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Kelvin K.L. Ip
Hong Kong Baptist University

Jian-Wen Qiu
Hong Kong Baptist University, qiujw@hkbu.edu.hk

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Invasive apple snails: ecology and management in Hong Kong

Kelvin K.L. Ip and Jian-Wen Qiu*

Department of Biology, Hong Kong Baptist University, 224 Waterloo Road, Kowloon, Hong Kong. E-mail: qiujw@hkbu.edu.hk
*Corresponding author

Abstract

Apple snails in the genus *Pomacea* (Ampullariidae) invaded Hong Kong in the early 1980s. It is unknown how many species have been introduced into Hong Kong. A recent study has shown that only one species (*Pomacea canaliculata*) is present in the New Territories, yet it is not present in Hong Kong Island nor Lantau Island, the two largest islands with streams and abandoned rice paddies. In the New Territories, it is widely distributed in various freshwater habitats (ponds, drainage channels, semi-aquatic vegetable gardens, abandoned rice paddies, rivers and streams). Elsewhere in Asia, *P. canaliculata* is often a pest of rice, but in Hong Kong where most rice paddies have been abandoned, the first negative impact of *P. canaliculata* was reported by farmers who discovered that the snails devoured semi-aquatic vegetables, especially watercress (*Nasturtium officinale*) and water spinach (*Ipomoea aquatica*). In recent years, it has become clear that *P. canaliculata* could have reduced wetland biodiversity by grazing on macrophytes and by predation on benthic invertebrates, and altered wetland function by releasing nutrients into the water. It also has the potential to out-compete local macroinvertebrates because of its high secondary production. Apple snails in vegetable gardens are controlled by hand-picking, supplemented by application of chemicals, especially lime and tea seed cake. Those in constructed wetlands are controlled by hand-picking. A recent field study showed that black carp could be used to control apple snails in constructed wetlands.

Additional keywords: Ampullariidae, biological control, grazing, macrophytes, Mollusca, nutrient, phytoplankton, *Pomacea*, secondary production
Introduction

With the increasing travel and trade associated with rapid economic globalization in recent decades, there has been a dramatic increase in species introductions (Blumenthal, 2006). Whether an introduced species will establish and become invasive is dependent on both the characteristics of the recipient ecosystem, such as its diversity, resource abundance and frequency and scale of disturbances (Davis et al., 2000), as well as the biology of the introduced species, including its dietary flexibility, reproductive potential, growth rate and tolerance to adverse environmental conditions (Kolar & Lodge, 2001). Invasive apple snails possess many characteristics of successful invaders. They exhibit high reproductive potential, fast growth rate, high dietary flexibility and strong resistance to a number of environmental conditions including hypoxia, high temperature and desiccation (Cowie, 2002; Estebenet & Martin, 2002; Boland et al., 2008).

*Pomacea* (Ampullariidae) is a large genus of apple snails with more than 100 described species (Cowie & Thiengo, 2003). They are indigenous to freshwater habitats in South and Central America, with one species native to North America. At least three species have been introduced into Asia since the 1980s (Jhang, 1985; Anderson, 1993; Yusa & Wada, 1999; Joshi et al., 2001; Chen et al., 2004; Cowie et al., 2006; Joshi, 2007; Hayes et al., 2008, 2012; Lv et al., 2013). *Pomacea canaliculata* was the first species introduced to Asia, through importation of egg clutches to establish snail aquaculture in Taiwan in 1980 (Hamada & Matsumoto, 1985; Cha, 1989). In addition to *P. canaliculata*, *P. maculata* and *P. scalaris* were also introduced into Asia (Cowie et al., 2006; Hayes et al., 2008, 2012, 2015). *Pomacea canaliculata* and/or *P. maculata* was soon introduced to Japan, China and several countries in Southeast Asia including the Philippines, Vietnam, Cambodia and Thailand, often without distinguishing them or under the assumption that they were *P. canaliculata* (e.g. Hamada & Matsumoto, 1985; Cha, 1989; Mochida, 1991; Joshi & Sebastian, 2006). In southern China, *P. canaliculata* and *P. maculata* exhibit a wide and mosaic distribution (Lv et al., 2009, 2013). In Taiwan, *P. canaliculata* is widely distributed, but *P. scalaris* is restricted to the southern part (Lee & Wu, 1996; Wu et al., 2011). Due to their rapid growth and high protein content, apple snails were initially widely promoted as human food and as a protein supplement in animal feed. However, apple snail aquaculture farms soon stopped operation because of the toughness of apple snail meat, high processing costs and infection with the nematode *Angiostrongylus cantonensis*, a cause of eosinophilic meningitis (Mochida, 1991; Yu et al., 2001; Lv et al., 2008). Abandoned snails soon established large populations in various
freshwater habitats by active crawling and passive transportation by water flow in drainage systems (Mochida, 1991; Yusa & Wada, 1999; Cowie, 2002). In this paper we review the ecology (distribution, secondary production and impacts on wetland flora and fauna and wetland function) and management of apple snails in the agricultural and non-agricultural areas of Hong Kong.

**Distribution and identity of apple snails in Hong Kong**

Hong Kong is situated on China’s south coast, facing the Pearl River estuary in the west and the South China Sea in the east and south (Fig. 1). The territory is small, 1104 km² in area. It consists of Hong Kong Island, Kowloon Peninsula, New Territories and over 200 offshore islands of which the largest is Lantau Island. Apple snails were first reported

![Fig. 1. Distribution of *Pomacea canaliculata* in Hong Kong. Sampling locations/habitat types are shown by different symbols (○ - stream, ▽ - drainage channel, △ - pond, □ - abandoned wet farmland). Filled/open symbols indicate presence/absence of apple snails. Figure is adapted from Kwong *et al.* (2008).](image)
in northern New Territories following a territory-wide survey conducted in 1988 by Yipp et al. (1991), who estimated that apple snails were introduced to this agricultural area in many vegetable gardens and abandoned rice paddies in 1980-1983. This estimate was consistent with the results of an earlier territory-wide survey of molluscs conducted in 1980-1981 by Yipp (1983), who did not find apple snails. There is no consensus about the source and invasion pathway for apple snails in Hong Kong. As the first report of apple snails in the agricultural area of the New Territories was very close in timing to the first report of apple snails in Guangdong (Yu et al., 2001), and as the agricultural areas of Hong Kong and Shenzhen (southern Guangdong) are connected by a network of streams and drainage channels, it was difficult to determine to which of these two areas apple snails were first introduced.

Within the subsequent two decades of their invasion, apple snails spread to most lowland wetlands in the New Territories including streams, ponds, freshwater marshes, abandoned rice paddies, vegetable gardens and drainage channels. The periodic flooding during the summer rainy season must have helped apple snail dispersal in the lowland wetlands, which are connected through streams and drainage channels. A territory-wide survey of apple snails conducted in 2006 (Kwong et al., 2008) revealed the wide distribution of apple snails in the New Territories. The sites inhabited by apple snails typically had high levels of phosphate and alkalinity, but apple snails were also occasionally found in streams where nutrient and alkalinity levels were low. Geographical isolation and a lack of agricultural activities may have halted the spread of apple snails to other areas with apparently suitable habitats in Hong Kong. Specifically, although the water quality of sites visited (i.e. abandoned rice paddies) on Lantau Island were apparently suitable for apple snails, they had not been colonized, probably because of a lack of physical connection with the New Territories. However, the building of a bridge connecting the New Territories and Lantau Island in recent years has greatly enhanced traffic, with development of ecotourism, and there is concern that apple snails will be introduced to Lantau Island during replanting of abandoned rice paddies with agricultural crops, on which apple snail eggs may be transported inadvertently.

There has been some confusion regarding the identity of apple snails introduced into Hong Kong (Kwong et al., 2008). Cha (1989) and Yipp et al. (1991) identified two species of apple snails as Ampullarius levior and A. gigas (Ampullarius is not a valid name, the correct genus name for these species is Pomacea). Although both species were recorded in the northern New Territories, they showed some differences in their
distributions (Cha, 1989). Yipp et al. (1991) concluded that *P. gigas* preferred habitats with bottom sediment of coarser grain, while *P. levior* was a dominant grazer in finer grain sediments. Lam (1994) identified the apple snails collected from a stream in the New Territories as *P. levior*, whereas Dudgeon & Corlett (2004) identified the species of apple snail widely distributed in Hong Kong as *P. lineata*. To determine more rigorously the identity of apple snails in Hong Kong, selected snails collected from different locations (Kwong et al., 2008) showing the greatest morphological variation with respect to size, shell colour and shell shape were sent to Robert Cowie and Kenneth Hayes at the University of Hawaii, who sequenced a segment of the COI gene from 12 individuals and showed that all the snails were *P. canaliculata* (K. Hayes, pers. comm.). Therefore *P. canaliculata* is probably the only species of *Pomacea* currently present in Hong Kong. Based on comparison of shell morphology, the records of *P. levior* by Cha (1989) and Yipp et al. (1991) and of *P. levior* by Lam (1994) were probably *P. canaliculata*. It is possible that the records of *P. gigas* by Cha (1989) and Yipp et al. (1991) were *P. maculata* (*P. gigas* is now considered a junior synonym of *P. maculata*), which can reach a larger maximum size than *P. canaliculata* (Hayes et al., 2012). *Pomacea maculata* has established in some areas of southern China (Lv et al., 2013), but if this is the correct identification of the snails recorded in Hong Kong as *P. gigas*, then this species may have become locally extinct in Hong Kong. It is also possible that these snails were simply large individuals of *P. canaliculata* and that *P. maculata* has never been present in Hong Kong.

**Secondary production of apple snails**

Secondary production is an integration of life-history traits and reflects resource use (Benke & Huryn, 2007), thereby indicating the role a species plays in energy flow and material transfer in an ecosystem (Hall et al., 2006). Determining secondary production of apple snails could help elucidate their ecological roles in the recipient ecosystems and offer a good indicator of their resource use and potential impacts on local fauna that may compete for the same food source. To this end, 1-year monthly surveys of *P. canaliculata* populations were conducted in four wetlands representing the diverse wetland habitats in Hong Kong (abandoned paddy, oxbow pond, drainage channel, river meander) (Kwong et al., 2010). The mean density of *P. canaliculata* ranged from 26 to 43 individuals m$^{-2}$.
and secondary production (ash-free dry mass [AFDM]) varied from 165.9 to 233.3 g m\(^{-2}\) y\(^{-1}\) among the four sites. There were considerable seasonal differences in secondary production, with relatively low values during the cool dry northeast monsoon, and high values throughout much (7-10 months) of the year, especially during the warm, wet summer months. Data from the four apple snail populations were compared with published secondary production estimates for macroinvertebrates in Hong Kong, as well as those for freshwater gastropods around the world (Kwong et al., 2010) and showed that apple snail annual production was >10 times greater than production estimates for other benthic macroinvertebrates in Hong Kong (0.004-15 g AFDM m\(^{-2}\) y\(^{-1}\), n = 29). Also, annual production estimates for three of the four apple snail populations (i.e. >230 g AFDM m\(^{-2}\) y\(^{-1}\)) were greater than published estimates for any other freshwater snails (0.002-194 g AFDM m\(^{-2}\) y\(^{-1}\), n = 33), regardless of climatic regime or habitat type. The high production by *P. canaliculata* in Hong Kong was probably facilitated by the tropical climate (annual mean temperature ~24 °C), which permits rapid snail growth and reproduction, as well as the dietary flexibility of *P. canaliculata* and a lack of predators to effectively control its populations. The high secondary production of *P. canaliculata* compared to other macrobenthic invertebrates in Hong Kong may mean that it can monopolize food resources and compete strongly for macrophytes with other primary consumers.

Grazing on macrophytes including semi-aquatic vegetables

Although *P. canaliculata* is considered “harmless and useless” in South America, its native range (Cazzaniga, 2006), it has become a major pest of rice in Asia and taro in Hawaii because of its voracious appetite for these semi-aquatic crops (Halwart, 1994; Naylor, 1996; Cowie, 2002; Joshi & Sebastian, 2006). Laboratory experiments have shown that *P. canaliculata* also feeds on various wild macrophytes in Argentina (Estebenet, 1995) and Hawaii (Lach et al., 2000). In general, *P. canaliculata* exhibited a clear preference for certain macrophytes, and its growth rates were high when fed with the preferred macrophytes. However, it is not known what properties of the macrophytes determined the snails’ preferences. In wetlands of Southeast Asia, Carlsson et al. (2004) reported population density of *P. canaliculata* (in fact probably *P. maculata*; R.H. Cowie, pers. comm.) to be negatively correlated with diversity of aquatic macrophytes but positively correlated with nutrient concentrations and phytoplankton biomass. Mesocosm experiments showed that grazing by apple snails caused a reduction in wild macrophyte
biomass and an increase in phytoplankton biomass (Carlsson et al., 2004; Carlsson & Lacoursière, 2005).

To assess the snails’ preference for macrophytes, the physical and chemical basis of food preference and the consequences of such feeding on water quality and phytoplankton in southern China, especially Hong Kong, snails collected from four sites were dissected to examine their gut contents (Kwong et al., 2010), and several experiments were conducted in the laboratory (Qiu & Kwong, 2009; Wong et al., 2010; Qiu et al., 2011) and in the field (Wong et al., 2009; Fang et al., 2010). The dietary analysis showed that apple snails mainly feed on detritus and macrophytes, despite considerable variation in the composition and cover of aquatic plants among the four sites (Kwong et al., 2010). Among the laboratory studies, Qiu & Kwong (2009) examined how fresh leaves from various macrophytes commonly found in Hong Kong influenced feeding rate, growth and reproduction differently. They used five cultivated macrophytes (Amaranthus gangeticus, Apium graveolens dulce, Ipomoea aquatica, Nasturtium officinale and Colocasia esculenta) and five wild semi-aquatic macrophytes (Eichhornia crassipes, Ludwigia adscendens, Murdannia nudiflora, Myriophyllum aquaticum and Polygonum hydropiper). The snails showed strong preferences, with daily feeding rates varying from 1.3 % to 22 % of snail body mass among the ten macrophytes. Among both cultivated and wild macrophytes there were species the snails preferred and did not prefer. Feeding rate was negatively correlated with plant phenolic content. Snail growth rate was significantly positively correlated with phosphorus and nitrogen content. And the number of eggs deposited during the experiment was significantly positively correlated with plant sodium, nitrogen and phosphorus contents. Thus in the field, when several species of macrophytes are present, P. canaliculata will probably feed selectively and voraciously on the preferred species and thereby change the floral composition. Also, the result that four of the five cultivated macrophytes were in general desirable may partly explain why this species has become a successful invader in wetland agricultural areas in Asia.

To further understand the food preference of P. canaliculata, Wong et al. (2010) conducted no-choice feeding assays to test the palatability of the fresh leaves of 21 species of freshwater macrophytes commonly found in Hong Kong. They found that snail daily feeding rate on macrophytes varied greatly from 1.1% to 22% of snail body mass, and there was a positive correlation with nitrogen content but a negative correlation with C:N ratio and dry matter content (DMC). No significant correlation was detected between snail feeding rate and plant phenolic content, but the feeding rate
on Myriophyllum aquaticum, the macrophyte with the highest phenolic content tested, was among the lowest. To determine whether chemical defence was involved in the food preferences of *P. canaliculata*, Wong *et al.* (2010) conducted another set of feeding assays with 15 species that were not palatable as fresh leaves. They reconstituted plant tissues by mixing dry plant powder with agar. The two species with the highest DMC (*Phragmites australis* and *Vallisneria natans*) were fed upon much more as reconstituted plant than as fresh leaves, suggesting that plant physical structure may be important in defence against snail herbivory. For two macrophytes (*Myriophyllum aquaticum* and *Alternanthera philoxeroides*) with moderate nitrogen and phosphorous contents that were consumed very little as either fresh or reconstituted tissues, their extracts were further incorporated into a palatable agar-based food, which for both species greatly reduced snail feeding rate, indicating the presence of chemical defences in these two macrophytes. Overall, these experimental results suggested that the feeding decisions of *P. canaliculata* are determined by structural and chemical plant traits. Macrophytes with high nitrogen content were favoured, whereas those with a high DMC were disliked. Such plant traits could be used in species screening when selecting plants for use in wetland restoration projects and when predicting the impact of invasion by *P. canaliculata*.

Since the spatial distribution of macrophytes is highly heterogeneous in local wetlands, and they exhibit clear seasonality (Dudgeon & Corlett, 2004), fresh macrophyte leaves may not be available throughout the year across different freshwater habitats in Hong Kong. This raises the question of whether and how *P. canaliculata* could use decaying leaf litter, and the consequences of consuming leave litter for snail growth. A study was thus conducted to compare the consumption and growth of *P. canaliculata* fed with fresh and decaying leaves of three macrophyte species with contrasting levels of nutrients (nitrogen) and general defence chemicals (phenolics) (Qiu *et al.*, 2011). Decaying leaves were obtained by placing fresh macrophyte leaves in mesh bags in a wetland pond for 8-28 days. Feeding assays using adult snails lasted one day, and a growth and mortality experiment using snails of various sizes lasted one month. The results clearly indicated that the three species had contrasting effects on the consumption and fitness of the apple snails, and nitrogen and phenolics content, rather than plant freshness, determined snail feeding rate, growth and mortality. Snails consumed very little fresh or decaying leaves of *Polygonum barbatum* (knotweed), a species with low nitrogen and medium phenolic contents, resulting in high mortality and no measurable growth. They consumed a lot of fresh leaves and a moderate amount of decaying leaves of *Murdannia nudiflora* (dayflower), a species with low phenolic content and
high nitrogen content; mortality was low in both fresh and decaying leaf treatments. In contrast, decaying leaves of *Myriophyllum aquaticum* (parrot feather) with moderate nitrogen and low phenolic contents were consumed more and supported better snail survival and growth than the fresh leaves with high nitrogen and high phenolic contents. These results provided evidence that leaf nutrient and phenolic contents matter more than leaf freshness and that the snails can use both fresh and decaying leaves with moderate levels of nutrients and low levels of phenolics to maintain fitness. This flexible feeding habit may have contributed to the species’ success as an invader in many types of freshwater wetlands lacking a constant supply of nutrient-rich fresh leaves.

**Predation on freshwater fauna**

Although several species of apple snails including *P. canaliculata* are polyphagous (Cowie, 2002), previous studies have emphasized the impact of grazing by *P. canaliculata* on crop production, and on wetland macrophyte biomass, diversity and productivity. Nevertheless, there have been reports of predation by this invasive species on other macrobenthic invertebrates. Specifically, *P. canaliculata* could prey on the eggs, neonates and adults of the planorbid snail *Biomphalaria peregrina* and the neonates of three other snail species (*Austropeplea ollula, Physa acuta, Melanoides tuberculata*) but not on the neonates of another snail, *Sinotaia quadrata* (Cha, 1989). It will also actively and selectively prey on freshwater bryozoans, including both tubular and globular colonies (Wood *et al.*, 2006). However, in these studies the predatory apple snails were not fed prior to or during the experiments and it is not known whether they would prey on macrobenthic invertebrates when alternative food is present. It is also unknown how the predatory snails detected their prey and why some macroinvertebrates are more susceptible to predation than others.

To answer these questions, a laboratory study was conducted to confirm whether *P. canaliculata* would prey on the early stages (i.e. egg masses and/or neonates) and adults of the above five species of snails, common in the freshwater environments of southern China, in the presence of alternative macrophytic food (Kwong *et al.*, 2009). Each species of potential prey was exposed to *P. canaliculata* in laboratory aquaria in the presence of macrophytic food for a period of either 24 h for egg masses or 72 h for neonates and adults, after which the prey consumed was determined.

The tested species and life stages differed in their susceptibility to predation by *P. canaliculata*. Eggs and/or neonates of all five species, and adults of the Heterobranchia,
(the ‘pulmonates’ *A. ollula, B. straminea* and *P. acuta*), suffered substantial mortality. However, *P. canaliculata* was not able to prey on the adult Caenogastropoda (the operculate species *M. tuberculata* and *S. quadrata*). This pattern of high susceptibility of early developmental stages of the five snails to predation by *P. canaliculata*, and the differential survival of adults of the five snail species highlighted the importance of shell size, hardness and structure in defence against predation. The eggs and neonates are poorly defended because of their fragility. However, among the adults, the heterobranchs have relatively thin and fragile shells and their shell aperture is not covered by an operculum when the animal withdraws into its shell, whereas the adult caenogastropods have a more robust shell, the aperture of which can be covered by an operculum. Observation of the prey searching behaviour showed that *P. canaliculata* was not able to detect its prey until it physically touched it. However, *P. canaliculata* glides quickly over the benthic substrate (17.8 cm min$^{-1}$; 2.6 to 8.5 times the speed of four common species of snails in Hong Kong; Dudgeon & Lam, 1985), which may permit ample opportunities for direct encounters with its potential prey.

A study conducted in a local stream compared aspects of the life-history of the snail *Radix plicatulus* in two sites, one with high and one with low densities of *P. canaliculata* (Lam, 1994). At the high density site, *R. plicatulus* exhibited delayed reproduction, a longer recruitment period and a larger number of cohorts per year, demonstrating that *P. canaliculata* can affect the life-history characteristics of sympatric, possibly prey, snail species. Data from two mesocosm studies also included treatments to examine the impact of *P. canaliculata* on other molluscs (Wong et al., 2009; Ip et al., 2014). The two studies are broadly consistent in showing a lower density of macrobenthos in enclosures with *P. canaliculata* than in enclosures without them, although the differences were not significant in the study of Ip (2013), probably because of large variation among replicates and loss of two control replicates, which reduced the power of the statistics.

A recent field manipulative experiment also demonstrated that apple snails could be important predators of amphibian eggs in local agricultural wetlands (Karraker & Dudgeon, 2014). They put apple snails together with the eggs of amphibians and with water spinach (*Ipomoea aquatica*) in local wetlands and found that the snails consumed the eggs of four of the five amphibian species tested. They did not consume the eggs of the frog *Polypedates megacephalus*, presumably because of the protection of the eggs by a dense, foam matrix and suspension on vegetation attached to the side of the test container above the water surface. These experimental findings are consistent with field
observations that apple snail densities are high (Kwong et al., 2010) and the eggs of ten species of amphibians could hardly be found in the area (Ma, 2012).

**Ecosystem level effects**

Several mesocosm studies conducted in natural wetlands in Southeast Asia have demonstrated the grazing impact of apple snails on macrophyte diversity and biomass, and on nutrient and chlorophyll a concentrations (Carlsson et al., 2004; Carlsson & Lacoursière, 2005). However, given that macrophytes vary widely in biological characteristics such as nutrient demand, growth rate and defence strategy against herbivory (Carpenter & Lodge, 1986), more data from different environmental settings are required before we can generalize the causal relationship between herbivory by apple snails and state shifts in Asian shallow wetlands. A mesocosm study was therefore conducted in a shallow wetland in Hong Kong (Fang et al., 2010) to examine how apple snail density might determine the magnitude of snail herbivory, and how macrophytes with different defence strategies (physical or chemical) might affect herbivory, water quality (nutrients) and floral structure (phytoplankton and filamentous algae). *Myriophyllum aquaticum* (parrot feather, with high content of general chemical defence phenolics in its leaves) and *Eichhornia crassipes* (water hyacinth, with high dry matter content in its leaves) were placed in enclosures with 0-8 individuals of *P. canaliculata* for one month (Fig. 2). The two macrophytes were grazed heavily, with higher biomass reduction at higher snail densities. Given that these two species were considered well-

**Fig. 2.** Experimental setup in a wetland pond testing the effects of apple snail grazing on macrophytes, nutrients, phytoplankton and filamentous algae (transparent acrylic enclosures), and the effects of common carp on apple snails, non-*Pomacea* apple snails, and macrophytes (rectangular mesh enclosures). (Photo: J.W. Qiu)
defended compared to other macrophytes commonly found in Hong Kong (Fang et al., 2010), the results from this field study further illustrated the high potential for *P. canaliculata* to damage wetland plants.

An interesting finding of Fang et al. (2010) was that filamentous algae grew substantially in the control (up to 80.3 g m$^{-2}$, forming pond scum), but not in the treatment with *P. canaliculata*, indicating that the snails might have controlled the growth of filamentous algae. This finding, together with experiments showing that apple snails could feed on the juveniles and eggs of other freshwater snails that are potential grazers (e.g. *Physa acuta*), reflects the probable complex interactions among *P. canaliculata*, local snails and filamentous algae. In contrast to the expectation that snail grazing would increase nutrient concentrations, nitrogen and phosphorous concentrations were low throughout both experiments, and were not correlated with apple snail density, indicating that the sediment must have absorbed a substantial amount of nutrients from the water and used them to support macrophyte growth. There were clear snail density treatment effects on chlorophyll a and phytoplankton composition, but the results differed between the *M. aquaticum* and the *E. crassipes* experiments, again showing that the effects of apple snails on wetland ecosystems cannot always be simply described by the trophic cascade of snail grazing - nutrient release - phytoplankton growth.

**Control of apple snail populations**

Since their first invasion in the 1980s, apple snails have become a major pest of rice in Asia and taro in Hawaii (Cowie, 2002). Although Hong Kong is one of the most densely populated cities with more than seven million people in an area of 1108 km$^2$, there are still approximately 51 km$^2$ of agricultural land. While existing rice paddies (approximately 10% of agricultural land) are mainly for demonstration of traditional rice cultivation in Yuen Long, small-scale farms still provide 8% of vegetables for local consumption. Several species of semi-aquatic vegetables, especially *Ipomoea aquatica* (water spinach), *Nasturtium officinale* (watercress), *Nelumbo nucifera* (Indian lotus) and *Sagittaria sagittifolia* (Chinese arrowhead) are commonly cultivated species. Apple snails are widely distributed in these semi-aquatic vegetable gardens and the drainage channels connecting them. In response to the infestation of apple snails in vegetable gardens, local farmers have adopted cultural and chemical control methods. The cultural method involves simple hand picking of apple snail eggs and large individuals throughout the year, especially in the summer when apple snails reach their peak of reproduction and
growth. The chemical methods involve application of lime or tea seed cake (residue of seeds in the Camellia family, after oil extraction, which contains saponin) to apple snails between crops (Wang, 2010).

Due to increasing development pressure, many wetlands in the New Territories have been lost to construction for residential buildings and associated roads. As required by the Environmental Impact Assessment Ordinance, compensation wetlands of similar or larger size to those destroyed were created, with various macrophytes used to build up the floral community (Lau, 2004). An example of such wetland loss is the large-scale (220 ha) residential development in Tin Shui Wai for a population of 340,000 (Cha, 2004). As part of the compensation, Hong Kong Wetland Park (60 ha) was created with channels of different depths connecting many ponds separated by weirs for flow and water depth control, and macrophytes were planted to filter intake water and to create habitats of different floral diversity. The invasion of apple snails into these constructed wetlands may have greatly reduced the floral diversity, and their value as habitats for animals, such as birds. Current management activities to control apple snail populations in constructed wetlands in Mai Po Nature Reserve (managed by WWF Hong Kong), Hong Kong Wetland Park (managed by the Agriculture, Fisheries and Conservation Department and by the Development Bureau, HKSARG) and West Rail wetlands in Kam Tin (managed by Mass Transit Railway Corporation Ltd., Hong Kong) mainly involve hand-picking, which can be an effective method, but is labour-intensive and requires repeated effort (Cowie, 2002; AFCD, 2011; Secretariat of the Terrestrial Biodiversity Working Group, 2014).

Biological control is an appealing method in the management of invasive species, but its effectiveness and potential non-target effects should be carefully evaluated before implementation (Cowie, 2002). To explore the utility of biological control for apple snails in constructed wetlands in Hong Kong, two mesocosm studies were conducted (Wong et al., 2009; Ip et al., 2014). Wong et al. (2009) studied the effectiveness and non-target effects of common carp (Cyprinus carpio) as a biological control agent against P. canaliculata in a 2-month enclosure experiment (Fig. 2). They examined the impact of common carp on nine species of gastropods, including apple snails, and on three species of macrophytes in a constructed wetland in Hong Kong Wetland Park. Common carp completely eliminated apple snail juveniles that were small enough to fit into their months. However, the size of the fish used was constrained by the size of the enclosures, and their ability to grow larger in local ponds may mean that common carp could be an effective biocontrol agent for larger apple snails. However, common carp also caused
a significant reduction of plant biomass and of the densities of most non-*Pomacea* gastropods, that is, strong non-target effects on the local wetland flora and fauna.

To further explore fish as a biocontrol agent for apple snails, a mesocosm study was conducted using black carp (*Mylopharyngodon piceus*) (Ip *et al.*, 2014). The aim of the study was to determine whether black carp were as effective as common carp as a biocontrol agent for apple snails, while having less impact on macrophytes and other snails. The experimental setup and duration was very similar to that of Wong *et al.* (2009), except for the use of the two fish species. Both common carp and black carp preyed effectively on *P. canaliculata*, removing almost all individuals that were small enough to fit into their mouths. However, while black carp reduced herbivory on macrophytes through reducing apple snail density, common carp reduced apple snail density but this did not result in a lower level of herbivory because it also fed on macrophytes. Non-target mollusc density was reduced by both fish species.

A manipulative field experiment was further conducted in three constructed wetland ponds (surface area 1000 to 2525 m$^2$, maximum depth 1.1-2.2 m in the wet season and 0.6-1.3 m in the dry season) to examine how black carp might affect apple snails, as well as non-target macroinvertebrates, macrophytes and water quality in more natural settings (Ip, 2013). In one of the ponds there was a natural earthen partition. In the other two ponds, a steel frame with woven nylon mesh was used to create a partition. Each pond was thus divided into one experimental and one control plot (Fig. 3). The partition prevented snails from migrating to the other side and minimized water exchange between control and treatment plot. Four black carp were introduced into the treatment plot in each pond. The experiment lasted one year. Four individuals were recaptured from experimental plot 3, but only 2 individuals were recaptured from each of experimental plots 1 and 2. Black carp recaptured at the end of the experiment had grown substantially in length to 69.4 ± 2.2 cm (mean ± S.D.) and in weight to 3598.3 ± 250.1 g from a length of 0.2 ± 1.4 cm and weight of 235.8 ± 47.5 g at the beginning of the experiment. The fish were remarkably tolerant of poor water quality conditions, surviving through a period of low dissolved oxygen down to 1.2 mg l$^{-1}$ during the winter. They were effective predators of apple snails with shell length below 25 mm. The predatory effect was non-specific and caused significant reduction in populations of at least two species of native snails. No conclusion could be drawn with respect to the effect of the fish on macrophyte biomass and diversity nor on the water quality (nitrogen and phosphorous).
Conclusions

Overall, studies since the 1980s have shown that although only one species of apple snail (*P. canaliculata*) is present in Hong Kong, it has become widespread and caused dramatic changes to lowland agricultural and non-agricultural freshwater ecosystems.
In agricultural areas, it causes economic loss by feeding on semi-aquatic vegetables. In non-agricultural wetlands, it feeds on macrophytes, thus probably triggering changes in algal production. It may also prey on other macroinvertebrates and alter the faunal composition. Control of apple snails in agricultural areas relies on hand-picking and application of molluscicides. In non-agricultural wetlands, apple snails reduce macrophyte diversity in constructed wetlands. Current management of *P. canaliculata* in constructed wetlands mainly relies on hand-picking of adult snails and their egg masses, but bio-control using fish is being explored. Specifically, a one-year field experiment was conducted in three pairs of wetland ponds to test the effectiveness and non-target effects of black carp (Ip, 2013), which showed that black carp is a non-specific bio-control agent for freshwater molluscs. It could only be used in shallow wetland ponds with low biodiversity of macro-invertebrates, where reducing apple snail abundance and maintaining high macrophyte diversity are of management concern. However, current findings were inconclusive regarding whether controlling apple snail population density could indirectly improve water quality in constructed wetlands.

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