Research Article

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Assessment of the socio-economic impacts associated with the arrival of apple snail (*Pomacea canaliculata*) in Mwea irrigation scheme, Kenya

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Abstract

Background: In Kenya, rice (*Oryza sativa* L.) is mainly produced under irrigation by small-scale farmers. Mwea irrigation scheme (MIS) in Kirinyaga County accounts for 80–88% of rice production. Here, rice is the main source of livelihood and a source of revenue generation for the county. However, a recently established invasive freshwater snail, *Pomacea canaliculata* (Lamarck) (family: Ampullariidae), a species of apple snail, presents a serious threat to rice production.

Results: Household surveys, focus group discussions and key informant interviews highlight apple snail as a serious problem in MIS. Households that observed at least a moderate level of infestation (>20% of cultivated area) experienced significant reductions in rice yield (∼14%) and net rice income (∼60%). Farmers reported increased use of chemical pesticides for management of apple snail. In addition, the cost of hired labor for physical removal of egg masses and snails is resulting in substantial negative effects on net income. Farmer age, area of land owned, responsibility for decision-making, receipt of extension advice, training, and membership of a farmer organization, were all statistically significant variables to explain farmers awareness of the need for area-wide apple snail management.

Conclusion: Strategies to limit the spread of apple snail are urgently needed. A Multi-Institutional Technical Team (MITT) has been established to spearhead management efforts and consolidate advice to farmers on how to manage apple snail. However, without action to mitigate spread, the consequences could be disastrous for rice production and food security in Kenya, and for other rice growing regions across Africa.

Keywords: apple snail; invasive species; rice; livelihood; Mwea; Kenya

1 INTRODUCTION

Globally, there have been consistent increases in the demand for rice (*Oryza sativa* L.) during the last three decades, accompanied by recognition of the crop's potential to improve rural livelihoods.[1] In many African countries, rice production has grown rapidly, constituting a major part of the diet and it is recognized as an increasingly important staple food.[2,3] According to the Kenyan Ministry of Agriculture, rice is the third most important cereal crop after maize and wheat in the country, with consumption increasing much more rapidly than production and expected to reach 1 292 000 tons by 2030.[4,5] Rice has therefore been identified as a priority value chain by the National Agriculture Investment Plan (NAIP 2018–2028), which seeks to encourage Kenya's agricultural transformation towards sustainable food and nutrition security and socio-

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economic development. However, national demand exceeds the country's production and Kenya is still largely reliant on import from international Asian markets.[6,7]

Rice farming in Kenya plays a significant role in increasing both household food security and farmers' incomes as well as reducing vulnerability to extreme weather conditions, especially given the country's high reliance on maize.[4] In Kenya, rice is grown by approximately 300 000 farmers, who not only provide labor but earn their livelihood from rice production.[6] The average national paddy rice cultivation (2016–2020) is reported at 27793 hectares (ha).[8] However, it is recognized that there is great potential to increase rice production, with an estimate of the production potential for irrigated rice of up to 1.3 million ha.[6]

In Kenya, rice is mainly produced under irrigation by small-scale farmers, with 80–88% of production occurring in Mwea Irrigation Scheme (MIS) in Kirinyaga County, central Kenya, north of Nairobi.[4,9–11] MIS covers an area of 9000 ha with potential for 4000 ha expansion.[12] Here, farmers sow two rice crops annually; the main rice crop is sown between July and August and harvested between December and January during the short rains,[13,14] and the second crop is grown and harvested during the long rains between January and June.[10]

The key constraints for rice production in Mwea include water shortages during the main growing season and rice blast attacks during the long rains resulting in reduced rice yields over the year.[10] Alongside a lack of water for irrigation and inefficient water management, are the high cost and low quality of inputs, poor land productivity, machinery shortages (resulting in high levels of manual labor), damage by birds, poor infrastructure (leading to difficulties delivering grain from farms to mills)[7] and lack of resilient and acceptable rice varieties. These challenges are exacerbated by the subdivision of land into smaller units which, alongside changes in weather patterns, worsen the situation, result in water rationing and, in some cases, lead to farmers abandoning rice production completely.[6] Other constraints include weeds, which contribute to high yield losses (from 30 to 80% depending on the cropping system), arthropod pests and diseases.[15,16]

Recently, rice production in Kenya has become threatened by a newly introduced invasive freshwater snail *Pomacea canaliculata* (Lamarck) (family: Ampullariidae), listed in 2000 by the World Conservation Union (IUCN), as ranking among '100 of the World's Worst Invasive Alien Species'.[17,18] In 2020, following reports of an unknown snail species in MIS, surveys and subsequent DNA barcoding analyses confirmed the presence of *P. canaliculata*.[19] This was the first record for Kenya. On mainland Africa, there was an unconfirmed report of *P. canaliculata* from Egypt and a report of *P. lineata* in South Africa which is very likely to have been a misidentification of *P. canaliculata*.[20,21] The arrival of *P. canaliculata* presents a serious threat to Africa's rice growing regions.[2]

The genus *Pomacea* is thought to consist of approximately 50 species.[22] Indigenous to South America, the two most documented species, *Pomacea canaliculata* and *Pomacea maculata* Perry have often been referred to collectively as 'golden apple snails'. There is also increasing evidence of hybridization between *P. canaliculata* and *P. maculata* in the native range (30% hybridization) as well as in South-East Asia.[23,24]

Pomacea canaliculata and *Pomacea maculata* were deliberately and repeatedly introduced into East and South-east Asian rice-growing regions during the 1980s, promoted as high protein food sources for both domestic consumption and gastronomic export.[2] However, they have become highly successful invaders in East and South-east Asian rice growing regions, with serious consequences for agricultural yields, livelihoods, biodiversity, natural ecosystems and human health.[2] Following introduction, a combination of prohibitive health import regulations from foreign markets, unpalatability and an associated decline in market value, resulted in negligence whereby snails were released/escaped into public waterways and irrigation systems.[2,25] Subsequent spread *via* irrigated systems was widespread and rapid. For example, Naylor (1996) assessed the occurrence of *Pomacea* snails in several Asian countries and found it increased from 2% up to 28% of total rice area within 4 years in Taiwan; in Japan, they infested 34 of 47 rice growing districts; in the Philippines infestation rose from under 3% to 15%; and in Vietnam within 5 years snails were reported in all rice growing provinces.

The arrival of *P. canaliculata* (hereafter referred to as apple snail) in Mwea is a serious concern with potentially devastating consequences for rice production in Kenya, as well as other African rice producing countries, should the snail spread across the continent. A field-scoping study was conducted in 2021 involving stakeholders, which included: the Ministry of Agriculture, Livestock, Fisheries and Cooperatives (MoALF&C), Capacity Development Project for Enhancement of Rice Production in Irrigation Schemes (CaDPERP), the County Government of Kirinyaga, the National Irrigation Authority Mwea Irrigation Agricultural Development (NIA-MIAD), the Kenya Plant Health Inspectorate Service (KEPHIS), Plant Protection and Food Safety Directorate, Pest Control Products Board (PCPB), Agrochemicals Association of Kenya (AAK), International Centre of Insect Physiology and Ecology (ICIPE), local agro-dealers and millers. All agreed that urgent action is needed to control apple snail in Mwea.[26] Subsequently, a Multi-Institutional Technical Team (MITT) was established to spearhead management efforts and consolidate advice to farmers on how to manage apple snail.

The aim of this study was to determine the socio-economic impacts of *P. canaliculata* on smallholder farmers in MIS. Since the snail appears to be a relatively new introduction into Mwea, the objectives were to (i) understand the level of impact smallholder rice farmers are currently experiencing, (ii) determine what control measures are being used to manage apple snail and the agricultural practices farmers employ, (iii) to establish what key information sources farmers had for apple snail, and their levels of awareness (and influencing factors) on area-wide management and (iv) to set out clear recommendations and next steps in the challenge of managing apple snail. The study will contribute to informing farmers and other rice stakeholders on practices that could be improved or implemented to mitigate impacts of, or ideally eradicate, apple snail in MIS. There is no information available on the impact of apple snail invasion on smallholder rice farmers in Kenya; this study aims to fill this knowledge gap. The study underlines the need for urgent action to prevent further apple snail spread in Mwea, as well as to other rice growing regions in Kenya, and beyond.

2 MATERIALS AND METHODS

2.1 Study area, populations and survey

The study was undertaken in MIS in Kirinyaga County, Kenya between November and December 2021 (Fig. 1). Mwea Irrigation Scheme is located within two sub-counties: Mwea East and Mwea West. Development of the scheme started in 1954 with approximately 26 ha under irrigation farming and has since grown to the current area of approximately 12 141 ha. Of these, 8903 ha have been developed for paddy rice production. It is the leading

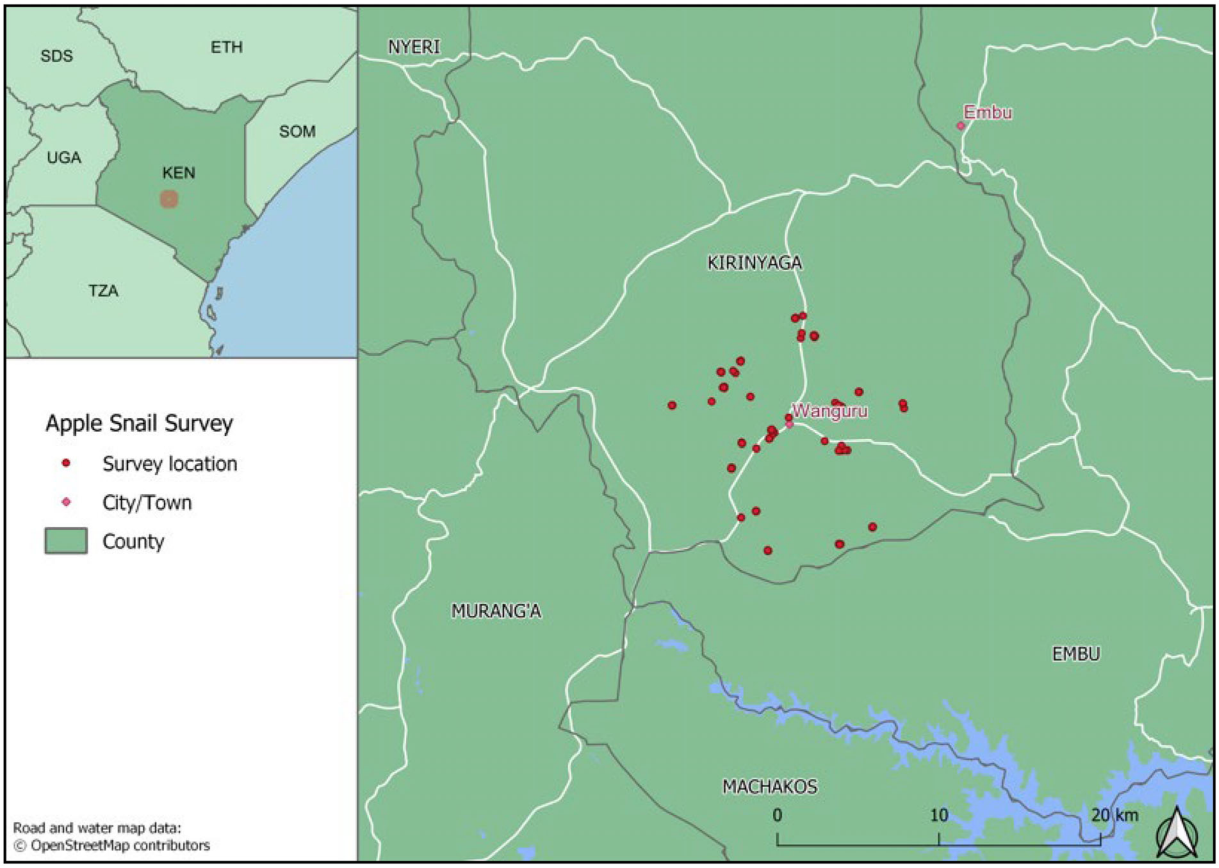

Figure 1. Location map – survey locations in Mwea Irrigation Scheme (MIS).

rice production scheme in the country, commonly known for its aromatic basmati rice. It is also the first place where apple snail was reported.

A survey was conducted using both qualitative and quantitative data collection techniques to understand smallholder knowledge and practices at the community level regarding rice farming, including challenges and management methods. In addition to structured interviews with smallholder farmers, focus group discussions were conducted in the selected areas. Key informant interviews were also undertaken with agricultural extension service providers and agro-dealers to assess their levels of apple snail awareness and the management advice that they provide to farmers.

Rice farmers were identified with assistance from Mwea Irrigation Agricultural Development (MIAD) center staff and sub-county agricultural officers (in Mwea East and Mwea West) through unit/block leaders and lead farmers who assisted in identifying the survey areas. For spread and to reduce bias, random sampling of farmers occurred at the Unit level from where the questionnaires were administered. Agro-dealers were identified by referral. Questions were asked about knowledge, attitudes and practices towards the management of apple snail. Interviews were concentrated around major themes associated with rice cultivation, productivity and inputs, management measures, good agricultural practice, water management/irrigation water supply, household assets, food security, cooperation, training, extension and information sources.

2.2 Household surveys

A household survey engaged with 706 smallholder rice farmers (441 men: 265 women). The survey was purposive and targeted rice farmers in the core scheme and the out-grower sections

Table 1. Sample size and distribution

		Number of respondents		
Sub-county	Ward	Women	Men	Total
Mwea East	Tebere	76	74	150
	Nyangati	6	31	37
Mwea West	Mutithi	10	49	59
	Thiba	173	287	460
Total		**265**	**441**	**706**

Table 2. Number of key informant interviews and focus group discussions participants

Key informant/focus group discussion	Number of respondents		
	Mwea East	Mwea West	Total
Agro-dealers	9	9	18
Extension	4	4	8
Focus group discussion	64	105	169
Total	**77**	**118**	**195**

(not managed by MIS). The majority of respondents were from Mwea West (74%) (wards Mutithi and Thiba) and the remainder from Mwea East (wards Tebere and Nyangati) (Table 1). The survey used a structured questionnaire, which was coded on Open Data Kit (ODK), and data was collected using tablet computers. During the interviews, household heads, spouses, or any family member responsible for making farming decisions, such as choice of crops to grow, inputs to use, and when to sell, were targeted for interviews. The enumerators used a pre-tested tablet-based questionnaire to collect information on household demographics, farm information and decision-making, rice cultivation, productivity and inputs, apple snail presence and management measures and information sources.

2.3 Key informant interviews

A questionnaire was completed by key stakeholders to (i) understand the history of apple snail infestation in Mwea, the management practices promoted by the extension agents and the agro-chemicals recommended by agro-dealers and, (ii) understand the interventions that have been taken by either national or county government since apple snail invasion in MIS, and the extent of spread of the pest across the scheme and in the out-grower scheme (Table 2).

2.4 Focus group discussions

To supplement the household surveys, focus group discussions (FGDs) were held with farmers and community members to gain further insight into their knowledge, attitudes and practices in rice farming and the management of apple snail. Open-ended survey questions were prepared and used as a flexible guide with the aim to promote discussion and provide respondents with the opportunity to elaborate on the topics discussed. In total nine FGDs were held with separate men, women and youth groups (Table 2).

2.5 Data analysis

Qualitative data were analyzed using content analysis while quantitative data were analyzed by comparing means using *t*-tests. To assess the economic effects of apple snail, we estimate the following equation using ordinary least squares (OLS) regression:

$$y_i = \beta_0 + \beta_1 GAS_i + \boldsymbol{\beta_2 x_i} + \varepsilon_i$$

where y_i represents two economic outcome indicators: rice yield and net rice income. Rice yield is measured by the quantity of rice harvested (expressed in kg/ha/year) by household *i* in the past year. Net rice income (expressed in USD/ha/year) consists of gross rice income minus production costs, such as costs of seed, fertilizer, manure, mechanization, water fees, agrochemicals (insecticides, herbicides and fungicides) for pest/disease/weed management and hired labor. The rice yield and net rice income variables were inverse hyperbolic sine (HIS) transformed in order to retain negative values and reduce the effect of outliers.[27] $\boldsymbol{x_i}$ is a vector of explanatory variables, with the associated parameters $\boldsymbol{\beta_2}$. The explanatory variables include household demographics (such as household size, age, gender, and level of education of household head); rice farm size; institutional and wealth-related variables (e.g., access to extension services, credit and off-farm activities, group membership and livestock holding); and a sub-county dummy to control for geographical differences. It also includes a set of controls for inputs when the dependent variable is rice yield. A description of the explanatory variables is presented in Table 4.

The main coefficient of interest is β_1, which measures the effect of apple snail on rice yield and income. ε_i is an error term, and β_0 is a constant term. We use three different measures of apple snail infestation. First is a dummy variable equal to one if household rice production was affected by apple snail during the past year; and zero otherwise. Second, we use self-reported estimates of the percentage of cultivated areas affected by apple snail in the past year. Thus, the second apple snail variable captures the extent of apple snail infestation, and ranges from 0 to 100%. Additionally, we differentiate between three groups of households based on self-reported information on cultivated areas affected by apple snail. The three groups include: no apple snail infestation (comparison group; $n = 106$); minor infestation (less than 20% of the cultivated area was affected by apple snail; $n = 479$); and moderate infestation (20% to 50% of the cultivated area was affected by apple snail; $n = 107$). A fourth group (major infestation: more than 50% of the cultivated area was affected by apple snail; $n = 14\%$) was excluded due to limited observations.

Area-wide management is a landscape level approach in which individual farmers work together in a coordinated manner to tackle a problem. Effective control of pests, such as apple snail, relies on area-wide management and coordination of management practices among farmers. A logistic regression analysis was conducted to determine the factors influencing farmers' awareness of area-wide apple snail management. The dependent variable is a dummy variable which equals 1 if the farmer is aware of area-wide management of apple snail in his/her community; and 0 otherwise. The explanatory variables include demographic characteristics of the farmer, such as age, gender and level of education as well as access to institutional support services, such as training, extension advice and farmer groups.

3 RESULTS

3.1 Descriptive characteristics

The majority of respondents (79%) were the household heads (almost all of the men and 46% of women interviewed). The

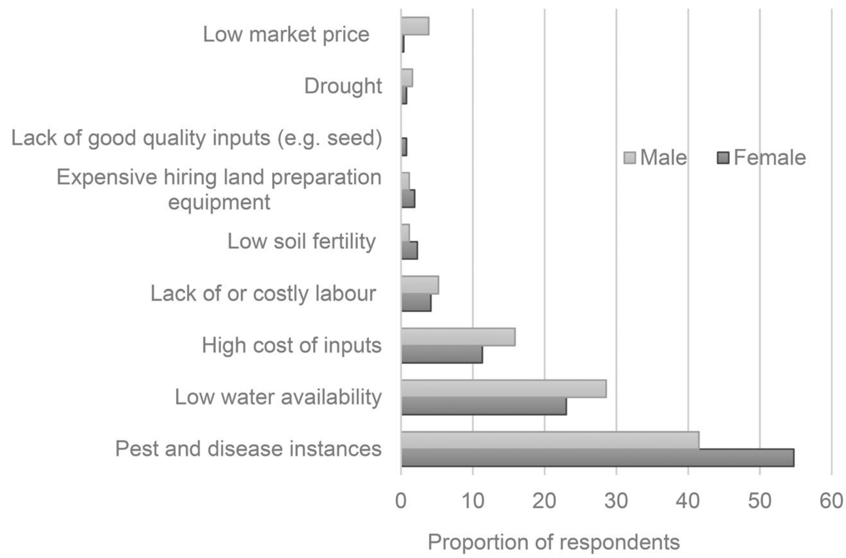

Figure 2. Key constraints to rice production reported by farmers (n = 706).

majority of household heads reported farming as their main occupation (80%), the remainder of household heads reported working on the farm part-time (19%). Off-farm employment (casual labor, permanent employment, or own business/trade) was engaged in on a part-time basis by 27% of respondents. The average age of the household head was 49 years and an average of four people living in a household. The majority of household heads had a primary or secondary education (68%). Although low, more male than female household heads had achieved higher levels of education (college/vocational or university) (6%) and 26% of household heads had no education. On average, two household members carried out agricultural activity in the last 12 months. On-farm activities, such as sale of produce, contributed to all or nearly all (90–100%) income for 68% of households or towards more than half (61–90%) for 24% of households (in the last 12 months).

The majority of respondents (89%) owned land, while a small proportion (11%) rented out a small area of land. Two-thirds of farm labor was hired and the proportion of non-hired labor (including household members, family and friends) was 14% for women and 21% for men. The household head primarily makes decisions about farm management (77%) and how to spend household farming income (56%). However, joint decision making between the household head and the spouse was also important (41%). If applicable, decisions on how to spend off-farm income were made by the household head (30%) or jointly by the household head and spouse (20%). Almost half (46%) of respondents did not have income from off-farm activities.

The average land area used for growing rice in the last 12 months was 0.7 (±0.02) ha. A small proportion of respondents also grew arrowroot alongside rice, on an average of 0.1 (±0.03) ha. For land preparation, all respondents commonly used tractors (98%), animals (90%) and human labor (89%). The majority of respondents sourced land preparation equipment through private hire (91%), a small proportion used group hire, owned their own equipment, or hired equipment through the government. By far the most frequently grown variety of rice was Basmati and most grew early maturing varieties (80%). A small proportion of respondents grew various other off-season varieties alongside Basmati. All farmers transplanted rice seedlings with almost all (97%) levelling their field prior to transplanting. Transplanting is a good agricultural practice since transplanted rice seedlings are more established and tougher than tender new shoots and thus better able to sustain apple snail feeding. Line transplanting and conventional (random transplanting) was used by 52% and 42% of farmers, respectively. The majority of farmers (87%) transplanted 2–5 week (16–28 day) old seedlings and almost two-thirds (62%) synchronized planting. Almost all farmers drained their fields after transplanting (96%) and a high proportion (76%) conducted periodic draining of fields to a depth of 1 cm or less, although most (75%) did not have access to a water pump. The majority of farmers used puddling, wet seeding and flooding (85%, 67% and 58%, respectively). Most farmers (91%) established one main crop plus a ratoon rice crop per year and purchased local (rather than improved) seeds (89%). There was awareness of optimum spacing/density (67%) but only 30% implemented this practice. Under half removed infested residues from the last season's harvest (42%) and few farmers (5%) protected their grain with stored product insecticide. The majority of farmers did not rotate their rice crop or conduct soil analysis. On average one household member worked on the rice paddy, irrespective of gender. Male household members reported working more days on rice production than female household members (37.2 and 25.5 days, respectively).

3.2 Challenges to rice production

Pests and diseases were the most important challenge to rice farming reported by almost half of farmers (46%), followed by low water availability (26%) and the high cost of inputs (14%). Women reported pests and diseases as the first constraint slightly more frequently than male respondents who reported low water availability slightly more than women (Fig. 2). Other constraints included costly labor, low market prices and low soil fertility. A small proportion of women reported lack of knowledge on good agricultural practices, ineffective pesticides, aggressive weeds and health issues, such as bilharzia disease, whereas other constraints reported by men included poor roads/transport facilities, limited or high land hire charges, exploitation by middlemen and adverse weather during harvesting, among others.

Table 3. Most frequently reported rice problem/pests by farmers using agrochemicals

Pest/problem	Women (n = 257)	Men (n = 433)	Average frequency (%)
Weeds	44.7	40.5	41.8
Stem borers	18.1	17.8	17.9
African armyworm	10.1	10.9	10.6
Leaf miners	11.4	14.7	13.7
Rice caseworm	4.8	7.1	6.3
Apple snail	3.6	1.9	2.4

Respondents were asked to provide information on the three key rice problems/pests/diseases affecting their rice crop, the most frequently mentioned issue was birds (Quelea/weaver birds and wild geese) (30%), followed by weeds (21%), stemborers (13%), rodents (8%), rice leaf miners (7%), armyworm (7%) and rice caseworms (5%), among others reported at lower frequencies (below 2%) for example, crickets, rice yellow mottle virus and brown leafspot. Most respondents (n = 690) reported using agrochemicals (insecticides, herbicides, fungicides) to control rice pests in general. Here, of the pest and disease instances reported, weeds were the most frequent problem followed by pests such as stem borers and African armyworm. Apple snail was reported as a frequent pest by a small proportion of farmers (Table 3). However, extension agents stated that apple snail is one of farmers' top five complaints, with 61% of farmers coming to them with apple snail problems on their rice crop. Agro-dealers reported that on a daily basis, 70% of complaints from farmers were for apple snail on rice.

In the last 5 years, irrigation water supply was reported to be declining (61%) and inconsistent (22%). The top three constraints on water management were: farmer interference (50%) (e.g. where farmers on the upper side of the scheme block or otherwise interfere with the flow of water to farmers downstream, or any farmer activities that interfere with the flow of water in the canals), inefficiency of infrastructure (35%) and drought/water rationing (35%). In terms of water availability, farmers complained that there are too many farmers and, alongside low rains, there is insufficient water available; vandalism was also reported as a problem (29%). Other problems reported by fewer farmers

Table 4. Definitions and descriptive statistics of regression variables

Variable	Description	Mean	SD
Rice yield	Quantity of rice harvested (kg/ha/year)	8697.14	2507.62
Net rice income	Net income from rice production (USD/ha/year)	3392.31	1662.80
Apple snail infestation	Experienced apple snail attack on crops (1 = yes)	0.85	0.36
Area affected	Share of rice cultivated area affected by apple snail (%)	11.40	14.72
Minor infestation	Share of rice cultivated area affected by apple snail was minor (1 = yes)	0.68	0.47
Moderate infestation	Share of rice cultivated area affected by apple snail was moderate (1 = yes)	0.17	0.38
Major infestation	Share of rice cultivated area affected by apple snail was major (1 = yes)	0.02	0.14
Age	Age of household head (years)	49.07	12.42
Gender	Gender of household head (1 = male)	0.82	0.38
Education	Household head has at least secondary education (1 = yes)	0.29	0.46
Household size	Number of household members	3.99	1.51
Off-farm	Household member has off-farm job (1 = yes)	0.37	0.48
Credit access	Household has access to credit (1 = yes)	0.59	0.49
Extension access	Household has access to extension services (1 = yes)	0.39	0.49
Farmer group	Household member belongs to a farmer group (1 = yes)	0.39	0.49
Livestock holding	Number of livestock owned in Tropical Livestock Unit (TLU)*	1.21	1.54
Rice area	Total area under rice (hectares)	0.68	0.58
Seed cost	Seed cost (USD/ha/year)	49.40	31.78
Fertilizer cost	Fertilizer cost (USD/ha/year)	211.16	112.38
Pesticide[†] cost	Pesticide cost (USD/ha/year)	45.15	43.49
Labor cost	Hired labor cost (USD/ha/year)	515.37	299.71
Mwea East	Household is located in Mwea East subcounty (1 = yes)	0.26	0.44
Mwea West	Household is located in Mwea East subcounty (1 = yes)	0.74	0.44
Area-wide	Awareness of area-wide management apple snail (1 = yes)	0.12	0.32
Training	Received training[‡] in the last 3 years (1 = yes)	0.49	0.50

*TLU aggregate livestock into one index using the following weights: cattle = 0.7, pigs = 0.2, sheep = 0.1, goats = 0.1 and chickens =0.01.
[†] Pesticide cost includes insecticides, herbicides and fungicides.
[‡] General training (i.e. crop/water management; mechanization; crop protection; pesticide use and safe handling; community-based management; integrated pest management/biological control; organic farming; conservation agriculture).

Table 5. Regression coefficients for effects of apple snail on rice yield and income

Variable	IHS (Rice yield) Coefficient	IHS (Rice yield) Std. Error	IHS (Net rice income) Coefficient	IHS (Net rice income) Std. Error
Apple snail infestation	−0.006	0.053	−0.134	0.240
Age	−0.001	0.002	−0.002	0.007
Gender	0.061	0.050	0.118	0.227
Education	0.056	0.042	0.319*	0.193
Household size	−0.013	0.012	−0.090	0.055
Off-farm	0.045	0.038	0.104	0.173
Credit access	−0.011	0.039	0.027	0.180
Extension access	0.025	0.038	0.036	0.173
Farmer group	0.111***	0.042	0.491***	0.189
Livestock holding	0.023*	0.012	0.118**	0.056
Rice area	−0.008	0.034	0.084	0.152
Seed cost	0.067	0.059		
Fertilizer cost	0.011	0.017		
Pesticide cost	0.112**	0.044		
Labor cost	0.007	0.006		
Mwea West Subcounty†	0.142***	0.044	0.256	0.196
Constant	9.285***	0.147	7.870***	0.618
No. of observations	706		706	

*** $p < 0.01$;
** $p < 0.05$;
*$p < 0.1$.
† The base subcounty is Mwea East.

(>4%), included extension of farms (requiring more water), poor leadership/management by the board/water use association, corruption, high water use fees, and people not paying for water. Most farmers were members of the Water User Association (WUA) (75%).

3.3 Apple snail presence and impact

The majority of households (85%) reported they had observed apple snail attack on their crops in the past year (Table 4). Most reported that they first saw apple snail in the last 2 years, with the pest mainly seen on rice (85%) although a small proportion ($n = 4$) also reported apple snail on arrowroots (*Maranta arundinacea*). In terms of level of infestation, 68%, 15% and 2% of the households reported minor, moderate and major apple snail infestation, respectively. On average, the proportion of rice cultivated area affected by apple snail was about 11%, indicating that the level of infestation was generally minor (Table 4).

The regression results for the effect of apple snail on rice yield and income show that apple snail infestation (irrespective of the extent of infestation) had a negative effect on rice yield and net rice income, but the coefficients are not statistically significant (Table 5). On the other hand, we found negative and significant relationships between the percentage of cultivated area affected by apple snail and rice yield/income (Table 6; full results in Table A1 in Appendix A). Specifically, the results show that a 10% increase in the cultivated area affected by apple snail is significantly associated with a 0.5% and 3.4% reduction in rice yield and net rice income, respectively. Table 6 also reports a summary of the results of the disaggregated effects of apple snail, based on the level of infestation (full results are presented in Table A2 in Appendix A). The results suggest that households that recorded a minor area of apple snail infestation did not experience significant declines in rice yield and net rice income, compared to households that were unaffected by the pest. Conversely, compared to unaffected households, households that observed at least a moderate level of apple snail infestation suffered reductions in rice yield and net rice income (roughly 14% and 60%, respectively) (Table 6).

3.4 Apple snail management measures

Almost all respondents (98%) used various agrochemicals to control rice pests, diseases and weeds. Most farmers used insecticide/chemical pesticides for a range of pests; the top three most frequently reported pests were stem borers, leaf-miners and African armyworm and the most frequently used products contained the active ingredients Chlorpyrifos, Alpha-cypermethrin and Lambda-cyhalothrin. A small proportion reported using chemical pesticides just for apple snail (16%), with Lambda-cyhalothrin being most frequently used. An increase in the use of chemical pesticides was reported since the arrival of apple snail (Fig. 3). The main advice given by agro-dealers was to use various chemical pesticides at the recommended dose, but if it did not work they advised farmers to increase dosage. Farmers reported that since there is no legal recommended chemical for apple snail control they resorted to other chemical pesticides, some of which are illegal and detrimental to human health and the environment.

Farmers used a range of non-chemical management options to control apple snail with the most frequently used method being physical/mechanical e.g. hand-picking egg masses and snails followed by water management e.g. draining and water spraying (Table 7). Water spraying involved the frequent spraying of eggs with pure water to dislodge eggs and can also reduce hatching rates provided water spraying occurs at regular intervals soon after the eggs are laid.[28] Other less commonly adopted methods

Table 6. Effects of level of apple snail infestation on rice yield and income

	IHS (Rice yield)		IHS (Net rice income)	
Variable	Coefficient (Std. Error)	Percentage effect†	Coefficient (Std. Error)	Percentage effect†
Area affected by apple snail‡	−0.005***	−0.05	−0.030***	−0.34
	(0.001)		(0.006)	
Minor apple snail infestation§	0.019	1.81	−0.006	−3.45
	(0.053)		(0.240)	
Moderate apple snail infestation§	−0.149**	−14.06	−0.863***	−59.72
	(0.067)		(0.306)	
Control variables included	Yes		Yes	
No. of observations	706		706	

*** $p < 0.01$;
** $p < 0.05$;
† The percentage effects of coefficients in models with IHS-transformed dependent variables were computed following Bellemere and Wichman, 2020.[27]
‡ The full regression results are presented in Table A1 in Appendix A.
§ The comparison group is no apple snail infestation. The full regression results are presented in Table A2 in Appendix A.

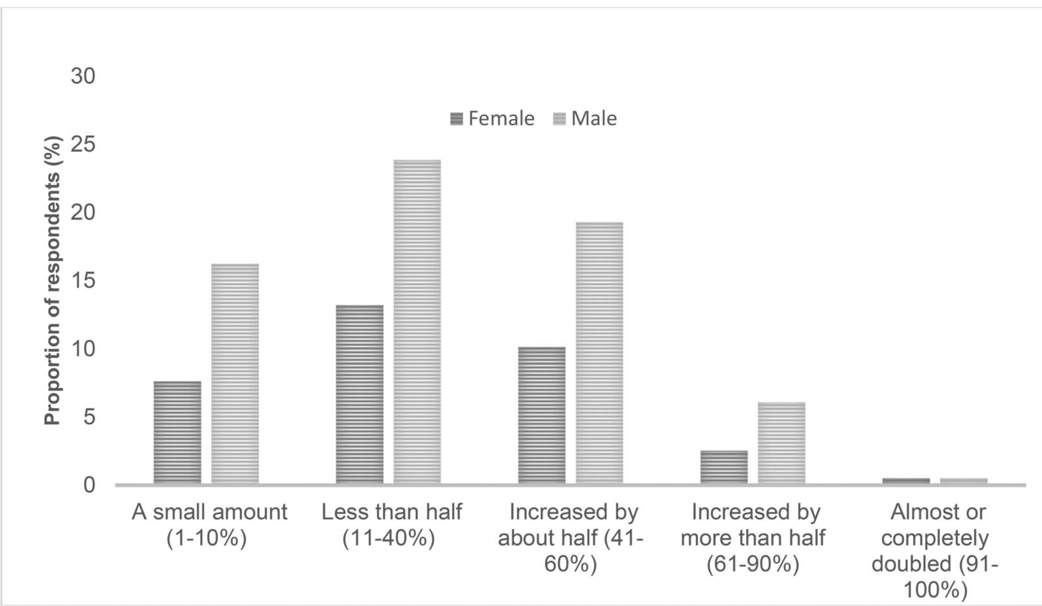

Figure 3. Farmer perception of change in level of chemical pesticide use due to apple snail (for those reporting an increase in chemical pesticide use) ($n = 197$).

include cultural control and the use of plant extracts such as neem and tobacco. Extension agents recommended physical removal of eggs and snails, water management including alternative wetting/drying and draining paddy fields, as well as cultural methods, erecting barrier feeder lines, screening inlets and cleaning canals.

For both of the most frequently used management practices (physical and water management), the main cost is the labor associated with the activity. The cost of hired labor for physical control (average US $75.6 (±28) per ha/year) associated with apple snail accounted for 70% of management costs compared to 10% for insecticides (US $8.8 (±1.8) per ha/year) (the latter not solely for apple snail) (Table 8). The cost estimates do not account for any family labor for these activities. Extension agents and agro-dealers both reported input costs associated with apple snail have increased by 10–40%. Despite the high labor intensity, farmers reported hand collecting and crushing snails was the most effective management method.

A relatively small proportion of farmers had a screen at water supply inlets (23%) and even fewer had screens at water outlets (6%), with limited frequency of cleaning (16% reported daily or weekly cleaning through to 6% rarely or never cleaning screens). On average, over 60% of farmers removed and destroyed snail and egg masses from their fields by hand with this task generally occurring at random times. The most frequently used method of destroying snails was by leaving them in a dry area to desiccate (55%) or a combination of crushing and leaving to desiccate (6%). Only 2% reported placing bamboo stakes around their fields – a management method that provides snails with good

Table 7. Non-chemical management methods used for apple snail

Management methods used	Proportion of farmers (%)		
	Women	Men	Overall
Physical/mechanical (e.g. hand-picking eggs/snails)	52.8	49.2	50.6
Water management (such as draining/water spraying)	35.1	37.2	36.4
Cultural (e.g. use of ash, field sanitation etc.)	1.9	2.3	2.1
Farm-level plant extracts (e.g. neem, tobacco, hot pepper, Tephrosia etc.)	1.1	1.4	1.3
Biological pesticides (botanical pesticides)	0.4	1.1	0.8
Weeding (reducing egg laying sites)	0.4	0.7	0.6
Biological control (e.g. fish, ducks, rats, red ants etc.)	0.0	0.2	0.1
Planting Napier grass alongside rice crop	0.4	0.0	0.1

Table 8. Costs associated with key management methods

Management method	Number of farmers using method	Average cost (USD/ha/year)	
		Product or equipment	Hired labor
Insecticides/chemical pesticides	690	13.4 (0.5)	8.8 (1.8)
Physical/mechanical	354	6.5 (1.8)	75.6 (28.0)
Water management	256	1.4 (0.3)	26.3 (14.0)

egg laying sites, the stakes can then be pulled up and the eggs easily knocked off. The majority of farmers (70%) constructed small canals/trenches along the edge of their rice plot – here snails are concentrated in these deeper parts when the water is drained allowing for ease of collection. Most farmers performed weeding of canals (removing plant substrates used by snails for egg-laying) to minimize snail habitats/hiding places; however very few (6%) used attractants or baits to attract snails. The majority of farmers (87%) reported cleaning tools and equipment after every use, but 5% reported rarely or never doing so. Most farmers mentioned birds as snail natural enemies (86%) followed by snakes (10%) and water bugs (3%). Rats, ants, cats and fish were also mentioned by a small proportion of farmers (<1% each). Few farmers wore protective clothing such as gloves and rubber boots (19%).

3.5 Information sources for apple snail

Farmers reported receiving information and advice for apple snail management from MIAD and government extension agents, as well as agro-dealers. Only 5 (of the 18 agro-dealers interviewed) had received training on apple snail management which was from agrochemical companies.

Interpersonal sources (IPSs) were generally the preferred source of information, as illustrated in Table 9. Among IPSs, neighbors/friends/relatives were the most frequent source of information (80%), followed by extension agents (10%). Agro-dealers were a source of agricultural information on apple snail for ~6% of respondents, and 2% indicated that trained lead farmers/farmer promoters are regularly available and provided apple snail information in the past 12 months.

Local radio channels were the most frequent mass medium for farmers to obtain agricultural information – 66% reported local radio as a source of information. Farmer-specific television shows were information sources for 32% of respondents.

Farmer recommended communication sources for apple snail information for any future awareness campaign were: (i) extension agents; (ii) community groups; and (ii) demonstration plots/field days/shows/field schools. This was followed by local radio channels, NGOs, farmer organizations, farmer specific television shows, and automated SMS messaging. The results for the logistic regression on the factors influencing farmers' awareness of area-wide management of apple snail in their community are shown in Table 10.

The variable household head age significantly (negatively) influenced respondents' level of awareness on area-wide management of apple snail. For each additional year of age, farmers are 0.2% less likely to be aware of any area-wide apple snail management *i.e.* the older the farmer, the less likely they are to be aware of any area-wide management of apple snail. For each additional increase in area of land owned, respondents are 1.5% more likely to be aware of area-wide management of apple snail. Farmers that had received extension advice were 13.7% more likely to be aware of area-wide apple snail management where each additional contact with extension increases the likelihood of farmers' apple snail awareness. Similarly, farmers that were members of a farmer organization were 4.5% more likely to be aware of apple snail management and each increase in years of membership increases the likelihood of farmers' apple snail awareness, suggesting the farmer organization has a positive effect on member farmers' awareness in contrast to non-members. Contrastingly, farmers who had received general training (in the last 3 years) are less likely (5.8%) to be aware of area-wide apple snail management, probably because of the training covering general topics unrelated to apple snail management.

4 DISCUSSION

The arrival of apple snail in MIS, a major rice growing area in Kenya, is of immense concern. The history of apple snail invasion in Asian agricultural systems demonstrates the snail's huge

Table 9. Distribution of information sources farmers used for accessing information on apple snail and farmers' preferred information sources for future awareness campaigns

	Current sources of information Frequency		Preferred sources of information
Information sources	Female	Male	Rank
Interpersonal sources			
Trained lead farmers/farmer promoters	3	6	10th*
Agro-dealers	13	24	9th
Research scientists	0	1	12th
Farmer organization	5	2	6th*
NGOs	0	1	5th
Community groups	2	1	2nd
Demonstration plots/field days/shows/field school	1	3	3rd
Extension agents	20	40	1st
Neighbors/friends/relatives	189	309	10th*
Mass media sources			
Local radio channels	3	22	4th
Farmer-specific television shows	5	7	6th*
Automated SMS messaging	0	1	8th
Other	24	24	13th

*Tied ranks for 6th and 10th preferred information sources.

Table 10. Factors influencing farmers' awareness of area-wide management of apple snail

	Awareness level		
Variables	Coefficient	Std. Error	Marginal Effects
Gender	0.005	0.273	0.000
Household head age	−0.021**	0.011	−0.002
Household head highest level of education	0.002	0.003	0.000
Land size owned	0.182**	0.075	0.015
Received extension advice	1.621***	0.302	0.137
Received training (general)	−0.683**	0.295	−0.058
Member of farmer organization	0.533**	0.256	0.045
Constant	−2.063***	0.550	
LR χ^2 (7)	46.11		
Prob > χ^2	0.000		
Pseudo R^2	0.091		
Log-Likelihood	−230.5		
Observation	706		

*** $p < 0.01$;
** $p < 0.05$;

impacts where these systems have been rapidly overwhelmed.[25] In addition to the damage done to agriculture, the snail could also push already fragile ecosystems into irreversible decline as it has done in Southeast Asia.[29] The apple snail infestation in Mwea is still relatively localized. However urgent action to promote pro-active prevention, containment and control is required if apple snail spread is to be effectively mitigated. The majority of farmers in Mwea are aware of the presence of apple snail on their land. Significant impacts are being experienced by farmers with at least a moderate apple snail infestation (i.e. more than 20% of their cultivated area affected), who experienced approximately 14% and 60% reductions in rice yield and net rice income, respectively compared to farmers not yet experiencing apple snail invasion. This implies that the negative economic effect of apple snail is substantial when more than 20% of the area cultivated to rice by a household is affected by the pest. Thus, it is essential to promote strategies to limit the spread of apple snail. In Malaysia, continuous control, containment and eradication programs for apple snail have occurred with success, albeit at greater crop production costs.[30]

Hired labor for physical/mechanical control, and to some extent water management (*e.g.* draining fields and/or spraying water), account for a high proportion of total apple snail management costs (70% and 20% respectively). These labor costs result in rice production becoming very expensive, whilst also not considering the cost of family labor which is likely to be significant as farmers struggle to manage this new invasive pest. It is highly feasible that apple snail management will have significant livelihood impacts for smallholders, particularly women and children, who will probably spend significant amounts of time in the physical removal of snails and eggs. Typically, as part of their routine management responsibilities, women spend more time in the field scouting for pests.[31] Women's contributions to crop production is often unacknowledged since cultural norms assert the farm as the male domain despite the fact that women play a significant role.[32–34] It has been recognized in Ahero irrigation scheme that Kenyan women undertake 80% of the work associated with rice production, such as preparing land for planting and weeding.[32] Such farm-level gendered labor practices are often overlooked e.g. demands on women and children's time for hand weeding invasive plants such as *Parthenium hysterophorus*.[35]

It is therefore essential that effective strategies are implemented to contain the spread of apple snail, especially since, in a relatively short period of time, damage can become significant.[18] For example, in the Ayeyarwaddy Delta in Myanmar average rice yield losses after 2–3 years reached 20–44%, despite the fact that initially apple snail did not cause significant damage or yield losses.[36] Farmers in Mwea manage water levels and transplant rice seedlings (rather than direct seeding) which are good agricultural practices that will help with apple snail management. Water management before and after transplanting rice seedlings is recommended to help protect this crucial growth stage, that is particularly vulnerable to snail damage (though less vulnerable than first shoots from direct seeding). Other low technology management practices are used to some extent in Mwea but could be improved upon. For example: increased use of screens that are regularly cleaned at water supply inlets and outlets; regular cleaning of tools and equipment/machinery, especially if shared and moved between farms; use of bamboo stakes, which provide snail egg laying sites and allow for ease of collection of both snails and eggs; use of attractants and baits in the trenches/canals along the edges of rice plots to attract snails and ease their removal; the use of repellents to deter snails along canals/inlets; and removal of snail and egg masses either early in the morning or in the evening. Use of protective clothing such as gloves and boots to protect farmers' health is also encouraged, since the snail acts as a vector for a number of parasites that cause human diseases (*e.g.* it is an important transmitter of *Angiostrongylus cantonensis*, the rat lungworm).[18] At present, only a small proportion of farmers reported using chemical pesticides specifically for apple snail, but this is likely to increase rapidly with snail spread, especially as currently this is the main management method recommended by agro-dealers. Indeed, when a new invasive pest arrives, and causes significant impacts, often farmers do not know how to manage it.[37] Farmers reported that because of lack of guidance on management options for apple snail, they are likely to use highly hazardous, and even banned products, which is unsurprising and has been documented for apple snail in other geographical locations as well as for other invasive pest species.[38]

Alongside improved snail management practices, there is an urgent need for raising awareness, outreach and capacity building at all levels – farm-level, extension and advisory services, through to regulation and policy level. Provision of the latest information on snail identification, life cycle and recommended management/control options should be prioritized. Use of accessible and varied communication approaches is recommended to engage farmers of all ages and educational backgrounds, to ensure rapid and widespread sharing of information on key management practices, as well as the impact of indiscriminate use of chemical pesticides on human health and the environment which is well documented.[39–42] The use of various methods to engage with stakeholders and build capacity is also paramount, for example, farmers particularly valued IPSs to gain information, such as neighbors/friends/relatives, as well as extension agents, and agro-dealers, with importance also placed on face-to-face communication, demonstration plots and field days. Targeted activities to raise awareness must be inclusive for all involved in apple snail management, including women and older farmers who are less likely to be aware of area-wide management of apple snail.

Mass campaigns to raise awareness are essential to increase knowledge and capacity to manage apple snail. Respondents in this study reported radio as the most effective form of communication after IPSs. Radio-based extension campaigns significantly increased farmers' knowledge and stimulated uptake of management measures for Fall Armyworm (FAW) (*Spodoptera frugiperda*) in Zambia.[43] The use of complementary mass-extension channels (plant health rallies, radio drama and SMS) have also been documented to enhance farmer knowledge and sustainable pest management practices.[44] However, any digitally based mass-communication must be combined with other low-cost face-to-face approaches.[44]

Coordination of stakeholders within an invasive species system is key for their effective management.[45] The established MITT has a central role as the coordinating body to guide apple snail management, and is responsible for coordinating the various stakeholders to ensure a united and rapid response. It is essential that community cooperation in management of apple snail is prioritized since management practices, such as physical control, will only be effective if applied by the whole community simultaneously.[46] A rigorous apple snail surveillance and monitoring program must be established to monitor for egg masses, all life stages of snails and provide timely information on spread. A range of clear, harmonized and cost-effective monitoring protocols is required in order that smallholders can incorporate these into their routine community management action plans as well as ensuring farmers implement a combination of recommended management options to minimize apple snail damage.[2] Greater economic, environmental and human health benefits are reported to occur when farmers adopt multiple integrated pest management approaches.[47]

A key requirement in managing any new pest in a cropping system, but particularly a highly invasive pest such as apple snail, is the allocation of sufficient resources for key activities to mitigate, or ideally prevent, further spread. For this to happen stakeholders at all levels must be engaged. Essential activities include mapping pathways of spread, development of risk assessments and rapid response plans for new incursions; as well as capacity building and implementation of a combination of effective management practices.

5 CONCLUSION

This study reports the status of apple snail invasion and impacts on rice farmers in MIS, Kenya. The negative impacts will only increase over time if *P. canaliculata* continues to spread. It is a call for urgent action. There is a rapidly narrowing window of opportunity for potential containment, or possibly even eradication, before apple snail becomes widespread in Kenya, and the only feasible option will become management, with its associated high economic, livelihood and environmental costs. In the absence of action to mitigate spread, the consequences could be disastrous, not only for farmers in Mwea but further afield. For example, if the snail spreads into the irrigated rice-production area of Ahero, at the edge of Lake Victoria, rice production in Tanzania and Uganda would be threatened, and from there inevitable further spread would occur.[2] There are also serious food security implications as apple snail threatens any progress that has been made towards Kenya's self-sufficiency in rice production.

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See https://www.cabi.org/what-we-do/how-we-work/cabi-donors-and-partners/ for full details.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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6 APPENDIX

Table A1. Effects of percentage area affected by apple snail (full regression results)

	IHS (Rice yield)		IHS (Net rice income)	
	Coefficient	Std. error	Coefficient	Std. error
Area affected by apple snail (%)	−0.005***	0.001	−0.030***	0.006
Age	−0.002	0.002	−0.004	0.007
Gender	0.060	0.049	0.113	0.221
Education	0.047	0.042	0.262	0.189
Household size	−0.010	0.012	−0.067	0.054
Off-farm	0.048	0.038	0.122	0.170
Credit access	−0.010	0.039	0.037	0.177
Extension access	0.023	0.038	0.026	0.170
Farmer group	0.114***	0.041	0.511***	0.185
Livestock holding	0.020	0.012	0.098*	0.055
Rice area	−0.003	0.033	0.105	0.150
Seed cost	0.078	0.059		
Fertilizer cost	0.018	0.017		
Pesticide cost	0.114***	0.043		
Labor cost	0.007	0.006		
Mwea West Subcounty	0.102**	0.044	0.009	0.193
Constant	9.390***	0.136	8.573***	0.563
No. of observations	706		706	

*** $p < 0.01$;
** $p < 0.05$;
*$p < 0.1$.

Table A2. Effects of level of apple snail infestation (full regression results)

	IHS (Rice yield)		IHS (Net rice income)	
	Coefficient	Std. error	Coefficient	Std. error
Minor infestation (1 = yes)†	0.019	0.053	−0.006	0.240
Moderate infestation (1 = yes)†	−0.149**	0.067	−0.863***	0.306
Age	−0.002	0.002	−0.003	0.007
Gender	0.060	0.050	0.112	0.224
Education	0.055	0.042	0.309	0.191
Household size	−0.012	0.012	−0.081	0.055
Off-farm	0.042	0.038	0.088	0.172
Credit access	−0.014	0.039	0.013	0.178
Extension access	0.031	0.038	0.064	0.172
Farmer group	0.107**	0.041	0.473**	0.187
Livestock holding	0.020*	0.012	0.105*	0.055
Rice area	0.006	0.034	0.146	0.152
Seed cost	0.076	0.059		
Fertilizer cost	0.014	0.017		
Pesticide cost	0.105**	0.044		
Labor cost	0.008	0.006		
Mwea West Subcounty	0.113**	0.045	0.114	0.197
Constant	9.335***	0.147	8.172***	0.617
No. of observations	706		706	

*** $p < 0.01$;
** $p < 0.05$;
*$p < 0.1$.
† The comparison group is no apple snail infestation.