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REVIEW

Recent Range Expansion of Apple Snails in East Asia and Novel Countermeasures

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Abstract

Some species of apple snail, genus *Pomacea*, as represented by *P. canaliculata* (Lamarck 1822), are serious invasive freshwater snails worldwide. These snails have threatened rice production in East Asia since their introduction in the 1980s. After the development and spread of countermeasures such as molluscicide application, crop rotation, rotary tillage, and the use of natural enemies, the level of injury caused to rice by the snails eventually settled. However, after about 2010, snail infestations became serious again, due to increments in population density in invaded areas and range expansion of populations to new areas because of recent climate change: warmer winters have resulted in the expansion of the snail's overwintering areas and better survival in winter; and higher temperatures in the rice transplanting season (spring to early summer) have activated the snails in rice paddies. The recently developed method of detecting apple snail invasions early from environmental DNA is effective in preventing the snails from localizing in new habitats. To mitigate rice damage, new control concepts, such as trapping snails using long-lasting attractants and applying molluscicides efficiently using climate data and drones, together with conventional countermeasures, should be of practical use.

Discipline: Agricultural Environment
Additional key words: freshwater, global warming, invasive alien species, mollusk, rice

Introduction

The genus *Pomacea* is a group of freshwater apple snails distributed initially across a wide range from the southern parts of North America to the central parts of South America (Hayes et al. 2015). Some species of this genus are known as invasive alien species worldwide. In particular, *P. canaliculata* is one of the most serious and is on the list of the world's 100 worst invasive alien species (Lowe et al. 2000). The snail was introduced as human food into East and Southeast Asia from its native range in Argentina in the 1980s (Hayes et al. 2008) and has since become a troublesome pest of rice, taro, and other aquatic crops (Joshi et al. 2017) (Fig. 1).

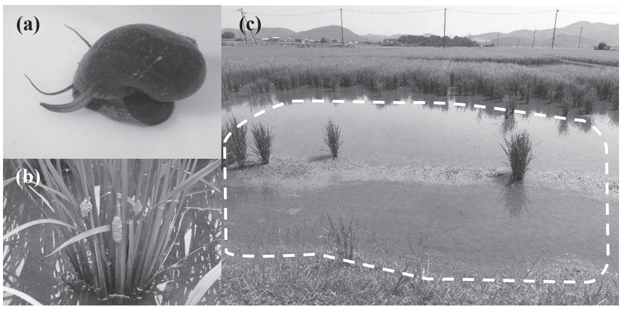

Fig. 1. (a) Adult and (b) egg masses of *Pomacea canaliculata*, and (c) a rice paddy field in Japan seriously injured by *P. canaliculata*
Because the snails feed on young rice seedlings, few rice plants grow where large numbers of snails occur (area enclosed by dashed line).

In temperate East Asia, invasion and colonization by apple snails have been confirmed in China, South Korea, and Japan (Hayes et al. 2008). In addition, farmers in North Korea seem to use the snails for weed control (Nakagawa 2023), despite a lack of records of the invasion and distribution of apple snails there. In East Asia, *P.*

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canaliculata is the most common species among introduced and localized apple snails, while other invasive apple snails (*P. maculata* and hybrids between *P. canaliculata* and *P. maculata*) are occasionally found (Matsukura et al. 2013, Yang et al. 2018). In addition, *P. occulta* has been found across a wide range in southern China, although its native origin in South America is unknown (Yang & Yu 2019, Yang et al. 2019). Because of the snails' severe impacts on food production and aquatic ecosystems in this region, studies of countermeasures based on the snails' biology have been well documented and reviewed (e.g., Wada 2004, Joshi 2007). The apple snails attack young rice shortly after transplantation in the paddy field. Therefore, snail control at transplanting and following the young rice stage by applying chemical molluscicides effectively prevents damage (Litsinger & Estano 1993). Decreasing the snail density by crop rotation (Wada et al. 2004), rotary tillage during winter (Takahashi et al. 2002), and using natural enemies (Yamanishi et al. 2012) are also effective. The spread of these countermeasures initially helped to mitigate the damage caused by the apple snails in East Asia.

Since about 2010, however, the damage caused to rice by apple snails in East Asia has again become serious. Not only has it escalated in areas already invaded by the snails, but there have also been outbreaks in new places where the snails have not previously been found. In this review, I describe the recent range expansion of the apple snails in East Asia, discuss the ecological factors affecting the range expansion, and introduce recently developed approaches for controlling the apple snails in the current situation.

Recent changes in the occurrence of apple snails in East Asia

1. Range expansion

Northward dispersal of the apple snails in and after the 2010s was observed in East Asia. In China, they were found in limited areas of the south and southeast, mainly from Hainan Province to the southern part of Jiangsu Province, until the mid-2010s (Lv et al. 2011, Yang et al. 2018). However, both *P. canaliculata* and *P. maculata* (or perhaps a hybrid with *P. canaliculata*) were found in the middle of Jiangsu Province (Sihong County, Suqian City) in 2020 (Pu et al. 2023) and in Shandong Province (Yanzhou County, Jining City) in 2021 (Wang et al. 2022), indicating that *Pomacea* species have spread north across the Qinling-Huaihe river line, which is generally considered to be the North-South geographic boundary of China. These newly established populations share mitochondrial *COI* sequences with other Asian populations (Pu et al. 2023). This suggests that the northern boundary of the distribution areas of apple snails in eastern China is shifting from south (~31° N) to north (~35° N) due to domestic transportation.

Recent range expansion has also been observed in Japan. After the apple snail was introduced into Japan in 1981, it immediately spread to the western and central regions of the country by humans, who tried to grow them to eat (Mochida 1991). The northernmost prefectures where *P. canaliculata* could overwinter were Ibaraki and Tochigi prefectures (~36° N) at the end of the 1980s, and this remains the case today (Matsukura 2019). Nevertheless, the distribution range of the apple snails is expanding locally within each prefecture. Wada (2015) reported the presence or absence of apple snails in 2012 in municipal units on western Honshu. The presence/absence map of the apple snails reported by Ishida (2020) for 2017-2019 showed further range expansion in some local cities over a 5- to 7-year period in the mid to late 2010s. According to Ishida (2020), apple snail distribution was recently reported on northern Awaji Island, in inland Hyogo Prefecture (in the town of Sayo), and in southern Kyoto Prefecture (in the cities of Kyotanabe and Kizugawa and the town of Seika). A similar trend was observed in Chiba Prefecture, which lies close to the current northern boundary of the apple snail in Japan. In this prefecture, numbers in infested paddy fields increased from the early 2000s to the early 2010s (Matsushita 2012).

Unlike in China and Japan, *P. canaliculata* has already been found in most regions of South Korea because farmers release the snails into their paddy fields as a popular way of weed control in eco-friendly rice production (Lee & Park 2020). Because of the severe winter climate, the snail can overwinter only in the central and southern parts of South Korea (Bae et al. 2012). The northern boundary of *P. canaliculata* overwintering gradually expanded from south to north in the 2000s, but it has not changed significantly in the past decade (Lee et al. 2019).

2. Increased population density in rice paddies in Japan

An increase in the snail density in paddy fields, particularly at the early cropping stage, is a significant cause of severe damage to rice (Wada 2004, Joshi et al. 2017). After about 2020, the damage caused to rice by *P. canaliculata* intensified over a wide range of Japan, where the apple snails had already been localized (NARO 2022). In fact, in and after 2017, four prefectural governments issued five notices on the emergence of *P. canaliculata* (Table 1). These notices are issued by pest

Table 1. Notices issued by the pest forecasting services of prefectural governments in Japan on the emergence of *Pomacea canaliculata*

Year	Prefecture	Snail density in paddy fields (/m^2)	
		this year	normal year[a]
2017	Chiba	0.17	0.09
2018	Okinawa	3	0.3
2019	Chiba	0.53	0.1
2019	Miyazaki	1.7	0.4
2024	Saga	6.8	2.1

[a] Average density over the previous several (usually ten) years

forecasting services under the Plant Protection Act of Japan when there is concern about severe damage to crops and vegetables by disease and insect pests. All five notices alerted farmers to snail densities several times higher in paddy fields than in previous years. The notice issued by Chiba Prefecture in 2017 was the first notice of a *P. canaliculata* outbreak issued in Japan in the 21st century.

The intensified occurrence of *P. canaliculata* in Japan is also suggested by the increased demand for chemical molluscicides. According to annual pesticide directories for Japan, published annually by the Japan Plant Protection Association (the 2024 edition being the latest), the total shipped amount of molluscicides specialized for use on *P. canaliculata* reached 1,200 t in 2022 (Fig. 2), almost double the amount in 2018 and approximately six times that in 2008, when the first molluscicides specialized for *P. canaliculata* entered the Japanese market. The increases in pest notice and pesticide use imply increased occurrence of *P. canaliculata* in Japan in recent years.

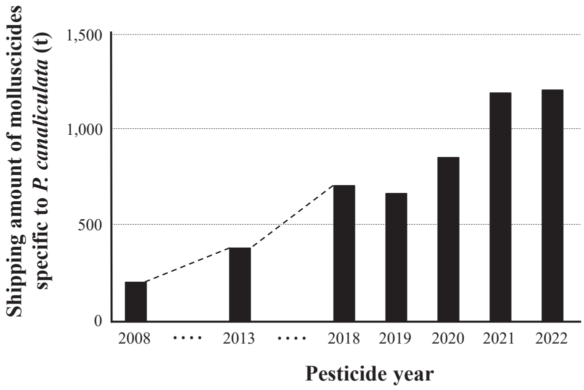

Fig. 2. Annual changes in the total shipping amounts of molluscicides used specifically to control *Pomacea canaliculata* in Japan
Data are the sums of shipping amounts of products that contain metaldehyde, thiocyclam hydrogen oxalate, or ferric phosphate and that can be applied to rice paddy fields to control *P. canaliculata*. The data were obtained from annual directories of pesticides in Japan, published by the Japan Plant Protection Association. Pesticide year indicates the period from October of the previous year to September of the current year (e.g., pesticide year 2022 covered October 2021 to September 2022); 2008 was the first year when a molluscicide specialized for *P. canaliculata* entered the market in Japan.

Factors influencing the recent range expansion and outbreaks

1. Range expansion due to warm winters

Apple snails—particularly *P. canaliculata*—can adapt to a variety of abiotic stresses, such as low temperatures (Matsukura et al. 2009), high temperatures (Seuffert et al. 2010), desiccation (Yoshida et al. 2014), and salinity (Bernatis et al. 2016). This biological plasticity under adverse conditions seems to have promoted the successful colonization of non-native ranges by invasive apple snails (Yang et al. 2023). In East Asia, the most marked environmental change causing the recent range expansion of *P. canaliculata* is the warming of winters. The annual mean temperature in East Asia increased by ~1°C during the first 20 years of the 21st century (World Meteorological Organization 2024), and an increased winter temperature is a primary determinant of the successful localization of invasive apple snails in temperate regions (Matsukura et al. 2016). The findings of several numerical model studies support the positive relationship between winter temperatures and the overwintering success of the snails. For example, Yoshida et al. (2022) developed a logistic regression model to estimate the overwintering risk of *P. canaliculata* based on the cumulative low temperature below 10°C. In this model, the probability, *y*, of overwintering success of the *P. canaliculata* population is calculated by

$$y = \frac{1}{1 + e^{-4.7931474 + 0.007574x}}$$

where x is the cumulative low temperature below 10°C (CLT10) from November to March. If CLT10 is ≥ 815.8 (i.e., if the winter temperatures are severe), then the overwintering success of *P. canaliculata* is < 20% (i.e., $y < 20$). On the other hand, when CLT10 < 449.7, the overwintering probability is ≥ 80% (Fig. 3).

The numerical models were used not only to confirm the ecological linkage between winter climate and the distribution range of apple snails, but also to estimate the potential risk of invasion in the future. Many of these

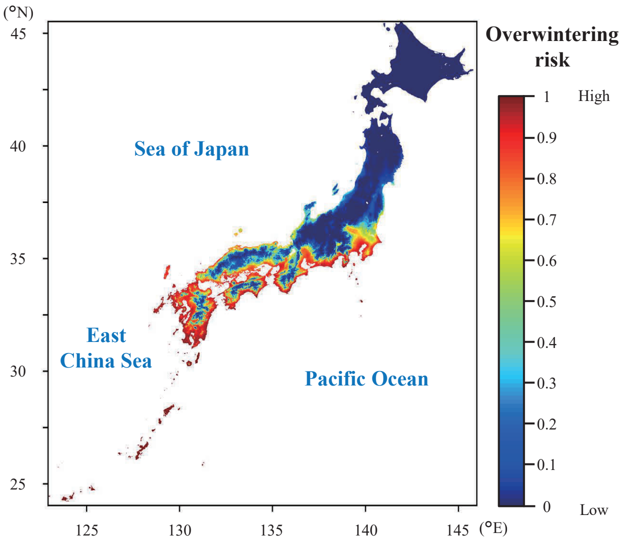

Fig. 3. Overwintering risk of *Pomacea canaliculata* in Japan, based on cumulative low temperatures during winter

The map was generated using a logistic model proposed by Yoshida et al. (2022) and 1 × 1 km geographical grid square climate data for all of Japan (averages of five winter seasons from 2019 to 2023), provided by the Agro-Meteorological Grid Square Data System operated by the National Agriculture and Food Research Organization.

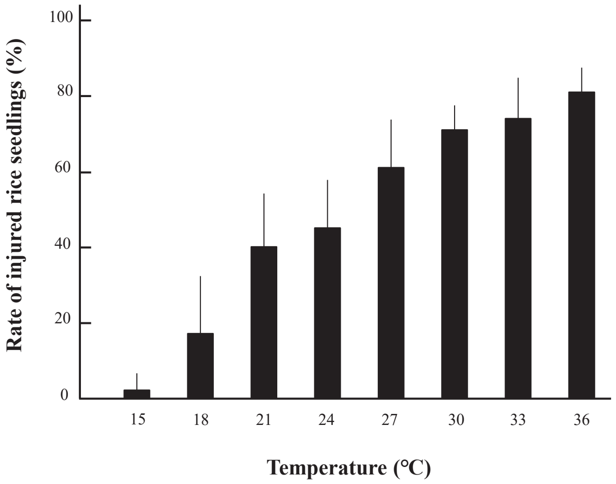

Fig. 4. Effects of temperature on the percentage of rice seedlings injured by the feeding of juvenile *Pomacea canaliculata*

For each temperature condition, 10 juveniles were released onto 20 rice seedlings (~150 mm high) transplanted into a small plastic container filled with andosol and tap water. The number of injured and intact rice seedlings were counted 24 h after snail release. There were five replicates for each temperature. Vertical lines indicate one standard deviation. Data were originally reported by Matsukura and Yoshida (2023).

models predicted that the distribution range of *P. canaliculata* in temperate regions will expand as global warming becomes more serious (Lei et al. 2017, Yang et al. 2023). In contrast, the areas suitable for *P. canaliculata* may contract in other regions, such as South America, Africa, and Australia (Seuffert & Martín 2024).

2. Climate-change-related outbreaks in rice paddy fields

Warm winters have also resulted in better survival of overwintering *P. canaliculata* in rice paddy fields. The majority of overwintering *P. canaliculata* in drained rice paddies in Japan are juveniles with shell height < 20 mm (Yoshida et al. 2009), whereas even adults with shell height > 50 mm can overwinter in irrigation canals adjacent to rice paddies (Yoshida et al. 2016). Because the overwintering mortality of juveniles in drained rice fields is significantly correlated with CLT10 (Syobu et al. 2001), high temperatures in winter cause the emergence of large numbers of overwintered juveniles and subsequently lead to snail outbreaks the following year.

Besides high temperatures in winter, increased temperatures in the transplanting season promote rice damage by *P. canaliculata*. This snail grows and reproduces well at water temperatures from 25°C to 30°C; some can survive for more than 60 days at 35°C (Seuffert & Martín 2017). This aptitude for high temperatures can also be observed in feeding efficiency. Juveniles of *P. canaliculata* and *P. maculata* can feed on and damage increasing numbers of rice seedlings as temperatures increase in the range between 15°C and 36°C (Matsukura & Yoshida 2023) (Fig. 4). Both increased overwintering rates due to high temperatures in winter and the appearance of more active snails due to high temperatures at transplanting (from spring to early summer) seem to have caused the recent critical damage by *P. canaliculata* to rice in East Asia.

Novel approaches to snail control

The recent range expansion and outbreaks of *P. canaliculata* in Japan require novel countermeasures. Here, I discuss four novel methods for efficiently detecting and controlling *P. canaliculata* in freshwater ecosystems, including rice paddies.

1. Detection of apple snails by using environmental DNA (eDNA)

Early detection of apple snail invasion of new sites is important to prevent the snails from reproducing and localizing. In most cases, apple snail invasion has been recognized by the presence of egg masses laid on water plants and on artifacts such as piers and walls along waterways. However, this detection is not early enough, because the presence of egg masses indicates the start of reproduction of the invasive population. For earlier snail detection, molecular detection methods using environmental DNA (eDNA) have been developed (Banerjee et al. 2022). Monitoring species-specific eDNA is a popular approach to examining species distribution and abundance, particularly in aquatic ecosystems (Rees et al. 2014). By designing freshwater snail-species-specific primers for a target region, Zhou et al. (2024) detected the eDNA of *P. canaliculata* in Poyang Lake in China, where a traditional collecting method could not detect the snail. This result suggests that the detection ability of eDNA is superior to traditional monitoring, although false-positive factors, such as nonspecific DNA amplification and the entry of snail DNA from external sources, need to be considered.

2. Traps and attractants

Traps to collect apple snails in the field have been proposed since the 1990s (Ichinose et al. 1998) but have not been used in practice. The reason for this is the absence of appropriate attractants that last longer than several days: young rice plants are attacked by the snails in the first two weeks after transplantation. Yoshida et al. (2021) found that traps with a mixture of rice bran, rice *koji* (fermented grains), and carp feed in a 1:1:1 ratio as a bait attracted a higher rate of *P. canaliculata* (> 300 snails per week・trap) than did these individual components in a rice paddy field. The mixture was effective for an extended period (~7 days in summer), probably because the rice malt slowed the progress of decay. Kitano et al. (2023) reported that more than half of all rice seedlings were saved from damage, even at high rates of snail occurrence (20 snails/m^2), by installing traps with attractants in the transplanting season.

3. Molluscicide application at optimal timing

Molluscicide application at the young rice stage is a direct and important way to relieve damage to rice (Litsinger & Estano 1993). Farmers usually apply molluscicides such as metaldehyde, thiocyclam hydrogen oxalate, or ferric phosphate when rice seedlings are transplanted. Molluscicide application with this timing often leads to decreased effectiveness, particularly in regions where the temperatures in the transplanting season are not high enough for the snails to be active (NARO 2022). Metaldehyde and ferric phosphate are bait-type molluscicides; they are therefore not effective on hibernating snails and are decomposed in the water about two weeks after their application, regardless of the status of the apple snails. Increased temperatures after the disappearance of the molluscicides cause snail activation and subsequent damage to rice.

To maximize the efficiency of molluscicides, they should be applied when it is warm enough for the snails to be active (Fig. 5). The threshold water temperature for *P. canaliculata* activity is about 15°C. For example, half of the snails in one study were active at 13°C to 15°C (Seuffert et al. 2010), and the snails rarely feed on rice seedlings at 15°C (Matsukura & Yoshida 2023; Fig. 4). A field test showed that snails can be controlled successfully by applying molluscicides on the first day when the water temperature reaches 17°C after transplanting (NARO 2022).

4. Site-specific molluscicide application using drones

Another approach to maximizing the efficiency of molluscicides is site-specific application. Because the amount of damage to rice seedlings by *P. canaliculata* depends on the water depth in the paddy field (Ozawa et al. 1988, Wada et al. 1999), it is not necessary to apply molluscicides to the entire area of the paddy, which is usually uneven and has varied water depths. Guan et al.

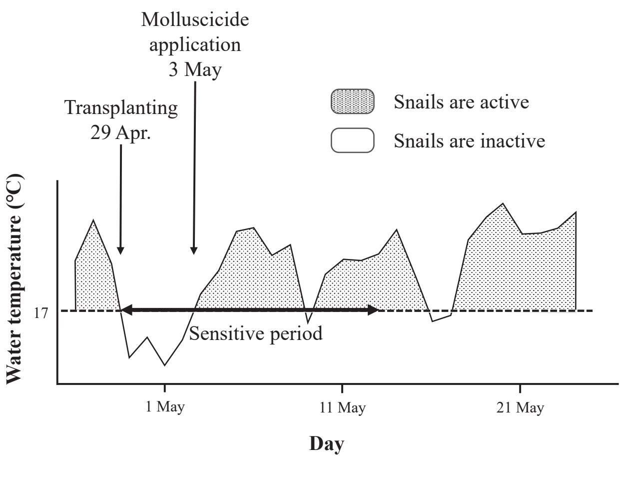

Fig. 5. Example for determining the optimal date of molluscicide application on the basis of water temperature

If molluscicide is applied on the day of transplanting (29 April), as is usual, the molluscicide will not work on the snails during the first 5 days from 29 April to 3 May, because snails rarely feed on the bait below 17°C. In this case, 3 May is the optimal day for application, because this is when many of the snails become active and start to attack the rice. Molluscicides applied at an appropriate timing should be able to cover all of the period when rice seedlings are sensitive to the snails (i.e., 2 weeks after transplanting in most cases in Japan).

(2023) developed a methodology for site-specific molluscicide application by drone. Before application, the variation in elevation within the target paddy field was estimated using high-resolution aerial imagery and a digital surface model. Based on the elevation map and a threshold water depth (4 cm), the drone automatically applies the molluscicide only to where rice damage can occur. This strategy is superior, saving labor and reducing the amount of chemical molluscicides used.

Conclusion and future directions

Recent climate change has promoted outbreaks of invasive apple snails—particularly *P. canaliculata*—in East Asia. These outbreaks consist of both range expansion into northern, colder areas and increments of population density in currently infested areas. Damage to rice is the most conspicuous impact of recent outbreaks (Table 1), although we also should pay attention to the potential impacts on native flora (Carlsson et al. 2004) and animals (Chaichana & Sumpan 2014).

Early detection of apple snails using eDNA is effective in preventing them from localizing to new habitats. In addition to conventional countermeasures to apple snails in rice paddies (e.g., Litsinger & Estano 1993, Takahashi et al. 2002, Wada 2004), the new control concepts mentioned in this review—trapping snails by using long-lasting attractants, and efficient molluscicide application by using climate data and drones—should mitigate damage to rice. From a broader perspective, understanding the process of invasion of the apple snails across East Asia and predicting the future risks brought by further climate change are important for better management of apple snails.

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