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Original article

Impact of invasive apple snails on the functioning and services of natural and managed wetlands

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A B S T R A C T

At least 14 species of apple snail (Ampullariidae) have been released to water bodies outside their native ranges; however, less than half of these species have become widespread or caused appreciable impacts. We review evidence for the impact of apple snails on natural and managed wetlands focusing on those studies that have elucidated impact mechanisms. Significant changes in wetland ecosystems have been noted in regions where the snails are established: Two species in particular (*Pomacea canaliculata* and *Pomacea maculata*) have become major pests of aquatic crops, including rice, and caused enormous increases in molluscicide use. Invasive apple snails have also altered macrophyte community structure in natural and managed wetlands through selective herbivory and certain apple snail species can potentially shift the balance of freshwater ecosystems from clear water (macrophyte dominated) to turbid (plankton dominated) states by depleting densities of native aquatic plants. Furthermore, the introductions of some apple snail species have altered benthic community structure either directly, through predation, or indirectly, through exploitation competition or as a result of management actions. To date much of the evidence for these impacts has been based on correlations, with few manipulative field or mesocosm experiments. Greater attention to impact monitoring is required, and, for Asia in particular, a landscape approach to impact management that includes both natural and managed-rice wetlands is recommended.

1. Introduction

Wetlands rank among the most productive ecosystems on the planet, providing a range of ecosystem services and economic benefits: they defend coastal and riverside areas against storms and floods, purify water, control erosion, retain pollutants, and they maintain a high diversity of animal and plant species, often functioning as nurseries for fish and shellfish, or as nesting sites for waterfowl (Mitsch and Gosselink, 2007). Wetlands provide major sources of human nutrition in the form of aquatic species that are hunted, fished or farmed in natural areas, but also from intensive and semi-intensive agriculture in managed or artificial wetlands such as rice fields. Macrophyte community structure (relative abundance and diversity) represents a key determinant of wetland form and function. Macrophytes purify water (by oxygenation and the conversion of toxic ammonia to usable nitrates), recycle nutrients, provide refuges, microhabitats and food for aquatic organisms, and provide physical structures (stems and leaves) that determine water flow patterns, sedimentation levels, and light and temperature gradients through the water body (De Nie, 1987; Petr, 2000). In agricultural wetlands, aquatic macrophytes (other than the crop species) are often regarded by farmers and agronomists as nuisance weeds that compete with the crop for resources (Ampong-Nyarko and De Datta, 1991). However, several crop-associated macrophytes are used as supplementary food for people and livestock, and as natural medicines (Cruz-Garcia and Price, 2011). For example, Kosaka et al. (2006) identified 11 species that are used as human food, two as animal fodder, and five medicinal plants from among 184 rice-associated weeds in Laos. Some macrophytes, including the free-floating fern *Azolla*, are encouraged in rice fields to increase nitrogen-fixation (Mandal et al., 1999). Changes in aquatic macrophyte communities can have marked effects on water turbidity and chemistry, particularly in shallow ponds and lakes (De Nie, 1987; Petr, 2000; Carlsson et al., 2004; Hargeby et al., 2004). Such changes are sometimes the effects of over-exploitation of native herbivores, the introduction of predators (cascades), or the invasion of wetlands by exotic herbivorous fish, crustaceans or mollusks (Hansson et al., 1987; Scheffer et al., 1993; Gunderson, 2000; Carlsson et al., 2004).

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Several species of aquatic snail have invaded wetlands outside their original distribution ranges. These invasions are often associated with enormous increases in secondary production and significant alterations in wetland conditions (habitat, structure of benthic communities, water turbidity) (Hall et al., 2003, 2006; Dana and Appleton, 2007; França et al., 2007; Arango et al., 2009). Many invasive snails feed predominantly on detritus, periphyton, lower aquatic algae and other microscopic organisms; but one group in particular – the apple snails (Ampullariidae) – are recognized for their tendency to feed predominantly on fresh macrophyte material (Estebenet and Martin, 2002a,b; Estebenet, 1995). Several species of apple snails have invaded regions outside their native distribution ranges (Table 1). Their diets together with their large body mass and generally high reproductive output (Table 2) allow some of these snails to effect rapid changes in macrophyte community structure, shift the nutrient balance and turbidity states of water bodies and cause huge losses to agricultural productivity and profitability (i.e., *Pomacea canaliculata* (Lamarck): Litsinger and Estano, 1993; Halwart, 1994; Naylor, 1996; Carlsson et al., 2004; Kwong et al., 2010). Because apple snails are predominantly tropical and subtropical, their negative impacts are mostly sustained in developing nations where rice is the main staple food and rice farming is the principal agricultural activity (Khush, 1997). Apple snails directly impact peoples' livelihoods in developing nations because of a relatively high reliance on local agriculture and natural ecosystems for food and materials (Cruz-Garcia and Price, 2011).

In this review, we report on the diversity of apple snails introduced to tropical and subtropical regions, examining their impact on aquatic macrophyte and benthic communities and consequently on wetland function. Although apple snails are often used for food and medicine, this review focuses mainly on their potential negative impacts cognizant that any benefits from introduced snails, particularly in South East Asia, could have been gained through better management of native snail species (i.e., Jahan et al., 2001; Thaewnon-ngiw et al., 2003). Since 2000, research attention has generally shifted away from exploring the impact and management

Table 1
Species of apple snail found outside their native distribution range.

Species and common name	Reason for introduction	Native range[a]	Invaded range[a]
Marisa cornuarietis (Linnaeus, 1758) – Giant rams-horn snail	Biological control of schistosomiasis vectors and weeds, pet trade	South America (Colombia and Venezuela) [1]	Costa Rica, Cuba, Dominican Republic, Egypt, French Guyana, Guadeloupe, Guyana, Panama, Puerto Rico, Sudan, Surinam, Tanzania, USA (Florida, Texas) [1]; Martinique, St Kitts [2]; New Zealand [3]
Pila conica (Wood, 1828) – Black apple snail[b]	Food	South-East Asia (Philippines) [1]	Guam, Palau, USA (Hawaii) [1]; India [4]
Pila globosa (Swainson, 1822) – Indian apple snail	Food, commerce, potential biological control of schistosomiasis vectors	Bangladesh, India (North) [5]	India (Kerala) [6]
Pila leopoldvillensis (Putzeys, 1889) – Giant African apple snail	Food	Africa [7]	Philippines [7]; Taiwan [1]
Pomacea bridgesii (Reeve, 1856) – Spike-topped apple snail[c]	Pet trade	Bolivia, Brazil [8]	Chile [9]; India (West Bengal) [10]; Sri Lanka [11]
Pomacea canaliculata (Lamarck, 1822) – Channeled apple snail	Food and commerce, pet trade	Argentina, Uruguay, Paraguay, Brazil, and Possibly Bolivia [1]	Cambodia, Chile, China, Dominican Republic, Egypt, Guam, Indonesia, Japan, Lao, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, South Africa, South Korea, Taiwan, Thailand, Vietnam, USA (Arizona, California, Florida, Hawaii) [1]; USA (Texas, North Carolina) [12], Pakistan [13], Russia (Siberia) [14];
Pomacea diffusa (Blume, 1957) – Spike-topped apple snail[c]	Pet trade	South America (Amazon Basin) [1]	Australia (western) [15]; Brazil (Pará, Pernambuco, Rio de Janeiro), Colombia, French Guiana, Panama, Sri Lanka, USA (Florida, Hawaii), Venezuela [1]; New Zealand [16]; Puerto Rico, USA (Alabama) [17];
Pomacea glauca (Linnaeus, 1758)	Biological control of schistosomiasis vectors and weeds, pet trade	South America (Northern) and Caribbean[d] [8]	Caribbean[d] [2]; Philippines [18]
Pomacea haustrum (Reeve, 1858) – Titan apple snail[e]	Pet trade	Bolivia, Brazil (Amazon region), Peru [12]	USA (Florida) [12]
Pomacea lattrei (Reeve, 1856)[f]	Aquaculture	Guatemala	Panama [19]
Pomacea lineata (Spix, in Wagner, 1927)[g]	Pet trade	Brazil and Guyanas [8]	South Africa [20][g]
Pomacea maculata (D'Orbigny, 1835) – Island apple snail[h]	Food, commerce, pet trade	Lower Paraná, Uruguay and La Plata Basins [15]	Cambodia, Singapore, South Korea, Thailand, USA (Alabama, Florida, Georgia, Louisiana, South Carolina, Texas), Vietnam [1]; Malaysia (Borneo), Taiwan [15]; Puerto Rico, USA (Arizona) [17]; Spain [21]
Pomacea paludosa (Say, 1829) – Florida apple snail	Pet trade	Cuba, USA (Florida) [8]	USA (Alabama, North Carolina) [22]; Puerto Rico [23]
Pomacea scalaris (d'Orbigny, 1835)	Food, commerce	Argentina, Bolivia, Brazil [15]	Taiwan [15]

[a] Numbers in parentheses indicate source references – 1, Cowie and Hayes (2012); 2, Cowie (2001); 3, Chapman et al. (1974); 4, Cowie (2002); 5, Jahan et al. (2001); 6, Thomas (1975); 7, Barcelo and Barcelo (1988); 8, Cowie and Thiengo (2003); 9, Letelier et al. (2007); 10, Raut and Aditya (1999); 11, Marambe et al. (2003); 12, Rawlings et al. (2007); 13, Baloch et al. (2012); 14, Yanygina et al. (2010); 15, Hayes et al. (2008); 16, Colloer et al. (2011); 17, United States Geological Survey (2012); 18, Mochida (1987); 19, Angehr (1999); 20, Dana and Appleton (2007); 21, European Food Safety Authority (2012); 22, Hayes (personal communication); 23, Williams et al. (2001).

[b] *Pomacea luzonica* is a synonym of *P. conica* that appears in some publications.

[c] *Pomacea bridgesii* and *P. diffusa* are often confused during identification; All reported *P. bridgesii* introductions have not yet been verified.

[d] This species might not be native to the Caribbean.

[e] *Pomacea haustrum* is possibly a synonym of *P. maculata* (Hayes, personal communication).

[f] Reports of introduction of *P. lattrei* have not been confirmed. The species may be a synonym of *P. flagellata* (Say, 1829) (Hayes, personal communication).

[g] Unconfirmed report of *P. lineata* in South Africa is likely *P. canaliculata* (Hayes, personal communication).

[h] *Pomacea insularum* and *P. gigas* are synonyms of *P. maculata* (Hayes et al., in press).