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Effects of Global Warming on the Distribution of Overwintering *Pomacea canaliculata* (Gastropoda: Ampullariidae) in Korea

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The golden apple snail, *Pomacea canaliculata*, is a freshwater snail native to tropical and subtropical South America. The species was introduced into Korea as a human food source in 1983 and was first applied as a weed control agent for the paddy fields in 1992. As the snail is well known as an environmentally friendly biological control agent for weeds, the area of cultivation in which the golden apple snail is used for biological control has been enlarged substantially each year. Currently, the species is observed in open water courses. It is possible that the snail may overwinter in these open water courses and may become a serious pest, as is already the case in many Asian countries. In this study, we determined the status of the overwintering golden apple snail based on a literature survey and investigated the potential distribution area of the snail, as a result from global warming in Korea. The potential distribution area of the overwintering golden apple snail would be enlarged under the influence of global warming; ranging from 45.5% of South Korea's land area in the 2020s to 88.4% in the 2080s.

Key words : golden apple snail, *Pomacea canaliculata*, global warming, prediction, temperature increase

INTRODUCTION

The golden apple snail, *Pomacea canaliculata* (Gastropoda: Ampullariidae, Lamarck, 1822) is a freshwater snail native to tropical and subtropical South America. It was initially introduced into Asian countries as a protein source (Halwart, 1994; Wada, 1999). However, the golden apple snail has become a serious agricultural pest, especially in young rice, in Asian countries (Hirai, 1988; Halwart, 1994; Lach *et al*., 2000; Teo, 2001; Lee *et al*., 2002) as a result of the escape of the snails into paddy fields. The first evidence that the golden apple snail feeds on rice was reported from Japan in 1984 (Hirai, 1989). As the area of distribution of the snail increased, the snail was observed in approximately 65,000 ha of paddy fields in Kyushu (Wada, 2004). For this reason, the Ministry of Agriculture, Forestry and Fisheries in Japan has designated the golden apple snail as an animal pest in the crop industry in the Plant

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Protection Act (Teo, 2001), and Taiwan has strictly prohibited the culture of the snail (Lee *et al*., 2002). Furthermore, numerous instances of damage to rice in paddy fields due to the vigorous feeding of the golden apple snail have been reported in Japan, Philippine, Brazil, Taiwan, Columbia, Bolivia and Venezuela (Tanzo and Barroga, 1989; Lee *et al*., 2002). The International Union for Conservation of Nature and Natural Resources (IUCN) has listed the golden apple snail as one of the 100 worst invaders worldwide (Bang and Cho, 2008).

The introduction of the golden apple snail in Korea is presumed to have occurred from Japan in 1981 (Rural Development Administration (RDA), 2004), and the snail was officially introduced in Asan, Chungcheongnam-do in Korea in 1983 as a human food source. The snail was applied as a weed control agent in paddy fields in 1992 (Lee *et al*., 2002). As the snail has been well known as an environmentally friendly biological control agent for weeds (e.g., weed removal rate: 98.6%) (Moon *et al*., 1997), the area of cultivation in which the golden apple snail is used has increased substantially each year (179 ha in farmland in 2000, 48,437 ha in farmland in 2007) (Lee *et al*., 2002).

When the golden apple snail was first used for weed control in paddy fields, it was considered unable to overwinter in Korea because it originated from a tropical area. However, the overwintering of the golden apple snail was observed in southern areas of South Korea (e.g., Haenam and Gangjin) as a result of acclimation to Korean weather conditions (Hwang *et al*., 2002; Lee *et al*., 2002; Kim *et al*., 2007). In addition, Lee *et al*. (2002) reported that golden apple snails that succeed in overwintering feed on young direct-seeded rice, resulting in serious problems in rice culture in Korea.

Temperature is one of the significant factors that determine the distribution of animal species in aquatic environments (Prosser and Heath, 1991). The distribution patterns of organisms are strongly related to maximum, minimum and mean temperatures, as well as to temperature fluctuations (Prosser and Heath, 1991). In addition, global warming influences the distribution and survival rate of intermediate hosts, causing changes in the maturation rate and the reproduction of parasites. For example, the golden apple snail represents a new suitable intermediate host for *Angiostrongylus cantonensis*, considered the primary cause of human eosinophilic meningitis (Nishimura *et al*., 1986). This development is possible because global warming provides opportunities for the snail, a stenothermal organism, to enlarge its potential habitat and colonize new habitats (Lv *et al*., 2006). However, to our knowledge, there is no research on the future distribution of the golden apple snail under a global warming scenario, especially in Korea. In this study, therefore, we aimed to determine the current status of the overwintering golden apple snail and the potential changes in its distribution caused by global warming in Korea.

MATERIALS AND METHODS

1. Ecological data

Data on the distribution of the golden apple snail were obtained from the literature (Table 1) (Hwang *et al*., 2001; Lee *et al*., 2002; Kim *et al*., 2007; Park, 2008; Seo *et al*., 2010). The distribution of the snail was initially monitored in Iksan, Jangseong and Haenam in Jeollanam-do in 2000 (Hwang *et al*., 2001), and the monitoring area was gradually enlarged in 2006 (total 75 sites) (Park, 2008). The samples reported in the literature were collected primarily in irrigation canals and ditches near paddy fields in conjunction with research on the use of the golden apple snail in environmentally friendly farming. Five to ten replicate samples were collected with a scoop net (30 cm in diameter) at each sampling site.

2. Temperature data

Surface air temperature data were obtained from the Korea Meteorological Administration (KMA, http://www.kma.go.kr). The output of the Hadley Centre climate model (HadGEM2-AO) was downscaled using HadGEM3-RA by the Korea Meteorological Research Institute (METRI) to produce a high-resolution (12.5 km) regional scenario based on the Representative Concentration Pathways 8.5 (RCP 8.5) scenario. The air temperature data were further downscaled to a 1 km scale to enhance the resolution of the regional scenario. The KMA provides monthly average air temperature data in a grid of 1 km $\times$ 1 km resolution for each year from 2010 to 2099. The water temperatures were calculated with a linear regression equation (*Water temperature* $=2.56+0.71$ *Air temperature*), following Morrill *et al*. (2005), who derived this equation from long-term data on 43 river sites in 13 countries.

The water temperatures tolerated by the golden apple snail have been reported to range between 2 and 38°C (Oya *et al*., 1986), although the thermal tolerance of the golden apple snail varies across different studies depending on the particular experimental conditions employed. Therefore, to evaluate the changes in the distribution of the snail caused by global warming, we estimated the potential distribution area in Korea on a nationwide scale and calculated the proportion (%) of the area represented by the potential distribution based on the annual water temperature in future decades (e.g., the 2020s, 2040s, 2060s and 2080s) according to the RCP 8.5 scenario. We defined the habitable area as the area showing water temperatures ranging between 2 °C (minimum annual mean temperature) and 38 °C (maximum annual mean temperature). The potential area for the distribution was calculated as follows:

$$\text{Potential distribution area (\%)} = \frac{\text{Area with water temperature between 2 and 38 (°C)}}{\text{Total area in Korea}} \times 100.$$

RESULTS AND DISCUSSION

The overwintering area increased after the introduction of the golden apple snail into Korea in 1981 (Hwang *et al*., 2001; Lee *et al*., 2002; Kim *et al*., 2007; Park, 2008; Seo *et al*., 2010) (Table 1, Fig. 1). The snail was observed to overwinter in 20 of the 75 sampling sites examined. Lee *et al*., (2002) suggested a possible overwintering temperature (−2°C) and an expected overwintering temperature (−4°C) based on the minimum air temperature data of their study sites where the golden apple snails were found. According to the two types of temperature limits given by Lee *et al*. (2002), the overwintering of the golden apple snail was only possible in southern parts of Korea, including Gwangju, Mokpo and Busan. How-

Table 1. Meteorological variables in the areas where overwintering golden apple snails were observed in Korea, based on the literature (Hwang *et al*., 2001; Lee *et al*., 2002; Kim *et al*., 2007; Park, 2008; Seo *et al*., 2010). Temperature and precipitation values are based on 10 years of data, from 2001 to 2010, provided by the Korea Meteorological Agency.

Location	Sampled year	Altitude (m)	Mean_T* (°C)	Max_T** (°C)	Min_T*** (°C)	Precipitation (mm)
Chungcheongnam-do						
Janghang, Seocheon	2001	165	10.5	29.2	−8.1	12.47
Gyeongsangbuk-do						
Geumcheok-ri, Gyeongju	2003～2004	74	13.3	30.8	−4.5	9.73
Seongdong-ri, Pohang	2004～2006	40	13.6	29.2	−2.5	12.50
Namgye-ri, Pohang	2004～2006	207	10.8	29.6	−8.5	10.06
Bonggye-ri, Seongju	2005	60	12.8	30.3	−6.4	10.14
Chogok-ri, Gumi	2003～2006	60	12.4	30.6	−6.8	9.06
Geumnam-ri, Chilgok	2004～2006	32	13.3	31.1	−5.0	9.85
Dujeon-ri, Yeongju	2006	140	11.6	30.1	−8.1	10.10
Jugam-ri, Sangju	2003～2004, 2006	60	12.4	30.7	−6.6	8.98
Gyeongsangnam-do						
Daedong, Gimhae	2006	69	14.5	29.7	−1.7	12.70
Galjeon-ri, Changwon	2004～2006	17	14.3	31.3	−3.7	11.08
Yerim-ri, Miryang	2006	10	13.5	31.2	−5.0	10.39
Jeon-ri, Sancheong	2003～2004, 2006	330	11.6	28.2	−5.5	15.56
Bu-ri, Sancheong	2003～2004, 2006	385	11.9	28.8	−5.3	14.98
Yeoui-ri, Hadong	2003～2004, 2006	73	13.8	30.8	−4.3	13.88
Jeollanam-do						
Damyang, Damyang	2004	60	13.2	30.5	−4.3	11.90
Beolgyo, Boseong	2004～2005	25	13.9	30.3	−2.4	13.13
Jeongjung-ri, Damyang	2005	40	13.4	31.2	−4.0	12.00
Sacho-ri, Gangjin	2005	20	13.7	29.8	−1.7	13.75
Haenam	2000～2001, 2004～2005	44	13.4	30.2	−2.7	11.30

*: Average air temperature; **: Maximum air temperature; ***: Minimum air temperature

ever, overwintering individuals have been found from southern to northern parts of Korea, including Haenam and Jeollanam-do in 2000, Chungcheongnam-do (2001), Gyeongsangnam-do (2003), Gyeongsangbuk-do (2004) and Gangwon-do (2005) (Table 1, Fig. 1).

In contrast to the endemic freshwater snail fauna, the golden apple snail is a macrophytophagous generalist, feeding on a wide range of aquatic macrophytes (Howells, 2002). The snails feed vigorously on aquatic macrophytic vegetation, and a dense population can completely consume aquatic macrophyte plant communities within a short time (Lach *et al*., 2000). An invasion of the golden apple snail can cause the complete disruption of an aquatic plant community, changing a plant-dominated, clear-water state to a turbid, algae-dominated area (Carlsson *et al*., 2004). In addition, the reduced biodiversity and biomass of the aquatic plants influence the nutrient retention capacity of the wetland. These findings show that grazing on macrophytes by the golden apple snail changes the function of the wetland ecosystem, as well as the ecosystem service value produced by the wetland.

The potential area of distribution of the golden apple snail would increase toward the northern parts of Korea under the influence of global warming (Fig. 2). The possible overwintering area would increase from 45.5% of South Korea in the 2020s to 88.4% in the 2080s (Fig. 3). The invasion of exotic species is one of the major threats to global biodiversity (Buchan and Padilla, 1999; Chapin *et al*., 2000; Kolar and Lodge, 2000; Sala *et al*., 2000; Strayer, 2001). Although the golden apple snail is found at very low densities in its native South America due to high predation pressures, efficient native predators are rare in Southeast Asia, resulting an increase in snail populations. In contrast to the native apple snail, the golden apple snails produce eggs by spawning. Mass propagation is relatively easy, and the emergence rate is high (95.8%) (Teo, 2004). The golden apple snail has

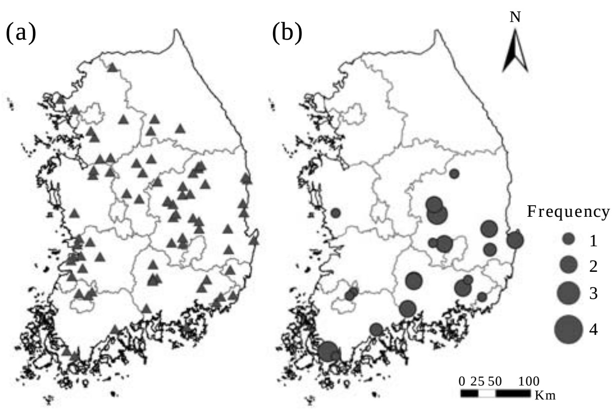

Fig. 1. The distribution of overwintering golden apple snails in irrigation canals and ditches near paddy fields surveyed from 2001 to 2006, based on the literature (Hwang *et al*., 2001; Lee *et al*., 2002; Kim *et al*., 2007; Park, 2008; Seo *et al*., 2010). (a) Sampling sites, (b) sampling sites where the overwintering individuals were found. Frequency indicates the number of times observed in the literatures at each site.

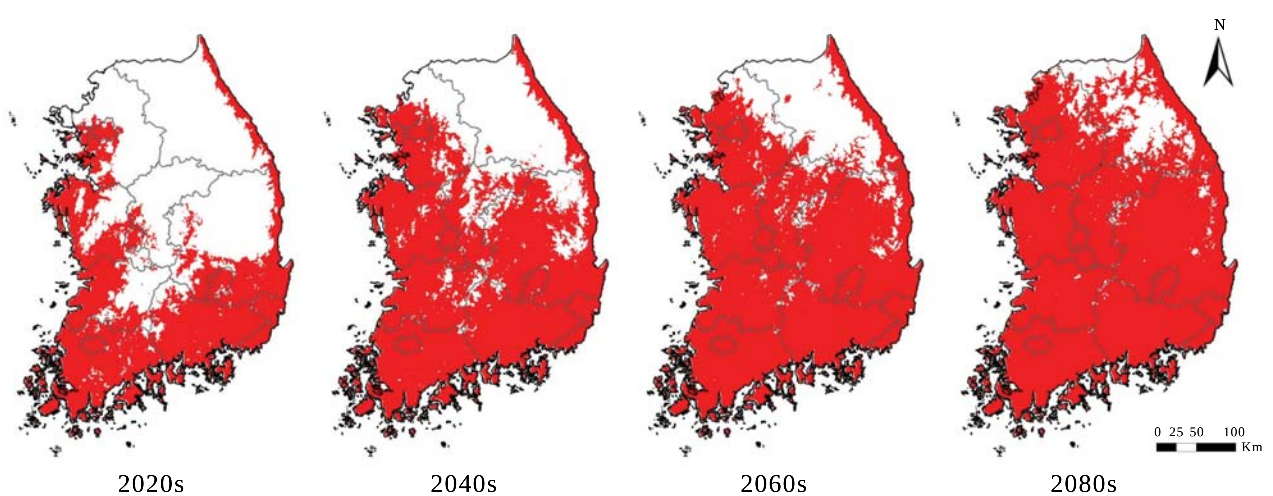

Fig. 2. The changes in the potential distribution area of the golden apple snail in Korea in different decades based on the RCP 8.5 scenario.

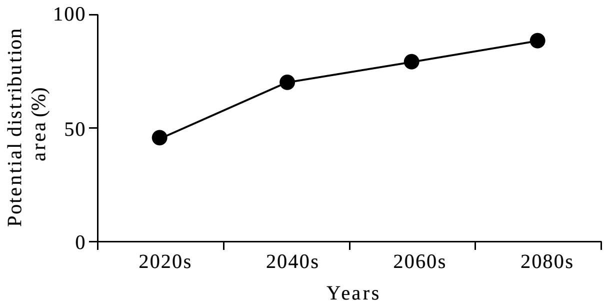

Fig. 3. The changes in the percentage of the potential distribution area in Korea in different decades based on the RCP 8.5 scenario.

already been naturalized in several Asian countries as a pest in paddy fields (Naylor, 1996). Similarly, it may become localized as a serious pest in Korea, and the expanded range of the golden apple snail caused by global warming could have serious effects on rice production. According to the United Nations Food and Agriculture Organization (2004), the economic losses caused by the golden apple snail in the Philippines are approximately 100 million US dollars. In addition, the USA has spent 10 billion US dollars on golden apple snail control (RDA, 2004).

However, it is difficult to prohibit the use of the golden apple snail in environmentally friendly farming in Korea. In addition, the Korean government, along with local governments, has recommended the use of the golden apple snail for weed control in paddy fields. For this reason, it is expected that the number of farms applying the golden apple snail in their paddy fields will tend to increase. In this sense, the control and management of the golden apple snail should be stressed to reduce the dispersal of the snail (Lee *et al*., 2002). Therefore, further studies are required to effectively control the escape of the snails from paddy fields to open water systems, as well as to understand the behavioral responses of the snails to temperature changes. In addition, it is important to strengthen both the education of farmers about the ecology of the golden apple snail and the interconnections between farmers and supervisory agencies such as the Rural Development Administration.

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