

The apple snail, *Pomacea canaliculata*: an evidence note on invasiveness and potential economic impacts for East Africa

Authors

Djamila Djeddour
Corin Pratt
Fernadis Makale
Ivan Rwomushana
Roger Day

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Djamila Djeddour, CABI UK, Bakeham Lane, Egham, Surrey, TW20 9TY, United Kingdom.
Email: d.djeddour@cabi.org; ORCID: <https://orcid.org/0000-0002-1421-4101>

Corin Pratt, CABI, CABI UK, Bakeham Lane, Egham, Surrey, TW20 9TY, United Kingdom.
Email: c.pratt@cabi.org; ORCID: <https://orcid.org/0000-0001-8070-7302>

Fernadis Makale, CABI, Canary Bird, 673 Limuru Road, Muthaiga, PO Box 633-00621, Nairobi, Kenya. Email: f.makale@cabi.org; ORCID: <https://orcid.org/0000-0002-6454-7705>

Ivan Rwomushana, CABI, Canary Bird, 673 Limuru Road, Muthaiga, PO Box 633-00621, Nairobi, Kenya. Email: I.Rwomushana@cabi.org; ORCID: <https://orcid.org/0000-0001-5840-8058>

Roger Day, CABI, Canary Bird, Muthaiga, PO Box 633-00621 Nairobi, Kenya.
Email: r.day@cabi.org; ORCID: <https://orcid.org/0000-0002-4854-7609>

Cover photo: *Pomacea canaliculata* feeding on rice plants, Mwea Irrigation Scheme, Kenya. Credit: Fernadis Makale, CABI.

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Abstract

The South American freshwater apple snail, *Pomacea canaliculata* (Lamarck) has been introduced and become invasive in many parts of the world, causing significant economic losses in wetland rice cultivation, threatening biodiversity and impacting on human health. The confirmed report in 2020 of this snail species damaging rice crops in Mwea, the most important irrigation scheme in Kenya, represents a new introduction to continental Africa and brings into focus the need for a rapid and coordinated response to contain and mitigate the risk to other rice schemes, as well as neighbouring countries. This evidence note provides a review of the global invasive spread of *P. canaliculata*, its biology and ecological adaptability and assesses the risks and potential economic/yield losses for sub-Saharan African rice production over the next decade under different control scenarios. Given the strategic importance of rice production in the region, the potential impacts on food security and farmer income could be considerable. Monitoring, sustainable management and good agricultural practice recommendations are synthesized from established global resources and information is collated to support preparatory action and rapid response. Given the relatively localized distribution of the snail in Kenya, the implementation of a coordinated snail containment and eradication plan is urgently called for, underpinned by countrywide awareness raising, education and outreach to facilitate community-based vigilance and management.

Executive summary

Background

Invasive apple snails commonly referred to as 'golden apple snails' (GAS), belonging to the genus *Pomacea* pose major economic, environmental and health problems across many parts of the world. They have been widely introduced, either intentionally, as a human food resource, through the aquarium trade as a domestic snail pet or for aquatic weed control in both natural wetlands and irrigated rice, or accidentally, through water systems and as trade contaminants. *Pomacea canaliculata* (Lamarck), widely regarded as the most devastating of these pest species, has been identified from Kenyan rice paddies, the first record for mainland Africa. This evidence note provides a summary of knowledge about the invasive apple snail, its impacts and a synthesis of options for management from other affected countries. It is imperative that ecologically and economically sustainable approaches are put into practice for the integrated control of this destructive invasive mollusc species in Kenya, together with the implementation of effective quarantine and contingency measures, to avoid further spread to vulnerable areas of the country and neighbouring rice-growing countries.

Strategic importance of rice

Rice has been identified as a crucial strategic crop for food security, income generation and nutrition in Kenya. The government has elaborated National Rice Development Strategies to guide and grow the promotion of the rice subsector, focusing on procedures that will enhance rice-production areas in order to achieve self-sufficiency and reduce the need for costly imports. Kenya's policy makers will need to acknowledge and act rapidly to mitigate the potential constraints to enhanced domestic rice production that invasions of *P. canaliculata* could entail.

Invasive apple snail life cycle and crop damage

Invasive apple snails have a high reproductive output, fast growth rate and an ability to rapidly adapt to ambient conditions, threats from predators and other mortality factors. Combined with a high plasticity in life cycle, these characteristics allow snail populations to survive environmental perturbations and to rapidly build up numbers, with management pressures leading to adaptation and avoidance. Snails are macrophytophagous but feed voraciously and indiscriminately in the absence of their preferred plants. Staple crops such as taro and rice, as well as other aquatic cultivated crops, suffer heavily from their destructive feeding, with young rice seedlings representing the most vulnerable stage. Entire fields can be lost, affecting smallholder farmer livelihoods in particular. Invasive apple snails also negatively impact wetland ecosystem functioning and human health as they are vectors for parasites such as rat lungworm and cause skin irritations.

Distribution and potential spread of invasive apple snail in East Africa

Invasive apple snails are naturally distributed in tropical and subtropical freshwater ecosystems globally, but the genus *Pomacea* is endemic to South and Central America. *P. canaliculata* is able to reproduce continuously, reaches maturity sooner, can complete more generations per year and maintain high populations of juvenile and mature snails year-round in tropical regions. Climate modelling of the current and potential geographic range and performance of *Pomacea* snails in different locations indicates that many of the rice-producing areas of eastern Africa (and SSA more broadly) are likely to be under threat, including all areas of Tanzania, the major producer in the region. Climate change will undoubtedly

contribute to wider establishment and colonization, with potential ‘hot spots’ for higher population density. Higher resolution modelling of population dynamics for those areas of Africa which may be at risk would be valuable and would facilitate potential crop loss estimates as well as informing management priorities and biosecurity measures.

Potential economic impacts of invasive apple snail in East Africa

Invasive apple snails will damage most aquatic crops, including taro, but it is for their impact on rice crops that they have gained notoriety around the world. Examples from Asia indicate that once present, *Pomacea* can spread rapidly (particularly if facilitated by intentional movement), and entry into waterways and irrigation systems results in widespread infestation of rice paddies. Mwea is the primary rice-growing area in Kenya and in this region alone, *P. canaliculata* has the potential to affect approximately 80% of Kenya’s rice production. Present and near-term losses are likely to be important, as *P. canaliculata* has a foothold and is already affecting production, but without efforts to manage populations and contain the snail’s spread, future losses across the region to rice and other host crops could be much greater. Were *P. canaliculata* to spread across the region to infest rice in parts of Tanzania, Uganda and Ethiopia in addition to Kenya, annual production losses of US\$122 million could be feasible within a decade of arrival without control measures. Even with control measures, regional losses of US\$67–116 million/year could be possible if the snail is not contained.

Management of invasive apple snail

The primary management approach for invasive apple snails must be prevention since eradication of established populations is very difficult. Strict quarantine must be enforced to prevent introduction and spread and if detected, snails must be contained and eradicated rapidly while it is still possible to do this. Attempts at management elsewhere include use of pesticides, with serious environmental and human health consequences; biological control, notably the use of fish and ducks; and a range of cultural and mechanical/physical control measures. None has proven entirely effective, safe, or economically viable and when used in isolation, they often only provide short-term solutions. Control approaches aim to either: i) reduce snail damage to the rice crop by reducing its vulnerability and impairing snail movement; or (ii) focus on reducing snail population density manually, mechanically, chemically or through biocontrol. Once snails are established, however, the best approaches tend to combine several techniques. Raising awareness of the threat among smallholders and implementing a coordinated and rapid response plan should form a crucial part of any management strategy, with community effort at its core.

Invasive apple snail advice and information

The Kenya Plant Health Inspectorate Service (KEPHIS) has outlined plans to work with stakeholders in the management of *P. canaliculata*. The stakeholders include the Kirinyaga County government, Ministry of Agriculture, National Irrigation Authority, Pest Control Products Board (PCPB), Kenya Agricultural & Livestock Research Organization (KALRO), Mwea Irrigation Agricultural Development (MIAD), National Government Administration Officers (NGAO), Water Resources Management Authority (WARMA), National Environment Management Authority (NEMA), Department of Public Health, the Presidential Delivery Unit, CABI, the International Centre of Insect Physiology and Ecology (ICIPE) and the University of Nairobi. This forms a multi-institutional technical team (MITT).

Recommendations

In light of the confirmed report of an established population of *P. canaliculata* in Kenya, (first record for continental Africa), the following recommendations are proposed for a range of stakeholders. In the absence of effective containment and sustainable management options, spread to other rice-growing regions of Kenya and neighbouring countries is highly likely. For countries which are free of snails, identifying potential introduction pathways, developing risk assessments, implementing a clean certification scheme for traded plants from contaminated areas and elaborating rapid response plans for new incursions will be important to help mitigate impact.

High-level policy makers:

- Determine the magnitude of the invasive apple snail threat (present and potential) and make policy decisions, backed by available economic estimates and science-based evidence.
- Lobby for budgetary allocation to facilitate an immediate, official national response backed by policy and legislation to enable coordinated (potentially mandatory) contingency action to contain and eliminate the invasive apple snail at the earliest opportunity.
- Outline a clear structure and division of responsibility between competent authorities for the development, implementation and support of eradication/containment measures in Kenya.
- Provide countrywide support for invasive apple snail ecology-based control and farmer/agency education and outreach by establishing a technical working group to spearhead management efforts.
- Make informed, science-based decisions at national level to protect biodiversity, consumers and trade from abuse and misuse of pesticides.

Regulators:

- Identify pathways for entry and spread of the invasive apple snail to vulnerable areas and contain/quarantine affected areas.
- Ensure awareness is raised to prevent further deliberate and accidental distribution of *P. canaliculata*.
- Organize regular and persistent monitoring schemes for snail egg masses and adults to inform rapid response and containment measures.
- Facilitate, promote and help fast-track registration of lower-risk 'green' products for snail management including biopesticides, botanicals, and the potential use of native natural enemies.

Researchers:

- Carry out countrywide distribution/delimiting, socio-economic and impact surveys to assess the extent of the problem.

- Investigate efficacy of native biocontrol agents and test locally available biopesticides and chemo-attractive baits and produce formulations that can maximize the toxic effect on adults and juveniles.
- No rice varieties are resistant to apple snails, but research into modern high-tillering plant types and more tolerant rice seedlings for transplanting can hold better potential to compensate for damage.

Advisory services:

- Communicate to farmers, using accessible and varied communication approaches, the negative impacts of indiscriminate pesticide use on their health and the environment.
- Consider efficacy, safety, sustainability, practicality, availability and cost-effectiveness when recommending control practices.
- Raise awareness (through media and pest alert flyers) and expand extension efforts to facilitate community-based management, coordinating immediate action if the invasive snail is detected.
- Promote good agricultural practice and low-risk, cost-effective options for management such as changes to planting patterns, water management, hand-picking, physical barriers and repellent plants.
- Develop an array of cost-effective, clear and harmonized monitoring protocols to be rolled out to smallholders.

Private farms:

- Follow good agricultural practice advice relating to sustained equipment hygiene, snail removal, alternative cropping systems and planting patterns (avoid ratooning postharvest), including managing water levels and crop establishment age.
- Maintain good records of agronomy, monitoring, interventions, yield, etc., and review regularly to determine the cost–benefit of the control methods used.
- Spraying of registered and crop-approved molluscicide should be based on an action threshold that takes into consideration the expected value of the crop, the expected loss if untreated, and the cost of treatment.
- Farm workers should use the proper personal protective equipment (PPE) when applying pesticides and use the suite of recommended agricultural and cultural practices to manage snail populations.
- Assess the efficacy of other lower-risk products, if available, and adopt for use.

Smallholder farmers:

- Engage with community extension, regulators, advisory and information services to obtain latest information on government-approved, recommended pesticide use and choose low-risk botanical options if available/affordable (e.g. repellent plants known to have toxic effect on snails across fields and canalettes).

- Engage with community extension, advisory and information services to obtain latest information on snail identification/life cycle and management.
- Engage in regular surveillance and monitoring for egg masses and adult snails on farms (use bamboo poles/attractants, locally available materials).
- Use a suite of management practices in combination to minimize damage (scouting, hand-picking, trapping, baiting, trenches, physical barriers, etc.), as part of routine, community management action.
- Follow good agricultural practice advice relating to hygiene protocols for equipment/machinery and alternative cropping systems and planting patterns, including managing water levels and crop establishment age (transplanted rice is less vulnerable than direct-seeded rice).

Acronyms and abbreviations

CAADP	Comprehensive Africa Agriculture Development Programme
CABI	CAB International (Centre for Agriculture & Biosciences International)
CARD	Coalition for African Rice Development
COVID-19	coronavirus disease 2019
DGIS	Directorate-General for International Cooperation
DOA	Department of Agriculture
EFSA	European Food Safety Authority
ETL	economic threshold level
EU	European Union
FSN	food security and nutrition
GAS	golden apple snail
ICIPE	International Centre of Insect Physiology and Ecology (<i>icipe</i>)
IPM	integrated pest management
IRRI	International Rice Research Institute
KALRO	Kenya Agricultural & Livestock Research Organization
KEPHIS	Kenya Plant Health Inspectorate Service
MIAD	Mwea Irrigation Agricultural Development
MITT	multi-institutional technical team
NEMA	National Environment Management Authority
NGAO	National Government Administration Officers
NIB	National Irrigation Board
NRDS	National Rice Development Strategy
PCPB	Pest Control Products Board
PPE	personal protective equipment
RD	recommended dose
SDM	species distribution model
SNNPR	Southern Nations, Nationalities, and Peoples' Region
SRI	System of Rice Intensification
SSA	Sub-Saharan Africa
WARMA	Water Resources Management Authority
WHO	World Health Organization
WHOPES	WHO Pesticide Evaluation Scheme
WPN	wettable powder of niclosamide ethanolamine salt

Introduction

The freshwater snail genus *Pomacea* (family: Ampullariidae) is native to South and Central America, parts of the Caribbean, and Southeastern USA. At least two species, *Pomacea canaliculata* (Lamarck) and *Pomacea maculata* Perry, have been spread intra- and inter-continently and are now widely established in many regions of the world. *P. canaliculata* is native to Argentina and Uruguay, while *P. maculata* is more widely distributed from the La Plata region of Argentina to the Amazon basin of Brazil, including Uruguay and Paraguay, and possibly Bolivia, Ecuador and Peru. These two species have commonly been referred to as 'golden apple snails' (GAS), often without clarifying specifically which species, perhaps both, was involved, or indeed simply assuming it to be *P. canaliculata* (Cowie *et al.*, 2017). They pose serious environmental and economic threats to wetlands and aquatic crops (Pimentel *et al.*, 2000; Cowie, 2002; Nghiem *et al.*, 2013). *Pomacea* species are also intermediate hosts for nematode parasites that can cause severe health problems in humans (Hollingsworth and Cowie, 2006; Levin *et al.*, 2006; Lv *et al.*, 2011; Vázquez-Silva *et al.*, 2011). *P. canaliculata* is a voracious generalist feeder, lacks natural enemies in the invaded range, has a high reproductive potential and a broad environmental adaptability (Lach *et al.*, 2000; Cowie, 2002) and is consequently regarded among the world's 100 worst invasive species (GISD, 2021), not least because of its impacts to paddy rice, especially across the Asian introduced range. Extensive documented evidence suggests that its capacity for damage to invaded wetland agricultural systems should not be underestimated, with annual global agricultural economic losses stated as ranging from US\$55 to US\$248 billion/year (R.E. Joshi, 2005). In the Philippines alone, estimates of cumulative economic losses associated with *P. canaliculata* ranged from US\$425 million to US\$1.18 billion by the mid-1990s (US\$860 million to US\$2.39 billion in 2021 values (US Bureau of Labor Statistics, 2021) since its first introduction in the early 1980s (Naylor, 1996).

Rice is an increasingly important staple food in many countries of Africa and constitutes a major part of the diet in many others. During the past three decades the crop has seen consistent increases in demand, with recognition of its potential to improve the rural lives of farming communities putting it at the forefront of strategic food-security planning policies for many countries.

The recent identification of *P. canaliculata* in Kenya (Buddie *et al.*, 2021) is the first record for mainland Africa and constitutes a clear and present threat to Africa's rice-growing regions. This evidence note therefore synthesizes global information about *P. canaliculata*, including a summary of the research and developments on control measures, estimations of potential losses to East Africa, and a distillation of recommendations for management and containment. This information should be of use for a wide range of stakeholders, including researchers, policy makers, donors and other high-level decision makers, to prioritize investment and interventions in responding to the continuing threat. This evidence note is structured into five sections as follows:

- **Section 1** reviews rice cultivation in Africa, the invasive apple snail impacts across rice-growing regions of the world and its potential establishment across East Africa.
- **Section 2** reviews the specific impacts on rice production around the world and projected economic losses for East Africa.
- **Section 3** reviews the control methods implemented across the world and provides a summary of pertinent recommendations for East Africa.
- **Section 4** summarizes the information, tools and advice sources available to stakeholders.
- **Section 5** summarizes recommendations for different stakeholders in Kenya (with relevance to neighbouring African countries).

1 Rice cultivation and the apple snail problem

1.1 History of rice production and trends in Africa

Rice (*Oryza sativa* L.) is one of the most important agricultural food crops for more than half of the world's population. It is grown in more than a hundred countries, with a total harvested area of approximately 158 million ha and an annual production of 512 million t in 2019 (milled basis), with year-on-year expansion predicting record highs for utilization in the next few years (FAO, 2020). Rice requires specific growing conditions to be successfully cultivated, it must be grown in several inches of water and once harvested, unprocessed rice is known as paddy rice. Asia represents 90% of global production and the area under rice represents 29% of the total output of grain crops worldwide, with Africa accounting for about 10–13% (Atera *et al.*, 2018).

The African continent has been experiencing a consistent increase in demand for rice. Over the last 30 years, rice has grown in popularity, to take first place on the list of fastest growing staple foods (Mohanty *et al.*, 2013), gradually shifting from consumption only during special events to replace yams, sweet potatoes and cassava in popularity. In certain countries like Tanzania, Nigeria and Niger this transformation is particularly evident and growth has been shown to have a direct link to the growing incomes, rapid urbanization rates, as well as population growth in many of the countries (Balasubramanian *et al.*, 2007; van Oort *et al.*, 2015).

Currently, rice is grown in over 75% of the 54 African countries and its territories, with a total population of nearly 800 million people depending on rice for their food and livelihoods (Atera *et al.*, 2018). Like Asian countries, almost all rice is grown in sub-Saharan Africa (SSA) is on small farms of 0.5–3 ha and across five main ecosystems, namely rainfed uplands, rainfed lowlands, inland swamps, irrigated ecosystem and mangrove swamps (Norman and Otoo, 2003). West Africa produced the largest share of rice (paddy) with an estimated 21 million t in 2019, compared to 3.8 million t in East Africa, 0.7 million t in Central Africa and 4.5 million t in southern Africa (excluding South Africa) (FAO, 2020). Becker and Johnson (2001) reported that nearly 90% of rice in Asia is grown under paddy-field conditions; in contrast, approximately 60% of rice in SSA is grown in upland ecosystems.

Over the last decade, the average annual growth rate of rice production on the continent was 10.1%. This increase was fuelled by an increase in rice areas (7.5%/year) rather than contributions from yield gains, possibly due to poor quality seed, poor adoption of improved varieties and lack of sound agricultural practices (Arouna *et al.*, 2017). Nigeria is currently the largest rice-producing country in Africa thanks in part to the conscientious efforts of government to place more emphasis on agrarian production rather than rely on oil, which had proved economically risky.

Tanzania is the most important rice-production zone in East Africa where agriculture is a top priority for economic development. Rice-growing areas have increased significantly due to governmental support and this has in turn reduced dependence on imported rice. In the past, farmers mostly focused on local rice varieties that had limited yields. A shift towards modern technology and improved varieties has also seen a marked increase in production levels. Government data shows that the milled rice production increased from 867,000 t in 2008/09 to 2,219,000 t in 2017/18. Although the domestic consumption also increased from 85,000 t to 1,789,517 t during the same period; the surplus production has put Tanzania as one of the first countries to achieve self-sufficiency in rice production in the region in recent decades. Rice varieties produced in Tanzania such as Supa and SARO-5 (generally referred as Tanzania rice) are extremely popular in markets in eastern and southern Africa (Rice for Africa, 2019). However, the rice yield gap can be high due to a combination of production constraints and suboptimal crop management (Senthilkumar *et al.*, 2018).

Almost 40% of the rice consumed in Africa is imported (Yamane, 2019), as the increase in production is not able to keep pace with the sharp increase in rice consumption (Soullier *et al.*, 2020). Despite many government drives towards self-sufficiency, the economic burden of imports remains high and many countries of the region, on average, allocate less than 5% of their budget to agriculture (Fontan Sers and Mughal, 2020). This is in spite of evidence of significant beneficial effects of public agricultural spending on food security for the countries which allocate greater proportions of their budgets to agriculture (Fontan Sers and Mughal, 2020).

Against this backdrop, the Coalition for African Rice Development (CARD) was established in 2008, led by a consultative group of international and African organizations and institutions which are prominent in rice development in Africa (Satoyama *et al.*, 2014). CARD aimed to double rice production in SSA, by providing countries with various supports for rice sector development. By building on existing structures, policies and programmes, such as the national agricultural research organization of Africa, the Africa Rice Center (AfricaRice), the Comprehensive Africa Agriculture Development Programme (CAADP) and the Africa Rice Initiative (ARI), CARD aimed to respond to the increasing importance of rice production in Africa. CARD Phase 2 started in 2019, with a renewed target of further doubling of rice production in SSA, from 28 million t to 56 million t for the next 12 years (by 2030). CARD supports its African member countries, including Kenya, by preparing their National Rice Development Strategy (NRDS) (Rice for Africa, 2021), through triannual workshops.

Rice production in Kenya dates back to 1907 when it was introduced from Asia by Europeans (Onyango, 2014). Rice is produced both under irrigation (involves continuous flooding) and upland conditions (Atera *et al.*, 2018). In Kenya, rice is mainly produced under irrigation by small-scale farmers in counties that include: Kirinyaga (Mwea), Busia (Bunyala), Tana River (Tana Delta, Bura), Kwale (Vanga cluster), Kisumu (Ahero, West Kano, South West Kano, smallholder irrigation schemes within Kano Plains), Migori (Lower Kuja), Homa Bay (Maugo,

Oluch Kimira), Siaya (Anyiko) and Taita Taveta (Kimorigho, Buluma). Rice is also grown under rainfed conditions in Busia, Bungoma, Kakamega, Kwale, Kilifi, Meru, Isiolo, Migori, Baringo and Murang'a and about 300,000 rice farmers provide labour and also earn their livelihood out of the crop's production (NRDS 1). The Mwea Rice Growers Multipurpose Cooperative Society (MRGM) is the largest farmer-run cooperative within the Mwea Irrigation Scheme in Kirinyaga County, producing 80–88% of rice in the country (Mati *et al.*, 2011; Ndiiri *et al.*, 2013; Onyango, 2014). Most farmers in Mwea grow rice once a year, sowing between July and August and harvesting between December and January (Abdullahi *et al.*, 2003; Ngige, 2004). The other large mills include government-owned Mwea Rice Mills and National Cereals Produce Board in Kirinyaga County, TARDA in Tana River as well as Western Rice Mills and Lake Basin Development Company in Kisumu. There are eight large private mills in Kirinyaga and one in Kiambu (Capwell Industries). In addition, there are several small privately owned mills spread across the major rice-growing counties.

Historically perceived as a cash crop, rice has rapidly grown in importance in Kenya as a food crop and annual rate of increase in consumption is 12%, compared to 4% for wheat and 1% for maize (Atera *et al.*, 2018). Since 2008, the area under rice cultivation has broadened by 55% from 16,734 ha to 25,966 ha in 2018, paddy production has increased four-fold from 21,881 t to 110,325 t in 2018, and on-farm productivity has more than doubled from 1.3 t/ha to 4.25 t/ha thanks to the Government of Kenya's efforts at enhancing production, processing and marketing of rice through the NRDS. There are two main cultivated species of rice, *O. sativa*, the most common and *Oryza glaberrima* L. Kenyan consumers prefer aromatic rice varieties (such as the pishori rice grown in Mwea) which have a niche market especially among households with improved incomes (Kioko *et al.*, 2015). However, according to the NRDS 2 (2019–2030), the retail price of these varieties is prohibitive. Though imported rice is of superior quality in terms of purity and percentage of broken grains compared to the local non-aromatic rice, it is usually cheaper. None the less, preference for the locally produced non-aromatic rice is higher, especially in Kirinyaga County. Despite the progress made, the national markets continue to be dependent on supply of rice from Asia and the region to meet consumer requirements (Rice for Africa, 2020). Rice is one of the priority crops in the Big4 Agenda in Kenya and a priority value chain in the Agriculture Sector Transformation and Growth Strategy (2019–2029). Rice consumption has been growing much more rapidly in the country than production and is expected to reach 1,292,000 t by 2030. In order for Kenya to attain self-sufficiency in rice production by 2030, the total domestic rice production must increase at the rate of 9.3% per annum (Atera *et al.*, 2018).

To meet the growing demand for rice, Kenya has embarked on an aggressive campaign, guided by its NRDS 2, which runs from 2019 to 2030. This aims to catalyse over a sevenfold increase in domestic milled rice production, from 112,000 t in 2018 to 846,000 t in 2030.

The recent coronavirus disease 2019 (COVID-19) crisis has negatively affected rice exports across Africa, largely due to delays from border closures or movement restrictions. Exporters to Kenya, Rwanda, Uganda and South Sudan (through Uganda) have indicated a slowdown with losses in export revenue of between 40% and 60% per month as a result of COVID-19 (Future Agricultures, 2020). To enhance rice production and hence boost food security, Kenya's policy makers must acknowledge and address the impediments that exist across the rice value chain and this includes biotic constraints such as non-native pests, of which apple snails are among the world's most damaging for this crop. This is particularly relevant as the

COVID-19 pandemic is a multiplier of vulnerability, compounding threats to food security and nutrition (FSN), while exposing weaknesses in food systems (GAIN, 2020).

1.2 Biology and identification of invasive *Pomacea* species

Pomacea canaliculata and *Pomacea maculata* have commonly been referred to as 'golden apple snails' or 'GAS', a term primarily applied in South-east Asia to South American species because their shells are often apple-like, large, round and sometimes greenish in colour (Lai *et al.*, 2005; Joshi and Sebastian, 2006). However, widespread confusion surrounding their taxonomy has meant that much of the extensive body of published (and unpublished) literature is difficult to interpret, with reports failing to clarify specifically which species, or if both, were involved, or indeed simply assuming it to be *P. canaliculata* (Cowie *et al.*, 2017). As is frequently the case in species with phenotypically variable shells, species boundaries have been differently interpreted (Cazzaniga, 2002), names have been synonymized and applied inconsistently (Hylton Scott, 1958; Thiengo, 1987; Thiengo *et al.*, 1993), or species have simply been identified incorrectly (Cowie *et al.*, 2006). The use of various common names for *P. canaliculata*, in both English and other languages has also added to the confusion (Cowie *et al.*, 2006).

There is no consensus on how many species are in the genus *Pomacea* (family: Ampullariidae), but it is thought to include around 50 species (Hayes *et al.*, 2015) and is a clearly distinguishable taxonomic entity, although the systematics of the genus remain dynamic. The two most documented species, *P. canaliculata* and *P. maculata*, together with *Pomacea lineata* (for which little information is available) form the '*canaliculata* complex' and the three are almost indistinguishable from each other in the field (EPPO, 2014). Differentiation of *Pomacea* species on a morphological basis is difficult, even for experts, as intraspecific variation is high across the distribution range and morphological similarities are shared between many different species. The traditional concept of a species does not fit well with the differences in morphology, life history, and other variation exhibited by these snails (Ramírez *et al.*, 2003; Cowie *et al.*, 2006; EFSA Panel on Plant Health, 2012) but none the less, ampullariid taxonomy has until recently relied almost exclusively on shell morphology (Keawjam and Upatham, 1990). *P. maculata* can be distinguished from *P. canaliculata* somewhat reliably as adults, based on features of the shell: that of *P. maculata* usually having a yellowish to reddish-orange wash round the edge of the shell aperture, while *P. canaliculata* is unpigmented; and more subtly in the greater angulation of the whorl shoulder in *P. maculata* (Hayes *et al.*, 2012). Definitive identification, however, must rely on molecular characters (Cowie and Hayes, 2005), internal anatomy or reproductive characteristics for a clear distinction (Hayes *et al.*, 2012, 2015). Hatchlings of the two species are readily distinguished as the number of eggs is greatest in *P. maculata* but the eggs are smaller; hence hatchlings of *P. canaliculata* are roughly twice as big as those of *P. maculata* (Hayes *et al.*, 2012). However, the two species differ most clearly genetically (Hayes *et al.*, 2012). Improving morphological and molecular sequencing has allowed the taxonomy of Ampullariidae and the genus *Pomacea* to be clarified further (Matsukura and Wada, 2017) and this has been particularly useful for distinguishing *P. maculata* (formerly often referred to as its junior synonym *Pomacea insularum*) from *P. canaliculata* (Rawlings *et al.*, 2007; Hayes *et al.*, 2008, 2009, 2012; Matsukura *et al.*, 2008; EFSA Panel on Plant Health, 2012). Results from molecular analysis have also highlighted possible hybridization events (Hayes *et al.*, 2012; Matsukura *et al.*, 2013).

Ampullariids are primarily freshwater snails, although some may be able to tolerate low levels of salinity (Prashad, 1925; Santos *et al.*, 1987; Fujio *et al.*, 1991), but they generally do not live in brackish waters. Many species, including *Pomacea*, inhabit slow-moving or stagnant water in lowland swamps, marshes, ditches, lakes and rivers (Keawjam, 1986) and some species can almost be considered pre-adapted for life in rice paddies, taro patches, and other similar artificial habitats in which aquatic crops are grown. The natural range of *P. canaliculata* was found to be restricted to the Lower Paraná, Uruguay and La Plata basins of Argentina, although it is possible that it may also occur in the lower reaches of the Upper Paraná and parts of southern Brazil which form a phytogeographic unit and have similar habitats and watershed connections. Hylton-Scott (1958) reported that *P. canaliculata* inhabited relatively still water and it is not present in the Amazon basin (CABI, 2020). Thus *P. canaliculata* appears restricted to a narrower southern range, whereas *P. maculata* ranges extensively throughout much of South America.

Unlike most other snails, *P. canaliculata* is not hermaphroditic and male and female snails reproduce if water conditions and food supply are adequate. Sexual maturity is reached when the snail reaches 2.5 cm in diameter. Copulation and spawning tend to be time-consuming activities. Intercourse can last 10–20 h (and males fast during this time) while the egg-laying process can take up to 5 h. In addition, males tend to choose larger females in order to produce more and healthier offspring (Estebenet and Martin, 2002). A single female of *P. canaliculata* can lay up to 500 eggs at a time. Hayes *et al.* (2012) provide the most comprehensive description of *P. canaliculata* and *P. maculata* and a brief summary of morphological characteristics and life cycle is provided below.

Pomacea eggs form an opaque and brightly coloured, conspicuous mass (Figure 1). Individual eggs are spherical (< 2.00 mm to > 3.00 mm in diameter), calcareous and deep pink-red to lighter orange-pink colour, becoming paler as the calcium hardens and eventually turning whitish pink before hatching. They are laid in a mass just above the water on emergent surfaces such as vegetation and other firm substrates (e.g. concrete bridges, walls, logs, rocks) as snails are unable to swim. The height above water varies from a few centimetres to ~2 m. The number of eggs per clutch averages from ~260 to ~1500, ranging from as few as 12 to as many as ~1000 (Tamburi and Martín, 2011; Hayes *et al.*, 2012). Females usually lay one egg batch about every fortnight if conditions are favourable and eggs need a good supply of air; hatching may be delayed if eggs are temporarily submersed (Pizani *et al.*, 2005) or at a lower temperature or fail altogether if they become submerged. Newly hatched snails are tiny, with shells that can be less than 2 mm in diameter, but grow rapidly and drop from where the eggs were laid into the water below. Hatchlings develop into juveniles 15–25 days after hatching, and the snails become mature adults 45–60 days later. *P. canaliculata* are first able to lay eggs when they reach a shell diameter of about 2.5 cm and oviposition takes place predominantly at night, or in the early morning or evening (Halwart, 1994; Albrecht *et al.*, 1996) with the interval between successive egg laying variably reported as 5–14 days (Chang, 1985; Albrecht *et al.*, 1996).

Ampullariids are dioecious (separate sexes), internally fertilizing and oviparous (producing eggs that hatch outside the body). Shells are smooth, thin, coiling dextrally (i.e. when viewed with the apex uppermost the aperture is on the right side of the shell). Colour may be dull brown to greenish-brown (Figure 2) or dark chestnut, sometimes with dark-brown spiral bands of variable number and thickness. The whorls are rounded and the suture between the whorls is deeply channelled. The aperture is usually ovoid to kidney shaped, and the inside lip of the

shell is unpigmented. *Pomacea* species have an operculum – a discrete trap-door-like structure attached to the upper part of the animal's foot that can seal the shell closed as it withdraws within and prevents desiccation. The foot is oval with a squarish anterior edge and they have four, long, tapering tentacles which are highly extensible with large but short eye stalks at their outer bases. A very long collapsible siphon allows them to breathe at the surface when extended, distinguishing them from other freshwater snails which often lack a siphon and possess only two triangular tentacles and no operculum. A structure within the mouth of *P. canaliculata* makes rasp-like cuts on its host plants; damage is rapid.

Pomacea spp. have an estimated lifespan of 1–4 years (Hayes *et al.*, 2015). In subtropical and warmer temperate zones, snails can aestivate in mud for many months (Hayes *et al.*, 2015) and their lifespan may be up to 3–4 years, with a lower number of generations per year and potential for high winter mortality. With elevated temperatures found in more tropical and subtropical zones, lifespan is shorter, lasting 1–2 years, as hibernation is not necessary (Hayes *et al.*, 2015), but the snails have a continuous reproductive period until death (Estebenet and Martín, 2002). R.E. Joshi (2005) observed that during the off-season (after rice harvesting but before rice planting) in the Philippines, the small-sized invasive apple snails (10–15 mm) have low mortality rates, but the mortality increased with their size. This has important implications on snail management. Reproductive activity was found to start after hibernation at a water temperature of 18°C (Wu *et al.*, 1995; Albrecht *et al.*, 1999; Estebenet and Martín, 2002; Yoshida *et al.*, 2009; Seuffert *et al.*, 2010).

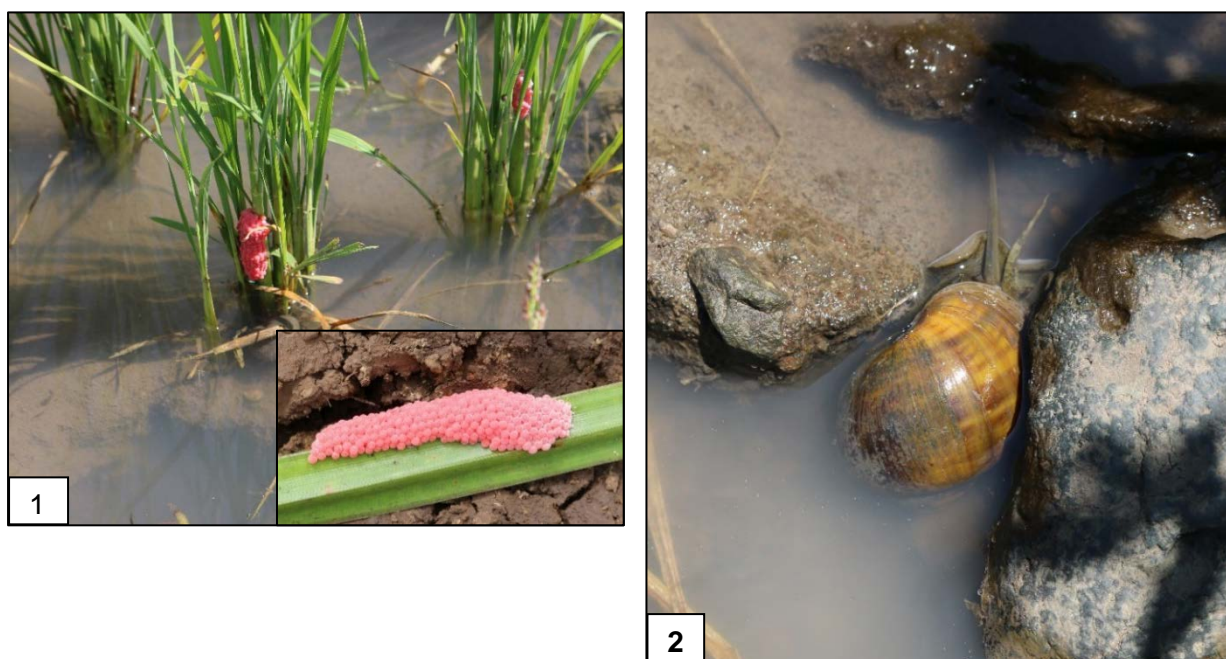


Fig. 1. Conspicuous pink egg clutches of *Pomacea canaliculata* on rice plants (from Mwea Irrigation Scheme Kirinyaga, Kenya, 2020). Credit: Fernadis Makale. **Fig. 2.** Adult *P. canaliculata* snail (from Mwea Irrigation Scheme, Kirinyaga, Kenya, 2020). Credit: Fernadis Makale.

1.3 Invasive apple snail spread around the world

The deliberate and repeated introduction of *P. canaliculata* and *P. maculata* from Argentina, into East and South-east Asian rice-growing regions in the 1980s has proved disastrous, with

long-lasting impacts on agricultural yields, farm income, human health and natural ecosystems (Naylor, 1996; R.C. Joshi, 2005a, b; Hayes *et al.*, 2008).

Introduced for cultivation as a high-protein source for domestic consumption and gastronomic export, its characteristic traits of polyphagous feeding (Wong *et al.*, 2010; Burks *et al.*, 2011; Morrison and Hay, 2011; Saveanu and Martín, 2013) and rapid, prolific breeding potential (Keller *et al.*, 2007; Kyle *et al.*, 2013), are the very traits which made this so-called 'golden miracle snail' such a successful invader (Naylor, 1996). Already a well-known pest of coastal rice-growing areas of Suriname in the 1950s (Acosta and Pullin, 1991), the promise of economic returns from snail cultivation none the less saw their introduction into Taiwan, Japan and the Philippines in the early 1980s, with subsequent introductions to China, South Korea, Malaysia, Thailand, Indonesia, Vietnam, Cambodia (Cowie, 1995a; Chanthy, 2002; Cuong, 2002, 2006; Huan and Joshi, 2002; Suharto, 2002; Lee and Oh, 2006; Preap *et al.*, 2006; Yahaya *et al.*, 2006; Marwoto *et al.*, 2018), and later in the 1990s into Laos (Anderson, 1993; R.C. Joshi, 2005a, b; EFSA *et al.*, 2020). However, a combination of unpalatability, prohibitive health import restrictions from foreign markets and the associated drop in market value resulted in negligence by would-be producers, and snails were released/escaped into irrigation systems and public waterways (Naylor, 1996). Spread thereafter was rapid and widespread; within 5 years, the proportion of wet-rice area infested by the GAS rose from less than 3% to between 15% and 25% in Taiwan and the Philippines (Mochida, 1991; Ketelaar, 1993) and to around three-quarters of rice-growing districts in Japan and Vietnam (Naylor, 1996; Yusa and Wada, 2002). Winter temperatures may limit the northern spread of *P. canaliculata* in Japan (Ito, 2002), although behavioural adaptations and acclimation to these cooler temperatures have allowed overwintering further north than would otherwise be possible (Wada and Matsukura, 2007; Matsukura *et al.*, 2008). The sheer abundance of snails in Asian agricultural systems led to unintentional introductions to Malaysia from Thailand on contaminated imports of water spinach (Naylor, 1996). In 2009, invasive populations of *Pomacea* species were discovered in Brunei Darussalam (Hanifah *et al.*, 2018) and a first record was reported in Southern Iraq (Al-Abbad *et al.*, 2015).

The Asian subcontinent is also threatened by apple snails' rapid spread in Pakistan, probably from the aquarium trade (Baloch *et al.*, 2012; Baloch, 2017), Sri Lanka (Nugaliyadde *et al.*, 2001; Epa, 2006) and Myanmar (Myint and Ye, 2017). The agricultural and environmental consequences of further spread to India and Bangladesh in particular, a country of rivers and canals and frequent flooding, would be serious.

P. canaliculata was introduced to the Pacific Islands, notably Hawaii through the domestic aquarium trade around 1989, although there are unconfirmed anecdotal accounts that it was present some years earlier (Cowie, 1995b; Levin *et al.*, 2006; Cowie *et al.*, 2007). Accidental spread has been reported in Hawaii from small juveniles, inadvertently transported on taro parts used for propagation (Levin *et al.*, 2006), and eggs have also been transported on boats (EFSA Panel on Plant Health, 2012). It was also recorded in Guam in 1989 (Smith, 1992) and in other areas of Oceania such as Papua New Guinea and New Zealand (Orapa, 2006; Hayes *et al.*, 2008; Collier *et al.*, 2011; Cowie *et al.*, 2017). In North America, *P. canaliculata* is now present in California, Arizona, Florida, Georgia, Texas (Howells and Smith, 2002; Howells *et al.*, 2006), Alabama (Martin *et al.*, 2012) and South Carolina (Benson, 2018). Invasive apple snails have also been reported in Europe, the first report from the Ebro Delta in Spain (López *et al.*, 2010; R.C. Joshi, unpublished trip report, 10–19 July 2015) with data suggesting that both *P. maculata* and *P. canaliculata* could be present (Andree and López, 2013). While they

were eradicated from this area, they subsequently spread to a new region in northern Spain (Joshi, 2016; Joshi and Parera, 2017) but were eradicated there too in 2020 (EFSA *et al.*, 2020). Small populations of *Pomacea* spp. were also successfully eradicated from municipalities in Switzerland and France (EFSA *et al.*, 2020). Unconfirmed reports of *P. lineata* (possibly misidentified and actually *P. canaliculata*) occur from South Africa (Berthold, 1991) and Shivambu *et al.* (2020) reported *P. canaliculata* from the South African pet trade. *Pomacea canaliculata* has also been detected in La Réunion and Mauritius (EFSA *et al.*, 2020; EPCO, 2020). *Pomacea* spp. invasions have also occurred in Dominican Republic (Rosario and Moquete, 2006), and in Haiti (R.C. Joshi, unpublished USAID consultancy report, 9–24 December 2018). The global distribution of the apple snail is shown in Fig.3.



Fig. 3. Global distribution of apple snails in the '*canaliculata* complex'. Reproduced from EFSA *et al.* (2020).

Natural dispersal rates are relatively low, as the snails are restricted to damp habitats and are not capable of rapid movement. Flooding from heavy rains contribute to their dispersal over low-lying areas and birds have been found to transfer egg clutches through nest-building activities (Levin *et al.*, 2006). *Pomacea* adults are not wholly restricted to water, and can move overland for short distances between sources of water. They are capable of dispersing downstream at a faster rate than upstream, as they can be carried along with floating vegetation and in water currents. The conspicuous egg masses are the most detectable life stage in the wild and adult snails are more cryptic, but if found, the sheer size of mature specimens is a strong indicator of identity (Hayes *et al.*, 2012). It is predicted that the climatically suitable habitats for *P. canaliculata* will further increase with projected scenarios of global warming (Lei *et al.*, 2017).

1.4 Invasive apple snail host range and general impacts

According to the classification of functional feeding groups of aquatic invertebrates by Cummins and Klug (1979), apple snails feed by shredding (obtaining pieces of submersed materials, mainly with the jaws), scraping (obtaining material adhering to submersed surfaces, mainly with the radula) and collecting (obtaining material from the water surface with the foot). All three mechanisms can be used by the same individual in rapid succession to obtain

vegetal, animal or microbial materials (Demian and Lutfy, 1966; Cazzaniga and Estebenet, 1984; Aditya and Raut, 2001; Cowie, 2002; Morrison and Hay, 2011).

The most widely recognized impacts of invasive *Pomacea* are therefore linked to this uncommon ability to successfully feed at rapid rates on a broad diet. Because of powerful enzymes and ingestion of lithic particles to amplify mechanical digestion, they can also effectively process their food (Martín *et al.*, 2019).

Apple snails such as *P. canaliculata* mostly inhabit lentic or slow-running water courses in tropical to warm temperate regions and their diverse feeding modes and trophic flexibility are a relevant trait in their broad and continued invasion success. They feed primarily on aquatic macrophytes, including a diverse number of crops such as rice (*Oryza sativa*), taro (*Colocasia esculenta*), morning glory (*Ipomoea aquatica*), lotus (*Nelumbo nucifera*), mat rush (*Juncus decipiens*), Chinese mat grass (*Cyperus monophyllus*), watercress (*Rorippa* spp.), Japanese parsley (*Oenanthe stolonifera*), water chestnuts (*Trapa bicornis*), wild rice (*Zizania latifolia*), azolla (*Azolla* spp.) and water lilies (*Nymphaea* spp.) (Mochida, 1991; Dancel and Joshi, 2000; Joshi *et al.*, 2001; Yusa *et al.*, 2006; Horgan, 2018). Although many of these plants are quite unpalatable, in monocultures they are almost the only trophic option. *P. canaliculata* can also consume other trophic resources (e.g. carrion) and that is likely to play an important role in its persistence and contribute to its impacts in invaded wetlands (Manara *et al.*, 2016).

Their ability to survive even after the most palatable aquatic macrophytes have been exhausted was highlighted by Saveanu and Martin (2015), who reported pedal surface collecting (capture of surface material) in *P. canaliculata* as an adaptation to cope with fluctuating trophic resources. Qiu *et al.* (2011) also found *P. canaliculata* was capable of utilizing both fresh and decaying leaves of adequate levels of nutrients allowing for greater colonization potential throughout the year. Apple snails can deplete the palatable aquatic vegetation, favour the dominance of unpalatable species or induce the expression of chemical defences (Saveanu and Martin, 2013) and their feeding provokes marked changes in wetlands as well as causing major economic losses in aquatic agricultural systems (Cowie, 2002; Carlsson *et al.*, 2004b; Joshi and Sebastian, 2006). *Pomacea* are also known to bioaccumulate toxins (Berry and Lind, 2010), pesticides (Coat *et al.*, 2011) and heavy metals (Deng *et al.*, 2008; Kruatrachue *et al.*, 2011; Dummee *et al.*, 2012; Vega *et al.*, 2012; Peña, 2017).

By virtue of its large size, high trophic flexibility, high feeding rates and high fecundity (Burlakova *et al.*, 2009; Burks *et al.*, 2011; Morrison and Hay, 2011; Hayes *et al.*, 2015; Saveanu *et al.*, 2017; Tiecher *et al.*, 2017), other species of snails are easily outcompeted and *P. canaliculata* is also able to prey on adults, young snails and egg masses of other snails (Cazzaniga, 1990, 2006; Kwong *et al.*, 2009). This, intraguild predation on egg masses has been shown to be an important interspecific interaction among freshwater pulmonate snails of similar sizes (Turner *et al.*, 2007) and is expected to be even more important in the case of *P. canaliculata*, due to its powerful radula and jaws and its larger size. The effects of *P. canaliculata* on other snails are expected to be strong in the areas invaded, where it can reach high densities, monopolize secondary production, and provoke ecosystem changes (Carlsson *et al.*, 2004b; Kwong *et al.*, 2010; Horgan *et al.*, 2014; Tricarico *et al.*, 2016).

In Thailand, introduced *Pomacea* species have also been found to predate bryozoans (Wood *et al.*, 2006), and may have a higher tolerance of variable environmental conditions, in addition to possibly being competitively superior to native snail species, including species which are

already threatened by habitat loss and modification (Köhler *et al.*, 2012; Marwoto *et al.*, 2018; Ng *et al.*, 2019).

The herbivory of invasive *Pomacea* and release of nutrients into the water and subsequent phytoplankton has also been linked to eutrophication (Martín *et al.*, 2019) while eradication of submersed macrophytes may also facilitate sediment resuspension and raise water turbidity, altering both biodiversity and the integrity and functioning of the ecosystem (Carlsson *et al.*, 2004b). Thus, the impacts of *Pomacea* are not only on closely related or congeneric species but also on other evolutionarily distant species and on the natural balance of the invaded area in general and they are thought to have pushed some particularly fragile ecosystems in ASEAN countries into irreversible decline.

Impact of opportunist predators has also been reported where ingestion of the poisonous eggs of *P. canaliculata* adversely affect the digestive system of amphibians (Brola *et al.*, 2021). *Pomacea* management has also had collateral impacts on ecosystems and in the Philippines for example, populations of native ampullariid snail species have experienced sharp declines perhaps as a result of extensive and indiscriminate application of pesticides to combat the introduced *P. canaliculata* (Anderson, 1993; Chaichana and Sumpan, 2014; Schneiker *et al.*, 2016; Cowie *et al.*, 2017).

1.5 Invasive apple snail impact on human health

Apple snails are species of concern not only because of their adverse agricultural and ecological impacts but also because of the potential risk that they pose to human health when used as a food resource. *P. canaliculata* and other species can serve as intermediate hosts of zoonotic nematode parasites, such as *Angiostrongylus cantonensis*, *Echinostoma ilocanum*, *Echinostoma revolutum* and *Gnathostoma spinigerum* (Brandt, 1974; Keawjam, 1986; Komalamisra *et al.*, 2009; Yang *et al.*, 2013). The rat lungworm nematode parasite (*A. cantonensis*) can cause potentially fatal eosinophilic meningitis in humans and animals if the infective larval stage is ingested either by eating infected snails or in mucus trails left by infected snails on edible plants (Wang *et al.*, 2008; Dorta-Contreras *et al.*, 2011), *G. spinigerum* reportedly parasitizes cats, dogs and humans in Thailand and Japan (Komalamisra *et al.*, 2009) and *Angiostrongylus costaricensis* causes abdominal angiostrongyliasis in humans (Miller *et al.*, 2006). They can also act as vectors for Schistosome cercariae, cause of cercarial dermatitis or swimmer's itch, and for a fluke that causes intestinal problems (Hollingsworth and Cowie, 2006).

Schistosome dermatitis occurs when a person becomes the accidental host of cercariae (the free-swimming larval stage) of non-human schistosome trematodes. The cercariae penetrate the skin where they soon die, causing a hypersensitive reaction of the skin (Hoeffler, 1974). Leedom and Short (1981) reported dermatitis caused by cercariae from *Pomacea* species in the USA. In Kenya, farmers expressed worries that the newly found *Pomacea* snails may cause waterborne diseases like schistosomiasis (bilharzia) as many cannot afford gumboots to protect themselves from such diseases.

The spread of *P. canaliculata* may therefore facilitate the spread of these zoonotic species by completing the life cycle required to infect mammalian hosts, with global warming providing further opportunities for the snail, a stenothermal organism, to enlarge its potential habitat and colonize new habitats (Lv *et al.*, 2006).

In addition, the empty shells of dead snails, perhaps following pesticide application, have been reported as a health hazard as they can cut the feet of people planting, harvesting or otherwise managing the crop (Cowie, 2002; Douangboupha and Khamphoukeo, 2006; Hendarsih-Suharto *et al.*, 2006). The overuse of pesticides to control the snails and the often poorly regulated application of dangerous formulations can also cause human health and environmental safety problems (Cowie, 2002). *Pomacea* species are also capable of toxin bioaccumulation (Berry and Lind, 2010) and this capacity also poses a potential threat to human and ecosystem health.

Apple snails have also been reported to accumulate high concentrations of metal pollutants in their tissues and thus can affect animals at higher trophic levels, including humans.

Burkett-Cadena and Unnasch (2013) found the Asian tiger mosquito (*Aedes albopictus*) was capable of exploiting discarded apple snail shells as larval development sites in Florida and could potentially contribute to mosquito proliferation.

1.6 Current spread and distribution of invasive apple snail in Africa

Ampullariids (apple snails) are thought to have originated from Gondwanan lineages that inhabited what is now Africa (Hayes *et al.*, 2009). Fossil records are scarce (e.g. Prashad, 1925; Pilsbry and Bequaert, 1927; Fischer, 1963; Boss and Parodiz, 1977; Martín and De Francesco, 2006) but the Gondwanan origin is supported in part by the distribution of the two most basal genera in the family, *Saulea* and *Afropomus*, in current-day Sierra Leone and Liberia on the African west coast, and the presence in Africa of two remaining Old World genera *Lanistes* and *Pila* (Hayes *et al.*, 2015). *Pila* occurs in Africa and Asia, *Lanistes*, *Afropomus* and *Saulea* only in Africa.

Due to the challenges of differentiating between the species, there have been uncertainties over the identity of apple snails found in different countries worldwide. However, up until recently, *Pomacea* snails in the '*canaliculata* complex' were not recorded from the African mainland and were only detected in Réunion and Mauritius (EFSA *et al.*, 2020; EPCO, 2020). *P. canaliculata* was detected in areas utilized for taro cultivation in La Porte Providence, Flacq (east part of Mauritius) and first detected in La Réunion in 2006.

Following reports that an unknown snail species had invaded the Mwea Irrigation Scheme in Kirinyaga County, where over 70% of the country's rice is grown (Atera *et al.*, 2018), surveys were undertaken by CABI in September 2020. Farmers had reported snails from close to 222 ha of Tebere and Ndekia section of the 10,117 ha grown, with associated damage to 92% of newly transplanted rice seedlings (Ivan Rwomushana, CABI Kenya, 2020, personal communication). DNA barcoding analyses confirmed the identity of the snails as *P. canaliculata*, which constitutes a first record for Kenya and mainland Africa (Buddie *et al.*, 2021).

Intense flood events are becoming more commonplace in Kenya due to extreme weather worsened by global warming. Many recent floods have ruined harvests in several rice-production hubs and could be a further pathway for snail spread into other regions.

According to the European Food Safety Authority (EFSA Plant Health Newsletter 2020), *Pomacea* eggs were first observed in Kenya but not recognized as a threat in 2019, though official reports suggest February 2020 was the first sighting. A great deal of media coverage subsequently ensued with the Kenya Plant Health Inspectorate Service (KEPHIS) and stakeholders, including the Kirinyaga County government, began an initiative to control the

snails. It had also been noted as a threat to the 1500 acres (607 hectares) of the bordering lower areas that receive water from upper units. The pathway for introduction to Kenya remains unknown and no permits for import have come to light although speculation of intentional introduction as a biological control agent for weeds has been raised in the press.

In Japan, introduction of *P. canaliculata* was reported as a biocontrol agent for weeds in rice systems (Okuma *et al.*, 1994; Wada, 2004). Great caution has always been urged when considering *P. canaliculata* as a biological control agent for aquatic weeds (Cazzaniga and Estebenet, 1985; Cazzaniga, 2006) as the risks very much outweigh the potential benefits and it is only appropriate in areas in which it is already established (Wada, 1997; Wada *et al.*, 2002; Lee *et al.*, 2019). Several species, notably the apple snails, *Pomacea* spp. and *Marisa cornuarietis*, and the thiarid *Tarebia granifera*, are known to have also been used as potential biocontrol agents of schistosomiasis host snails because they prey on or compete with pulmonates such as *Biomphalaria* spp. and *Bulinus* spp. Whether this competition is for resources, such as food, or due to interference (e.g. physical contact) facilitated by the invasives' greater population densities, is not clear.

In their natural habitat, apple snails can remain active throughout the year given the right environmental conditions (i.e. warm and relatively humid), but they usually aestivate during parts of the year to prevent drying out. Temperatures and rainfall are the two main factors that determine their activity levels (Coelho *et al.*, 2012). High humidity allows the snails to remain out of water for some time without desiccation and they can reportedly disperse across land during these high humidity periods (Kappes and Haase, 2012). Such land dispersal activities account for localized spread, and do not make up the majority of apple snail dispersal; *P. canaliculata* has the ability to float and can move long distances within a water system; in canals it was found to move more than 100 m upstream or more than 500 m downstream in 1 week (Ozawa and Makino, 1989). Snails need access to flowing water or flooding events to move naturally (e.g. caused by heavy rain). Connected rice fields, rivers, natural and artificial canals provide an effective structure for the snails to spread (Yusa *et al.*, 2006; EFSA Panel on Plant Health, 2012). Downstream movement (by drifting) in rivers is at least ten times further than upstream movement (by crawling) (Kappes and Haase, 2012; EFSA Panel on Plant Health, 2013). This is mostly effective at local and regional levels and passive natural spread over several kilometres during 1 year is possible.

In addition, studies on snails other than *Pomacea* spp. showed that waterbirds may contribute to the spread of those aquatic invertebrates, which can remain attached to the body of flying birds or on being ingested survive the passage through the digestive system (van Leuwen and van der Velde, 2012; van Leuwen *et al.*, 2012). Ichinose and Yoshida (2001) reported that fast water flow may impede movement and prevent snails from expanding their range upstream and Ito (2002) found established populations remained restricted to small areas if the flow was very still.

However, factors restricting the dissemination of snails within a water system are not fully understood and the broad ecological and thermal tolerance of *P. canaliculata* is well documented (Eversole, 1992; Schnorbach, 1995). In the native range, studies indicate that *P. canaliculata* distributions are determined by a combination of physicochemical (salinity, alkalinity) and geographic (mountains) barriers in conjunction with stochastic patterns of extinction-colonization events related to local variability of climatic and hydrological conditions (Martín *et al.*, 2001; Martín and De Francesco, 2006; Seuffert and Martín, 2013). However, in

the non-native range this species can be found in suboptimal habitats, indicating that it can at least survive in these habitats for a period of time (Kwong *et al.*, 2008).

Unintentional movement by humans from areas where the snail is already present into currently pest-free areas may be possible, for instance on cultivation tools where egg masses had been deposited and when transplanting rice plants from infested rice paddies (Cowie, 2002; Smith, 2006; EFSA Panel on Plant Health, 2012). The expected rate of human-assisted spread can be effective over large distances, but these are difficult to estimate. In tropical regions, however, released from the seasonality of its natural range, with rapid growth and breeding, and hence rapid succession of generations all year round (Naylor, 1996), *P. canaliculata* population expansion is a distinct possibility.

Preliminary status surveys undertaken in late 2020 in the three major rice-growing schemes of Kenya (Mwea, Ahero and West Kano) suggest that *P. canaliculata* was restricted to the Mwea Irrigation Scheme (Fernadis Makale, 2020, unpublished work). A restricted distribution could offer a strong opportunity to contain or even eradicate the snail before it becomes more widespread. Further spread, for example into the irrigated rice-production area of Ahero (see Yamane, 2019), at the edge of Lake Victoria could have huge consequences. Were *P. canaliculata* to enter and persist in Lake Victoria, its spread into surrounding rice production in Tanzania and Uganda could be rapid, and ongoing dissemination throughout catchments and into major river systems such as the White Nile could be disastrous for the region.

1.7 Modelling the distribution of invasive apple snail

Climate models applied to the potential expansion of the species, inferred high colonization ability of many non-infested areas of the world (Baker, 1998), facilitated by the increased activity of the snails at higher temperatures (Heiler *et al.*, 2008).

A number of models have been developed to describe the potential range and performance of *P. canaliculata* in different geographic locations, using various approaches and combinations of parameters to predict distribution, density and population dynamics (e.g. Baker, 1998; EFSA Panel on Plant Health, 2012; Lei *et al.*, 2017; Reilly, 2017). Distribution models have also been developed for additional invasive apple snails including the congeneric species *P. maculata* (e.g. Byers *et al.*, 2013; Barbitta *et al.*, 2020).

Several studies implement correlative habitat modelling approaches (e.g. CLIMEX and MaxEnt) to infer potential range and suitability of specific regions to *P. canaliculata* including South-east Asia and Australia (Baker, 1998), Europe (EFSA Panel on Plant Health, 2012) and Florida (Reilly, 2017). Lei *et al.* (2017) use multi species distribution model (SDM)-based ensemble forecasting to predict the potential distribution of *P. canaliculata* worldwide under recent conditions (see Fig. 4) and future climate change scenarios. These models suggest that much of rice production in eastern Africa (and SSA more broadly) is likely to be under threat from the snail under current climatic conditions, including all areas of Tanzania, the major producer in the region. Mwea, Kenya looks to be nearing the edge of the climate suitability envelope, though field surveys suggest that the area is hosting a healthy population of *P. canaliculata* and future surveys would be useful to determine long-term population persistence. Eastern areas of Ethiopia including much of Somali appear less at risk, although rice grown in this region is typically irrigated and it is unclear if this factor would make Somali rice paddies viable sites for *P. canaliculata* to persist as water availability was not included in the model. Climate change scenarios indicate that eastern Africa is likely to become more suitable for *P. canaliculata* over the next 30–60 years, particularly so under Canadian Centre

for Climate Modelling and Analysis climate scenarios compared with CSIRO (Commonwealth Scientific and Industrial Research Organization) scenarios.

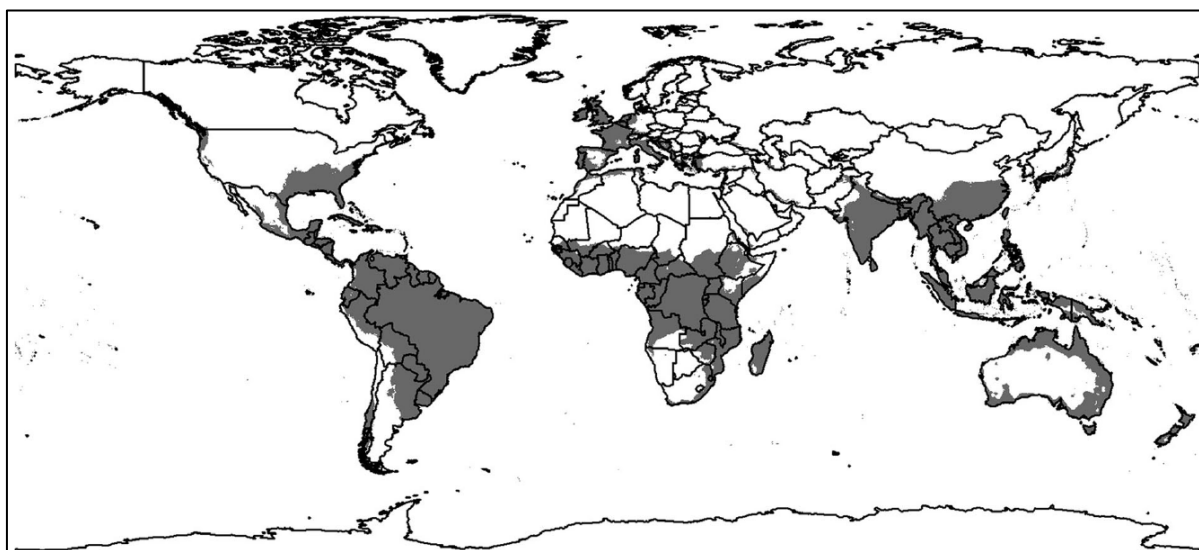


Fig. 4. Current climatically suitable habitats for *Pomacea canaliculata* (grey). Reproduced from: Lei *et al.* (2017).

Mechanistic niche models incorporating the effects of various environmental variables on certain components of snail performance have also been used. For example: (i) the effects of fallow periods and biocontrol agents on population dynamics of *P. canaliculata* were modelled by Halwart *et al.* (2006); (ii) a simple degree-day model for maturity was developed by Zhou *et al.* (2003) to model the snail's spread in China using air temperatures; and (iii) a population dynamics model was developed to model areas of potential establishment and likely high density 'hot spots' in Europe by EFSA Panel on Plant Health (2013). Temperature is a key environmental factor for *P. canaliculata* performance and survival and Gilioli *et al.* (2017) present a temperature-dependent physiologically based model for the snail to predict population density and associated impacts in different environments with high spatial resolution. Both air and water temperatures are considered, for the egg and aquatic stages, respectively. The model is validated against known distribution data for South America and Japan and produces realistic patterns of reproduction, development and mortality according to conditions in different regions and climates. The model also demonstrates that *P. canaliculata* will use two different reproductive strategies (semelparity and iteroparity) depending on conditions, a plasticity which may help to explain the snail's invasive success across a wide range of habitats and climates. *P. canaliculata* is also reported to have a higher tolerance to both low and high temperatures than other introduced *Pomacea* and this capacity is likely to be another key factor in explaining the invasiveness of this species (Mu *et al.*, 2015; Matsukura *et al.*, 2016). According to the model of Gilioli *et al.* (2017), within the potential areas of establishment, *P. canaliculata* population density may vary significantly and determining potential snail 'hot spots' would be valuable to guide management. A mechanistic, physiologically based model to determine *P. canaliculata* population dynamics for 'at-risk' regions in eastern Africa (and SSA more broadly), potentially in combination with correlative climatic modelling for the region could be extremely useful to identify areas at significant risk of crop losses, to guide management approaches and timings and identify potential corridors

of spread. Higher resolution modelling would also allow for improved crop loss estimates to be calculated, with highest losses expected in hot spots at particular risk from *P. canaliculata* coinciding with important crop growing habitats.

1.8 Environmental suitability for invasive apple snail colonization

Kwong *et al.* (2008) summarize the key factors likely to influence freshwater gastropod distribution as: i) biological (food, competition, predation); (ii) chemical and physical (calcium, salinity, flooding, current speed, substratum, temperature, desiccation, geographic barrier); or (iii) cultural (aquarium trade). In relation to *P. canaliculata*, limiting factors are typically considered to be primarily chemical and physical as evidence that competition or predation can effectively control the species is lacking (Kwong *et al.*, 2008).

In an assessment of the relative importance of environmental factors and geographical isolation on the distribution of *P. canaliculata* in Hong Kong, Kwong *et al.* (2008) found that water with high total phosphate and alkalinity was typical of sites inhabited by *P. canaliculata*. This is different from the situation in its home range, with saline, alkaline waters forming a physiological barrier limiting the snail's expansion in Buenos Aires (Martín *et al.*, 2001) – although the snail was also found at low density in streams with relatively low alkalinity and dissolved mineral concentration. Drainage channels with cement lining and high wet-season water velocity were free from the snail. Sites on Lantau Island thought suitable for the snail remained free, likely due to geographic isolation from other populations.

Temperature is a primary factor in determining environmental suitability for *P. canaliculata* (and related snail species), with all aspects of *Pomacea* biology highly dependent on temperature, including feeding, growth, sexual activity and egg laying (Gilioli *et al.*, 2017). *P. canaliculata* does, however, appear to have a higher resistance to both higher and lower temperatures than congeneric species (Gilioli *et al.*, 2017), with resistance to higher temperatures stronger than resistance to lower temperatures (Lei *et al.*, 2017). Broad climatic requirements for Ampullariidae survival are estimated to include an annual average minimum temperature above 10°C and 600 mm annual rainfall (Berthold, 1991), although with high uncertainty for *Pomacea* species (EFSA *et al.*, 2020). In temperate Japan, *P. canaliculata* develops cold hardiness prior to winter (Wada and Matsukura, 2007), but does not seem to tolerate freezing (Matsukura *et al.*, 2009). Overwintering survival in water with low temperatures of 2–8°C was determined by pH, dissolved oxygen and water depth in water channels in the northernmost population of *P. canaliculata* in Japan (Ito, 2002). Over winter snails can remain inactive for several months, but can respond rapidly to increases in temperature and the onset of more favourable conditions (EFSA *et al.*, 2020). Wada and Matsukura (2007) demonstrated that *P. canaliculata* show enhanced cold hardiness after a period of acclimation and that cold-tolerant snails can better withstand desiccation than cold-intolerant snails without cold acclimation. High temperatures can also have a detrimental effect on *P. canaliculata*, with egg viability at 30°C very low and snails reared at 35°C unable to produce eggs; snail survival was found to be highest at 15–20°C where no mortality was observed over 2 years of laboratory rearing (Seuffert and Martin, 2010). *P. canaliculata* is able to reproduce continuously, reaches maturity sooner, can complete more generations per year and maintain high populations of juvenile and mature snails year-round in tropical regions (Gilioli *et al.*, 2017), going some way to explaining the huge impacts the snail has had in tropical rice-growing parts of Asia. Winter mortality in temperate regions is considered an

important factor in the population dynamics of the snail, however, during the summer months temperate thermal regimes may allow maturation almost as fast as those in tropical climates (possibly due to detrimentally high temperatures in the latter). Results of temperature-dependent physiologically based modelling by Gilioli *et al.* (2017) suggest that in temperate climates *P. canaliculata* eggs would fail to survive winter. The authors suggest that in these regions, managers should aim to manage snails late in winter (e.g. hand-pick, till or manage water level), when population densities are at a minimum but before water temperature rises above 15°C and the snails reactivate.

2 Impacts of apple snail on rice and other socio-economic variables

2.1 Documented global impacts

P. canaliculata feeds on a wide range of aquatic plants of economic value but the greatest damage by far has occurred in irrigated rice ecosystems, which provide an ideal environment for the dispersal and growth of the snail (Halwart, 1994; Joshi *et al.*, 2003; R.E. Joshi, 2005). In the Philippines, snail production was promoted by the government as a national livelihood programme to increase the protein intake of low-income Filipino farmers and as an additional source of income (Ang, 1984; Adalla and Rejesus, 1989), but their associated health hazards caused demand to drop and cultures to be disposed of without precautions, such that rice fields were soon invaded. Economic losses in the Philippines accumulated over roughly the first decade of invasion (early 1980s to mid-1990s) were estimated to be up to US\$1.2 billion (Naylor, 1996; Sin, 2003), even without taking into account the non-crop damage to human health and natural ecosystems, with farmers spending US\$10 million on pesticides in a 3-year period alone (Anderson, 1993). The expenditure for synthetic molluscicides in 1998 in the Philippines was estimated at US\$2.4 million (Dancel and Joshi, 2000). In 1993, Filipino farmers spent about US\$9/ha for apple snail management (Medrano *et al.*, 1993). Even with proper use of registered commercial molluscicides, the cost is approximately US\$23/ha, with a countrywide expenditure of US\$7.4 million/year and still the snails remain a major biotic constraint in all rice-growing regions of the Philippines (Joshi *et al.*, 2001), despite claims that infestations had decreased thanks to integrated management approaches (Cagauan and Joshi, 2003). In 2003, of about 3 million ha of rice fields in the Philippines 1.4 million ha were still infested (Adalla and Magsino, 2006).

Similarly, in Taiwan, loss of rice was estimated at US\$2.7 million in 1982, which increased rapidly to US\$30.9 million by 1986 (Mochida, 1991). Between 1982 and 1990, annual expenditure on molluscicides was US\$1 million but in 2002–2003 budget cuts saw a reduction in this number to US\$170,000–300,000 (Cheng and Kao, 2006). Annual figures of US\$200 million and US\$175.6 million have been given for costs of damage in the ‘agricultural and ecological environment’, by Cheng and Kao (2006) and Yang *et al.* (2006), respectively.

In Japan, control of the snail on just 176 ha cost US\$64,385 (Mochida, 1991). The first record of rice damage caused by *P. canaliculata* was reported in 1984 (Yusa and Wada, 1999) and that same year it was designated as a quarantine pest by the Japanese Government. Since then, its distribution has gradually expanded such that in 1998 it was in 28 prefectures throughout south and central Japan (Wada, 2006). By 2004, it had infested 770,000 ha of rice fields, about 60% of this area being in Kyushu (Wada, 2006). The level of damage may have stopped increasing during the 1990s because of the application of various control methods.

However, *P. canaliculata* is still a serious pest in areas of Kyushu where very young seedlings are transplanted and where it rains heavily during the transplanting season. In addition, the presence of the snail is a constraint in promoting direct seeding in Kyushu (Wada, 1997, 2006; Yusa and Wada, 1999).

Nghiem *et al.* (2013) estimated the total annual loss caused by *Pomacea* snails to rice in Thailand and Vietnam as US\$74.8 million, based on: the average gross production value of rice over the previous decade, the proportion of surveyed locations with serious infestations of snails (density of one snail/m² or more; 19% and 90%, for Thailand and Vietnam, respectively), and a damage ratio of 0.7%. Engelhardt and Ritchie (2001) suggested that estimates were likely to underrepresent the true cost as they failed to include human health and environmental impacts (e.g. impacts on wetland ecosystem services, reduced biodiversity and biomass of aquatic plants affecting the nutrient retention capacities and economic/cultural value of wetlands).

In mainland China, *P. canaliculata* was first recorded in Guangdong province in 1981 and by 1988 the damaged area had grown to 9,130,000 ha in 37 counties in the province (Wu and Xie, 2006). Now much more widespread in China (Lv *et al.*, 2011), damage has been proportional to levels of direct-seeded rice but economic costs are not readily available.

Pomacea spp. are also considered a serious rice pest in Malaysia and Indonesia and require regular interventions but yield losses and control expenses in these countries have not been documented (Nghiem *et al.*, 2013).

Snails spread rapidly through waterways and irrigation canals, eventually infesting rice fields (Cowie, 1995b; FAO, 1998) which provide an ideal habitat; the snails are voracious, nocturnal feeders and attack young succulent plants such as newly transplanted rice seedlings and emerging tillers as well as weeds, quickly increasing their population and causing devastating losses (FAO, 1998). If the rice field is flooded, the germinated seeds are consumed first, with the early seedling phase also proving most vulnerable to attack (in the first 4 weeks when directly seeded or 2 weeks when transplanted) (Halwart, 1994); snails will eat the aerial part of the seedlings, severing the plants just above ground level and consuming the stem and leaves. Snails under 1.5 cm in diameter do not attack rice plants, however, larger snails can destroy 7–24 seedlings/day. A reduced rice plant population is an indicator of high infestation (EFSA *et al.*, 2020) and missing plants and floating leaf fragments of the rice plants characterize damage to newly transplanted rice (Joshi *et al.*, 2002). The extent of damage to rice depends on snail size, its density, and the growth stage of the rice plant (Morallo-Rejesus *et al.*, 1989). A density of three snails/m² causes significant yield loss, with much greater damage being inflicted on direct-seeded rice and young seedlings transplanted at 18–21 days after sowing (Litsinger and Estano, 1993).

Joshi *et al.* (2002) reported that snails of 40 mm were generally the most destructive size, irrespective of rice establishment method used, causing 100% destruction of rice seedlings in the germinating stage and at least 20% in transplanted seedlings. In Malaysia, *P. canaliculata* and *P. maculata* are serious pests of rice agriculture (Salleh *et al.*, 2012; Arfan *et al.*, 2014, 2016), causing losses of approximately RM82 (US\$20) million (2010) in rice fields in the peninsula (Yahaya *et al.*, 2017).

The economic costs associated with *Pomacea* species arise both directly, through the destruction of rice and other crop plants by the snails, as well as indirectly, through payment for pesticides and labour costs for physical removal of the snails.

In Hawaii, *P. canaliculata* has cultural and lifestyle impacts. Taro is a spiritually important crop, especially for native Hawaiians, and farming taro is an important lifestyle. Taro is also important educationally, as students, teachers and community groups use irrigated taro systems to explore topics in art, science, mathematics, health, capacity building and Hawaiian culture. The introduction of *P. canaliculata* and the subsequent impacts on taro growing threaten all of these activities (Levin, 2006; Levin *et al.*, 2006) as it will feed on all parts of taro plants, including corms, stems and leaves.

The farm value of taro was reported as US\$2.7 million, but as a result of losses of 18–25% suffered over the year by snail damage, it dropped to US\$2.2 million (Levin, 2006).

2.2 Prediction of economic and yield loss due to invasive apple snail in East Africa

There are many variables that may influence invasive *Pomacea* population dynamics and associated crop losses experienced by rice growers, including the following: (i) rice variety; (ii) method of propagation (direct seeding vs transplanted); (iii) irrigation approach (irrigated vs rainfed); (iv) climatic conditions (e.g. tropical, temperate, highland, lowland, coastal); (v) water levels through the season; (vi) local management approaches and cooperation between growers; (vii) affordability and availability of labour for snail management; (viii) affordability and availability of molluscicides; (ix) timing of control implementation (e.g. rapid early eradication vs management of widespread and high density infestation); (x) age/size distribution of snails (larger snails are more damaging); (xi) role of natural enemies/biocontrols (e.g. fish, birds); (xii) availability of additional/alternative food sources across the season; (xiii) connectivity of rice paddies (e.g. along a river catchment or across a floodplain); and (xiv) implementation of containment measures to limit movement within/between regions.

To give an indication of the scale of losses that could be suffered by rice growers given continued population-density increase and spread both within Kenya and beyond to neighbouring countries, invasion scenarios and associated economic losses over a timeframe of roughly a decade from first arrival are provided. For Kenya this period could feasibly cover a decade from 2020 as *P. canaliculata* is now present with potential to become well established and spread. However, for the other eastern African countries assessed this will depend on how well and for how long they are able to exclude the pest and remain free from establishment and associated impacts. The period of a decade is a rough approximation, guided by the scale of loss to *P. canaliculata* by rice farmers in the Philippines indicated by Naylor (1996) for 1990, following the arrival of the species in the country in 1982. Examples from Asia indicate that once present in a country, *Pomacea* can spread quite rapidly (particularly if facilitated by intentional movement), and entry into waterways and irrigation systems can allow rapid and widespread infestation of rice paddies. Some examples of rapid spread have been reported for important rice-growing countries in Asia: (i) in Taiwan 2% of the rice area was infested in 1982 increasing to 28% of the rice area by 1986; (ii) by 1986, 34 of 47 rice-growing districts in Japan were infested by *Pomacea* following its introduction in 1981; (iii) in the Philippines, the proportion of wet rice area infested rose from below 3% in 1982 to ~15% (of > 3.44 million ha) by 1991; and (iv) within 5 years of its introduction to Vietnam, *Pomacea* snail infestations were reported in every rice-growing province and three-quarters of rice-growing districts (Naylor, 1996).

As described in Naylor (1996) for the Philippines, losses to apple snail can be highly variable (for a variety of reasons, some of which are described above) but may range from < 5% to

100% depending on the region and severity of snail infestation. The stage of rice attacked is particularly important, with rice seedlings most vulnerable up to 2 weeks after being transplanted or up to 4 weeks after direct seeding. In uncontrolled fields, experimental data described indicates that damage to rice seedlings at the germinating stage can be as high as 100%, rather than an average of 20% at the transplanting stage (Naylor, 1996). Sin (2003) found at a density of three snails/m² in typical paddy-water depths damage to transplanted rice was high but lessened with increasing planting age, however, direct-seeded rice was extremely susceptible to the snail even at one snail/m²; by contrast at zero water depth the snail did not cause significant damage to rice. Direct seeding versus transplanted rice seedlings (and at what age) and depth of water, particularly early in the growing season, are important considerations for rice farmers seeking to manage losses in areas affected by invasive *Pomacea*. Rice crop losses exceeding 90% are also reported in Naylor (1996) given a snail density of eight snails/m², in an experimental setting. This would be a very high density of GAS with 1–5 snails/m² more typical in highly infested fields in the Philippines, although peak densities in low-lying regions could reach ~150 snails/m² (Halwart, 1994). Some examples of *Pomacea*-associated costs are provided in Section 2.1. However, despite the relatively long and damaging history in Asia, detailed reports of economic losses associated with the snail's invasion are quite limited. One of the most widely quoted is the analysis for the Philippines by Naylor (1996) mentioned above, cited for example in the assessment of invasive species impacts in South-east Asia by Nghiem *et al.* (2013). Following from Naylor (1996) for direct-seeded paddy, at the level of one snail/m² average production losses of 20% across affected rice-growing areas, without control measures or replanting, are feasible, and used here to calculate potential economic costs for eastern African countries (with some areas expected to lose more and others less depending on specific snail density and other key parameters as described above). Where snail control measures (hand-picking and molluscicide application) and replanting are undertaken, rice losses are reduced to 5–8% (estimated from loss calculations in Naylor, 1996), but the additional costs of these actions are 6–11% of the affected crop value in well and poorly controlled regions, respectively. Combined, the cost of apple snails to farmers when management and replanting are undertaken is estimated at 11–19% of the affected rice-production value ('Lower' and 'Upper' loss values, respectively, in Table 1). This scale of costs and economic losses will vary by region, with differences in the availability and price of molluscicides, labour and rice seed/seedlings (compared with the Philippines and between regions in the study area), but the general management approaches available are similar and the magnitude of costs indicative. It is assumed that labour costs across the predominantly smallholder-farmer production system are low, as preventative and corrective control measures (such as hand-picking and repeated replanting) can be labour intensive and may not be feasible in countries where labour costs are high (Halwart, 1994).

The specific prevalence and impact of apple snail is likely to vary considerably over the study area, with differing agroecological conditions across eastern Africa and variations in altitude, rainfall and temperatures between rice-growing regions and across seasons. However, the figures provided may be useful in planning and developing loss mitigation strategies. Broad-scale modelling of environmental suitability for *P. canaliculata* has been carried out, for example by Lei *et al.* (2017) using SDM ensemble forecasting, indicating that much of eastern Africa (along with western and central SSA) is climatically suitable for *P. canaliculata*, increasingly so with climate change. Physiologically based demographic models have also been developed (e.g. Gilioli *et al.*, 2017) which can be used to better understand population

dynamics and potential high-density ‘hot spots’ (which could be valuable to guide management efforts in eastern Africa) and these are discussed further in the modelling section (Section 1.7). It is apparent that temperature can be limiting for *P. canaliculata* distribution, with increased winter mortality in temperate regions (potentially crucial in population dynamics in Japan) and slower development to maturity compared with populations in tropical regions. However, lifespan can be longer in temperate climates and in some cases temperate summers may allow developmental rates close to those in tropical climates, possibly due to the detrimental effects of temperatures exceeding 30°C in the latter (Gilioli *et al.*, 2017). As such, despite ecoclimatic variations across the study area, for economic loss calculations the assessed ‘at-risk’ regions in eastern Africa fall within the climatic suitability envelope indicated by Lei *et al.* (2017) and the impact of *P. canaliculata* in each region is calculated at the same rate. Benefits are not considered here but are covered in other sections and thought to be greatly outweighed by the snail’s costs.

In Kenya, significant infestations of *P. canaliculata* have been observed in Mwea and spread to other regions is perhaps inevitable given the water connectivities and extensive reproduction indicated by widespread presence of egg masses (Buddie *et al.*, 2021). In addition, Mwea, located in the tropical highlands, is the primary rice-growing area in the country and in this region alone, *P. canaliculata* has the potential to affect approximately 80% of Kenya’s rice production (Samejima *et al.*, 2020) and it is this figure that is used in calculating potential losses. This level of loss would still require long-term measures to contain the pest and prevent movement of the snail to other rice-production areas. Kenya is one of many SSA countries with a growing demand for rice, relying on imports to meet requirements and seeking to increase rice production and self-sufficiency (Atera *et al.*, 2018). Additional considerations must now be addressed if *P. canaliculata* cannot be eradicated and must be managed. For example: (i) With expansion of rice production, what effect would an increase in rice irrigation have on the survival and spread of the snail (reduced drought period, water network connectivity)?; (ii) Would multiple croppings per year bolster snail populations (no fallow period)?; and (iii) What rice varieties should be grown and would direct seeding be viable or would transplanted rice suffer reduced losses?

Tanzania is a major rice-growing country, producing an average of around 3 million t/year of paddy rice (2014–2018; approaching 3.5 million t in both 2018 and 2019 FAOSTAT database, (FAO 2019)) and one of few SSA countries approaching rice self-sufficiency (along with Madagascar and Mali) (Tadesse *et al.*, 2019). Around half of production is concentrated in Morogoro, Shinyanga and Mwanza, with Mbeya, Rukwa and Tabora also important rice-producing regions (Tanzania Ministry of Agriculture, 2009; Wilson and Lewis, 2005). Rice production is carried out across the country, unlike in Kenya, where most production is focused in a single region, Mwea. To estimate the proportion of at-risk production for calculating potential losses, a scenario in which widespread snail infestation of the three key production areas (Morogoro, Shinyanga and Mwanza) – which are also the most proximate to Kenya – is envisaged, with 50% of Tanzania’s rice production affected.

Much of Uganda has good potential for rice growing, however, up to around two-thirds of rice is produced in Eastern Uganda (Nanfumba *et al.*, 2013), particularly the low-lying wetlands in the Lake Kyoga catchment and foothills of Mount Elgon. For the calculation of losses, a scenario in which the primary growing region (and nearest to Kenya) of Buginyanya in Eastern Uganda suffers widespread snail infestation is envisaged, affecting half of the country’s rice production (Uganda Bureau of Statistics, 2020).

In Ethiopia, the dominant region for rice production is Amhara to the north of the country, with as much as three-quarters of the country's production coming from the area (Tsega *et al.*, 2013; Tadesse *et al.*, 2019). Other production areas of note include Oromia, Tigray, Somali, Benishangul Gumuz and Southern Nations, Nationalities, and Peoples' Region (SNNPR). The vast majority of national production is rainfed (both lowland and upland), with limited irrigated rice. Rice is a relatively recent addition to the cropping systems of Ethiopia and to date production increases have been outpaced by increasing demand, with self-sufficiency in the crop dropping as low as 30% (Tadesse *et al.*, 2019). Ethiopia is, however, thought to have extensive areas with suitable agroecology for rice production, with as much as 30 million ha suitable for rainfed growing and 3.7 million ha for irrigated rice production (Tadesse *et al.*, 2019). There is a drive to substantially increase rice production in the country, with the crop considered strategically important for food security, to reduce poverty and to provide income for farmers (Tadesse *et al.*, 2019). Given the great distance of Ethiopia from Mwea and potential to limit incursions, with the key production area Amhara further north still, an economic loss scenario is presented for Ethiopia with widespread infestation in the lowland rainfed rice-growing district of SNNPR, bordering Kenya and producing an estimated 5% of Ethiopia's rice (Tsega *et al.*, 2013).

The losses provided in Table 1 are calculated using average rice-production levels for 5 years to 2018 (where available; fewer years for data-limited countries). These data are used because they represent the recent/current production capacity for each country, however, as net rice importers each of these countries is striving to become more self-sufficient in rice production (Tadesse *et al.*, 2019).

Table 1. Potential annual economic costs of *P. canaliculata* to rice producers in eastern Africa approximately 10 years after introduction to a country for a scenario with specific rice-production areas (provided in text) affected. Losses are provided for no management, good control ('Lower') and poor control ('Upper').

Country	Proportion of national production at risk	National production (t) (5-year average 2014–2018)	Crop value (US\$/t) (average 2014–2018 where available)	Projected cost without snail control (US\$) [~10 years]	Projected cost with snail control (US\$) [~10 years]	
					Lower	Upper
Ethiopia	0.05	137,080	414	568,086	312,447	539,682
Kenya	0.8	108,487	558	9,692,698	5,330,984	9,208,063
Tanzania	0.5	2,900,801	347	100,764,157	55,420,287	95,725,950
Uganda ^a	0.5	248,848	440	10,950,852	6,022,968	10,403,309

^a Uganda crop value is estimated from the average of Ethiopia, Kenya and Tanzania.

A targeted expansion is driven by the Coalition for African Rice Development (CARD) which seeks to greatly increase rice production in SSA to fulfil the ever-growing demand for this staple crop across the region (see Section 1.1). The major expansion in rice production underway across SSA, but particularly relevant to eastern Africa for this assessment, emphasizes the growing importance of rice both for food security and as a cash crop, but also the increasing risk of and potential losses to key pests such as apple snail. Present and near-

term losses are likely to be important, particularly for Kenya where *P. canaliculata* has a foothold and is already affecting production, but without efforts to manage populations and contain the snail's spread, future losses across the region could be much greater, as has been observed in parts Asia with a long history of apple snail invasion and associated impacts across a huge scale of rice production. Tanzania particularly is a large-scale rice producer in the region and could suffer costly losses and potential food insecurity under widespread snail infestation. The losses to *P. canaliculata* may also be additional to those for other pests and diseases and will primarily affect smallholder farmers who are responsible for the bulk of rice production and depend on the crop as a staple and for sale to market. *P. canaliculata* impacts on rice are expected to be the most important for the areas assessed, but other crops grown in the paddy-type environment may also be at risk, as seen with taro in Hawaii (Halwart, 1994). Impacts on other crops would result in economic losses additional to those provided for rice. The estimates provided also do not account for human health and ecosystem impacts, each of which could be significant but difficult to quantify. Improved modelling specific to eastern Africa (or SSA) to provide higher resolution mapping of at-risk and hot spot areas for *P. canaliculata*, ideally combined with field studies to 'ground truth' the models would enable more accurate assessments of crop loss and risk.

To date, delimiting surveys in Kenya indicate that *P. canaliculata* is present only in Mwea, however, this is the major rice-production scheme in the country. If practicable, containment would be desirable for rice production across the region, with measures implemented to prevent the movement of snails along water courses or via infested plant materials essential. To fundamentally halt the spread of and losses to *P. canaliculata* across the region (at least until a next introduction event), eradication of the population(s) in Mwea would be extremely advantageous. This approach can be achievable, particularly if enacted swiftly and before it becomes too widespread, as has been demonstrated at various scales in Europe against *Pomacea* spp. For example eradication of *Pomacea* spp. is thought to have been achieved in an artificial pond in Switzerland, an area of rice fields in Girona, Spain and also in the French municipality of Fréjus (EFSA *et al.*, 2020). The challenge of attempted eradication of *Pomacea* spp. once well established and spreading, however, can be significant. *Pomacea* spp. of the '*canaliculata* complex' discovered in rice paddies in the Ebro Delta, Catalonia in Spain in 2009 have been under ongoing eradication efforts, however, are spreading along the riverbeds of the Ebro river (EFSA *et al.*, 2020). Some control and limitation of agricultural impact has been achieved, but at a cost of €5.3 million in the period 2010–2012 and with a further €5 million allocated by the Government of Catalonia for the period 2014–2020 (Bertolero and Navarro, 2018). If feasible, rapid investment in eradication (or effective control and containment) in Mwea and surrounds could significantly reduce longer term losses across the region. As described in Section 1.6, spread into the rice-production area of Ahero, for example, could lead to infestation of Lake Victoria, its surrounding rice-production regions and beyond via river catchments including major tributaries such as the White Nile, with major implications for the region.

In the broader context of SSA rice production, losses in eastern Africa could be significant and a risk to food security and income. However, strong measures must also be implemented to prevent movement across the continent to the tropical and subtropical rice-growing regions of West Africa, where production can be on a huge scale (e.g. Nigeria ~8 million t/year of rice paddy), conditions may be even more conducive to snail establishment and spread and potential impacts on food security and farmer income could be considerable.

2.3 Potential impacts of invasive apple snail on trade

Three main value chains can be identified within the Kenyan rice sector (i) the vertically integrated large farm chain; (ii) the highly concentrated chain on the National Irrigation Board (NIB) schemes; and (iii) the traditional market value chain of the non-NIB irrigated production and rainfed producers.

Kenya is a member of both the East African Community and COMESA (the Common Market for Eastern and Southern Africa) regional trading blocs. It is bound by the common tariffs that apply to the member states of these trading blocs but there is a lot of informal cross-border trade with neighbouring countries. There is also rice seed movement across the borders which may not have undergone formal certification processes that could be detrimental to the rice subsector development.

Plants other than rice grown in the paddy environment or in proximity to *P. canaliculata* populations may also be at risk of harbouring snails which could then be moved around within the country or across national borders. An example of this type of movement occurred when water spinach (*Ipomoea aquatica*) imported to Malaysia from Thailand was found to be contaminated with young snails, which led to a temporary government ban on the import of vegetables into Malaysia from Thailand (Naylor, 1996; Halwart, 1994). *Pomacea* spp. are classified as quarantine pests in the European Union (EU), and the trade of aquatic aquarium plants (considered the main potential pathway of spread) is regulated (EFSA *et al.*, 2020). To avoid the risk of produce export bans and to prevent the spread of *P. canaliculata* to currently unaffected trading countries or areas (with the associated responsibility for the introduction of a damaging invasive pest), measures may be required to ensure crops traded out of Mwea are snail free, for example with certified 'clean' production areas or suitable treatment of plant material to be traded. Plant material grown to be propagated elsewhere would be a particular risk, as is the movement of machinery between rice-growing schemes. Certainly, an assessment of crops grown and traded out of Mwea would be valuable to establish risk pathways. There is therefore need to have quarantine regulation, traceability and inspection rules by all the partner states.

3 Control methods

Any attempts at management should be grounded in a clear understanding of the identity and biology of the pest species so that control measures can be more reliably developed and quarantine efforts more targeted (Eversole, 1992; Halwart, 1994; Cowie, 2002). The molecular diagnosis of *P. canaliculata* in Kenya provides crucial confirmation and should highlight the need for rapid response and early intervention to halt the spread and monitor the extent of the invasion. *P. canaliculata* is the most widespread and damaging species of *Pomacea* introduced around the world and as such, the bulk of the literature on management of apple snail pests undoubtedly refers to this species. However, because of the past confusion regarding the identities of the species introduced to Asia and elsewhere, some of the information purportedly relating to *P. canaliculata* may relate to either or both *P. canaliculata* and *P. maculata* (CABI, 2020).

In the main, eradication of invasive snails has proved extremely difficult (Cowie, 2011) and is only likely to be achievable with a rapid response in the very early stages of invasion and when the infestation is highly localized (Cowie, 2002). The consequences of delayed intervention have been evident in many countries: in Vietnam it took only 5 years from initial introduction

for *Pomacea* spp. (probably both *P. canaliculata* and *P. maculata* (Hayes *et al.*, 2008)) spreading to every rice-growing province of the country (Naylor, 1996). Similarly, in Cambodia, recommendations to eradicate the snails from a few isolated areas were not headed in time and they subsequently spread to at least ten provinces (Preap *et al.*, 2006).

Economic incentives promoting the use of snails as a protein-rich food source have been controversial (Levin, 2006) and have the potential to precipitate further introductions and ultimately exacerbate the problem.

Various management measures have been trialled to control the impact and spread of invasive *Pomacea* species around the world (Joshi *et al.*, 2003; R.C. Joshi, 2005a) and in order to facilitate best practice in Kenya, regulations need to be in place to facilitate coordinated action and raise awareness of the threat they pose. Farmers in Asia have tended to base their actions on past experience and the potential damage caused by *P. canaliculata* in rice has been shown to be closely linked to water depth, seedling age and pest density, in decreasing order of importance (Teo, 2003). Therefore appropriate agricultural practice will play a key role in limiting impact.

The challenge will be to prevent *P. canaliculata* damage through low-cost, technically efficacious and environmentally sustainable management options (R.C. Joshi, 2005a).

Measures are needed in terms of both regulation and farmer/public education to reduce the negative consequences, safeguard yields and income for rice farmers, prevent further introductions and prevent spread across the African rice belt. The following sections provide a synthesis of control methods from around the world.

3.1 Chemical control

For many countries detecting *P. canaliculata* invasion, the first responses have tended to be drastic and involved excessive spraying of indiscriminate molluscicides (many of them banned) with unwanted side effects (traditional pest resistance, elimination of non-target beneficial animals such as fish and frogs, phytosanitary issues, phytotoxicity, modification of size distribution of the population favouring larger individuals and risks to human health) (Ochoa Chumaña and García Onofre, 2012; Horgan, 2017). Wetlands are often located close to or even connected to rice fields and this means that snail control efforts that are focused only on rice fields are likely to be short lived, as new snails enter the fields from nearby wetlands through irrigation canals and during floods (Carlsson *et al.*, 2004b).

None the less, in some countries, the application of chemical molluscicides remains one of the most utilized methods of snail control (Khay *et al.*, 2018).

This section consolidates the literature on chemical control of invasive apple snails, however, many pesticides historically used are either no longer recommended or indeed discontinued. Before using a molluscicide product, users should ensure the product is registered with the national regulatory body. Regulatory authorities should be consulted before implementing snail control programmes. There are no synthetic molluscicides registered for use in Kenya.

Historically, snail control has relied primarily on a single compound, namely, niclosamide World Health Organization (WHO) classification U, unlikely to present acute hazard). Currently, it is the only compound recommended by WHO Pesticide Evaluation Scheme (WHOPES) for use as a molluscicide globally because of its low toxicity to mammals and low concerns of pesticide residue, however, it has been found to be toxic to fish and other aquatic animals. It is not registered for use in Kenya (PCPB, 2021). Niclosamide was selected as a

molluscicide in the 1950s after screening well over 20,000 compounds for toxicity against the schistosome-transmitting snail *Biomphalaria glabrata* (Andrews *et al.*, 1983). Application in rice fields was recommended immediately after transplanting rice (Dela Cruz and Joshi, 2001). Joshi *et al.* (2004) observed the detrimental effects of niclosamide 250 EC at pre-seeding in direct-seeded rice culture. Seedlings treated with niclosamide 250 EC had low and uneven emergence and were stunted. Uneven crop establishment also exposed the seedlings to invasive apple snails' damage for a much longer time.

Endosulfan (WHO Class II, moderately hazardous), fentin acetate (WHO Class II, moderately hazardous) and the now obsolete calcium cyanamide have also been used (Halwart, 1994; Dela Cruz and Joshi, 2001). In Thailand, apple snail has been effectively controlled using copper sulfate (WHO Class II). Wada (2004) reported use of metaldehyde (WHO Class II) for direct-seeded rice fields in the Philippines.

In the Philippines, where *Pomacea* are widely considered to be the most serious rice pest, about 40% of farmers applied pesticides for control (Revillia *et al.*, 1991; Ketelaar, 1993). However, a number of species are also reportedly suffering from the direct impacts of molluscicides employed to reduce gastropod species, which are vectors of bilharzia (Kristensen and Brown, 1999).

In Malaysia, synthetic molluscicides have been used to try to control *P. canaliculata* without much success. A study by Sisa *et al.* (2016) found that spot spraying higher concentrations on the egg clutches with metaldehyde (5%) and niclosamide (81.4%) could have significant impacts on hatchability of eggs and could provide a more confined treatment, reducing the amount of molluscicides used and thus making it more economically feasible to use for resource-poor farmers.

In China, over 2000 chemicals have been developed and used since the 1950s for snail control but among these synthetic molluscicides, only niclosamide is recommended by the WHO. Therefore, a 50% wettable powder of niclosamide ethanolamine salt (WPN) is the only synthetic compound available in China, where it has been widely used in snail control in areas endemic for schistosomiasis (Xia *et al.*, 2014). A novel molluscicide, quinoid-2', 5-dichloro-4'-nitrosalicylanilide salt, has been developed that has the same molluscicide effects as WPN but is cheaper and is significantly less toxic to fish while another, a niclosamide suspension concentrate, was found to be physically more stable, more effective, and less toxic than WPN (Dai *et al.*, 2008).

Hanifah *et al.* (2018) report on molluscicides registered in Brunei Darussalam, with niclosamide ethanolamine (traded by Bayer Company, Malaysia as Bayluscide) recommended for use in rice fields, but it is likely some rice farmers would have also used other available and more hazardous chemicals like metaldehyde in their paddy fields. Molluscicide formulations are sold under a government incentive programme and are applied twice per season, during the first month after transplanting, when young rice seedlings are particularly vulnerable to attack.

Dela Cruz *et al.* (2003) reported a basal application of complete fertilizer in combination with urea at the recommended rate incorporated into the soil could reduce snail populations by 54%, thus preventing damage to the crop immediately after planting. However, while higher fertilizer concentrations have been found to increase snail mortality, they have also been highlighted to cause phytotoxicity, to impact on beneficials and to lead to eutrophication which in turn increases snail recruitment (Stuart *et al.*, 2014).

Chemicals used for the control of invasive apple snails are mostly persistent, dose-cumulative organotins which can have negative consequences for many organisms in the natural environment, including people, with reports of health effects such as loss of nails, skin problems, blurred vision and blindness (Mochida, 1991).

3.2 Microbial pesticides

Little is known of microorganisms associated with ampullariids that might be useful in control. In the Philippines, 12 bacterial isolates were tested, seven of which were effective against *P. canaliculata* (Cowie, 2002). Treatment of *P. canaliculata* eggs with the parasitic fungus *Paecilomyces lilacinus* led to 100% mortality of 1-day-old juvenile snails, susceptible to the conidia and only 12% of eggs hatched in contrast to 100% in controls (Maketon *et al.*, 2009). However, the fungal susceptibility of juvenile snails was found to decrease as they aged, limiting its use as a biological control agent (Schnorbach *et al.*, 2006). Further research into microbial pesticides would be beneficial.

3.3 Botanicals

Due to the high cost, toxicity, environmental contamination, and possible development of snail resistance to chemical molluscicides, natural molluscicides are rapidly being developed and a range of plant extracts with molluscicide properties have been identified to replace toxic chemicals (Joshi *et al.*, 2005; Horgan, 2017). Many plant species have been assessed for molluscicidal activity, and some plants have been found to have potential value, such as *Yucca desmetiana*, *Nerium indicum*, *Eucalyptus globulus*, *Jatropha gossypifolia* and *Saraca asoca* (Yang *et al.*, 2017). Several plants have active ingredients that may hold potential as biodegradable molluscicides, including saponins, flavonoids, steroids, tannins and other secondary metabolites (Valverde *et al.*, 2010).

Among these, tea tree meal (from *Camellia sasanqua* seeds), a by-product of tea tree oil extraction has gained popularity in some countries and is noted to give up to 95% mortality (Yang *et al.*, 2006). Other plant extracts developed for control which have variable efficiency depending on water conditions include quinoa (*Chenopodium quinoa*), *Solanum* spp. and *Eucalyptus* spp. (San Martin *et al.*, 2008; Horgan, 2017), though registration has proved difficult for agricultural use because their safety has not been evaluated and some have lethal effects on beneficial aquatic organisms.

In Indonesia, the search for more eco-based cultural control techniques as alternatives to molluscicides has included the use of locally available and cost-effective plant-based traps (Syamsul *et al.*, 2016). Results showed jackfruit skin and damaged pomelo were relatively more effective than tapioca leaves, water spinach leaves and old newspaper. Snails also displayed preference for fresh materials as compared to rotten materials. Demetillo *et al.* (2015) suggested *Cymbopogon citratus* (lemongrass) could be a potentially non-harmful organic substitute to synthetic molluscicide since crude extracts could alter the normal growth of *P. canaliculata*, preventing embryonic development, altering the incubation or hatching period of the egg and increasing mortality rates on both adult and juvenile stages. Antifeedant activity of essential oil from *C. citratus* and betel (*Piper betle*) were also suggested by Latip *et al.* (2017) for controlling GAS.

A pesticide formulated as an extract from the neem plant (*Azadirachta indica*) was also trialled in Malaysia in the laboratory with some effectiveness but has yet to be evaluated in the field (Latip *et al.*, 2013). Huang *et al.* (2003) found powder extracts of soap nut pericarp from

Sapindus mukorossi (Sapindaceae) attained 62% mortality to GAS in paddy fields while bioassay experiments with a new acetylated triterpene saponin, hederagenin, also revealed molluscicidal effects against *P. canaliculata*. However, it was concluded that farmers tended to prefer the use of conventional pesticides as none of the botanical molluscicides identified had been produced commercially (Joshi, 2007).

Among the many molluscicidal compounds investigated, saponins are considered to be the most important group owing to their high molluscicidal activity (Yang *et al.*, 2017).

3.4 Resistant varieties

In South-east Asia, rice plants were also found to be more resistant once they exceeded a certain age, 20–40 days depending on variety and a study conducted by Dela Cruz *et al.* (2002) reportedly found least-preferred varieties to be PSB Rc36, PSB Rc38, PSB Rc40 and PSB Rc68.

In Africa, agronomic development has enabled new varieties of rice, named ‘New Rice for Africa’ (NERICA) to be investigated; crosses between *O. glaberrima* and *O. sativa* combine the hardiness of the African species with the productivity of the Asian species (Linares, 2002) and can also shade out weeds, resist pests and droughts, grow in poor soils, and mature 30–50 days earlier than traditional varieties, increasing productivity. This means that yields can be increased without major inputs and this could help offset losses to apple snails.

While there are no varieties resistant to the feeding of apple snails, modern high-tillering plant types can hold better potential to compensate for damaged tillers over time than low- and medium-tillering types. This may be helpful in long-duration (late-maturing) varieties, but may not help in short-duration (early-maturing) ones (Ranamukhaarachchi and Wickramasinghe, 2006). Use of high-tillering rice varieties such as PSB Rc36, PSB Rc38, PSB Rc40 and PSB Rc68 has been suggested (PhilRice, 2001; Dela Cruz *et al.*, 2002).

Flooding fields with seawater has been used as a strategy to curb the presence of the invasive apple snail, taking advantage of the fact that it does not tolerate high salinity levels. Unfortunately, the residual salinity following the treatment with seawater generates losses in the crops which, in the worst cases, can affect up to 30% of production. As salt stress is one of the main environmental factors affecting rice growth and rice yield worldwide, major efforts have been made to increase the salt tolerance of rice through conventional and molecular breeding worldwide, but the extent of increase in salt tolerance has been limited, especially under field conditions (Hoang *et al.*, 2016). In Spain, an EU-funded effort (NEURICE, 2016) has been focused on developing strategies for rice productivity, stability and quality by breeding hybrid varieties that carry the salt-resistant gene. These new varieties of rice may allow the sector to have new tools to combat the salinization of fields arising from rising sea levels due to climate change and to combat the apple snail (*Pomacea insularum*) invasion (IRTA, 2020). Of these, six varieties have already begun the process of varietal registration to be legally marketed.

3.5 Biological control

The versatility of a biological control approach for use in paddy fields as well as canals and ponds (Yusa and Wada, 1999) could be advantageous for snail control but none of the predators of apple snails in their native ranges have been shown to have a significant impact on their populations. *Pomacea* spp. have complex immunological defences, which include

molecular and cellular components and as well as barrier organs which means they are not susceptible to infestation by many parasites.

Over the last decade or so, various *P. canaliculata* biocontrol candidates have been observed and investigated with variable results (Yusa *et al.*, 2006; Guo and Zhang, 2015). The relatively small size of *P. canaliculata* hatchlings and their relatively thin shells allow them to be readily consumed (Hayes *et al.*, 2012). An additional suite of predators target juvenile apple snails in their native range including crayfish (*Procambarus* sp.) and aquatic insects (water bugs, *Belostoma* sp.; dragonfly naiads, *Coryphaeschna ingens*; and diving beetles, *Dytiscus marginalis*) (Snyder and Snyder, 1971). However, in general, apple snails become decreasingly vulnerable to predation with size, and after reaching 20 mm, relatively few predators in the non-native range in Asia can prey on them. The effectiveness of carp, tilapia, ducks and turtles has been evaluated in the field in the context of biological control (Cagauan and Joshi, 2002; Yusa, 2006; Yoshie and Yusa, 2008).

In some Asian, southern Latin American countries and in taro fields in Hawaii, the use of various duck varieties has proved a moderately effective, albeit expensive, strategy (Levin, 2006). Ducks are bred and herded into rice fields to eat young snails either prior to transplanting or when seedlings are 4 weeks old (5–10 ducks/ha), although results varied with race of duck and time of release (Teo, 2001; Brito and Joshi, 2016). Paddy-field dermatitis in farmers (Cagauan and Joshi, 2003) from the fluke-vectoring duck faeces has also deterred farmers from using this method.

The African catfish (*Clarias gariepinus*), Nile tilapia (*Oreochromis niloticus*) and common carp (*Cyprinus carpio*) have been released in paddy fields to predate snails (Halwart, 1994, 2006; Halwart *et al.*, 1998; Ichinose *et al.*, 2002) and as the more adaptable species in farmed environments, the common carp has been recommended for use in rice cultures at a density of ten fish per plot or 2041 fish/ha (Teo, 2006). Halwart *et al.* (2014) found common carp could suppress snail populations (including larger snails) by 58–87% compared to 48–87% by Nile tilapia, however, these proved ineffective against infestations by snails of a larger size as they ingest the whole shell. In Japan, black or Chinese carp (*Mylopharyngodon piceus*) and *C. carpio* fingerlings have been released to feed on newly hatched snails (Mochida, 1991). The practice of raising Chinese soft-shelled turtles (*Pelodiscus sinensis*) has also been adopted for use in wild rice fields (*Zizania latifolia*) in China and were a means of increasing revenue. However, the practical limitations of using fish, which need water deeper than normal rice fields, and ducks which inherently need care, infrastructure and rearing experience and maintenance preclude widespread use as biocontrol agents and are often incompatible with modern agricultural practices (Yoshie and Yusa, 2008). Furthermore, the use of molluscivorous fish for biocontrol should focus not only on potential effectiveness but also on the undesirable consequences of these introductions on non-target plants and animals (Ip *et al.*, 2014).

Research by Savaya-Alkalay *et al.* (2018) found that the development of all-male prawn populations of *Macrobrachium rosenbergii* had the potential as a biocontrol agent over hatchlings and adults of *Pomacea*, with medium to large prawns preying on snails up to 15 mm in size, and small prawns effectively consuming snail hatchlings. Salcedo (2013) evaluated the pathogenicity of the nematode *Heterorhabditis bacteriophora* and showed that the inoculation of up to 16,000 nematodes per snail leads to 100% snail mortality in 96 h.

In the Asian-introduced range, unintentionally introduced ant species such as fire ant (*Solenopsis geminata*) and *Pheidologeton* spp. were found to eat eggs (and newly hatched

snails) in the field despite their toxicity (Yusa, 2001, 2006), but their impact has not been evaluated. Predators like leeches (Ozawa *et al.*, 1989), firefly larvae (Kondo and Tanaka, 1989) or dragonfly larvae (Suzuki *et al.*, 1999) have been found to consume snails in laboratory conditions but few predators are reported in the field (Yusa *et al.*, 2000). Both rats and snakes have also been observed to prey on invasive apple snails (Ngoc, 2002; Dela Cruz *et al.*, 2003).

Apple snails have evolved a number of remarkable life strategies to evade predation: as adults, they are moderately amphibious, their tubular siphon allowing them to breathe air while underwater, making them less vulnerable to snail-eating birds and their shell 'door' enabling them to close themselves off to predators and survive in the mud in periods of drought. By depositing their eggs above the waterline, cemented in a calcareous clutch, these snails can also defend their progeny against fish and other water inhabitants. Calcium-binding protein allows *Pomacea* to form a hard eggshell that physically protects the egg and prevents them from drying out. Apple snails avoid predators by crawling out of the water, situating themselves near the water surface, burying themselves in the mud, and falling from substrates on which they were crawling (Snyder and Snyder, 1971; Ichinose, 2002; Carlsson *et al.*, 2004a; Aizaki and Yusa, 2009, 2010). In *P. canaliculata*, this behaviour is size dependent: hatchlings tend to crawl out of the water; juveniles mainly bury themselves or use near-surface habitats; larger snails are less responsive (Ichinose, 2002). While these behavioural responses are largely evolutionary, there have also been learned adaptations when exposed to novel predators (Aizaki and Yusa, 2010) and they may also be predator specific (Ueshima and Yusa, 2015).

Irrespective of their bright colouring, the lack of predators in their native South American range could also be attributed to their unpalatability. Dreon *et al.* (2014) found that the eggs are filled with a neurotoxic perivitellin called PV2 which helps defend against terrestrial predators. These life strategies, together with the relative absence of natural predators in the invaded range, have allowed *P. canaliculata* populations to rapidly establish and grow in new habitats (Brito and Joshi, 2016). Snails can also drop to the bottom of the water body and bury themselves in the mud until they get into contact with a hard object like a stone (Chan, *et al.*, 2009).

Halwart (1994) recommended that specific natural enemies for *P. canaliculata*, such as the predatory Sciomyzidae, should be sought in its native home in South America but ultimately no truly successful biocontrol options have been found for *P. canaliculata* to date and indeed their use may in turn have negative impacts on other aquatic animals and plants (Yoshie and Yusa, 2008; Wong *et al.*, 2009). As such, stringent evaluation prior to introduction would be required.

3.6 Good agricultural practice

Specific agricultural practices have been found to go some way to mitigate impact, with some of the most effective methods relating to land preparation and crop establishment. Studies have concluded that the magnitude of crop damage by invasive *Pomacea* depends on the technique used to grow rice (Wada *et al.*, 1999; Sanico *et al.*, 2002; Teo, 2003; Wada, 2006, in Burlakova *et al.*, 2009). Snail damage to rice seedlings is correlated with the depth of water on the field, and damage decreases as seedling age increases. Increasing seedling age before planting from 2 to 5 weeks resulted in significant reductions in snail damage (Sanico *et al.*, 2002). Arfan *et al.* (2016) found cultivation of rice using 28-day-old plants and transplanting seedlings at 2 cm water level reduced the damage by *Pomacea* spp. and achieved

comparable yield to controls. Planting healthy and vigorous seedlings is also important. Despite the advantages of transplanting older seedlings, however, under high snail densities, even older seedlings will succumb to heavy damage (Sanico *et al.*, 2002) and this should be combined with other damage reduction methods.

Limited moisture conditions immobilize and prevent the snail from causing severe damage even at high densities. Dry direct seeding, which uses a minimal amount of water in the early stages of growth, can limit snail damage compared to other methods (Teo, 2003) and increased seeding rate can also compensate for snail damage. Wada *et al.* (1999) found that draining after sowing/transplanting greatly reduces snail damage, and 3 weeks of drainage can almost prevent all damage. Since snails can withstand long periods of desiccation, draining will not kill them but because standing water facilitates their movement and they are immobile at depths less than half of their shell height, periodic draining of fields to a depth of 1 cm can effectively prevent *P. canaliculata* from moving and feeding (Wada *et al.*, 1999; Wada, 2004). Farmers with their own pumps can manage water levels better than those served by large irrigation systems. Constraints to draining as a management tool are that rice seedlings may become stressed under dry conditions and that drained fields may suffer from greater weed incidence and competition with delicate rice seedlings (Horgan, 2017).

Wang *et al.* (2012) found water spraying and in particular submersion of eggs could dramatically decrease the hatchling rates to maximal 5.8% and increase the hatchling duration up to 26.4 days with both time of initiation of water treatment and the frequency of spray proving critical.

Because of their conspicuous and generally accessible egg masses, hand-picking eggs (and matured adults when they are active in the morning and evening) can also prove effective as an early intervention method (Bernatis and Warren, 2014). Furthermore, by placing bamboo stakes around the fields to provide places for snails to lay eggs, this can facilitate collection/destruction of eggs (Jahn *et al.*, 1997). Dark pink eggs have been freshly laid and adult snails may be located close to the base of the stake, while pale pink eggs are close to hatching (Levin, 2006).

Construction of small canals or trenches, 15–25 cm wide and 5 cm deep for instance, along the edges of rice plots after the final land preparation, facilitate drainage and act as attractants for snails making manual collection or killing easier (PhilRice, 2001). Such canals can be dug for a distance of 5–15 m depending upon the degree of infestation of snails. Salleh *et al.* (2012) suggest using attractants like rotten jackfruit skin, papaya, cassava leaves, tapioca leaf and spinach and trap crop cultivation is also suggested by Gilal *et al.* (2016). These hand-picking methods, baited or not, while simple and potentially effective to remove congregating snails, are, however, very labour intensive (Horgan, 2017).

The use of physical barriers is also recommended, such as wire mesh or woven bamboo screen at the water inlet and outlet of the paddy planting area to prevent ingress and exit of snails to and from rice fields. Again, these methods can prove very labour intensive, particularly in highly infested areas, as they require frequent monitoring and cleaning (depending on mesh size) and if left unattended, could cause flooding. Overall, agricultural options for apple snail control recommend a combination of hand-picking and/or paddy rotation with canal screening could provide effective and cheap control. Removal of snails by hand-picking during the period from the final harvest of the preceding crop to the final harrowing for the succeeding crop reduces the snail threat for the next crop (Wada, 2004). Recognizing the

dynamics of water flow surrounding the fields can also help determine likely sources of invasion.

In Spain, paddies have been flooded with seawater in an attempt to control snail invasions (Loctier and Hackwill, 2018) but associated damage to the rice crop makes this a controversial method.

In direct-seeded rice, crop rotation may help reduce attack (Wada, 2004). When the soil is drained for the dryland crop, snails will burrow until the conditions become suitable for them. Using highland crops that require good soil aeration can render snails inactive until they starve and die. An alternate crop planted in rice fields in Japan, for example, is soybean, however, there are no research results on the minimum time period which the snails can survive and crop rotation may not be practical in marshy areas and those with frequently high-water levels or stagnant water. The System of Rice Intensification (SRI) is gaining popularity in many rice-growing regions of the world, including Kenya and is based on a principle of reduced water use and greater yields (Kaloi *et al.*, 2020). Though the economic returns of SRI are reportedly higher than conventional flooding systems, the labour requirement of SRI are reportedly high during the initial stages of land preparation and weeding (Kaloi *et al.*, 2020). Any systems used and/or promoted in the rice-growing schemes in Mwea and other areas in Kenya should be mindful of the recommendations for snail control and ensure compatibility.

3.7 Integrated pest management (IPM)

Farmers globally have found a suite of practices, used in combination and taking a holistic approach, help to minimize snail damage. The key to success appears to be heightened vigilance and fine-tuning control practices to the environment and conditions.

One of the most important actions when a pest, such as this one, is detected is outreach education: informing and training farmers to help them contribute to reducing the impact and finding appropriate channels and formats to relay information. Rodriguez *et al.* (2017) reviewed actions taken in Ecuador where control measures were largely unsuccessful and slow to be implemented following first reports of the pest in 2005. The need for coordinated strategies and affordable recommendations which can be implemented by small-scale farmers with limited capacity for economic response were highlighted. Achandi *et al.* (2018) highlighted the importance of extension and advisory services for delivery and dissemination of information and new agricultural technologies to resource-poor farmers. Furthermore, gender-based constraints among women producers and workers in rice-hub-related activities need to be addressed to enhance the impact extension services can have. For instance, increasing the number and the interactivity of demonstration plots to allow better observation and adoption, and creating centralized and easily accessible communal spaces where flexible training, extension services (farmer field schools) and farmer-to-farmer exchanges and cooperation in management can be organized.

Summary and recommendations on control methods

The official identification of *P. canaliculata* in Kenya (Buddie *et al.*, 2021) brings into sharp focus the need for rapid containment and KEPHIS have proposed measures to do so which reflect mitigation and management options recommended around the world. These include: (i) training and awareness raising in all rice-growing regions; (ii) use of physical barriers where water enters and exits fields; (iii) hand-picking snails and eggs; (iv) community-based snail management; (v) fast track pesticide registration; (vi) change cropping systems and planting

patterns (avoid ratooning); (vii) manage water levels; (viii) emergency pesticide application; (ix) use of biocontrol and natural repellents; and (x) identify pathways for movement and incursions. Table 2 provides a synthesis of management and best practice recommendations for a range of stakeholders.

Given the relatively localized presence of snails, rapid response and early eradication in the affected agricultural area should be prioritized and preparation and implementation of a coordinated snail containment or eradication plan is urgently needed. Delimiting surveys (considering local and regional spread through connected fields, canals, rivers) and a census of the degree of infestation should be undertaken. Training and information to raise awareness should be disseminated to farmers to alert them of the threat as well as the suite of management and preventative measures available to mitigate spread. Intensive monitoring, through ongoing censuses is also recommended to provide insights regarding not only the impact of initial implementation, but also highlight where/when rapid corrective action is necessary (e.g. delimitation of demarcated areas, buffer zones around the infested areas, the concerted, community-based destruction of the pest in this area, enhanced hygiene protocols for any agriculture and aquaculture machinery).

Many countries and other administrative regions have developed quarantine restrictions related to *Pomacea* spp. and these should be adopted, if not already, together with investments to support consistent inspection. Identifying invasion risk pathways and preventing the movement of snails, either accidental along water courses or human mediated via traded infested plant materials or contaminated equipment is essential.

Without coordinated and decisive action, the invasive apple snails will continue to spread across both irrigated and rainfed lowland rice areas incurring serious crop losses or resorting to chemical concoctions as registered molluscicides are not readily available in the agrovets. Aside from phytotoxic damage to the rice crop, use of pesticides in water will have negative impacts on non-target fauna and flora including human health and the environment. Thus, long-term control and containment is crucial to reduce ecological and economic losses.

With a large number of invasive pest species affecting crops across Kenya, the recommendation to establish a collective technical working group on invasive species in the country has been proposed which would aim to prioritize and spearhead management efforts of species threatening livelihoods and food security. This unit should provide much-needed support and coordination to tackle invasions such as apple snail.

Table 2. Recommendations on management and best practice.^a

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
Monitoring	<ul style="list-style-type: none"> Visual inspection for adults and egg masses should be carried out in rice fields, irrigation and drainage canals and connected rivers with suitable habitat for the snails Seedling damage should be monitored up to the vulnerable rice growth stages regularly (every week) (ETLs: one snail and three snails/2 m², for direct-seeded and transplanted rice, respectively) Use bamboo stake traps to observe egg masses (every 5 m) Observe natural enemies (birds, snakes, water bugs) 	<ul style="list-style-type: none"> Ongoing and regular monitoring and mapping of spread Regular scouting and surveillance for egg masses and adults should be carried out in rice fields, irrigation and drainage canals and connected rivers with suitable habitat for the snails Seedling damage should be monitored up to the vulnerable rice growth stages regularly (every week) (ETLs: one snail and three snails/2 m², for direct-seeded and transplanted rice, respectively) Use bamboo stake traps to observe egg masses (every 5 m) Observe natural enemies (birds, snakes, water bugs) 	<ul style="list-style-type: none"> Determine the magnitude and impact of the apple snail incursion, delimit spread and identify risk pathways for entry and movement Facilitate certification scheme for clean trading and buffer zones to limit spread from infested areas Develop action plan and actors to raise awareness of problem and its impacts, improve participation in community and protect snail-free zones Develop an array of cost-effective, clear and harmonized monitoring protocols to be rolled out to farms. Issue invasive species alert with clear reporting mechanisms (phone, email, regional coordinators) and appoint national agency or regional agencies responsible for rapid response to new incursions 	

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
Good agricultural practice	<ul style="list-style-type: none"> Remove and destroy snail and egg masses from field by hand or mechanically (use bamboo stakes and traps). Organize field days to collect and destroy snails. Egg masses/snails collected are either crushed or left in dry areas to desiccate and die Unmanaged water supply in the farm can aggravate invasive apple snail infestation. Continuous source of water enhances snail growth and development, which results in rapid growth, reproduction and dispersion of snails A well-levelled field facilitates water management and this plays a big role in controlling movement and feeding activities of the snails Raise healthy and vigorously growing seedlings for transplanting. Raise these in low-density nursery beds (i.e. less than 100 g seeds/m²) Seedlings should be sturdy enough to discourage the snails from attacking them. They should be at the three-leaf stage or 21–25 days old before transplanting. Sturdy seedlings have erect, light- 	<ul style="list-style-type: none"> For rice and taro fields, use plants from areas that are known to be apple-snail free and ensure material is examined closely Use screens/barriers but ensure these are cleaned regularly to reduce obstruction and chances of flooding Coordinate timing of control measures across farms in connected systems Coordinate long-term fallows within the whole farming system to reduce movement of snails and monitor regularly, reducing egg-laying sites and keeping vegetation down Ensure snail-free water sources to avoid reintroduction Clean tools and equipment after every use Observe good water management, keep levels shallow when planting and use bait to concentrate snails for hand-picking 	<ul style="list-style-type: none"> Disseminate information on good agricultural management options and low-cost rapid action for affected areas and support community mobilization and synchronization of efforts 	<p>Reduce snail populations as quickly and persistently as possible</p> <p>Burning vegetation and removal of plants along riverbanks to prevent egg laying and survival of snails will have a negative effect on flora and fauna of river ecosystems in wetlands when applied on a large scale and over many years</p>

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
	<p>green-coloured leaves with long fibrous roots</p> <ul style="list-style-type: none"> • If snails are a big problem, transplant 25–30-day-old seedlings to reduce the snail attacks for early maturing (90–105 days) rice crops and 30–35-day-old seedlings for late-maturing varieties • To reduce missing hills from snail damage, multiple seedlings per hill can be planted • Keep shallow water depth of 1–2 cm from transplanting. In direct-seedling, pre-germinated seeds should be broadcast to saturated field with 1 cm water depth. Farmers should drain water from the field the day after broadcasting. Keeping the field drained for 2–3 weeks after seeding is the most effective way to avoid snail damage in direct-seeded areas • Drain the field occasionally to limit snail mobility and feeding activity • Construct small canals (e.g. 15–25 cm wide and 5 cm deep) after the final land preparation around field edges and inside 	<ul style="list-style-type: none"> • Keep weeds down to reduce egg-laying sites 		

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
	<p>fields to facilitate drainage and act as focal points for snails to help manual collection</p> <ul style="list-style-type: none"> • Use screen traps with 5 mm mesh (e.g. wire meshes, wire nets, woven bamboo screens), placing them at the main water supply inlets and outlets • Use baited traps in water along field edges filled with papaya, tapioca, lettuce, banana, cassava and taro leaves, and old newspaper, to facilitate collection of snails • Dry plough after harvest as this enhances snail mortality. This method exposes the snails to the heat of the sun, which they cannot stand for a long time. It also makes them susceptible to predators • Rotate rice with a dryland crop or fallow period between flooded rice and combine with a tight-rooted cover crop, limiting snail movement to the surface that can be tilled in • Clean equipment to avoid spreading to other fields • Keep weeds suppressed in and near seedbeds and out in the production fields 			

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
	<ul style="list-style-type: none"> • Uses rubber boots to reduce chances of cuts and infection as snails can be a vector for serious diseases • Desilt canals to minimize habitable areas 			
Botanicals	<ul style="list-style-type: none"> • Place toxic plants such as tobacco leaves in waterlogged areas of the field or in trenches (also lilac and citrus, neem, tea seed cake) 	<ul style="list-style-type: none"> • Investigate efficacy of chemo-attractive baits and produce formulations that can maximize the toxic effect on adults and juveniles 	<ul style="list-style-type: none"> • Facilitate efficacy trials for locally available botanicals 	
Biological control	<ul style="list-style-type: none"> • Some natural predators like red ants feed on the snail eggs while ducks (and sometimes rats) will eat young snails • Domestic ducks have been used in Asia during final land preparation before planting or after crop establishment when plants are big enough (30–35 days after transplanting on the early-maturing varieties, and 40–45 days after transplanting in the late-maturing varieties). Herd ducks in rice paddies immediately after harvest up to the last harrowing for the succeeding crop 	<ul style="list-style-type: none"> • Investigate efficacy and predation by local natural enemies and facilitate this by using management options with minimal disturbance of native biocontrol agents (ducks, ants) 	<ul style="list-style-type: none"> • Work with international agencies to keep abreast of latest developments regarding biological control agents from the native range 	Duck pasturing may not be cost-effective as this has high maintenance costs and has been linked to health problems

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
IPM	<ul style="list-style-type: none"> Maintain good records of agronomy, monitoring, interventions, yield, etc. and review regularly Engage in community-based management and training in identification and management. Synchronize egg collection during land preparation, planting and crop establishment 	<ul style="list-style-type: none"> Maintain good records of agronomy, monitoring, interventions, yield, etc. and review regularly 	<ul style="list-style-type: none"> Carry out research on integration of options for smallholders and compatibility with existing growing schemes Training plant protection officers – develop a training programme to increase farmers' awareness of the damage caused by <i>Pomacea</i> snails and management, with particular focus on IPM and the use of good agricultural practice Launch national monitoring and mapping programme across Kenya to assess spread and impact 	Many IPM strategies are available but are largely ineffective when used as the sole method. Maintain good records of agronomy, monitoring, interventions, yield, etc. and review regularly
Resistant varieties	<ul style="list-style-type: none"> There are no varieties resistant to apple snail feeding. Modern high-tillering plant types have better potential to compensate for damaged tillers over time than low- and medium-tillering types and this may be helpful in long-duration (late-maturing) varieties, but may not help in short-duration (early-maturing) ones. Use rice varieties that have rapid elongation after seedling establishment 	<ul style="list-style-type: none"> Investigate modern high-tillering plant types to compensate for damage Use rice varieties that have rapid elongation after seedling establishment 	<ul style="list-style-type: none"> Facilitate research and market availability of modern rice varieties which can compensate more effectively for damage 	

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
Biopesticides	<ul style="list-style-type: none"> Use registered biopesticide products instead of pesticides if available 	<ul style="list-style-type: none"> Use registered microbial biopesticides if recommended by government Test locally available biopesticides 	<ul style="list-style-type: none"> Accept supporting data from other countries for registration of biopesticides Fast track registration for products already registered in America and Asia for this pest 	Not commercially available in Africa
Chemical control	<ul style="list-style-type: none"> Use pesticides as a last resort, and only when economic thresholds are reached When all the non-chemical options failed, farmers could apply approved molluscicide Application should be done early in the morning or late in the afternoon when the snails are out and active Use only pesticides (molluscicides) recommended by the government for rice Follow all advice on safety, dilution, etc. on the product label Buy only from registered pesticide dealers Use proper PPE when applying pesticides, and observe the DOA and RD recommendation for dosage and method 	<ul style="list-style-type: none"> Use pesticides as a last resort, and only when economic thresholds are reached Spray regime should be based on an action threshold that takes into consideration expected value of crop, expected loss if untreated, and cost of treatment Do not spray as a preventative measure Use pesticides recommended by the government, especially those with lower environmental impact Use proper PPE when applying pesticides, and observe the re-entry intervals and pre-harvest intervals of the product Apply products only to low spots and canalettes rather than to the whole field. 	<ul style="list-style-type: none"> Facilitate efficacy trials and fast-tracking for registration of safe 'green' products for use on the pest through the PCPB in collaboration with agrochemical industries and institutions Monitor the health and environmental impacts of pesticides. Niclosamide is toxic to fish and amphibia (frogs and toads) Prepare a technical guidance standard for pesticides covering procurement, risk reduction and resistance management Monitor for pesticide resistance to most popular active ingredients 	Note that pesticides are highly toxic to fish and other non-target animals and have been linked to human health hazards idely used

Method	Recommendations for rice smallholders	Recommendations for private farms/mills	Recommendations for government	Comments
	<ul style="list-style-type: none"> • Apply products only to low spots and canalettes rather than to the whole field. Always ensure safe application. Spray in the morning and afternoon when snails are active • If used as emergency measure in high-risk areas, molluscicides should only be used immediately after transplanting or during the seedling establishment phase in direct-seeded rice; and only for rice younger than 30 days old • Prior to the application of molluscicide irrigate the field to activate the snails and so they emerge out of the soil. This is important for the snails to get in contact with the pesticide • Consider ETLs of snails for direct action (one snail/2 m² and three snails/2 m², for direct-seeded and transplanted rice, respectively) to prevent risk of damage and yield loss with rapidly increasing population 	<p>Always ensure safe application. Spray in the morning and afternoon when snails are active</p> <ul style="list-style-type: none"> • If used as an emergency measure in high-risk areas, molluscicides should only be used immediately after transplanting or during the seedling establishment phase in direct-seeded rice; and only for rice younger than 30 days old • Prior to the application of molluscicide irrigate the field to activate the snails and so they emerge out of the soil. This is important for the snails to get in contact with the pesticide • Consider ETLs of snails for direct action (one snail/2 m² and three snails/2 m², for direct-seeded and transplanted rice, respectively) to prevent risk of damage and yield loss with rapidly increasing population 	<ul style="list-style-type: none"> • Publish and make public the list of pesticides registered 	

^a DOA, Department of Agriculture; ETL, economic threshold level; IPM, integrated pest management; PCPB, Pest Control Products Board; PPE, personal protective equipment; RD, recommended dose.

4 Advice, information and communication

4.1 Sources of information on apple snail control

Smallholder rice farmers in Kenya rely on the government's National Irrigation Authority for information, occasioned by synchronization of activities. For Mwea, MIAD (Mwea Irrigation Agricultural Development) also plays a pivotal role when it comes to research and training in irrigated agriculture. Extension officers are drawn from the Ministry of Agriculture and NIB to provide information and some have had training through Plant Clinics. Agricultural trade fairs may also be a source of information. Farmers are also known to get information from agro-dealers and input-suppliers to manage pests and diseases, with mass media channels, agricultural pieces on radio and TV, the internet, newspapers and magazines also playing a role in disseminating information. As for other pests, neighbours, friends, family and lead farmers will also be a source of information. As invasive snails are a new pest, farmers may not be familiar with management options and identification and the multi-institutional technical team (MITT) will aim to develop technical materials to disseminate to raise awareness. The National Irrigation Authority will also aim to undertake training and demonstrations on the management of the pest to farmers and stakeholders, with the support of other county teams. A socio-economic survey could provide a valuable baseline on the information farmers have had and the management methods currently adopted to tackle the snail where it has invaded, as well as establishing the level of knowledge in areas which remain free of snails but could be at risk.

4.2 Criteria for control advice

The criteria for control advice presented in this section are adapted from Abrahams *et al.* (2017) and are relevant for any method for managing an invasive pest.

We recommend the following criteria for control advice:

Efficacy. This is often assumed to be the most important criterion, even if this is not stated explicitly. If a practice is to be recommended there should be some evidence that it will be effective in at least some situations. Where a product has to be registered, this generally includes demonstration of efficacy, but many IPM practices do not involve a registered product. Results from controlled trials in an appropriate context are desirable, though not always available.

Safety. Even registered products can be hazardous to human health without precautions. Safety should thus be considered based on a consideration of how the product is likely to be used rather than whether recommended safety precautions are adequate. Some practices not requiring registration can also be hazardous, such as some plant extracts.

Sustainability. Possible effects on non-target organisms, such as native molluscs, natural enemies and other organisms, should be considered. A control method may also have potential to create new problems, such as resurgence of other pests or pesticide resistance.

Practicality. Some methods may be impractical for some farmers, particularly those requiring elaborate safety precautions. Others may be only practical at a small scale.

Availability. Availability of regulated products is initially determined by their registration status, but even registered products may not be widely stocked if distribution is expensive and/or the perceived market is small.

Cost-effectiveness. At the simplest level the cost of control must be less than the value of crop loss avoided, for it to be worthwhile. Opportunity and other costs may need to be considered.

In practice, many of these criteria are context specific, so recommendations and advice are unlikely to suit all farmers in all situations. This highlights different underlying approaches to the role of advisory services. The linear 'transfer of technology' approach emphasizes prescriptive advice on the use of new technologies. Participatory approaches emphasize educating and empowering farmers to use information and experience to make their own choices. Both approaches have advantages and disadvantages.

4.3 Information resources and tools

A large number of international resources are available for *P. canaliculata*:

Global Invasive Species Database – *Pomacea canaliculata* (mollusc).

<http://www.iucngisd.org/gisd/species.php?sc=135>

PaDIL – Golden Apple Snail Australian Plant Biosecurity Cooperative Research Centre. Pests and Diseases Image Library. <https://www.padil.gov.au/pests-and-diseases/pest/main/136489>

Plantwise Technical Factsheet – Golden Apple Snail (*Pomacea canaliculata*). CABI. Plantwise Knowledge Bank. <https://www.plantwise.org/knowledgebank/datasheet/68490>

Pest survey card on *Pomacea* spp. from EFSA.

<https://efsa.onlinelibrary.wiley.com/doi/pdfdirect/10.2903/sp.efsa.2020.EN-1877>

Invasive Species Compendium: This is a free encyclopaedic resource that brings together a wide range of different types of science-based information to support decision making in invasive species management worldwide. www.cabi.org/isc

Crop Protection Compendium: This is an encyclopaedic resource that brings together a wide range of different types of science-based information on all aspects of crop protection. It comprises detailed datasheets on pests, diseases, weeds, host crops and natural enemies. <https://www.cabi.org/cpc>

For Africa:

KEPHIS has outlined plans to work with stakeholders in the management *Pomacea* snails. The stakeholders include the Kirinyaga County government, Ministry of Agriculture, National Irrigation Authority, PCPB, KALRO, MIAD, NGAO, WARMA, NEMA, Department of Public Health, the Presidential Delivery Unit, CABI, ICIPE and the University of Nairobi. This forms a MITT.

Rice Knowledge Bank: Golden Apple Snail. International Rice Research Institute.

<http://www.knowledgebank.irri.org/step-by-step-production/growth/pests-and-diseases/golden-apple-snails>

5 Recommendations

Invasive apple snails remain a problem across their introduced range because of their inherent biological and ecological characteristics and their adaptability to harsh environments. Prevention is the best form of management and strict quarantine must be enforced to prevent further spread across the continent. For countries which are free of snails, identifying potential introduction pathways, developing risk assessments, implementing a clean certification scheme for traded plants from contaminated areas and elaborating rapid response plans for new incursions will be important to help mitigate impact. Once detected, containment is crucial and while eradication is not impossible, it will rely on a swift, coordinated high-level strategy to highlight the threat among smallholders and commercial growers and to engage the community to contain and mitigate the pest. Continuous vigilance and integrated management approaches including hand-picking of adults, destruction of egg masses, baiting and trapping, barriers and the adoption of mitigating agricultural practices, such as crop rotation and water management, will need to be carried out to try to keep the snails below an economic threshold. Regular monitoring and delimiting surveys are also essential.

Awareness-raising programmes should also aim to relay the importance of sustainable management in *P. canaliculata* control to conserve the environment and native invertebrates, with special emphasis on molluscs as important engineers in rice ecosystems. It is essential to identify the most effective and rapid pathways for dissemination of knowledge on *P. canaliculata*, its impacts and management so that it reaches as many farmers as possible and includes regions where it has not yet arrived.

High-level policy makers:

- Determine the magnitude of the invasive apple snail threat (present and potential) and make policy decisions, backed by available economic estimates and science-based evidence.
- Lobby for budgetary allocation to facilitate an immediate, official national response backed by policy and legislation to enable coordinated (potentially mandatory) contingency action to contain and eliminate the invasive apple snail at the earliest opportunity.
- Outline clear structure and division of responsibility between competent authorities for the development, implementation and support of eradication/containment measures in Kenya.
- Provide countrywide support for invasive apple snail control and farmer/agency education and outreach by establishing a technical working group to spearhead management efforts.
- Make informed, science-based decisions at national level to protect biodiversity, consumers and trade from indiscriminate molluscicide/pesticide use.

Regulators:

- Identify pathways for entry and spread of the snail to vulnerable areas and contain/quarantine affected areas.
- Ensure awareness is raised to prevent further deliberate and accidental distribution of *P. canaliculata*.
- Organize regular and persistent monitoring schemes for snail egg masses and adults to inform rapid response and containment measures.

- Fast-track registration and efficacy trials for safe pesticides to use on the pest (PCPB in collaboration with agrochemical industries and efficacy trials institutions).
- Facilitate and promote fast-track registration of lower-risk 'green' products for snail management including biopesticides, botanicals and the potential use of native natural enemies.

Researchers:

- Carry out countrywide distribution, socio-economic and impact surveys to assess the extent and awareness of the problem.
- Investigate efficacy of native biocontrol agents and test locally available and legally approved biopesticides and botanicals and produce formulations that maximize the toxic effect on *P. canaliculata* and reduce side effects on beneficial fauna.
- No rice varieties are resistant to apple snails, but research into modern high-tillering plant types can hold better potential to compensate for damage – investigate tolerant rice varieties.

Advisory services:

- Communicate to farmers, using accessible and varied platforms, the negative impacts of indiscriminate pesticide use on their health and the environment.
- Consider efficacy, safety, sustainability, practicality, availability and cost-effectiveness when recommending control practices.
- Raise awareness of the snail problem (through media and pest alert flyers) and expand extension efforts to facilitate community-based management, coordinating immediate action if the invasive snail is detected.
- Promote good agricultural practice and low-risk, cost-effective options for management such as changes to planting patterns, water management, hand-picking, physical barriers and repellent plants.
- Develop an array of cost-effective, clear and harmonized monitoring protocols to be rolled out to smallholders.

Private farms:

- Follow good agricultural practice advice relating to alternative cropping systems and planting patterns (avoiding ratooning postharvest), including managing water levels, desilting and crop establishment age.
- Maintain good records of agronomy, monitoring, interventions, yield, etc., and review regularly to determine the cost–benefit of the control methods used.
- Spraying of registered and crop-approved molluscicide should be based on an action threshold that takes into consideration the expected value of the crop, the expected loss if untreated, and the cost of treatment.

- Farm workers should use the proper PPE when applying pesticides and use the suite of recommended agricultural and cultural practices to manage snail populations.
- Assess the efficacy of other lower-risk products, if available, and adopt for use.

Smallholder farmers:

- Use only pesticides recommended by the government for this pest and choose low-risk botanical options if available/affordable.
- Engage with community extension, advisory and information services to obtain latest information on snail identification and management.
- Engage in regular surveillance and monitoring for egg masses and adult snails on farms (use bamboo poles/attractants, locally available materials).
- Use a suite of management practices, in combination to minimize damage (scouting, hand-picking, trapping, baiting, trenches, physical barriers, etc.) as part of routine, community management action.
- Follow good agricultural practice advice relating to hygiene protocols for equipment and machinery, alternative cropping systems and planting patterns (avoiding ratooning postharvest), including managing water levels, desilting and crop establishment age (transplanted rice is less vulnerable than direct-seeded rice).

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contact CABI

Africa

Kenya

CABI, Canary Bird
673 Limuru Road, Muthaiga
PO Box 633-00621
Nairobi, Kenya
T: +254 (0)20 2271000/ 20
E: africa@cabi.org

Ghana

CABI, CSIR Campus
No. 6 Agostino Neto Road
Airport Residential Area
P. O. Box CT 8630, Cantonments
Accra, Ghana
T: +233 (0)302 797 202
E: westafrica@cabi.org

Zambia

CABI, Southern Africa Centre
5834 Mwange Close
Kalundu
P.O. Box 37589
Lusaka, Zambia
T: +260 967 619 665
E: westafrica@cabi.org

Americas

Brazil

CABI, UNESP-Fazenda Experimental
Lageado, FEPAF (Escritorio da CABI)
Rua Dr. Jose Barbosa de Barros 1780
Fazenda Experimental Lageado
CEP:18.610-307
Botucatu, São Paulo, Brazil
T: +5514-38826300
E: y.colmenarez@cabi.org

Trinidad & Tobago

CABI, Gordon Street, Curepe
Trinidad and Tobago
T: +1 868 6457628
E: caribbeanLA@cabi.org

USA

CABI, 745 Atlantic Avenue
8th Floor, Boston,
MA 02111, USA
T: +1 (617) 682-9015
E: cabi-nao@cabi.org

Asia

China

CABI, Beijing Representative Office
Internal Post Box 85
Chinese Academy of Agricultural Sciences
12 Zhongguancun Nandajie
Beijing 100081, China
T: +86 (0)10 82105692
E: china@cabi.org

India

CABI, 2nd Floor, CG Block,
NASC Complex, DP Shastri Marg
Opp. Todapur Village, PUSA
New Delhi – 110012, India
T: +91 (0)11 25841906
E: cabi-india@cabi.org

Malaysia

CABI, PO Box 210,
43400 UPM Serdang
Selangor, Malaysia
T: +60 (0)3 89432921
E: cabisea@cabi.org

Pakistan

CABI, Opposite 1-A,
Data Gunj Baksh Road
Satellite Town, PO Box 8
Rawalpindi, Pakistan
T: +92 (0)51 9290132
E: sasia@cabi.org

Europe

Switzerland

CABI, Rue des Grillons 1
CH-2800 Delémont, Switzerland
T: +41 (0)32 4214870
E: europe-CH@cabi.org

UK

CABI, Nosworthy Way
Wallingford, Oxfordshire, OX10 8DE, UK
T: +44 (0)1491 832111
E: corporate@cabi.org

CABI, Bakeham Lane
Egham, Surrey, TW20 9TY, UK
T: +44 (0)1491 829080
E: cabieurope-uk@cabi.org
E: microbialservices@cabi.org