ring bighead carp in outdoor experimental raceways. However this effectiveness was relatively low in contrast to the results obtained from the integrated SPA driven BAFF and GEFB experiment. Additional experiments are planned to determine the effectiveness of the SPA driven BAFF using various other sound signal compositions and frequencies in order to ascertain if a stronger avoidance response by bighead carp in the presence of this behavioral guidance system is possible. We will also be evaluating the effectiveness of the GEFB (excluding the SPA driven BAFF) system in order to determine its effectiveness in deterring bighead carp in outdoor experimental raceways.

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BIOINVASIONS

A South American Invades Asia

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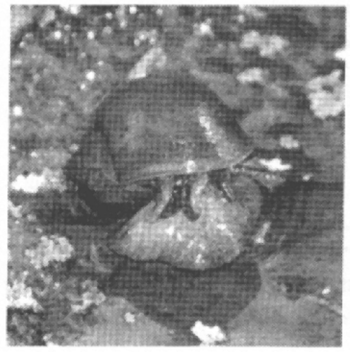


Figure 1. *Pomacea canaliculata.*

Introduction

Pomacea canaliculata (Lamarck, 1822), golden apple snail or "ampularia", is a common native snail in streams, rivers and ponds of the Plata Basin in South America (Figure 1). This snail belongs to the family Ampullariidae. Among the species belonging to this family, *P. canaliculata* has the widest distribution. It inhabits the Plata and the Amazon Basins and it is found from Colombia and Guayanas to the center of Argentina (up to the south of Buenos Aires Province) (Figure 2).

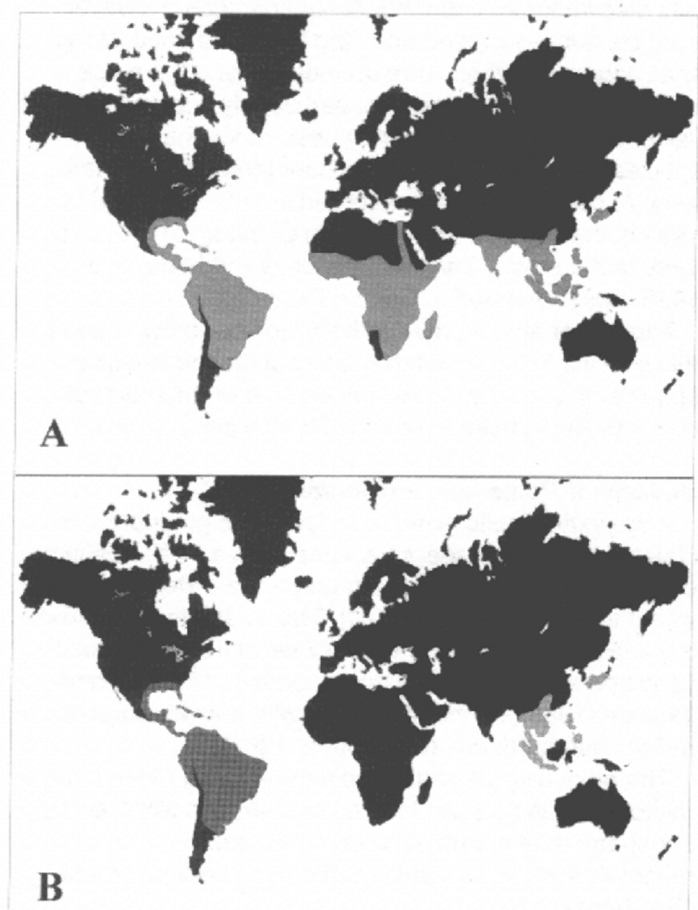
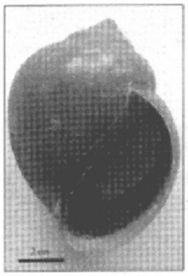


Figure 2. A. Ampullariidae distribution (grey). B. Natural distribution of *Pomacea* species (dark grey), Area invaded by *Pomacea canaliculata* in Southeast Asia (light grey).



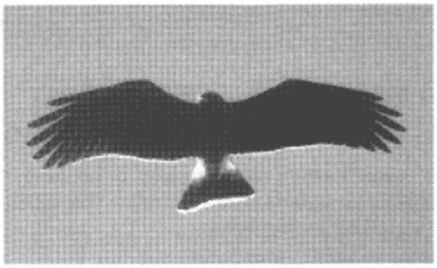


Figure 3 (above left). *Pila* species are used as a human food source in the Southeast Asia and they are reared in the rice fields (the specimen belongs to the Colección Malacológica del Museo de La Plata, FCNyM, UNLP).

Figure 4 (above right). *Rosthramus sociabilis*, a predator of *P. canaliculata* (Photo Dr. Carlos Darrieu).

P. canaliculata is an abundant species in argentine freshwater bodies (Darrigran, 1989).

No species of *Pomacea* sp. are indigenous to Asia, but *Pila*, another Ampullariid genus, has several native and widespread species especially in Southeast Asia (Figure 3). Several *Pila* species are used as food resource by the inhabitants of that region. These species are in dynamic equilibrium within their native area.

Pomacea canaliculata was intentionally introduced in Asia in 1979. Snails were first imported to Taiwan from Argentina as a potential source of high protein food for local human consumption as is done with the native *Pila* species. Initially the profits were attractive and the snail was also imported into other Asian countries. However local consumers proved unwilling to eat the snail. Many snail enterprises then were abandoned and the snails invaded natural water bodies, particularly rice paddy fields, becoming a serious rice pest. Since then, this species has colonized different countries within Southeast Asia. *P. canaliculata* was recorded in 1981 in Japan, in 1982 in the Philippines, in 1985 in China and Korea, in 1989 in Indonesia, Thailand, Vietnam and Laos, and in 1995 it was recorded in Cambodia.

This paper aims to review the biological knowledge of this species in their southern distribution, the invasive status of this species in Asia and some of the methods currently being used to control this rice pest.

Biology of *Pomacea canaliculata*

Ampullariid snails exhibit both primitive prosobranch characteristics and specializations such as the presence of a ctenidium (used to breath under the water) combined with a lung (used to breath air). This characteristic allows the species of this family to resist severe ambient conditions and survive during long dry periods (Bonetto and Tassara, 1988). It inhabits waters with a wide range of salinity and hardness (Bachmann, 1960).

The golden apple snails show three types of feeding: microphagous (deposit feeding and surface film feeding); zoophagous (e.g. predation on eggs); and macrophytophagous, which is the most common habit (Estebenet, 1995).

It is also a part of several natural trophic chains. A very common avian species in South America, *Rosthramus sociabilis*, preys selectively on the snail and is one of the natural controls for snail populations (Figure 4). Caimans, turtles and other native vertebrates eat them (Cazzaniga, 1990). *P. canaliculata* is also a definitive and intermediate host for several parasite species of wild animals (Martorelli, 1987; Ostrowski de Nuñez, 1992; Damborenea, 1996, 1998; Damborenea and Gullo, 1996; Digiani and Ostrowsky de Nuñez, 2000).

There are few field studies describing the reproductive cycle of this snail (Estebenet and Cazzaniga, 1993). Sexual dimorphism in the shape of the shell aperture and opercule has been reported (Cazzaniga, 1990; Estebenet, 1998). Studies undertaken in Argentina report that the apple snail has a lifespan of three years (Bachmann, 1960), reaching maturity after two years, at 25 mm of valve length (Martin, 1986). Water temperature regulates the age of the first oviposition and the length of the reproductive period, which extends between October and April in the temperate area of the Plata Basin. Bachmann (1960) reports that females have only one reproductive season. However, due to the permanent habitats, iteroparity is expected. Estebenet and Cazzaniga (1993) studied two cohorts maintained in the laboratory for four years and reported that the species reproduced more than once when reared at variable temperatures.

The egg masses are reddish and are deposited aerially. Females lay their eggs several centimeters above water level attached to emergent plants or other objects (Figure 5). Egg size, color and clutch size show great variability (Albrecht *et al.*, 1996). Estebenet and Cazzaniga (1993) state that highly significant differences were detected in egg size among the egg clutches coming from one field population, but differences were not evident between localities.

In two or three weeks the eggs hatch and the juveniles drop in the water to continue their growth. Growth was examined under laboratory conditions (Estebenet and Cazzaniga, 1992). The survivorship of *P. canaliculata* under optimal conditions does not differ significantly between sexes. The growth rate of females and males was the same until the age of sexual maturity. Thereafter the females grow faster (Estebenet and Cazzaniga, 1998).

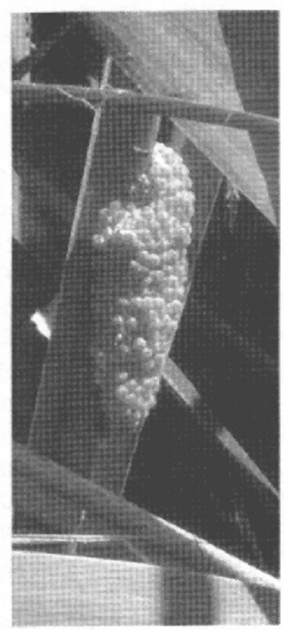


Figure 5. Egg masses of *P. canaliculata* on a rush.

Martin and Estenebet (2002) describe life-history interpopulation variation. Interpopulation differences in size or age at maturity, egg size, and clutches were observed in three natural populations from the same drainage and under the same climatic regime. Females from the unstable sites show a faster prematurity growth and higher oviposition rate than those from stable and productive sites.

Pomacea canaliculata as an Invasive Species

Pomacea species exhibit a high polymorphism in shell shape, size and thickness. This morphological variability confuses the taxonomy of *Pomacea* species and there is disagreement about the number of species that have been introduced into Asia.

P. canaliculata invaded waterways and rice fields in several Asian and other countries (Taiwan, Philippines, Japan, China, Korea, Indonesia, Malaysia, Singapore, Hong Kong, Vietnam, Thailand, Laos, Papua, New Guinea, Cambodia and Hawaii) (Baker, 1998) very rapidly.

Lach *et al.* (2002) mention several characteristics that facilitate its invasive potential: it is a food generalist; there is an absence of natural enemies in many places; its tolerance to a wide range of temperatures and levels of water pollution; and it is highly fecund. The apple snail found a climate suitable for reproduction during much of the year in Southeast Asia, numerous potential habitats to colonize and the absence of natural enemies. These factors allowed it to spread in Asia along natural and artificial water bodies (rice fields included). It is generally accepted that *P. canaliculata* is the most significant pest in rice fields in this region. As it is a generalist herbivore, it also feeds on other paddy crops as lotus, rush, morning glory, taro and *Azolla* sp. (Yusa and Wada, 1999).

Rice is the most important economic resource in many of these countries and is essential in peoples' basic diet. These countries depend on rice production. Twenty-two years following the first record of *P. canaliculata* in the Southeast Asia, this species has become a major crop pest of rice (Figure 6) and caused damage to a wide range of other plants of agricultural importance.

Today, several countries have been invaded by *P. canaliculata* and each of them has different problems:

• Snails were imported repeatedly to Japan from Taiwan or directly from Argentina (Yusa and Wada, 1999). In the early '80s culture of apple snails for human food was popular. Culture soon declined because consumers did not like the taste of the snails. *P. canaliculata* escaped and was first record in the wild in 1983. Since then, the range of the snail has constantly expanded in rivers, streams and crop fields. In 1997, about 7% of the cultivated fields were infested. Several methods are currently used by Japanese farmers to control the snails. These measures are used throughout year, particularly during transplanting season.

• The invasion of the apple-snail in the Philippines in 1988 was estimated at over 400,000 ha in rice fields. In recent years, the infestations seem to decrease because of control efforts using an integrated management approach. However, the use of molluscicide in several areas is common (Cagauan *et al.*, 1998).

• The golden apple snail was introduced to Vietnam in 1988 for rearing as a source of protein for human and

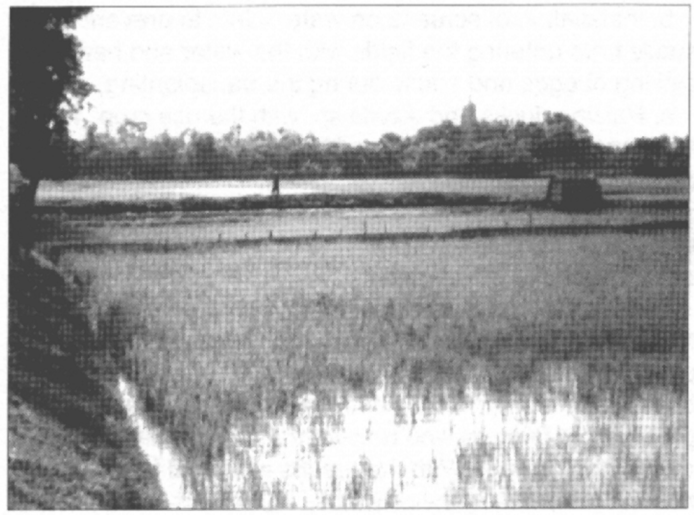


Figure 6. Rice field in the Nghe An Province, Vietnam.

aquatic animals (ducks, fish, etc.). In 1992, two companies in Southern Vietnam established two farms to raise apple snails for export to Taiwan. Since then it has multiplied and spread very fast, beginning to damage different crops, especially rice and morning-glory (*Ipomea aquatica*), other food sources for the area.

• The golden apple snail was introduced to Cambodia by refugees when they returned from Thailand. Farmers then intentionally placed the snails in their rice fields to rear them as food, as they usually do with native *Pila* species, which do not eat rice. People were unwarned that it was a rice pest.

Control

The last international meeting about golden apple snail management (A. de Lara and Y. Yusa, personal communication) was the International Workshop on the Integrated Management of the Golden Apple Snail in Rice Production, held on August 1998, in Nghe An, Vietnam, organized by FAO.

As a result of this International Meeting, several control and prevention points were stressed in order to minimize the impact of this invasive species:

1. Periodic monitoring of apple snail distribution and density to identify the infested areas and monitor snail population increase. This information will help prevent the infestation of new areas and help evaluate the effectiveness of control methods.

2. Sustainable control strategies.

• Different fish species were raised (*Clarias fucus* + *C. garie-pinus*, *Cyprinus carpio* and *Mylopharyngodon*). All of them are good snail consumers and survive well in captivity. Not only are these fishes effective consumers of small snails, but some also can eat the larger ones. Stocking fish in rice fields, which were infested by golden apple snails, has reduced snail density.

• Other methods are used, especially those related to farming practices:

a. Keeping low water levels in rice fields and timing transplanting to reduce the snail activity.

b. Installation of screens on water inlets to prevent the snails from entering the fields with the water and hand picking of eggs and adults during the transplanting,

c. Raising ducks and *Azolla* sp. with the rice crop. This is a very common practice and has been demonstrated to be effective, especially in Philippines.

• Use of botanical attractants. Many species act as apple snail attractants. These may be a complement *P. canaliculata* control efforts.

• Education of farmers about apple snail problem through farmer field schools. Trainers have been dispatched to different localities in order to give farmers the best information on snail control with the hope that progressive farmers who receive training will discuss and train other farmers. With the results achieved from the training program, many provinces in Vietnam have limited the areas of infestation and damage caused by snails.

3. Non-sustainable control strategies.

• The use of molluscicides. The effectiveness of several molluscicides is known but their use increases costs, many of them are not allowed and they may adversely affect human health and damage other species associated with the rice ecosystem.

Pomacea canaliculata occurs naturally in Argentina were the climate is temperate. However, the natural distribution of this species extends northwards into the Amazon basin (a tropical area). This fact demonstrates that this species is extremely flexible ecologically (Lach, *et al.*, 2000) and may be one reason for its success when it is transported to new environments.

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BIOINVASIONS

Facilitative Interactions Among Introduced Species: A Growing Problem for Aquatic Conservation and Resource Management

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This is a brief summary of a forthcoming book chapter: Ricciardi, A. 2002. "Facilitative Interactions among Introduced Aquatic Species", In: *Invasive Alien Species: Searching for Solutions.* H.A. Mooney, J. McNeely, L.E. Neville, P.J. Schei, J.K. Waage (eds). Island Press, Washington, D.C.

Species invasions are generally treated as isolated events whose effects are independent of one another. However, invaders may interact in ways that alter or exacerbate each other's impact. Through mutualistic and commensalistic interactions, one introduced species may promote the establishment, range expansion or population growth of another introduced species, with cascading repercussions in the food web (Simberloff and Von Holle 1999, Ricciardi 2001).

The most conspicuous examples of this are in terrestrial systems, e.g. animals pollinating and dispersing plants. Less obvious are the effects of facilitation in aquatic systems, which are becoming increasingly invaded throughout the world. However, a growing number of documented studies suggest that facilitation is not uncommon among aquatic invaders. These include the zebra mussel *Dreissena polymorpha*, whose intense filtration activity enhances water clarity, thereby stimulating the growth of native and introduced macrophytes such as Eurasian watermilfoil *Myriophyllum spicatum*. Increased water clarity and the expansion of macrophytes in some areas of the Great Lakes has led to the replacement of commercially-important walleye *Stizostedion vitreum*, which prefer turbid water, by bass *Micropterus* spp. and northern pike *Esox lucius*, which thrive in weed beds (MacIsaac 1996). A similar series of cascading impacts occurred in the Potomac River following the introduction of the filter-feeding Asiatic clam *Corbicula fluminea*, which facilitated dense growths of *Myriophyllum* and *Hydrilla*, to the benefit of introduced largemouth bass *Micropterus salmoides* (Phelps 1994; Serafy et al. 1994).

Cascading impacts may also occur when one invader suppresses the predators or competitors of another invader. For example, the reduction of the top predator in the Great Lakes, lake trout *Salvelinus namaycush*, by the parasitic sea lamprey *Petromyzon marinus* during the mid-20th century paved the way for the population explosion of another exotic species, the alewife *Alosa pseudoharengus*. The alewife subsequently outcompeted native planktivores and caused a decline in fishery productivity in the Great Lakes (Smith 1970).

A more recent example is the on-going replacement of native kelp beds on the Atlantic coast of Nova Scotia by the Japanese alga *Codium fragile*. *Codium* is being facilitated by kelp defoliation caused by the European bryozoan *Membranipora membranacea*, which encrusts kelp fronds and renders them brittle. Loss of kelp canopy has permitted *Codium* to become established in subtidal areas that were historically dominated by kelp beds. Because *Codium* is apparently unpalatable to sea urchins, this transition threatens the future of the urchin fishery in Nova Scotia (Scheibling et al. 1999; Scheibling 2000).

Introduced species may thus act synergistically, i.e. their joint impact may be greater than the sum of the effects of individual species acting alone, with potentially serious consequences for biodiversity and fisheries management. The previous examples demonstrate that facilitative interactions can magnify the impact of an invader across multiple trophic levels. Aquatic ecosystems might be particularly susceptible to such impacts because (1) trophic cascades occur more frequently in aquatic ecosystems than in terrestrial ecosystems (Strong 1992), and (2) facilitations are common in the Great Lakes and likely in other highly-invaded aquatic ecosystems (Ricciardi 2001). Aquatic ecosystems could become increasingly disrupted by a non-linear accumulation of invaders and their synergistic impacts—a process termed "invasional meltdown" (Simberloff and Von Holle 1999). If so, then even a partial