geographic range of introduced birds and amphibians in Australia (Sutherst, Floyd & Maywald, 1995; Duncan *et al.*, 2001). Carp are established in regions that encompass almost all climatic conditions in Australia. In south-east Australia, Driver *et al.* (1997) found carp to occupy all types of habitats up to 500 m a.s.l., though they were less common in clear, cool, swift-flowing waters. Koehn & Nicol (1998) showed carp to prefer slow flowing waters, including billabongs and backwaters compared with some other native species, and Gehrke (1997) found increased carp numbers correlate with the amount of environmental disturbance, notably the degree of river regulation. The large number of dams and water storages in south east Australia also provide a vast array of still water habitats that favour carp (Koehn, 2001). Native fish were found to be more likely to be detrimentally affected than carp by altered environmental conditions, hence leaving them with a comparative advantage.

Source regions and dispersal pathways are important factors assisting range expansion of invasive species (Ricciardi & Rasmussen, 1998). Carp are already widespread in south-east Australia and have been found to be a mobile species, so within catchments migrations and downstream larval drift will be effective methods of dispersal (Koehn & Nicol, 1998; Stuart, Jones & Koehn, 2001). Between catchments, transfers are most likely to come from adjoining or nearby regions. However, transfers from New Zealand, or from Papua New Guinea into northern Australia may also be possible. Such 'saltatory' jumps in distribution, including those between catchments (Johnson & Carlton, 1996), can effectively only occur through human intervention. Transfer of carp by anglers, either through accident or ignorance, or deliberately to establish new fishing grounds, has been recognised as a major source of invasion into new catchments both in Australia and New Zealand (McDowall, 1997; Koehn *et al.*, 2000). Such actions have occurred despite the illegality of keeping, transport or release of carp in most states in Australia (Koehn *et al.*, 2000). The continued legal sale and distribution of ornamental 'Koi' carp in New South Wales (J. Harris, pers. comm.) has severe implications for carp dispersal in east Australia and it has been recommended that this legal status be changed (Georges & Cottingham, 2002).

Areas of most concern for future range expansion by carp are: the remaining upper reaches of the Murray–Darling Basin, remaining coastal river systems in south-east coastal and Indian ocean regions, Tasmanian river systems and the Lake Eyre/Bulloo-Bancannia drainage division (division 10) (which may link to Murray–Darling tributaries under high flow events). The Lake Eyre drainage basin has a catchment of more than 1.3 million km^2 and already contains goldfish, with carp having been introduced but successfully eliminated from a mine tailings dam near Leigh Creek (Koehn *et al.*, 2000). Dried carp carcases found on the banks of the Cooper Creek in the Lake Eyre Basin are believed to have been bait discarded by anglers (Wager & Unmack, 2000). Given these occurrences, the introduction of carp into this catchment appears inevitable unless prompt and effective action is taken. This low gradient, slow flowing river system, with extensive floodplains and a terminal lake, would appear to provide ideal habitats for carp.

Transport vectors (Cohen & Carlton, 1998), a depauperate biota and environmental disturbance (Ross, 1991; Cohen & Carlton, 1998) are suggested as reasons for accelerating invasion rates. All of these conditions are met in the Murray–Darling Basin and other regions of south-east Australia, providing the basis for the witnessed rapid expansion of carp. Species richness is also sometimes cited as a major factor in reducing invasibility (Elton, 1958; Ross, 1991; Lodge, 1993; Stachowicz, Whitlatch & Osman, 1999) because of a more complete utilisation of resources (Stachowicz *et al.*, 1999). Given that many Australian fish communities are in general species-poor, they may be particularly susceptible to invasion. Establishment of carp in north Australia, where rivers are generally less degraded, have a larger number of species and greater numbers of piscivorous species (Kennard *et al.*, 2001), may be less rapid or less successful, but it should be noted that carp rapidly became established in some tropical river systems in Papua New Guinea, which are similar in diversity and structure to those in north Australia (Coates & Ulaiwi, 1995).

Predation does not appear likely to be a limiting factor for carp in southern Australia where there are few large fish predators (Allen, 1982; Cadwallader & Backhouse, 1983), most predatory native species have already suffered massive declines (Cadwallader &

Lawrence, 1990) and serious predation by birds is unlikely (Barker & Vestjens, 1989a,b). The rapid expansion of carp within these regions may have been assisted by this lack of predatory pressure. However, even in the presence of predators, a highly fecund species such as carp may simply overwhelm predators with large numbers of juveniles, and as the growth rates of juveniles are rapid, they can quickly reach a size that precludes their consumption by most predators.

The ability to modify habitats and ecosystems is a trait of many successful invasive species (Bomford, 2001). Carp have been shown to increase turbidity (King *et al.*, 1997), destroy aquatic vegetation (Roberts *et al.*, 1995) and change the composition of invertebrate communities (Robertson *et al.*, 1997). Carp's specialist feeding mechanism of sieving through the substrate allows them take advantage of potentially under-utilised resources, including detritus at a base level of the food chain. Detritus is likely to be abundant, especially given that true detritivorous fish are lacking from most Australian freshwater fish communities (Bishop *et al.*, 1980; Bunn & Boon, 1993; Coates, 1993; Pusey & Kennard, 1996; Pusey *et al.*, 2000). With few effective predators, sequested detrital carbon, rather than passing up through subsequent trophic levels of macroinvertebrates and smaller fish (Bunn & Davies, 1999), may become 'locked' away from the trophic chain for their lifetime (up to 50 years) (Banarescu & Coad, 1991).

Carp can be described as a stressor in Australian aquatic environments and there is a need for their economic and environmental impacts to be quantified to allow assessment of costs and benefits of management actions. Management options for the world's best known biotic invasions, the zebra mussel *Dreissena polymorpha* into the north American Great Lakes region (Nalepa & Schloesser, 1993), have been supported by high levels of public concern and an evaluation of both environmental and economic impacts (e.g. Lodge, 1993; Strayer, 1999; Pimentel *et al.*, 2000). Whilst there are high levels of public concern in areas where carp are already present, this is not necessarily so in areas they are yet to invade.

Potential control techniques for carp are explored in detail by Roberts & Tilzey (1997) and Koehn *et al.* (2000) and potentially include removal (commercial and recreational); environmental rehabilitation, environmental manipulation, biomanipulation (e.g. adding predators), exclusion; poisoning, and future biological controls. 'Biocontrol' options have yet to be developed and tested, and are not available at present. Given the remote nature and range of habitats that carp now occupy, commercial harvesting may only reduce populations of carp in certain localised areas and thus is unlikely to achieve wide-scale population reductions. It has been suggested that fishing to levels of <10% of original population abundance would be required to make any real impact on these fish populations (Thresher, 1997). This would be difficult in most of the Australian habitats in which carp occur and could not be undertaken on a commercial basis. The lack of realistic options highlights the need to support actions of the *National Carp Management Strategy* (Braysher & Barrett, 2000; Carp Control Coordinating Group, 2000a,b), which include community support and emphasis on the prevention of future spread. As carp in Australia are continuing to invade new areas, they provide an opportunity to study and quantify their impacts.

On mainland Australia, the total number of established alien fish species (21) (Arthington *et al.*, 1999) is comparable with the number of alien mammals (25), birds (20), amphibians (1) or reptiles (4) (Bomford, 2001), but to date fish have received far less attention than these other groups. Whilst attention needs to be directed to species that are potential new invaders, those invasive species already present but which have the potential to invade new areas should not be ignored. These are the species most likely to invade new catchments. The risk assessment approach outlined in this paper should also be undertaken for other alien fish species to better understand their future spread and impacts and to prioritise management options.

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