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Current and potential distribution of the invasive apple snail, *Pomacea canaliculata* in Eastern Africa: evidence from delimiting surveys and modelling studies

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Abstract

The invasive apple snail *Pomacea canaliculata* has become a significant concern in invaded habitats beyond its native range. It was reported in Kenya in 2020 invading one of the largest rice-producing schemes, the Mwea irrigation scheme. Delimiting surveys were conducted across five key rice-producing schemes (Mwea, Bura, Hola, Ahero and West Kano) in Kenya to establish the extent of the invasion and develop effective quarantine and management strategies within the Mwea scheme and other risk areas. Additionally, the ensemble model approach was used to model the potential distribution of *P. canaliculata* in Eastern Africa (as defined by the United Nations Geoscheme). Over 80% of the Mwea scheme was infested with *P. canaliculata*, an expansion from the initial infestation point (Ndekia). The mean number of adults/m^2 and egg clutches/m^2 were 8.4 ± 0.9 (SEM) and 7.7 ± 1.4 (SEM), respectively, with varying densities across sections. No adults or eggs of *P. canaliculata* were found in the four schemes outside the Mwea scheme. The model predicted high suitability for *P. canaliculata* in the southwest of Kenya,and in coastal areas, with all surveyed areas marked as highly suitable.. Regionally, high-risk areas include Malawi, Madagascar, and Uganda. Mozambique, Tanzania, and Ethiopia showed localised areas of high suitability. Conversely, Sudan, South Sudan, Eritrea, Djibouti and Somalia were largely unsuitable for *P. canaliculata*. Given the potential for further spread, strict quarantine measures are essential to prevent the spread of *P. canaliculata* in Kenya and its introduction to uninvaded regions of Eastern Africa. Alongside this, implementing IPM e strategies is crucial for effective pest management and the protection of agricultural ecosystems.

Keywords *Pomacea canaliculata*, Delimiting survey, Invasion boundary, Ensemble modelling, Invasive, Ampullariidae, Apple snail

Introduction

Pomacea canaliculata (Lamarck), is a prolific invasive species that invades freshwater systems and is listed among 100 of the worst invasive alien species in the world (Lowe et al. 2000). Native to South America (Hayes et al. 2012), it has spread widely and is now considered a serious global pest causing significant economic and ecological impacts (Constantine et al. 2023; Joshi et al. 2017; Cowie 2002) The invasiveness of this snail, like

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many other successful invasive species, can be attributed to various factors. They include broad habitat tolerance (Qin et al. 2020a, b; Qin et al. 2020a, b) and exceptional adaptability to stressful environmental conditions, including agrochemical applications and intermittent drainage (Horgan 2018; Lach et al. 2000; Wada & Matsukura 2011). Furthermore, the combination of high reproductive rates and significant genetic diversity (Lv et al. 2013; Yang et al. 2018) enables a rapid population increase within invaded regions. The snail's invasiveness is also amplified by its robust defence mechanisms and competitive advantage over native species (Qin et al. 2020a, b; Qin et al. 2020a, b), along with a lack of effective natural predators or controls in invaded areas. Its ability to breathe air enables this freshwater species to survive in terrestrial environments for short periods, while its ability to aestivate buried in the substrate during dry periods provides a means of survival. Additionally, irrigation water and sufficient food sources—rice and other plants e.g. taro (Cowie 2002)—have facilitated the establishment and spread of this pest, especially in rice fields. These combined characteristics make *P. canaliculata* highly successful in establishing and spreading to new environments, posing a significant challenge for management and conservation efforts. Invaded rice-producing areas continue to suffer from significant damage and economic losses caused by *P. canaliculata* because of the need for replanting to replace the damaged crops and the increased production costs associated with implementing management practices (Salleh et al. 2012; Ranamukhaarachchi & Wickramasinghe 2006; Halwart 1994;). A recent study in Kenya to assess the socio-economic impacts associated with the arrival of *P. canaliculata* reported significant reductions in rice yield (~14%) and net rice income (~60%) at a moderate infestation level (> 20% of cultivated area) (Constantine et al. 2023). Elsewhere, yield reduction of up to 50%, resulting in millions of US dollars in economic losses have been reported (Djeddour et al. 2021; Naylor 1996; Halwart 1994). Furthermore, the detrimental effects extend beyond crop-related concerns and encompass impacts on human health (as vectors for parasites such as rat lungworm parasite (*Angiostrongylus cantonensis*) which can cause potentially fatal eosinophilic meningitis in humans and animals) (Yang et al. 2013) and natural ecosystems (Joshi 2007). These combined factors contribute to the ongoing challenges rice farmers face, necessitating effective management strategies to mitigate the negative consequences and ensure sustainable rice production.

Rice is the third most important crop in Kenya, playing a crucial role in household food security and farmers' incomes (MoA 2019). Approximately 80% of the country's rice production is under irrigation, with the remaining 20% being rainfed (MoA 2019). The recent completion of the Thiba Dam in Mwea in 2022 is expected to expand the area and volume of irrigated rice production. *Pomacea canaliculata* arrival adds to the long list of rice production constraints threatening an important value chain in the country. Therefore, identifying the current and potential spread of this pest can provide early warnings to decision-makers, enabling them to mitigate the impact of potential invasions. This proactive approach will also aid in developing contingency plans to address any future invasions effectively in the region.

Since its first report in Kenya in 2020 (Buddie et al. 2021), *P. canaliculata* continues to expand its range from the invasion point where damage to rice crops continues to be reported by farmers. However, the pathway of introduction of this snail in Kenya remains unknown. While unconfirmed media reports suggest that it was introduced for research and weed biocontrol purposes, no authorized organization in the country has issued import permits for the species. In Kenya, the management of this pest has predominantly relied on physical and cultural practices, with some farmers resorting to the desperate use of unregistered and potentially illegal broad-spectrum synthetic chemicals. Other strategies employed by farmers include handpicking adults, crushing egg masses, and implementing water/flood management techniques such as alternate wetting and drying (AWD). Unfortunately, most of these practices have proven ineffective in containing the spread of *P. canaliculata*. Compounding the issue is the absence of registered pesticides specifically formulated for controlling *P. canaliculata* in the country.

Following a status survey in September 2020, to assess the extent of the invasive apple snail presence, samples were collected and subjected to molecular analysis for accurate identification. Upon confirmation of their identity, CABI and Kenya Plant Health Inspectorate Services (KEPHIS) collaborated to conduct a delimiting survey in the five major rice production areas (risk areas): Mwea (Kirinyaga County), Bura and Hola (Tana River County), and Ahero and West Kano (Kisumu County) irrigation schemes. The objective was to determine the boundaries of the spread of *P. canaliculata* since its initial report and to aid in the development of management and quarantine strategies to restrict its further expansion. Additionally, species distribution modelling using an ensemble model approach was carried out to predict the potential distribution of *P. canaliculata* in Eastern Africa. These efforts aim to enhance understanding of the pest's geographic range and support effective measures for its control and containment.

Materials and methods

Study sites

The delimiting survey covered five major rice schemes in Kenya: Mwea, Ahero, Bura, Hola, and West Kano (see Fig. 1 and Table 1). Mwea irrigation scheme, located in Kirinyaga County, covering approximately 12,282 hectares, is responsible for over 70% of the country's rice production. Kirinyaga County experiences a temperature range of 12–26 °C, averaging around 20 °C, while the annual rainfall ranges between 1,100 mm and 1,250 mm. The Hola and Bura irrigation schemes are in Tana River County and cover 5111 ha and 2023 ha, respectively. The climate in this area is generally hot and dry, with average temperatures exceeding 25 °C and averaging over 27°C in some areas. The mean annual precipitation is ~ 500 mm. Ahero and West Kano irrigation schemes, located in Kisumu County, have a combined area of around 4047 ha under rice production and rely on water from the Nyando River and Lake Victoria. Kisumu County is generally warm and humid throughout the year, with mean annual temperatures ranging from 21 °C to 23°C in most areas. Table 1 shows the survey locations including GPS coordinates in the different locations.

Delimiting survey

Following the invasion of rice fields in Mwea in 2020, a delimiting survey (according to International Standards for Phytosanitary Measures, ISPM No. 6 (Secretariat of the International Plant Protection Convention 2018) was conducted for *P. canaliculata* in the above-mentioned rice irrigation schemes in Kenya (Fig. 1). With the help of scheme managers, field officers and lead farmers in these schemes and through trace-back information about the source and spread of apple snails in Mwea identifying earlier and recently invaded areas, potential points of invasion were identified. These became the starting points for the surveys. Sampling was conducted in the rice paddies in each scheme, along the watercourses (irrigation canals) and in other suitable habitats in the vicinity bordering the paddies. Field surveys were conducted in December 2020 and February 2022.

Sampling procedure

Sampling followed the protocol described by Seuffert & Martín (2013) with amendments depending on the snail presence, size of paddy, length of the canal shore and accessibility. The sites considered as inhabited by *P. canaliculata* were those where eggs masses or live snails were found/observed after a preliminary inspection from the shores. Briefly, 3–10 points were sampled within inhabited sites depending on the length/size of canal and/or paddy. These sampling points were *ca.* 10 m long along shores located within less than 100 m of each other; at sites without *P. canaliculata* only confirmatory inspections were conducted. Where snails were found after inspection a full sampling was conducted following the procedure described above. Sampling comprised 401 points from 68 georeferenced sites distributed across the five schemes (Table 1). Location details were recorded using a handheld GPS.

At each sampling point, a two-person inspection was carried out in the rice paddies, terrace walls and irrigation canal shores while wading upstream in search for egg masses on the emergent aquatic vegetation and other substrata; *P. canaliculata* were searched for among the submerged vegetation, under stones or buried in the substrate. Within each sampling point, three 1 m^2 wooden frame quadrats were randomly placed, and all visible adult snails (> 2 cm in diameter) and eggs masses within them were counted and recorded. Mean counts from the three quadrats at each point were calculated and used in the analysis. Information on rice crop variety and other plants infested were recorded. To minimize the potential of spreading *P. canaliculata* during sampling, the process began from the lower (low or no-infestation) sections and progressed towards the upper ends of the scheme (where infestation was present). This was based on trace-back information from the National Irrigation Authority (NIA) staff and farmers. Special attention was given to drainage and irrigation canals as they are significant for the dispersal of the pest. Besides the main schemes, outgrowers (individual farmers bordering the scheme but not part of the main scheme setup and who do not have the advantage of good infrastructure e.g. canals, water supply) were surveyed in all the schemes.

Data analysis

We used a generalized linear negative binomial model to analyse the effect of section area within the Mwea scheme on both the number of adults collected and the number of egg masses collected. An analysis of deviance was conducted on all the models to determine the overall effect of the survey area, followed by a Tukey's post hoc test to further investigate any significant results. Note, this analysis was only conducted on data from the Mwea irrigation scheme, as no *P. canaliculata* were found at any of the other irrigation schemes.

Species distribution modelling

Environmental data

Based on the environmental requirements of *P. canaliculata* (Ito 2002; Qin et al. 2020a, b; Seuffert et al. 2010), the following climatic variables were selected: annual precipitation; precipitation of driest quarter, maximum temperature of warmest quarter and minimum temperature of coldest quarter. BioClim's

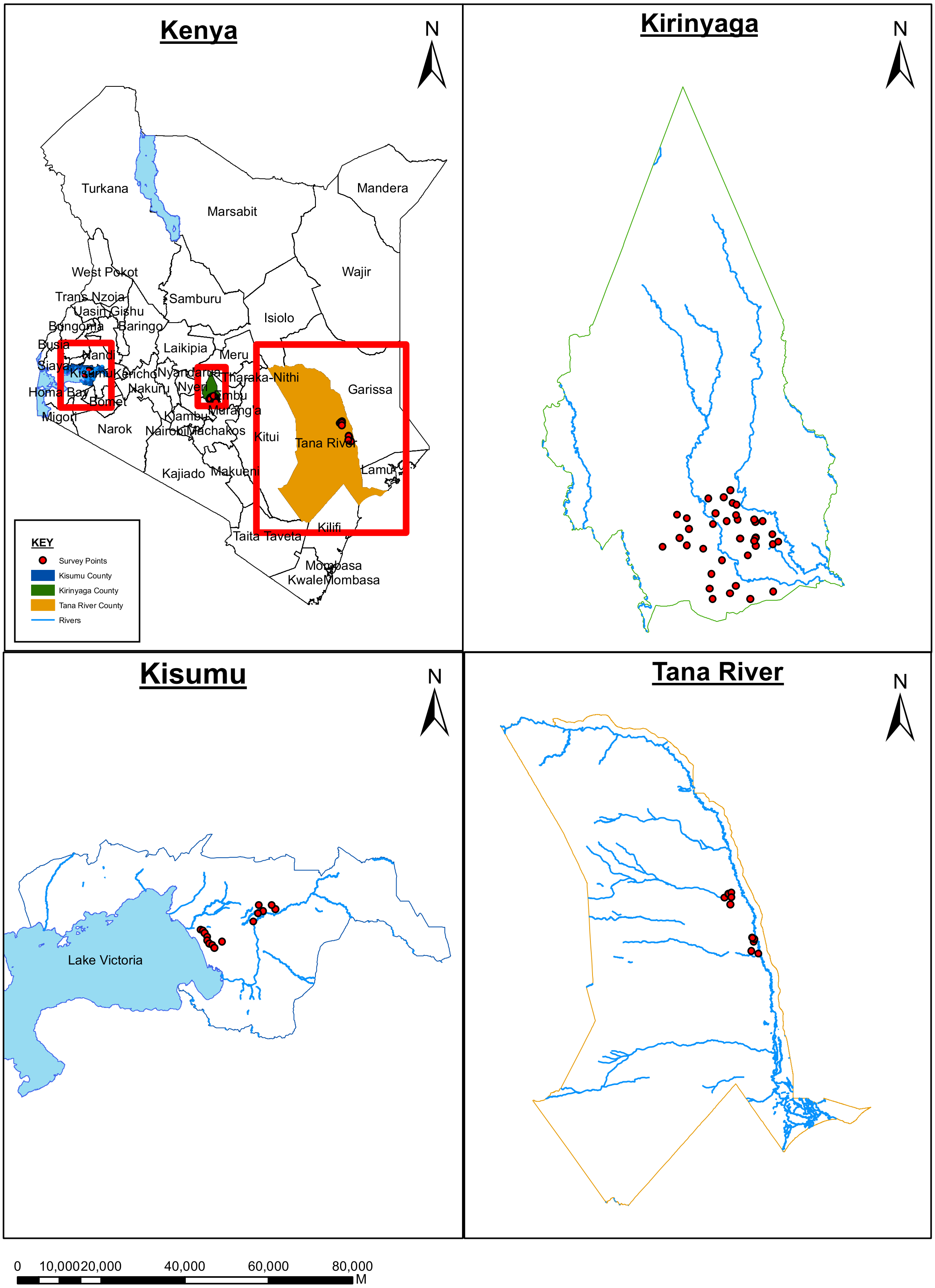

Fig. 1 Invasive apple snail (*P. canaliculata*) survey locations in Mwea (Kirinyaga County), Bura and Hola (Tana River County) and Ahero and West Kano (Kisumu County)

Table 1 Survey site locations showing (left-to-right): name of county, name of irrigation scheme, section name, block name, latitude, longitude and altitude

County	Scheme	Section	Block	Latitude (m)	Longitude(m)	Altitude (m)
Kirinyaga	Mwea	Kiamanyeki	Kiamanyeki	– 0.69598	37.38399	1130.964
Kirinyaga	Mwea	Tebere	T22	– 0.6826	37.41321	1130.789
Kirinyaga	Mwea	Tebere	T25	– 0.68013	37.41974	1127.933
Kirinyaga	Mwea	Tebere	T11	– 0.67137	37.41266	1136.626
Kirinyaga	Mwea	Tebere	T8	– 0.65554	37.40119	1148.359
Kirinyaga	Mwea	Tebere	T6/7	– 0.65648	37.39282	1156.951
Kirinyaga	Mwea	Tebere	T67	– 0.65394	37.39147	1156.443
Kirinyaga	Mwea	Tebere	T15	– 0.67471	37.39326	1144.631
Kirinyaga	Mwea	Tebere	T18	– 0.67598	37.39271	1141.957
Kirinyaga	Mwea	Tebere	T21	– 0.68456	37.39308	1135.785
Kirinyaga	Mwea	Tebere	T17	– 0.67916	37.39133	1135.878
Kirinyaga	Mwea	Tebere	T20	– 0.67643	37.37517	1146.468
Kirinyaga	Mwea	Tebere	T16/13	– 0.67643	37.37522	1145.216
Kirinyaga	Mwea	Tebere	T13	– 0.65388	37.37233	1172.261
Kirinyaga	Mwea	Tebere	T5	– 0.64891	37.37055	1178.281
Kirinyaga	Mwea	Tebere	T2	– 0.635	37.36634	1190.863
Kirinyaga	Mwea	Tebere	T3	– 0.63667	37.37067	1187.551
Kirinyaga	Mwea	Ndekia	2B	– 0.65557	37.3596	1156.595
Kirinyaga	Mwea	Ndekia	3	– 0.64652	37.3462	1189.205
Kirinyaga	Mwea	Ndekia	4	– 0.62942	37.33787	1193.442
Kirinyaga	Mwea	Ndekia	1	– 0.62793	37.35605	1191.451
Kirinyaga	Mwea	Mwea	M4	– 0.65947	37.34339	1181.241
Kirinyaga	Mwea	Mwea	M6/7	– 0.65274	37.31306	1189.667
Kirinyaga	Mwea	Mwea	MIAD	– 0.64865	37.30164	1193.927
Kirinyaga	Mwea	Mwea	M17	– 0.66471	37.31534	1178.342
Kirinyaga	Mwea	Mwea	M14	– 0.68421	37.31312	1166.108
Kirinyaga	Mwea	Thiba	H20	– 0.68795	37.33216	1163.23
Kirinyaga	Mwea	Thiba	H5	– 0.71707	37.34196	1151.891
Kirinyaga	Mwea	Wamumu	W7	– 0.73445	37.33957	1142.041
Kirinyaga	Mwea	Wamumu	W5	– 0.74663	37.34327	1136.672
Kirinyaga	Mwea	Wamumu	W3	– 0.73131	37.37017	1128.687
Kirinyaga	Mwea	Thiba	H7	– 0.70129	37.35384	1121.972
Kirinyaga	Mwea	Outgrower	Ngothi/ Mugaa	– 0.68567	37.28479	1145.008
Kirinyaga	Mwea	Outgrower	Kandongu Upper	– 0.67544	37.30454	1176.011
Kirinyaga	Mwea	Karaba	K2	– 0.7401	37.36328	1130.389
Kirinyaga	Mwea	Karaba	K4	– 0.74651	37.38684	1136.36
Kirinyaga	Mwea	Karaba	K7	– 0.73796	37.41393	1114.962
Kirinyaga	Mwea	Kimbimbi	Kimbimbi	– 0.61966	37.36361	1172.615
Kisumu	West Kano	West Kano F	F2	– 0.18069	34.80642	1135.034
Kisumu	West Kano	West Kano E	E1	– 0.18243	34.8114	1137.53
Kisumu	West Kano	West Kano E	H	– 0.187556	34.81456	1130.178
Kisumu	West Kano	West Kano J	J	– 0.195628	34.82079	1131.656
Kisumu	West Kano	West Kano C	C3	– 0.202834	34.82034	1130.011
Kisumu	West Kano	West Kano C	C4	– 0.209996	34.82514	1135.788
Kisumu	West Kano	West Kano B	B2	– 0.212803	34.83126	1128.359
Kisumu	West Kano	West Kano A	A	– 0.219084	34.83573	1134.457
Kisumu	West Kano	West Kano	West Kano Outgrower1	– 0.205708	34.85217	1139.142
Kisumu	Ahero	Ahero	Ahero A	– 0.1361154	34.96645	1167
Kisumu	Ahero	Ahero	Ahero C	– 0.1403756	34.94051	1161

Table 1 (continued)

County	Scheme	Section	Block	Latitude (m)	Longitude(m)	Altitude (m)
Kisumu	Ahero	Ahero	Ahero F	– 0.127424	34.95957	1165
Kisumu	Ahero	Ahero	Ahero K	– 0.1453987	34.92973	1155
Kisumu	Ahero	Ahero	Ahero L	– 0.1453987	34.92973	1155
Kisumu	Ahero	Ahero	Ahero N	– 0.1629546	34.91958	1137
Kisumu	Ahero	Ahero	Ahero Outgrower	– 0.1276082	34.93182	1163
Tana River	Hola	Hola	Hola Area 6	– 1.49819	40.03611	62
Tana River	Hola	Hola	Hola Commercial farm1	– 1.421	40.00595	71
Tana River	Hola	Hola	Hola Commercial farm2	– 1.40727	40.00875	74
Tana River	Hola	Hola	Hola Area 4–5	– 1.39731	39.99625	75
Tana River	Hola	Hola	Hola Commercial farm3	– 1.39927	39.99839	73
Tana River	Bura	Bura	Hola Area 1	– 1.48108	39.99122	72
Tana River	Bura	Bura	Chewele Branch	– 1.14718	39.82289	102
Tana River	Bura	Bura	Village 6	– 1.12421	39.84693	98
Tana River	Bura	Bura	Village 6a	– 1.12436	39.85062	99
Tana River	Bura	Bura	Village 4–5	– 1.1147	39.86814	93
Tana River	Bura	Bura	BCF- Bura Commercial Farm	– 1.14595	39.86618	96
Tana River	Bura	Bura	Village 8	– 1.14593	39.86628	96
Tana River	Bura	Bura	Village 10	– 1.188393	39.85943	98

definition of a quarter is any consecutive 3 months. These were extracted from the 10 arc-minute resolution WorldClim dataset (http://www.worldclim.org).

Precipitation data often do not reflect the amount of water input into irrigated areas. As such, the chosen variables relating to precipitation, i.e. annual precipitation and precipitation of the driest quarter, were modified to reflect irrigation patterns. The irrigation correction was based on the general principle that irrigation compensates for water loss through evapotranspiration (Brouwer & Heibloem 1986) and uses methods fully described by Federman et al., (2013). In summary, the difference between evapotranspiration and precipitation was calculated for both annual data and for data representing the driest quarter. These differences were then applied to annual precipitation and the precipitation of the driest quarter in irrigated areas, to give variables adjusted for irrigation. Irrigated areas were identified from (Siebert et al. 2005). Evapotranspiration data were extracted from ENVIREM (Title & Bemmels 2018) and the precipitation data from the WorldClim dataset.

Multicollinearity amongst the four variables was tested for using the Pearson correlation coefficient. A value of more than 0.7 is considered to indicate variables that covary too much; however, this did not apply to any of the four variables.

Distribution data

Global distribution data for *P. canaliculata* were downloaded from GBIF (www.gbif.org). Only records that were labelled as "human observation" or "occurrence" were retained. These records were then filtered to remove any coordinates with high levels of uncertainty. To ensure that only records of *P. canaliculata* and not other species (e.g. *Pomacea maculata* and *Pomacea occulta*) were included in the dataset, we only included data from academic institutions or those from museums. Data on the presence of *P. canaliculata* collected during this current study were then added to the cleaned GBIF records. This represented our overall dataset. This dataset was filtered so that only one presence was recorded in each climatic grid-cell, resulting in a working dataset of 91 distributional records.

Statistical Species Distribution Models (SDMs) require information on where a species is absent. Often there is insufficient verified data, and thus "pseudo-absences" must be used. To allow us to use, and test the predictive accuracy, of statistical SDM methods, ten sets of pseudo-absences were sampled at random. Each of the sets of pseudo-absences were restricted so that they were always within 500 km of a verified *P. canaliculata* location but were outside of a grid cell occupied by a presence location. An upper distance for the pseudo-absences was specified as this has been shown to prevent models from contrasting completely different climate conditions, e.g. temperate vs. tropical (VanDerWal et al. 2009). The number of pseudo-absence points in each set was equal to the number of presence points (i.e. 91).

Modelling

An ensemble model approach was used to predict the distribution of *P. canaliculata* in Kenya and more broadly across Eastern Africa and Madagascar. Ensemble modelling can generate a more robust model and overcome the uncertainties involved with interpreting results from individual models (Araújo and New 2007; Hao et al. 2019). The ensemble used included ten modelling techniques: Surface Range Envelope (SRE), Generalized linear models (GLM), Generalized additive models (GAM), Multivariate adaptive regression spline (MARS), Classification tree analysis (CTA), Flexible Discriminant Analysis (FDA), Artificial neural network (ANN), Random Forest (RF), Generalized boosting method (GBM) and maximum entropy (MAXENT). All analyses were conducted in R (R Core Team 2023) using the biomod2 package (Thuiller et al. 2013) and default SDM settings (Appendix 1).

Occurrence data were split randomly and 70% were used as training data for model calibration and the remaining 30% were used to evaluate the model's predictive performance. The Area under the receiver operating curve (AUC) and True Skill Statistic (TSS) were used to assess the accuracy of the model predictions compared to the validation data.

Ensembles were created using all models for which the validation $TSS \geq 0.4$, a value that is considered to signify models with moderate performance (Landis and Koch 1977). To construct the ensemble, the mean suitability predicted by all the retained models was calculated, weighted by the accuracy (TSS) of each model.

The importance of the environmental variables in the distribution of *P. canaliculata* was calculated using all models. For each variable, the variable was randomised and model predictions were made with this shuffled dataset. Pearson's correlation (r) was then calculated between the model predictions made with the original and those made with the shuffled data.

Results

Delimiting surveys

Findings from this survey showed an expansion of the invasion boundary from the initial point of infestation in the Mwea rice scheme, with 80% of the scheme being infested with *P. canaliculata*. There were no adult or egg masses recorded in any of the other irrigation schemes.

In the Mwea irrigation scheme, the average number of adults and egg masses.

was $8.4/m^2 \pm 0.9$ (SEM) and $7.7/m^2 \pm 1.4$ (SEM), respectively, with significant variations across sections: Adults ($\chi^2(7) = 232.87$, $p < 0.01$) and eggs ($\chi^2(7) = 203.59$, $p < 0.01$). No adults or eggs were found in the Mwea-MIAD section of the scheme(Figs. 2 and 3).

Species distribution modelling

Whilst all the individual SDM techniques yielded good results ($AUC > 0.8$), RF had the best performance ($AUC = 0.99$) compared to ANN which had the poorest performance ($AUC = 0.80$) (Table 2). All models had

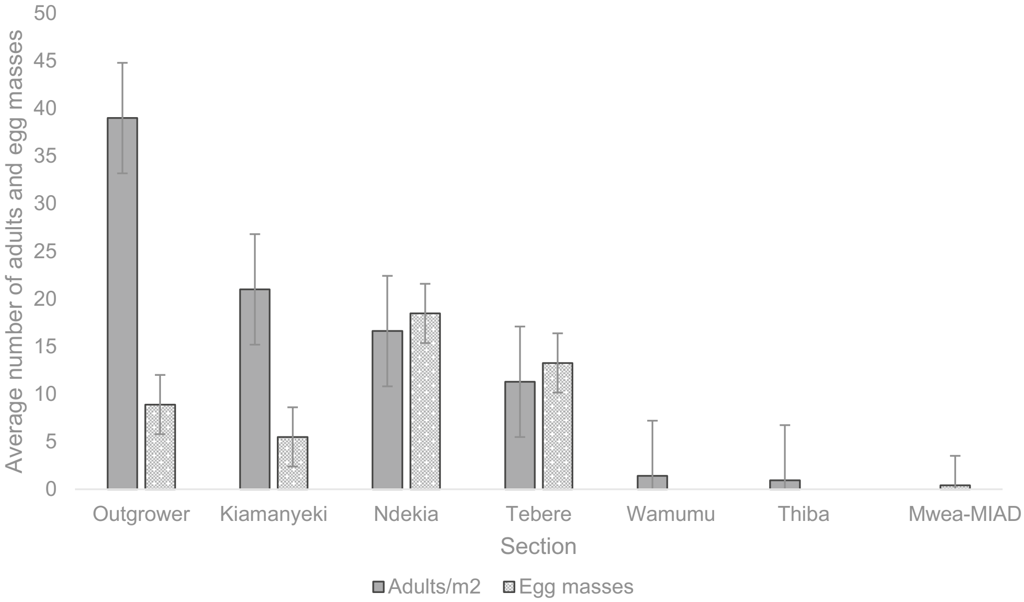

Fig. 2 Average number of adults/m^2 and egg masses, by section in Mwea irrigation scheme

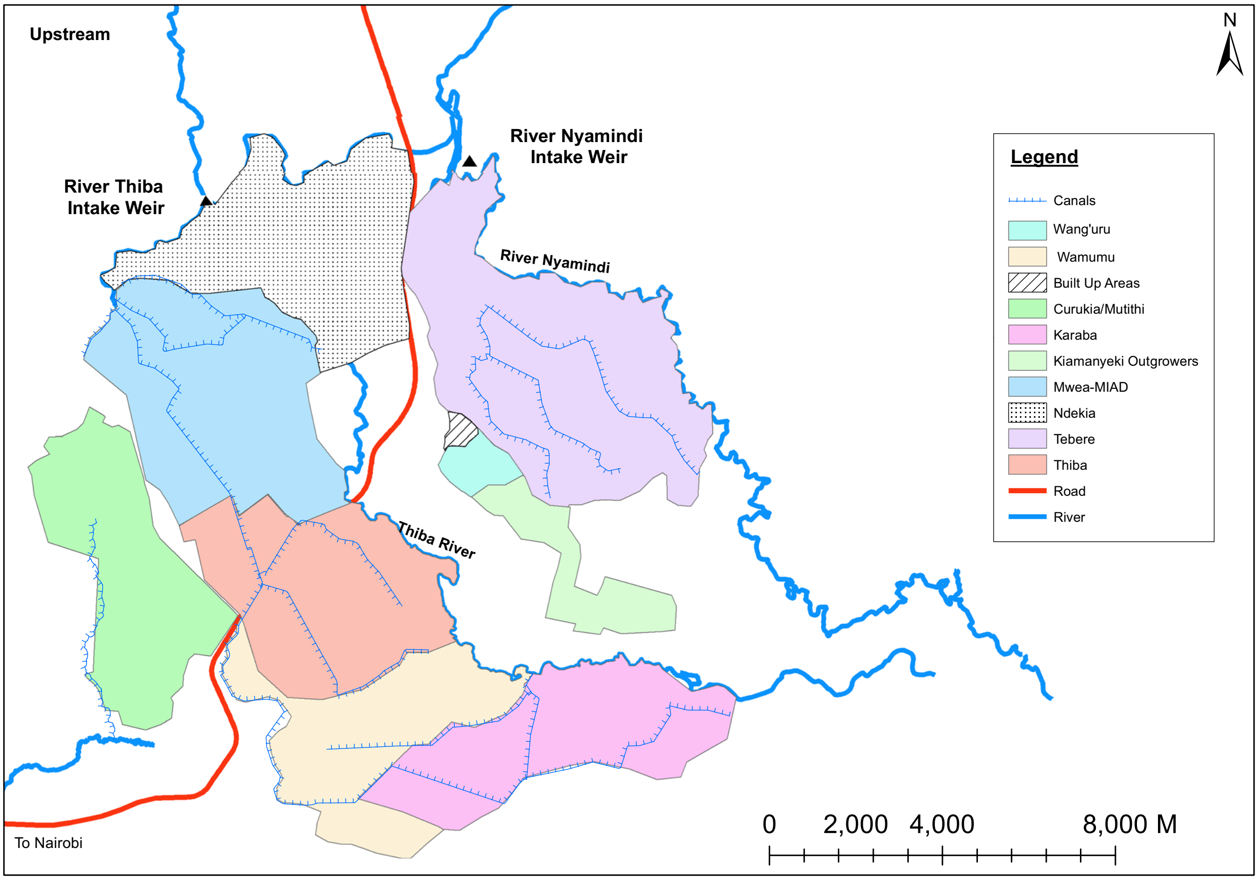

Fig. 3 Map of Mwea irrigation scheme showing different sections

Table 2 Summary statistics for all the models made, along with standard deviations of the values in parentheses

Model technique	Mean AUC (+SD)	Mean TSS (+SD)
SRE	0.84 (+0.01)	0.68 (+0.02)
GLM	0.91 (+0.01)	0.74 (+0.01)
GAM	0.93 (+0.02)	0.79 (+0.03)
MARS	0.93 (+0.01)	0.77 (+0.02)
CTA	0.92 (+0.03)	0.81 (+0.03)
FDA	0.93 (+0.01)	0.77 (+0.02)
ANN	0.88 (+0.03)	0.74 (+0.04)
GBM	0.97 (+0.01)	0.84 (+0.02)
RF	0.98 (+0.01)	0.98 (+0.01)
MAXENT	0.95 (+0.01)	0.68 (+0.02)

TSS scores above 0.4 and thus were all included in the final ensemble model.

The final ensemble model had good predictive ability as indicated by a TSS score of 0.80 and an AUC value of 0.95. Analysis of the importance of the environmental variables showed that the driest quarter was the most important, followed by minimum temperature of the coldest month and maximum temperature of the warmest month. Adjusted annual precipitation was the least important variable (Table 3).

Table 3 Importance of variables for species distribution models (SDMS) of P. CANALICULATA. Values are the mean (+standard deviation) of the results across all SDM techniques

Variable	Importance
Adjusted precipitation in the driest quarter	0.37 (±0.16)
Adjusted annual precipitation	0.23 (±0.16)
Maximum temperature of the warmest month	0.25 (±0.11)
Minimum Temperature of Coldest Month	0.31 (±0.13)

Potential distribution of P. Canaliculata

There was good suitability for *P. canaliculata* in the south-west of Kenya, along the Tana River and in the coastal areas near Mombasa (Fig. 4). All three survey

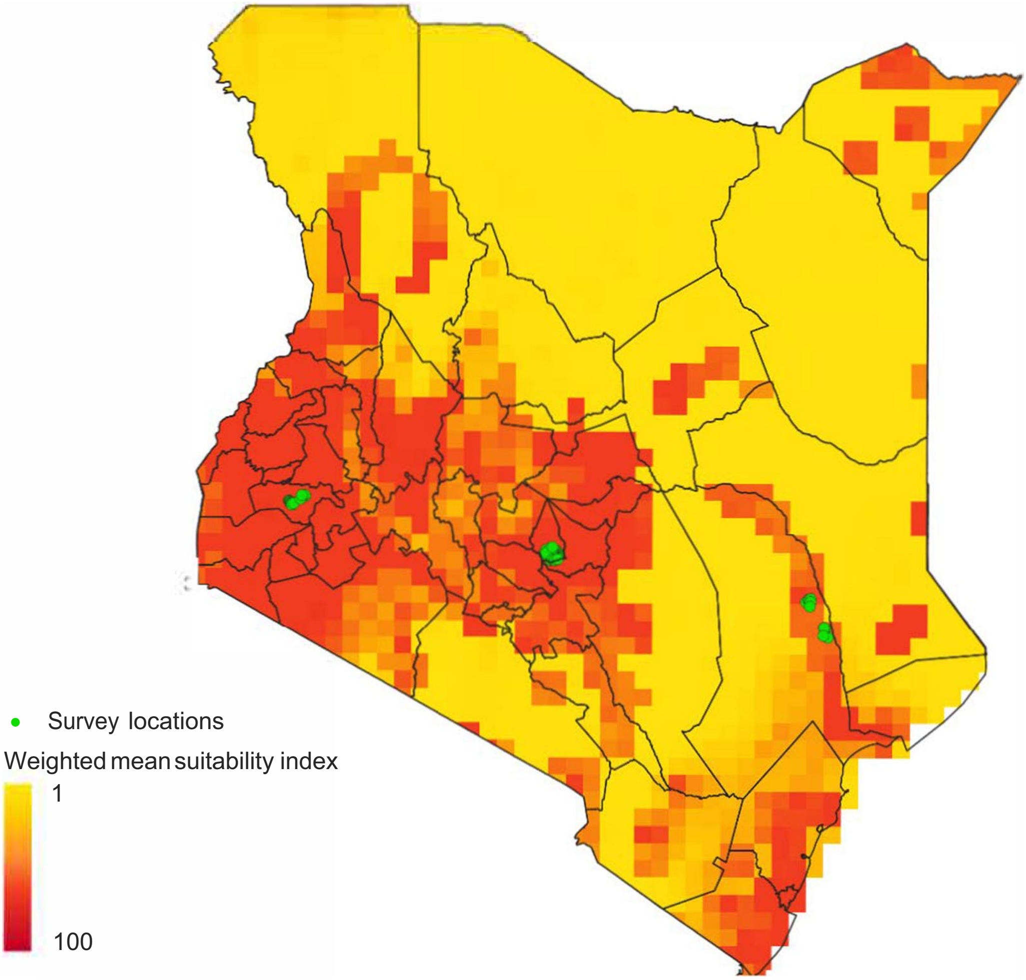

Fig. 4 Environmental suitability for the invasive apple snail *P. canaliculata* across Kenya as predicted by an ensemble of SDMs. Points represent survey locations described in this paper

areas were modelled as having high suitability for *P. canaliculata*. Whilst no *P. canaliculata* were found in the Tana River and Kisumu counties during the surveys, the high suitability of these areas highlights the potential for further spread of *P. canaliculata* into these areas. Across the region, suitability for *P. canaliculata* was broadly high across Malawi, Madagascar and Uganda. Mozambique, Tanzania and Ethiopia also had areas of high suitability, but these were more concentrated in specific areas of these countries. Conversely, Sudan, South Sudan, Eritrea, Djibouti and Somalia were largely unsuitable for *P. canaliculata* invasion, although the areas along the Nile in Sudan were moderately suitable. Additionally, the model showed that the Ethiopian highlands are suitable for *P. canaliculata* but are bordered by unsuitable regions: eastern Ethiopia, Eritrea, Djibouti, Somalia, northern Kenya, South Sudan and Sudan (Fig. 5).

Discussion.

Delimiting surveys are important in helping to establish the boundary of the spread of a pest and to help in the management and development of quarantine strategies to limit its spread to other risk areas (McMaugh 2005). Knowledge of the boundary of invasion is important in guiding appropriate resource (financial, personnel, time etc.) allocation for surveillance and management of the pest. The surveys conducted in this study have demonstrated an expansion in the range of *P. canaliculata* from the initial point of infestation (Ndekia) to other sections of the Mwea scheme since its first report in 2020.

The density of snails and egg masses varied significantly across different sections of the Mwea scheme with the highest concentrations found in the upper and initial points of introduction. The spread appears to follow the direction of water flow in the interconnected

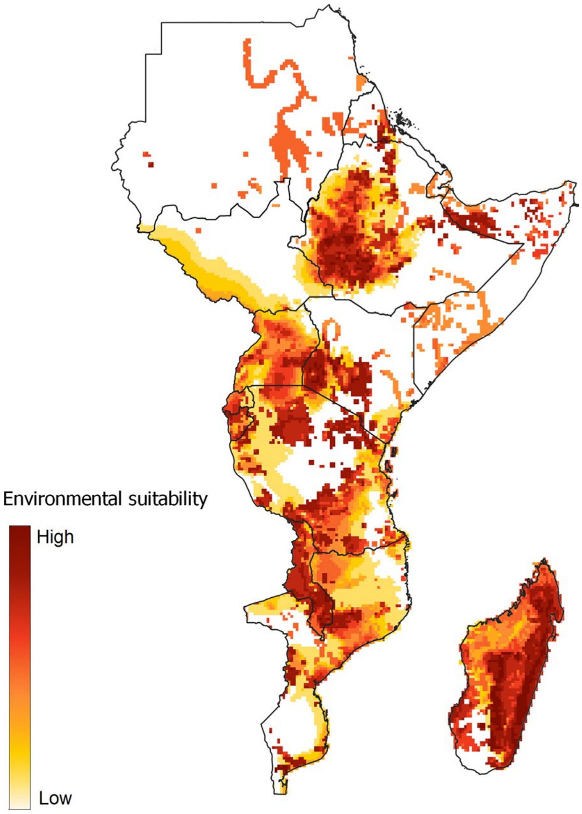

Fig. 5 Environmental suitability for the invasive apple snail *P. canaliculata* across Eastern Africa as predicted by an ensemble of SDMs

rice fields, rivers, and canals with sufficient host plants, which provide efficient pathways for natural dispersal, consistent with previous research (Joshi et al. 2017; Kappes & Haase 2012). Access to flowing water or flooding events provides an efficient pathway for the spread of *P. canaliculata,* and increasingly frequent intense floods in Kenya, exacerbated by climate change, may further contribute to its dispersal into new regions increasing the risk of crop damage and economic losses (Constantine et al. 2023; Djeddour et al. 2021). Additionally, Martín et al. (2017) reported that the *P. canaliculata* disperses in streams via both crawling and drifting, with downstream movement at least ten times faster downstream than upstream dispersal (Kappes & Haase 2012). The rapid infestation of the scheme is likely a result of these combined factors. Notably, the irrigation waters of Mwea, through various river systems, drain into the Tana River, which supplies the Bura and Tana Delta irrigation schemes in Tana River County, potentially increasing the risk of spread.

Knowledge of local risks is critical in instituting and implementing any management practices for a pest (Finch et al. 2021). Species distribution modelling for *P. canaliculata* highlighted areas in Kenya and more broadly across Eastern Africa that are highly suitable for invasion. In Kenya, those areas that were modelled as highly suitable in the southwest and along coastal areas of the country, host the major paddy rice production schemes in the country.. While *P. canaliculata* has not been reported in other countries in Eastern Africa, our results suggest large areas, including Madagascar, are at risk.. Madagascar a major rice producer in the region, according to FAOSTAT data (FAO 1998) and could face significant economic losses from a *P. canaliculata* invasion.. Additionally, if *P. canaliculata* were to spread to areas surrounding Lake Victoria from the Kenyan side (through rice schemes in the western part of the country), the surrounding rice production areas in Tanzania and Uganda could likely be infested. This spread could potentially infest major river systems such as the White Nile causing a disaster in the region (Djeddour et al. 2021).

Management options

As a new pest in Kenya and indeed Africa, management of *P. canaliculata* has mainly relied on cultural and physical approaches, and, in desperation, a trial-and-error approach with chemical practices. Similar approaches have been reported around the world for control of *P. canaliculata* in rice fields (Joshi 2007; Joshi et al. 2017). Unfortunately, most of these practices have proven to be either cumbersome, impractical, expensive or ineffective. The situation is exacerbated by the lack of available registered molluscicides in Kenya, leading to indiscriminate pesticide use, which negatively impacts environmental safety, human health, and biodiversity.. Given the ecology of *P. canaliculata*, its potential impacts following invasion and the climatically suitable areas for its spread, implementing an integrated management approach is imperative.

Although no adult *P. canaliculata* or their eggs were found in the Ahero, Bura, Hola or West Kano schemes, the extensive material transfer, including the aromatic Basmati rice seedlings and farm machinery (especially the combine harvesters and rotavators) from Mwea (an infested area), could facilitate the spread into these areas.. This could pose a serious risk to rice farming in these areas should *P. canaliculata* invade, further compounding the already- constrained rice industry. While we did not find data on material (rice seedlings) exchange between Kenya and neighbouring countries, farm machinery exchanges are ongoing, indicating potential for pest introduction.. The distribution model highlights these areas as highly suitable for invasion. As such, it is crucial to intensify phytosanitary and quarantine measures in these regions.. Material transfer, mechanisation and other human-mediated activities can facilitate the spread and introduction of pests in new areas (Gippet et al. 2019; Ranamukhaarachchi and Wickramasinghe 2006; Litsinger and Estano 1993;). This combined information is important for early warning and contingency planning in the uninvaded areas.

To manage and curb further spread especially to other risk areas, the following containment measures are proposed: (1) undertake training and awareness regarding *P. canaliculata* through the relevant national and regional or international organisations; (2) prevent field entry by snails, using field screens as physical barriers especially into the uninfested sections; (3) practice physical/mechanical control through hand picking of snails and crushing eggs and/or knocking eggs into the water; (4) community-based snail management through synchronised farm activities like land preparation, irrigation and application of control measures (an area-wide management approach); (5) introduce changes to the cropping system by avoiding ratoon crops to limit resource availability for *P. canaliculata*; (6) practice cultural practices like alternate wetting and drying (AWD) of paddies and creating shallow hollows in paddies to form small ponds where snails gather, aiding efficient collection and disposal; (7) change planting patterns by encouraging transplanted rice over direct seeding, as seedlings are especially vulnerable to apple snail herbivory; (8) manage water in paddies by limiting water levels to less than 2 cm above the soil surface to reduce *P. canaliculata* movement and dispersal; (9) desilting of canals to minimize the habitable areas where the snails lay their eggs and reduce their populations; among other practices (Cowie & Hayes 2012; Horn et al. 2008; Wada 2004).

Conclusions

This delimiting survey has confirmed the rapid spread of *P. canaliculata* within the Mwea Rice Scheme. The National Government, in collaboration with relevant national and international agencies, should engage stakeholders in the rice value chain. Enforcement of phytosanitary and quarantine measures in these areas be intensified to mitigate the dispersal and introduction of pests in new areas. Urgent actions, including immediate awareness creation and implementation of proposed control measures from an early warning and preventive perspective is imperative. This proactive approach aims to prevent the further spread of *P. canaliculata* to identified risk areas in rice-growing regions and beyond. Given the large-scale cultivation of rice in Kenya, area-wide control measures, particularly community-based snail management and integrated pest management, should be prioritized. Active involvement of outgrowers is essential to achieve this success. Additionally, collaboration between national and international research organizations is recommended to develop sustainable, environmentally safe long-term control methods, such as the use of snail-specific parasitic microorganisms.. Establishing pest-free areas in regions without reported infestations, through the development of a policy brief for National Government consideration, will further enhance the production of snail-free seedlings and management.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-024-00301-7.

Supplementary material 1.

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Author contributions
FM, DC, AM and IR contributed to the study conception and design, undertook the initial survey and provided detail on the survey methodology. EF performed modelling studies and data analysis; IM conducted data analysis. FM and EF wrote the first draft of the manuscript. All authors revised and approved the final manuscript.

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Availability of data and materials
The data that support the findings of this study are available from the current study (presented in the article); the survey that first discovered *P. canaliculata* in Kenya (Buddie et al. 2021), and from GBIF, which archives the data open access. All the data have been published previously.

Declarations

Competing interests
The authors have no relevant financial or non-financial interests to disclose.

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