

The global invasion of the American brine shrimp *Artemia franciscana* (Kellogg, 1906) and its potential impact on Australian inland waters

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Abstract. Brine shrimp (*Artemia* species) are a major faunal element in many hypersaline biotypes throughout the world that are used extensively in aquaculture, the aquarium trade, solar salt fields and in toxicity bioassays. Commercially available brine shrimp are generally *Artemia franciscana* cysts primarily harvested from Great Salt Lake, Utah, U.S.A. The invasive potential of this species raises concerns about its presence in Australia. We reviewed recent overseas reports of the occurrence of *A. franciscana* populations and confirm that the use of this species has extended its natural geographic range through both deliberate and inadvertent releases. In Australia, *Artemia* species have been previously identified as being a threat to ecosystem health and biodiversity, however, the specific recognition of *A. franciscana* was not made. In reviewing the biogeography of *Artemia* species in Australia, we provide a collation of the reported populations of *A. franciscana*. The biological attributes of this species contributing to its invasive success are also compiled. The implications of further releases and increases in the range of this species to Australian inland waters are discussed. We appeal for increased vigilance regarding the importation and use of this potentially highly invasive species and monitoring for its presence.

Introduction

The brine shrimp *Artemia* (Crustacea, Branchiopoda, Anostraca) is a primitive arthropod with a segmented body growing to an adult size of 8-12 mm long and about 4 mm wide (Criel and Macrae, 2002a). The adult animal is characterised by two stalked lateral complex eyes, a series of similar limbs, known as thoracopods, and an elongated trunk with no clear demarcation into thorax and abdomen. It is a major faunal element in many hypersaline biotypes throughout the world (Van Stappen, 2002), such as inland salt lakes and coastal saltworks, where it feeds primarily on phytoplankton and is an important secondary producer. *Artemia* is economically important as it is used as a food source for the commercial larvaculture of fish and crustaceans and by the aquarium trade (Treece, 2000; Van Stappen, 1996). It is also used to increase efficiency and productivity of sodium chloride production in solar saltfields where it serves two functions: 1) the control of phytoplankton blooms, and 2) waste material from *Artemia* provides proteinaceous nutrients promoting the proliferation of red pigmented bacteria which absorb solar

radiation, thereby, accelerating evaporation (Jones et al., 1981). *Artemia* is of great scientific interest, with a variety of applications such as its use as test organism in toxicity studies (Nunes et al., 2006; Van Steertegem and Persoone, 1993) and as a useful educational model in science education (e.g. Dockery and Tomkins, 2000; Lieberman, 1999).

Artemia was first described by Schlösser in 1775 who reported its presence in the solar saltworks of Lymington, England, U.K. (population now extinct) referred by Kuenen and Baas-Becking (1938) (in Sorgeloos, 1980). In 1758, Linnaeus classified it as *Cancer salinus* and then in 1818, Leach renamed it *Artemia salina* (Artom, 1931). Until the early 1980's, many researchers considered all populations of *Artemia* as strains of a single species (*A. salina*) due to similar morphology, however, it is now unequivocally recognised that there are a variety of *Artemia* species (Abatzopoulos et al., 2002; Clark and Bowen, 1976; Gajardo et al., 2002; Sorgeloos and Beardmore, 1995; Triantaphyllidis et al., 1998). In the 1990s, the use of the binomen *A. salina* caused considerable confusion worldwide (Sorgeloos and Beardmore, 1995), with many contemporary works still erroneously referring to the use of this species even when the origin of the material indicates otherwise (Ruebhart et al., in press). This practice, unfortunately, counters advances in multidisciplinary taxonomic research (see Triantaphyllidis et al., 1997).

Artemia salina Leach 1819 is now recognised as a valid name only for Mediterranean bisexual populations (i.e. populations that contain both males and females) which is regarded conspecific with the extinct Lymington population (Baxevanis et al., 2006; Triantaphyllidis et al., 1997). Thus, reference to species of *Artemia* should be in accordance with the recommendations of Sorgeloos and Beardmore (1995) with applying diligence in citing the correct taxonomic identity, or by providing accurate details concerning the geographical and/or commercial origin of the cysts used. It is also advisable that packaged material is marked with batch numbers and accessible information of the cyst harvest site. (An up to date listing of brine shrimp harvesters at Great Salt Lake, Utah, U.S.A. is maintained by the Utah Division of Wildlife Services and is available from: <http://www.wildlife.utah.gov>).

In addition to bisexual populations of *A. salina*, the Mediterranean region is also home to a variety of parthenogenetic (unisexual reproduction by females alone) diploid and tetraploid

species (Amat et al., 2005; Van Stappen, 2002). This diversity of *Artemia* in this region (Gajardo et al., 2002), in addition to allozyme studies (Abreu-Grobois and Beardmore, 1982; Abreu-Grobois, 1987; Badaracco et al., 1987), has given rise to the hypothesis that ancestral *Artemia* evolution and radiation originated in the Mediterranean region some 5.5 million years ago. This is supported by geological evidence which shows that the Mediterranean Sea was physically separated from the Atlantic Ocean resulting in an event known as the Messinian Salinity Crisis between 5.96 and 5.33 million years ago where desiccation of the Mediterranean Sea reduced it to a string of briny lakes (Duggen et al., 2003; Hsu et al., 1977) which become an epi-centre for *Artemia* evolution (Abreu-Grobois, 1987; Badaracco et al., 1987) in which ancestral forms experienced colonisation, extinction and recolonisation cycles with different degrees of reproductive isolation (Amat et al., 2005).

Radiation in *Artemia* lead to this genus becoming the major faunal element in many hypersaline biotopes throughout the world, except in Australia, where the genus *Parartemia* (family Branchipodidae) is endemic (Geddes, 1981; Van Stappen, 2002). The evolutionary separation of these two genera, both physically and temporally, was demonstrated in a study by Coleman et al. (1998) who compared DNA sequences in haemoglobin of both genera. This study found that the common ancestor for *Parartemia* and *Artemia* existed about 85 million years ago which coincided with the isolation of Australia in the late Mesozoic. Thus, it is quite apparent that the genera of *Artemia* and *Parartemia* each have long and separate evolutionary histories.

Two decades ago Geddes and Williams (1987) discussed the potential deleterious effects of exotic *Artemia* species introductions on inland saline ecosystem health and indigenous biodiversity. Ten years later the impact of exotic aquatic invertebrates was recognised as an emerging issue of environmental concern for Australian inland waters with direct reference to *Artemia* species introductions (Arthington and McKenzie, 1997). Recently, there have been reports of the spread of *A. franciscana*, mainly in the Mediterranean region (Amat et al., 2005; Green et al., 2005; Mura et al., 2006). In this study, we review recent overseas reports of *A. franciscana* invasions and consider the implications of further releases and increases in the range of this species in Australian inland waters. Additionally, we appeal for increased vigilance

regarding the importation and use of this potentially highly invasive species and development of monitoring programs for its presence.

Artemia franciscana

The ancestral form of *Artemia*, living in the Mediterranean region diverged, radiated and gave rise to the extant species that can be categorised into two broad groups: the bisexual (Old and New World) and parthenogenetic forms (Old World) (Gajardo et al., 2002). Endemic to the New World (North and Central America) is *Artemia franciscana* (Kellog, 1906), which is considered to be a superspecies (a set of ecologically isolated and physiologically distinct semispecies and species) (Bowen et al., 1985). *A. franciscana* is the best studied of the *Artemia* species (Gajardo et al., 2002); where it is estimated that it is used in over 90% of studies where *Artemia* is either an experimental test organism or food source, very often using material from Great Salt Lake, Utah, U.S.A. (Sorgeloos and Beardmore, 1995). It is also estimated that 90 % of the world's annual commercial harvest of 2 000 metric tons of dry *Artemia* cysts comes from Great Salt Lake (Van Stappen, 1996). Thus, it is fair to infer that almost all introductions of *Artemia*, both intentional (e.g. saltworks) and unintentional, have been *A. franciscana* sourced from Great Salt Lake.

A. franciscana is recognised as a bisexual species (Criel and Macrae, 2002b; Gajardo et al., 2002). A recent study by Campos-Ramos et al (2003), however, has revealed both bisexual and parthenogenetic reproductive strategies from North American material. Using morphological, reproductive and molecular analyses this research demonstrated that, in a sample of commercially harvested cysts from Great Salt Lake, there was a mixture of parthenogenetic (60 %) and bisexual (40 %) strains. It was hypothesised that this finding was possibly due to: 1) parthenogenetic *Artemia* being native to Great Salt Lake, 2) that this strain was introduced to this location, or 3) foreign parthenogenetic cysts were mixed with *A. franciscana* cysts and packaged for commercial distribution. In any case, the finding of a mixture of bisexual and parthenogenetic strains is noteworthy as it presents the possibility that the quality control of this commercial product does not guarantee homogeneity despite the claim that it is harvested from Great Salt Lake. Given this single source of the material, it is likely that many consumers will presume that the material is bisexual *A. franciscana*.

Global *A. franciscana* invasions

The spread of *A. franciscana* and establishment of permanent non-indigenous populations world wide has recently been the focus of many recent studies (see Abatzopoulos et al., 2006; Amat et al., 2005; Green et al., 2005; Mura et al., 2006). In these studies, there is a common theme that *A. franciscana* populations originate as intentional and non-intentional inoculations through aquacultural, solar saltworks or pet trade activities with native brine shrimp being at danger of, or actually, being replaced by this species.

A. franciscana has been described as an invasive species when introduced outside of its natural range (Abatzopoulos et al., 2006; Amat et al., 2005; Green et al., 2005; Mura et al., 2006). According to Colautti and MacIsaac (2004), the term ‘invasive’ has been used synonymously for various other terms in ecology, often to the detriment of management efforts. For this review, the invasional model, which provides a compartmentalised approach in defining the invasion process, is used (Colautti and MacIsaac (2004). According to this model, the two stages that appear to apply to populations of *A. franciscana* outside of its natural range are: localised but dominant (stage IVa) and widespread and dominant (stage V). Thus, this definition of ‘invasive’ is in agreement with its use in the reviewed literature as a descriptor of allochthonous *A. franciscana* populations. Examples of invasive populations of *A. franciscana* world wide are shown in Table 1.

The ability of *A. franciscana* to out compete other *Artemia* species has been identified through experimental laboratory trials and field observations. In laboratory competition experiments (incorporating intra and interspecific variability and food level variation) *A. franciscana* populations out competed parthenogenetic populations in 91% of the scorable trials, while parthenogens displaced *A. salina* in 98% of the trials (Browne, 1980; Browne and Halanych, 1989). Thus, in laboratory experiments the competitive abilities of the *Artemia* species are *A. franciscana* > parthenogenetic populations > *A. salina*.

In an extensive survey of *Artemia* sites in Iran, Abatzopoulos et al. (2006) found, that in a constructed saline impoundment in the Nough catchment, *A. franciscana* (originating from Great

Salt Lake, which was deliberately introduced by a private company), had become the dominant population, out competing the former parthenogenetic population in 4 years. In the western Mediterranean, *A. franciscana* is now the dominant *Artemia* species in a number of areas including, Portuguese salterns, the French Mediterranean coast and Cadiz bay, Spain (Amat et al., 2005). The occurrence of *A. franciscana* has also been identified at Italy’s largest saltwork on the Adriatic coast, representing an eastward expansion of this species in the Mediterranean basin (Mura et al., 2006). The data available suggest that once *A. franciscana* is detected among native *Artemia*, the native populations disappear within a few years due to competitive exclusion (Amat et al., 2005; Green et al., 2005).

“[Insert Table 1 about here]”

Table 1. Examples of invasive populations of *A. franciscana*.

Location	Reference
Australia	(Timms, 2006)
Brazil	(Camara, 2001)
France	(Amat et al., 2005)
Iran	(Abatzopoulos et al., 2006)
Italy	(Mura et al., 2006)
Madagascar	(Triantaphyllidis et al., 1998)
Morocco	(Amat et al., 2005)
New Zealand	(Vanhaecke et al., 1987)
People’s Republic of China	(Triantaphyllidis et al., 1994)
Portugal	(Amat et al., 2005)
Spain	(Amat et al., 2005)

A case study which dramatically highlights exponential population growth and dispersal after a single inoculation of *A. franciscana* occurred in Brazil. In 1977, just 250 g of *A. franciscana* cysts (San Francisco Bay, California, U.S.A) were used to inoculate a single saltwork in Macau,

Rio Grande do Norte, Brazil (Camara, 2001; Persoone and Sorgeloos, 1980). A few months after inoculation, the first kilogram of cysts was harvested, and by around 1980 the harvest exceeded 20 metric tons per year with *A. franciscana* spread throughout the entire 3 000 ha saltworks (Persoone and Sorgeloos, 1980). Approximately two decades after the initial release, this species was found at all 55 saltworks sampled in north eastern Brazil (Camara, 2001). This dispersal was presumed to be via wind and waterfowl (Camara, 2001; Persoone and Sorgeloos, 1980).

The hypothesis that migratory waterbirds facilitate dispersal of *Artemia* cysts has been long held (e.g. Royan et al., 1969), however, empirical data to support this hypothesis has only recently been obtained in a study by Green et al. (2005) who successfully extracted viable cysts from faeces and pellets of migratory shorebirds. This study demonstrated that large numbers of viable cysts from both *A. franciscana* and *Artemia parthenogenetica* were dispersed by a variety of migrating shorebirds. Additionally, it is likely that cysts may adhere to the feet and feathers of birds, and disperse by wind or upon landing in water (Persoone and Sorgeloos, 1980). This ability of migratory shorebirds to disperse invertebrates such as invasive *A. franciscana*, within and between continents, according to Green et al. (2005), “makes the need to control the importation and release of exotic species at a global level all the more urgent.”

The biological attributes which contribute to the invasive success of *A. franciscana* have been discussed by Amat et al. (2005) and Mura et al. (2006). Here we provide a list of readily identifiable characteristics of *A. franciscana* which are likely to contribute to its invasive success (see Table 2). We concur with Mura et al. (2006) that the biology of *A. franciscana* predisposes it as an efficient coloniser, rather than environmental tolerance *per se* or ecosystem's invasibility. The biotic potential reported for *Artemia* (presumably a North American species widely used in aquaculture, i.e. *A. franciscana*) is impressive, with fecundity of up to 300 nauplii (or cysts) every four days, with nauplii growing and developing into adults in only eight days with a life span of several months (Van Stappen, 1996). Thus, among other factors, the high biotic potential of *A. franciscana* may contribute to its success as an invasive species.

“[Insert Table 2 about here]”

Table 2. Characteristics of *A. franciscana* contributing to its invasive success.

Characteristic	Reference
Human commensal (solar saltfields, aquaculture and aquarium trade)	(Jones et al., 1981; Treece, 2000)
Dispersal of cysts via waterbirds	(Green et al., 2005; Persoone and Sorgeloos, 1980)
Dispersal of cysts via wind	(Persoone and Sorgeloos, 1980)
Broad native geographic range	(Bowen et al., 1985; Van Stappen, 2002)
High genetic variability	(Abreu-Grobois and Beardmore, 1982; Gajardo et al., 1995; Torrentera and Abreu-Grobois, 2002)
High level of phenotypic plasticity	(Browne and Wanigasekera, 2000)
Euryhaline and eurythermal	(Browne and Wanigasekera, 2000)
Euryoxybiont	(Persoone and Sorgeloos, 1980)
Cysts have high tolerance to ultraviolet radiation and high temperature	(Tanguay et al., 2004; Triantaphyllidis et al., 1994)
Two reproductive strategies - ovoviviparity (nauplii) and oviparity (cysts).	(Criel and Macrae, 2002b)
Sedimentary cyst bank - cysts can remain viable for over 300 years.	(Marcarelli et al., 2005)
Ability to filter feed over a wide range of particle sizes (6.8 to 27.5 μm)	(Gelabert, 2001)

Introduced *Artemia* in Australia

While biogeographical reports list two species of *Artemia* occurring in Australia, *A. franciscana* and *A. parthenogenetica* (Van Stappen, 2002; Vanhaecke et al., 1987), it is important to note that the binomen *A. parthenogenetica* is used to uncritically group hundreds of parthenogenetic populations of *Artemia* (Triantaphyllidis et al., 1998; Van Stappen, 2002) for taxonomic convenience (Gajardo et al., 2002; Sun et al., 1999). The origins of this ‘species’ are heterogenous with at least four independent origins of parthenogenesis being deduced (Baxevanis et al., 2006). Thus, the application of the binomen *A. parthenogenetica* may be at odds with the biological species concept (Abatzopoulos et al., 2002).

Van Stappen (2002) reported that *Artemia* was not thought to exist in any natural Australian salt lake and occurred exclusively in coastal saltworks. This is contrary to a previous study by Geddes and Williams (1987) who reported the occurrence of unidentified *Artemia* from a variety of natural or semi-environments including, a natural salt lake south of Perth, a samphire swamp at Port Adelaide, a hypersaline lake at Port Augusta and a saline pool in Cooper’s Creek in central Australia. A study by McMaster et al. (2007) revealed that there was a recent (< 10 y) spread of *A. parthenogenetica* into the inland playa salt lakes in the wheatbelt of south-west Western Australia. The salt lakes of Rottnest Island, Western Australia, are permanent hypersaline environments (Bunn and Edward, 1984) where the occurrence of *Artemia* has also been documented as early as the 1950s (*A. salina*) (see footnote Hodgkin, 1959) through to recent times (*A. parthenogenetica*) (McMaster et al., 2007). It is clear that *Artemia* species in Australia occur not only in coastal saltworks but in a variety of other environments, some of which are natural and/or inland.

Footnote: Van Stappen (2002) p. 191 has incorrectly cited Edward and Watson (1959) as the original record for the occurrence of *Artemia* on Rottnest Island. This paper, as the title indicates, deals in, “Fresh water and brackish water swamps of Rottnest Island”. There is no mention of *Artemia* in this manuscript. The paper by Hodgkin (1959), which is the preceding article in the same journal edition, involves a faunal survey of the salt lakes of Rottnest Island and reports *Artemia salina* as the principal planktonic animal.

It appears that the first documented intentional introduction of *A. franciscana* in Australia occurred circa 1961 at the saltfield situated on mud flats on each side of Inkerman Creek in the Fitzroy River delta at Port Alma (central Queensland), near the Tropic of Capricorn, (Clark and Bowen, 1976; Jones et al., 1981; Vanhaecke et al., 1987). This location is in close proximity to the large regional centre of Rockhampton which is often cited, presumably for convenience, as the location of the central Queensland *A. franciscana* population (e.g. Abreu-Grobois and Beardmore, 1982; Clark and Bowen, 1976). This practice may be responsible for reports of *A. franciscana* populations being present at both Port Alma and Rockhampton (e.g. Triantaphyllidis et al., 1998; Van Stappen, 2002). The original source of material used to inoculate the Port Alma saltwork was a commercial product which was deemed to be from either Great Salt Lake or San Francisco Bay origin (Clark and Bowen, 1976). The origin of the cysts was subsequently confirmed by electrophoretic studies (Abreu-Grobois and Beardmore, 1982; Bowen et al., 1978) which revealed a close relationship between the Queensland population and *A. franciscana* from Great Salt Lake or San Francisco Bay.

Recent reviews (Timms, 2006; Van Stappen, 2002) maintain the occurrence of *A. franciscana* in the coastal Queensland locations of Port Alma/Rockhampton and Bowen while the potential expansion to north west and south west coastal regions of Western Australia is reported by Timms (2006) alone. The source of *A. franciscana* in Western Australia (e.g. Dampier and Hutt River) appears to be the result of cysts imported by Fisheries Western Australia from a Queensland population (McMaster et al., 2007).

In any case, most, if not all, of the data on the occurrence of *A. franciscana* in Australia relates to field studies from the 1970s and 1980s (e.g. Abreu-Grobois and Beardmore, 1982; e.g. Clark and Bowen, 1976; Geddes, 1979); this has been the source of information for subsequent reviews detailing its biogeography (e.g. Timms, 2006; Triantaphyllidis et al., 1998; e.g. Van Stappen, 2002; Vanhaecke et al., 1987). This highlights the need for new field studies to be conducted to ascertain the current distribution of *A. franciscana* in Australia (i.e. with respect to the current knowledge of the occurrence of *A. franciscana*, absence of evidence is not evidence of absence).

A review of the distribution of *A. parthenogenetica* by Timms (2006) revealed that this species, intentionally introduced to many Australian salt works, is present in South Australia's gulfs and the south west coast of Western Australia. A recent survey of *A. parthenogenetica*, in coastal and inland areas of Western Australia by McMaster et al. (2007) indicated that it had spread and advanced inland in the last 10 years. The authors hypothesised that birds may act as transport vectors for cysts both within Australia and between Australia and Asia. While the dispersal of *A. parthenogenetica* inland by nomadic bird species is very likely, importation of cysts by overseas migratory birds lacks empirical evidence at this stage, and by the admission of Mc Master et al. (2007), requires further studies (e.g. mtDNA) comparing local populations with those of Asia (natural bird dispersal) and European populations (human introduction). A study not mentioned by McMaster et al. (2007) is the work of Bowen et al. (1978) who demonstrated that the Western Australian population of parthenogenetic *Artemia* was electrophoretically very similar to populations in India, France, Russia and Japan, although there were slight differences in Hb-1 relative mobility. This data does not clearly support either an Asian or European source of introduction into Western Australia (as suggested by Mc Master et al. (2007)), and indicates that the point of origin of *A. parthenogenetica* is rather more complex, a finding now confirmed by the work of Baxevanis et al. (2006). Some authors consider that *A. parthenogenetica* may indeed be an Australian native species, dispersed to this continent via a natural vector such as birds, (McMaster et al., 2007; Timms, 2005). At this point, however, this hypothesis lacks empirical data. The presence of this species, which clearly has its origins in the Mediterranean region, can not be considered as a relict or autochthonous subelement of Australia's Gondwanan biogeography, but perhaps at best, a representative of a very recent intrusive element.

Timms (2005) tentatively assigned the binomen *A. franciscana* to the *Artemia* species reported to be present in the Dry Creek Saltfields, South Australia by Geddes and Williams (1987). This is in line with evidence suggesting that this population was derived from San Francisco Bay material based on biometrical and electrophoretic affinities and that the cysts were derived from the company's Port Alma site in Queensland in 1980 (Geddes and Williams, 1987). Interestingly, this probable population of *A. franciscana*, in South Australia, has not been reported in many other relevant works (Timms, 2006; Triantaphyllidis et al., 1998; Van Stappen, 2002; Vanhaecke et al., 1987). Once again, this highlights the need for new field studies to be

conducted to ascertain, at the very least, the distribution and species identity of *Artemia* in Australia. Table 3 shows reported populations of *A. franciscana* in Australia.

The unintentional release of parthenogenetic strains through the deliberate release of *A. franciscana* is also possible given that commercially harvested cysts from North America (sold as being sourced from Great Salt Lake) are known to contain parthenogenetic strains (Campos-Ramos et al., 2003). This points to the need for better characterisation and control of *Artemia* cysts being released to the environment.

“[Insert Table 3 about here]”

Table 3. Reported populations of *A. franciscana* in Australia.

State	Locality	Geographical coordinates	Reference
Queensland	Bowen	*20°00'S 148°16'E	(Geddes, 1979; Geddes, 1981)
	Port Alma	*23°40'S 150°36'E	(Clark and Bowen, 1976)
	Rockhampton	23°22'S 150°29'E	(Abreu-Grobois and Beardmore, 1982; Clark and Bowen, 1976)
Western Australia	Dampier	20°40'S 116°42'E	(McMaster et al., 2007; Timms, 2006)
	Hutt River	-	(McMaster et al., 2007)
	Onslow	21°40'S 115°08'E	(Timms, 2006)
	Port Hedland	20°20'S 118°38'E	(Timms, 2006)
	Shark Bay	25°15'S 113°20'E	(Vanhaecke et al., 1987)
	Useless Loop	26°08'S 113°24'E	(Timms, 2006)
South Australia	**Adelaide	-	(Geddes and Williams, 1987)

*Geographical coordinates corrected. Longitude incorrectly cited as 184°16E by Vanhaecke et al. (1987) and subsequently by other authors (e.g. Triantaphyllidis et al., 1998). Geographical coordinates 23°22'S 150°32'E cited by Vanhaecke et al. (1987) for Port Alma are similar to that for Rockhampton.

**Dry Creek Saltfields; population has affinities with San Francisco Bay *Artemia*; probable that this saltwork, owned by the same company as the Port Alma saltwork, was inoculated (1980) with cysts from the Queensland site (Geddes and Williams, 1987).

The potential threat of *A. franciscana* to the biodiversity and ecology of Australian inland waters.

Australia's biodiversity is unique due to its Gondwanan history which has contributed to a high level of endemic taxa. While the brine shrimp *Artemia* is a major faunal element in many hypersaline biotopes throughout the world (Van Stappen, 2002), Australia is the only continent where a distinctly different halobiont anostracan has evolved (Geddes and Williams, 1987). This genus, *Parartemia*, comprising at least eight species, has an Australia wide distribution (Geddes, 1981; Timms, 2006).

There is no doubt that the conservation of *Parartemia* requires protection of its environment. Australian salt lakes are threatened with many challenges including anthropogenic salination, mining, groundwater extraction, global climate changes, stream flow diversions, and sedimentation (Timms, 2005). With respect to biological disturbances, and more specifically the introduction of exotic species, Timms (2005) states that Australian salt lakes are almost pristine due to their remoteness and the physiological harshness of the environment. The author discusses the spread of *A. parthenogenetica*, into disturbed saline lakes in Western Australia and the replacement of native *Parartemia* species, under the premise that this *Artemia* species is native, thus making this a natural process. As stated previously, we do not subscribe to this view. At best, if the hypothesised dispersal of *A. parthenogenetica* into Australia by migratory birds is valid, then this species would be representative of a very extraordinary recent intrusive element.

Predatory species, which have shared a long evolutionary history with *Parartemia* species, may not be adapted to feeding on *A. franciscana* due to differences in its size (approximately half the size of some *Parartemia* species) and behaviour. Additionally, *Artemia* strains are known to vary in nutritional content and energy value (Van Stappen, 1996) and it is highly likely that *A. franciscana* would provide a different nutritional profile than *Parartemia* species. The introduction of *A. franciscana* into waters devoid of native brine shrimp may also disturb the

ecosystem by influencing food webs, nutrient cycling, algal biomass and primary production. However, as yet the ecological effects of introduced *A. franciscana* have not yet been quantified.

Of particular concern is the proximity of the *A. franciscana* population at Bowen to Lake Buchanan, which is located less than 300 km inland. Lake Buchanan is the northern outlier of Australia's central and eastern inland salt lake region which extends from the central upland of Queensland, through the Paroo area down to the lower Lake Eyre basin in South Australia (Timms, 2007). If *A. franciscana* was introduced to this lake, it is possible that it could then colonise and populate this entire region and pose a potential threat to the nationally significant wetlands of both Lake Buchanan and Lake Eyre (Environment Australia, 2001), for example, which are home to *Parartemia minuta* and other endemic fauna (Timms, 1987; Williams and Kokkinn, 1988). Furthermore, the detection of *A. franciscana* in this region may be delayed due to the infrequent filling of these lakes, e.g. Lake Eyre has only filled three times in the last century.

It has recently been demonstrated in laboratory trials that *A. franciscana* is capable of spreading *Cryptosporidium* oocysts and *Giardia* cysts (protozoan parasites that infect a wide range of vertebrates) (Mendez-Hermida et al., 2006). As *A. franciscana* is the most common live food used in the larviculture of fish and crustaceans, produced for human consumption, the possibility for it to act as a vehicle of infection gives rise to economic and public health concerns. To minimise risk, Mendez-Hermida et al. (2006) recommend that caution be exercised in aquaculture industries when hatching and culturing *A. franciscana* to ensure that the water used is free of these parasites. The risk to the inland saline ecosystem of *A. franciscana* spreading these parasites is unknown, however, these parasites are recognised as a human (NHMRC and NRMCC, 2004) and livestock (Olson et al., 2004) pathogens.

Suggested Action

In assessing the risk posed by the importation of an exotic organism, such as *A. franciscana*, into Australia, there are a number of issues which need to be addressed. Firstly, it is of paramount importance that the species identification of *Artemia* reflects the state of current taxonomic

knowledge. The practice of using the binomen *Artemia salina* for all *Artemia* is no longer acceptable (Sorgeloos and Beardmore, 1995).

According to Nairn et al. (1996) the goal of national quarantine should be to prevent the establishment and spread within Australia of exotic pests that are deemed to have a significant deleterious effect on the natural environment. At present, there is no data suggesting that *A. franciscana* is a threat to biodiversity in Australia; however, overseas case studies show that this species is capable of replacing native brine shrimp populations. The issuing of permits for the importation of *Artemia* into Australia is primarily concerned with addressing risk of infectious agents associated with the cysts with no apparent concern for the invasive potential or environmental consideration for the release of the species itself. The invasive potential of *Artemia* has been addressed elsewhere (e.g. the National Invasive Species Strategy for the Bahamas recognises *Artemia* as an invasive alien species (BEST Commission, 2003)) and similar assessments are required in Australia.

The potential hazards associated with the introduction of *Artemia* into natural populations of brine shrimp, (Geddes and Williams (1987) are still relevant. In particular, the loss of biodiversity, is a reality in other regions where introduced *A. franciscana* is replacing native brine shrimp species (Abatzopoulos et al., 2006; Amat et al., 2005; Green et al., 2005; Mura et al., 2006). To ameliorate or control the spread of exotic species, such as *A. franciscana*, it has been suggested that aquaculture activities should be subject to tighter regulation and, where possible, the use of native brine shrimp cysts should be encouraged. (Amat et al., 2005). The economic value (e.g. suitability for aquaculture) of the Australian *Parartemia* is almost totally unexplored (Geddes and Williams, 1987), however, it has been proposed that business plans for *Artemia* cultivation could serve as a benchmark for the cultivation of *Parartemia* with estimated start-up capital investment ranging from AUD \$50 000 to \$200 000 (Actis Environmental Services, 1999). A potential shortcoming associated with the commercial use of *Parartemia* is that it produces cysts which sink, making harvesting difficult (Geddes and Williams, 1987). Of positive note, however, is that species of *Parartemia* may show promise in biomass production as they can attain a much larger size than *Artemia* species (Geddes and Williams, 1987). .

Recent toxicology work in our laboratories involved the procurement of a commercial kit containing the cysts of *Thamnocephalus platyurus* (Anostraca). Importation of this kit required a permit issued by Australian Quarantine and Inspection Services (AQIS) with strict guidelines governing its use. This contrasts starkly with the availability of *Artemia* species which can be bought commercially over the counter or the internet. *T. platyurus* is not known to be an invasive species, *A. franciscana* is; thus we consider this dichotomy of introduced species management to be inconsistent with biological knowledge. We do not propose the reduction of *T. platyurus* importation and use conditions. Rather we appeal for the awareness that the genus *Artemia* is comprised of many species, of which at least one, *A. franciscana*, has been demonstrated to be highly invasive. Unanswered questions remain on the degree of niche separation between *Parartemia* and *Artemia* and/or if *Parartemia* is out competed by introduced *Artemia* (Van Stappen, 2002). Until these issues are resolved, the management of *A. franciscana* should reflect its invasive potential accompanied by guidelines that aim to prevent further releases of the organisms into Australian waters.

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