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Costs to Ecuador's rice sector during the first decade of an apple snail invasion and policy recommendations for regions at risk

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ABSTRACT

Invasive Alien Species (IAS) can become a tremendous burden to national economies; however, few studies have quantified the economic impacts of IAS, particularly for developing nations. The golden apple snail, *Pomacea canaliculata* (Lamarck), was introduced into Ecuador in 2005. By 2012, the snail had affected 94% of Ecuador's rice-growing areas. We used government surveys of rice production and snail distributions, as well as yearly production costs and rice prices, to estimate snail-associated losses to rice productivity and profitability between 2005 and 2015 – the first decade of *P. canaliculata* in Ecuador. Based on the intensity of the invasion and changing management practices, we estimate that the golden apple snail caused accumulated losses of 35.65 K tons of rice grain (worth US$23.10 M) with further productivity losses (lost inputs and labour) of US$9.61 M (total = US$32.71 M), until 2015. Based on survey information, we estimate that 90% of affected fields were treated with pesticides during the 5 years following initial establishment of the snail on individual rice farms. Pesticides potentially saved up to $10 M in damage during peak snail densities in 2012. By 2015, prophylactic molluscicide treatments were costing the nation US$15.24 M annually (including application costs: accumulated 10-year cost = $123.46 M, assuming 90% coverage). Increasing pesticide and labour costs, but relatively stable farm-gate rice prices, suggest that the continued chemical control of golden apple snail in Ecuador is economically unsustainable. We discuss possible alternatives to prophylactic molluscicide applications that can increase the economic and environmental sustainability of rice production in the face of high densities of apple snails during post-introduction outbreaks. We suggest that nations at high risk from invasive apple snails (e.g., Bangladesh, India, Colombia and Peru) could avoid substantial losses by pre-emptively researching and adopting mechanized crop establishment practices that not only reduce labour costs, but also prevent potential damage from apple snails to rice.

1. Introduction

Global trade, the breakdown of geographical and ecological barriers between habitats, and the increased movement of people and goods between nations have contributed to the spread of animals and plants to new regions outside their native distribution ranges (Perrings et al., 2002; Hulme, 2009; Bradshaw et al., 2016). Once established, the ecological or economic impacts, if any, of these Invasive Alien Species (IAS) are often unperceived. This may include species that coexist with similar native species or fill available ecological niches, but without appreciable economic impacts (Lobo, 2000; Burger et al., 2001; Keller et al., 2007); however, a proportion of IAS have such substantial impacts on natural or derived ecosystems and such serious consequences for ecosystem functions, that they become apparent to the general public and to policy makers (Bradshaw et al., 2016; Hoffmann and Broadhurst, 2016; Wild, 2017). Despite the importance of IAS globally and the tremendous focus on invasion biology in scientific literature and government policy, only a few studies have reported the monetary costs of invasions, particularly in developing nations (Meyerson and Mooney, 2007, but see Cook et al., 2007; Wise et al., 2012; Bradshaw et al., 2016; Hoffmann and Broadhurst, 2016; Ngorima and Shackleton, 2019). Because management often contributes most to the accumulated

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costs of biological invasions, ex-post appraisals of management actions and of possible alternatives to established management practices can indicate trajectories to reduce the economic and environmental impacts of some of the most challenging IAS.

Apple snails are widespread throughout the tropics and subtropics of Africa, Asia and the Americas. However, two species, *Pomacea canaliculata* (Lamarck) and *Pomacea maculata* Perry, originally from the Amazon Basin and Pantanal in South America (Martín et al., 2001; Hayes et al., 2012; Seuffert and Martín, 2013), have established outside their original distribution ranges to cause considerable ecological and economic impacts. These snails have spread to South East Asia, Southern Europe, North America and the Caribbean, and to the west of the Andes in South America (Cowie and Hayes, 2012; Cowie et al., 2017; Horgan, 2018; Schrader et al., 2020). Recently, one or both of these snails have established in Pakistan and in western Myanmar where they represent a considerable threat to aquatic and semi-aquatic ecosystems (Baloch, 2017; Myint and Ye, 2017). High densities of invasive apple snails in western Myanmar also represents a considerable threat to India and Bangladesh should the snails spread to these neighbouring countries. During the 1980s and 1990s, the rapid spread of both species in South East Asia was linked to the promotion by governments and development organizations of cottage industries aimed at escargot production for export markets. More recently, their continuing spread has been associated with the pet industry (EFSA (European Food Saftety Authority), 2012); Cowie et al., 2017) and unauthorized releases for the biological control of weeds (Lee et al., 2002; Horgan et al., 2014a). In many of the regions where they have been introduced, invasive apple snails represent a considerable challenge for producers of semi-aquatic crops such as taro (*Colocasia esculenta* [L.] Schott), water spinach (*Ipomea aquatica* Forssk.), and rice (*Oryza sativa* L.) (Sin, 2004; Cowie and Hayes, 2012).

Evidence from country reports demonstrate that once an invasive apple snail becomes established in a new region, the interactions between the invading population and affected sectors will generally follow a series of common phases. These include:

a) An establishment phase where the snail species is present but often at low densities and therefore unperceived or non-damaging. This can last from one or two seasons to several years depending on the species or the environment (Naylor, 1996; Myint and Ye, 2017; Yahaya et al., 2017);
b) An outbreak phase where the snail species undergoes rapid population increases to reach proportions that alter energy and biomass flows through the ecosystem (Carlsson et al., 2004; Yamanishi et al., 2012). At this stage, governments begin to react with education campaigns, monitoring, research into control options and investments in active control measures. Producers caught off guard during this phase will lose productivity (EFSA (European Food Saftety Authority), 2012; Horgan et al., 2014a; Gilioli et al., 2017; Schrader et al., 2020);
c) An adaptation phase where producers and other stakeholders learn how to reduce losses using available management tools. Often, these tools depend on chemical pesticides and other poisons, but may also include hand picking, trapping, flood management or biological control (Halwart, 1994; Naylor, 1996; Horgan, 2017, 2018);
d) A sustained management phase begins after pre-invasion productivity has been regained. Here stakeholders continue to invest in reducing invasive snail populations and their impacts to acceptable levels, thereby incurring additional production costs. The management phase may last for several years or many decades (Naylor, 1996; Schneiker et al., 2016; Castillo-Ruiz et al., 2018).

The ultimate costs of invasive apple snails to agriculture are therefore from direct production losses mainly during the relatively short adaptation phase (productivity losses) and continued management costs (profitability losses) during a sustained management phase.

In the present study, we examine the relative costs to the rice sector of production losses and of management responses during the first 10 years of a relatively recent invasion of the golden apple snail, *P. canaliculata*, in Ecuador. We modelled the spatial and temporal patterns of invasion and of farmer responses to snail damage, and estimated the annual and accumulated losses to the rice sector of the invasion. We trace events to determine the duration of the different phases of interaction between the invasive snail populations and rice growers, and make policy recommendations to reduce pesticide use and thereby increase the environmental and economic sustainability of the rice sector under the new reality of high densities of the invasive apple snail. Finally, we highlight how governments in high-risk regions might improve preparedness for the eventual arrival of invasive apple snails, to potentially save millions of dollars in economic losses to their relative rice sectors.

2. Methods

2.1. Study species

The golden apple snail was introduced into Ecuador in 2005 (Horgan et al., 2014a; Correoso Rodríguez et al., 2017) having likely arrived from Southern Brazil or Northern Argentina. It is believed that the snail was first introduced as an unauthorized biological control agent for aquatic weeds in a freshwater reservoir at El Triunfo in Guayas. During the next 5 years, the snail spread through Guayas and into Los Ríos, the main rice producing regions of Ecuador, where it caused considerable damage to rice. Specimens collected in Guayas, Los Ríos and Manabí were identified as *P. canaliculata* by D.G. Robinson (United States Department of Agriculture – Animal and Plant Health Inspection Service [APHIS]) and by A. Stuart (International Rice Research Institute [IRRI] – Philippines) (Horgan et al., 2014a). The snail is currently managed in much of Ecuador's rice fields using chemical molluscicides (Horgan et al., 2014a; Deknock et al., 2019).

2.2. The Ecuadorian rice sector

Rice production in Ecuador is largely concentrated in the tropical lowlands where there are marked wet (December–May) and dry (June–November) seasons. About 300–400 K ha of rice are planted in Ecuador each year. This produces up to 1.5 million tons of rice grain annually (Table S1). Production is concentrated in the Guayas (≈240 K ha – 11.5% of provincial area) and Los Ríos (≈115 K ha – 18.1% of provincial area) Provinces. However, rice is also produced (less than 1% of provincial areas) in the Provinces of Manabí (12 K ha), Loja (5–6 K ha), El Oro (2–3 K ha), Cotopaxi (< 1 K ha), Cañar (< 1 K ha), Bolívar (≈100 ha) and Esmeraldas (< 100 ha) (INEC (Instituto Nacional de Estadística y Censos), 2019). Two crops are sometimes harvested in the main rice producing areas, with planting from December to February (wet season crop) and from May to July (dry season crop). Crop establishment is by direct-seeding or transplanting. The proportion of farmers direct seeding rice has increased in recent years but the rate of adoption varies between cantons: in the main rice producing regions of Guayas and Los Ríos, between 30 and 70% of rice is direct seeded (INEC (Instituto Nacional de Estadística y Censos), 2019; Moreno Aguirre and Salvador Sarauz, 2014). A portion of Ecuador's rice is produced in natural wetlands known as ‘bajos’. On higher ground, rice is often rotated with dry crops such as maize (*Zea mays* L.) or soya (*Glycine max* [L.] Merr.) and is mainly direct seeded (Aguilar et al., 2015) (for estimated areas see Section 3.1). Further information on rice production trends in Ecuador are presented in Table S1.

2.3. Data sources

Table 1 presents details of the available field data used in the present study. Two types of information were available for the time period covered in this study. These were as follows:

1) Field surveys: Following the introduction of the golden apple snail to Ecuador in 2005, the government initiated a series of mapping studies to record the incidence and spread of the snail in rice paddies. This was largely coordinated through Agrocalidad (Agencia de Regulación y Control Fito y Zoosanitario) in Guayaquil with results sent by field technicians during irregular field visits between 2009 and 2014. Generally, only the presence/absence of snails was reported during field visits. Fields were arbitrarily selected for sampling, and sampling was conducted in February and March (51% of records), or June and July (49% of records) at the sites. During field visits, technicians recorded egg masses or adults during transects through rice fields (transect length varied depending on the first observations of golden apple snails in the fields). In 2009, the species was identified as the golden apple snail by APHIS; this was verified in 2011 and 2012 by IRRI (see Section 2.1). Field mapping was also conducted in 2013. During July 2013, rice fields were monitored along roads in Guayas, Los Ríos, and Manabí, noting geographical coordinates, rice crop stages, damage to direct-seeded and transplanted rice, snail densities, and surrounding habitat types. Information was collected from a total of 391 waypoints.
2) Farmer survey: A farmer survey was conducted in February 2012 and June-July 2013 by personnel of Agrocalidad. Farmers were interviewed using a structured questionnaire during visits to arbitrarily selected farms in ten cantons (Ecuador's second-level political division below provinces) in Guayas and two cantons in Los Ríos (Table 1), noting the geographical coordinates of the farmers' fields (using GPS), the presence/absence of snails and the levels of damage to recently established rice crops. The questionnaire was developed following stakeholder meetings at Portoviejo (Manabí - 2011) and Daule (Guayas - 2011) and Focus Group Discussions with rice producers at two cooperatives in Daule (in 2011 and 2012). The questionnaire was pre-tested with farmers in Daule in February 2012. Information gathered from the farmers included: 1) their usual crop establishment methods and planting practices; 2) the history of apple snails on their farms; 3) the type and extent of damage experienced in the wet and dry seasons; and 4) their experiences with different management practices to reduce snail damage. A total of 164 farmers were interviewed during the survey. Farmers were not individually interviewed using the questionnaire in Manabí because these farmers were generally consistent in their production practices according to information from the stakeholder interviews (i.e., 100% rice transplanting during a single crop in 2011). At the time of the interviews, the golden apple snail had not been reported, or was at low densities in rice at Provinces other than Guayas, Los Ríos and Manabí.

Based on the recorded presence/absence of snails from sites in different years (Table 1), the years of first establishment by snails in different cantons could be estimated. At heavily sampled cantons, these data also permitted an estimate of the intensity of the invasion behind the expanding distribution range.

2.4. Calculating costs

We estimated management costs (*Cm*) related to the apple snail invasion as a product of the total area of rice fields affected by the snail over time (*t*) and the costs of minimizing damage within the affected areas. The equation is as follows:

Table 1
Available data used to estimate the extent and intensity of the snail invasion of Ecuadorean rice fields between 2005 and 2015.

Dates	Effort	Regions[a]	Reported	Source
July 2005–July 2009	Occasional farmer communications	DA, NA, SM	*Pomacea* sp. damage to rice	Agrocalidad Guayas farmer reports and narratives
August 2009	24 sites	CO, DA, NA, PA, SM, NO	Presence/absence of *Pomacea* spp.	Agrocalidad Guayas field reports
Mar 2010–Nov 2010	39 sites	CO*, DA, DR*, LS, LT, NA, NJ*, PA, SA*, SB*, SM, YA	Presence/absence	Agrocalidad Cañar, Guayas field reports
Jan 2011–Nov 2011	174 sites	CO, DA, ET, GU, JU, LS, NA, NO, PA, PC, SA, SL, SM, YA	Presence/absence	Agrocalidad Guayas field reports
Mar 2011–Nov 2012	388 rice and estuary sites	AR, BA, BB, BF, DA, ET, JU, LA*, LM**, LT, MC*, MR*, NA, NO, PA, PQ, PU, PV, QD, QU, SA, SD*, SL, SM, TE**, UR, VA, VI, VT, YA, ZA*	Presence/absence, positive identification	Agrocalidad national survey (Cañar, El Oro, Guayas, Loja, Los Ríos, Manabí, Napo, Santo Domingo, Sucumbios)
2011	156 sites	DA, JU, ML, NO, PA, SA, SM, YA	Presence/absence	Agrocalidad Guayas field reports
2012	56 sites	BA, CO, DA, ET, GU, JU, LT, NA, SA, SL, VT, YA	Confirmed presence	Agrocalidad Guayas field reports
2010–2012	581 farmers/sites	DA, SA, SM	Presence/absence	Agrocalidad Guayas field reports
Feb 2012–July 2013[b]	164 Farmers/sites	BA[10-13], CO[10-11], DA[07-12], ET[05-10], JU[09-12], MO[11-13], NA[07-11], NO[10-11], SA[08-11], SL[09-12], SM[09-11], YA[09-10]	Year of damage, presence/absence, damage levels, crop establishment	Agrocalidad Guayas, Los Ríos farmer survey; Horgan et al. (2014a)
June 2012–Nov 2014	145 sites	BL*, CO, DA, ET, JU, NA, NO, PA, SB*, SL, SM, YA	Presence/absence	Agrocalidad Guayas field reports
July 2013	391 waypoints/sites	BA, BB, DA, ML, NJ, PV, RC, SM, SU, TO, VI	Presence/absence, snail densities, damage levels, crop establishment	Horgan, unpublished
2008–2012	Unreported	Added cantons CU, EC, LM, PC, RO, TE	Presence	Correoso Rodríguez et al. (2017)

a: Cantons are abbreviated as follows: El Oro: AR = Arenillas; Cañar: LT = La Troncal; Guayas: BL = Balzar, CO = Colímes; DA = Daule, DR = Duran, ET = El Triunfo, GU = Guayaquil, JU = Jujan, LS = Lomas de Sargentillo, ML = Milagros, NA = Naranjal, NJ = Naranjito, NO = Nobol, PA = Palestina, PC = Pedro Carbo, SA = Salítre, SM = Samborondón, SL = Santa Lucia, SB = Simón Bolívar, YA = Yaguachi; Loja: MR = Macara, ZA = Zapatillo; Los Ríos: BA = Babahoya, BB = Baba, BF = Buena Fe, MC = Mocache, MO = Mon-

talvo, PQ = Palenque, PU = Puebloviejo, QU = Quevedo, QD = Quisadoma, UR = Urdaneta, VA = Valencia, VT = Ventanas, VI = Vinces; Manabí: PV = Portoviejo, RC = Rocafuerte, SU = Sucre, TO = Tosagua, PC = Pichincha; Napo: TE = Tena; Santo Domingo: SD = Santo Domingo; Sucumbios: LA = Lago Agrio; Bolívar; EC = Echeandía; Cotopaxi: LM = La Mana: Chimborazo: CU = Cumandá; Esmeraldas: RO = Río Cayapas; * = snail not observed; ** = snail observed but species not verified.
b: Superscript numbers in regions column indicate years when snails were observed, where 07 = 2007, 08 = 2008, etc.

$$Cm = \sum_{t=1}^{N}\sum_{i=1}^{N} A_{it} I\,(M + P)\,k_i \tag{1}$$

where A is the rice area under crop management i affected by snails at time t, I is the intensity of the infestation, i.e., the proportion of fields affected within the invasion area, M is the cost of mitigating damage by replacing damaged seedlings, P is the cost of pest management actions and k is a weighting factor that corrects for rice ecologies and crop establishment practices relative to type i. Our initial estimates were based on double-cropped, transplanted rice during the wet season. Weighting (k) for other seasons and crop management practices was based on information from the farmer interviews that evaluated relative production costs and losses, numbers of extra labourers hired, areas of land replanted and seeding densities used for different cropping systems. Values for k are presented in Table 2. Details of data sources and methods for calculating M and P are presented in Table S2.

The predominant cropping practices ($A_{i\text{-}N}$) were estimated for each canton using information presented by Aguilar et al. (2015). These authors collected digitized information on rice and corn planting during three 4-month periods in 2014. Based on open access data from their study, we used ArcGIS to distinguish areas of double cropping based on the areas planted with rice during the April–June and August–November periods and single cropping based on areas planted during either December–March or April–June. We further differentiated single cropped areas into 'bajos' and rice-maize rotations by noting overlaps with flooded wet season fields (≤ 0 m asl: using the DEM dataset at 30 m from the United States Geological Survey [(USGS , 2019)]), and corn planting respectively. Although proportions may change from year to year, we assumed that such changes would be relatively small (compared to the large, total production area) because rice production practices are largely defined by water availability and topography. We therefore set the 2014 proportions for each cropping practice as a standard throughout our study period.

For areas invaded by snails, we assigned average management responses according to the prevailing production system and crop establishment method (i) based on information from the farmer interviews and from information presented by Aguilar et al. (2015) and Viteri and Zambrano (2016). This included estimates of the proportions of damaged rice crops that were replanted and the number of times farmers replanted their fields following damage (based on data for individual cantons from the farmer survey). We also estimated the proportion of farmers that applied molluscicides or insecticides to control the snails in each canton as the invasion progressed.

Table 2
Cost weightings for different production regimes based on damage to transplanted double-cropped rice during the wet season (based on typical replanting costs reported during 2013).

Rice crop management	Crop establishment	Season	Damage weighting
Double cropping	Transplanted	dry season	0.84
	Direct seeded	wet season	0.65
	Direct seeded	dry season	0.48
Single crop	Transplanted	wet season	0.58
	Direct seeded	wet season	0.87
Rice after flooding (bajos)	Transplanted	dry season	1.61
Wet season crop after upland crop	Direct seeded	wet season	0.08

Estimates of seeding rates per production system and crop establishment method for each canton, and the average work days required to seed 1 ha were used to calculate replanting costs. Seeding rates and establishment methods were based on information from the farmer surveys and from survey results presented by Moreno Aguirre and Salvador Sarauz (2014). Similarly, the average costs of pesticides per hectare, and the costs of labour required to apply pesticides were used to estimate pesticide-related costs. We used records from various public sources (supplier websites, government records, etc.) of the costs of products each year and the recommended doses per hectare. Products included Endosulfan, Metaldehyde and Niclosamide. In general, the costs of treatments were similar regardless of product. We therefore used the costs of the main product until 2013 and an average cost based on the three products after 2013 (Table S1). All costs are presented in 2020 US dollar equivalents.

We estimated productivity losses (Cy) as the sum of yield losses together with lost investments (inputs and labour) to damaged areas. The equation is as follows:

$$Cy = \sum_{t=1}^{N}\sum_{i=1}^{N} A_{it} I\left(f\,(y * s)\,p_i + F + H\right) \tag{2}$$

We used a damage function, f, that related farmer experience with snails (time since introduction) to the proportion of rice damaged by the snails in individual fields. As farmers gain experience of a snail invasion, they are predicted to adopt and improve pest management actions and successively reduce damage. Having estimated damage levels, we then applied a damage to yield loss rule, y, based on published sources to estimate consequent reductions in rice yields (Table S2). To convert yield losses to dollar amounts, we applied relative yields across cantons and used farm gate prices, s, based on published national records. Data on rice prices from 2005 to 2012 were based on information presented in Viteri and Zambrano (2016). After 2012, we used prices according to published government bulletins prepared by the Ministerio de Agricultura y Ganadería (MAG). Data on average yields per canton were based on information presented by Moreno Aguirre and Salvador Sarauz (2014) and Moreira (2014). Further details are included in Table S1.

When converting from damage to yield losses we distinguished between damaged areas that were replanted or not-replanted based on the farmer surveys. We used a weighting factor p to correct for the proportion of farmers reseeding damaged areas according to crop establishment methods. Replanted areas produced a final rice crop albeit with some losses due to poor synchronization and continued snail grazing. We calculated losses to the replanted areas using a 2% loss of average yield according to information in Naylor (1996) and Horgan et al. (2014b). Damaged patches that were not replanted were initially regarded as causing an equivalent 50% yield reduction where patches represented transplanted rice and based on information in Sanico et al. (2002) or 100% where patches represented direct-seeded rice and based on information in Horgan et al. (2014b). According to interviewed farmers, damaged or destroyed rice during the first year of invasion in 'bajos' was not replanted. Productivity losses from wasted fertilizer, F, and herbicide, H, to damaged areas, including associated labour costs were included in the calculations and were not differentiated by cropping pattern or crop establishment method (i.e., these were considered the same across establishment methods). We assumed that no fungicides were applied to the crop during establishment (after transplanting or seeding) and that insecticides were used only to control apple snails at this early crop stage. Details of data sources and methods used to estimate *f*, *y*, *p*, *F* and *H* are indicated in Table S2. All costs are presented in 2020 US dollar equivalents.

3. Results

3.1. Rice production areas

Our analysis indicated a majority of rice (75%) in 2014 was produced as a single wet season crop (Fig. 1A), with about half of the remaining rice from double cropped paddies (12%). Most of the double cropping was along the Daule and Babahoyo Rivers (Fig. 1B). In Guayas, 6227 ha, and in Los Ríos, 476 ha of rice was produced below 0 m asl, representing 2% of the rice area (Fig. 1C). We considered this as rice produced in 'bajos'. Rice-maize rotations werer mainly restricted to higher land before the western Andean slopes (Fig. 1D). We estimated the area of rice-maize rotations as 2496 ha in Guayas, 8325 ha in Los Ríos, and 155 ha in Manabí, representing 11% of the rice area.

3.2. Snail spread and damage estimates

After its initial introduction, the golden apple snail first spread relatively slowly through the cantons of El Triunfo, Naranjal and La Troncal in Guayas Province (this study), and possibly into Cumandá in Bolívar Province (Correoso Rodríguez et al., 2017). These cantons represent the initial areas of establishment and consequently the areas with the longest exposure to the snail (Zone 1: Fig. 2). Following severe flooding in Guayas during 2008, the snail invaded a large area of that Province and reached damaging densities by 2010 (Zone 2: Fig. 2). Apple snails were recorded in Manabí and El Oro in 2011, but relatively high densities suggest that the snails had arrived some years before (i.e., 2008–2010). The snail continued to spread throughout Guayas Province during 2010 and 2011 to cause sporadic damage in Los Ríos Province (Zone 3 in Fig. 2). The snail spread to the most northerly can-

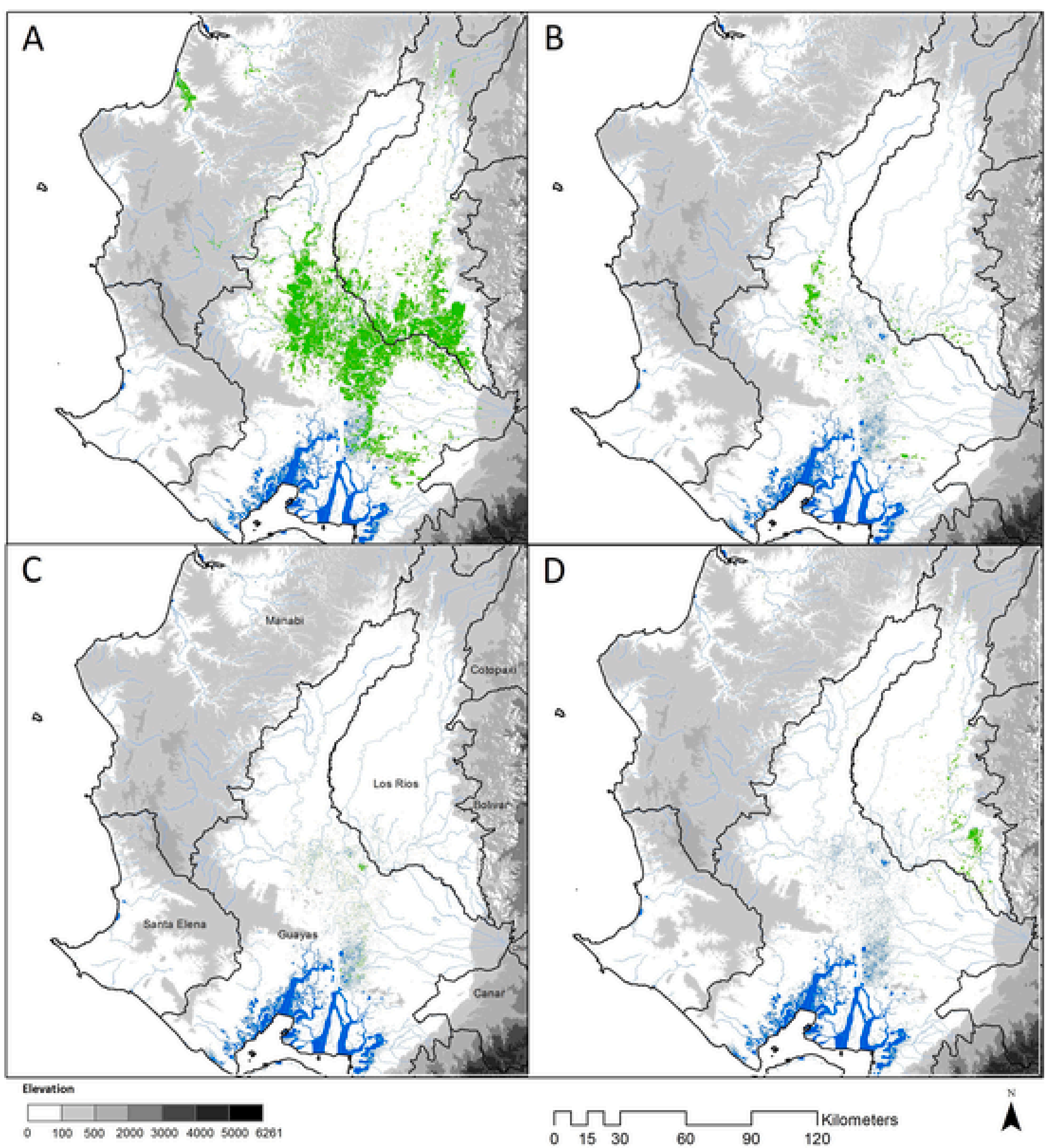

Fig. 1. Distribution of rice paddies in Ecuador based on 2014 data from Aguilar et al. (2015). Maps indicate (A) single cropped rice, (B) double cropped rice, (C) flood-prone rice, and (D) single cropped rice rotated with corn.

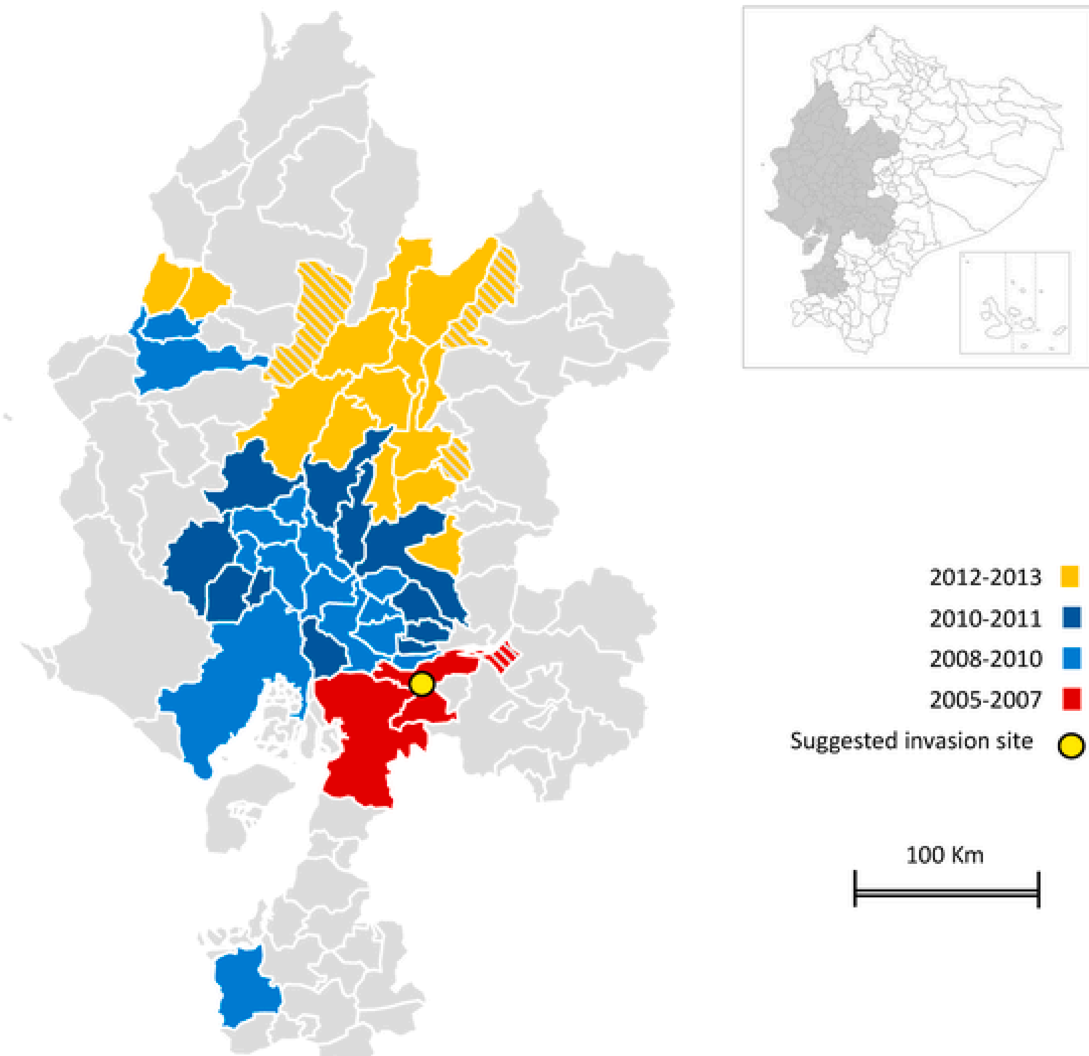

Fig. 2. Spread and current known distribution of *Pomacea canaliculata* in the western provinces of Ecuador (shaded area in inset Ecuador map) based on information from the mapping and surveys indicated in Table 1. Shaded areas are cantons. Hatching indicates information from Correoso Rodríguez et al. (2017) with the year of spread based on the incidence of apple snails in proximate provinces. Colours indicate four invasion regions as Zone 1 (red), Zone 2 (light blue), Zone 3 (dark blue) and Zone 4 (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

tons in Guayas and Los Ríos, and expanded its range in Manabí, during 2012 and 2013 (Zone 4: Fig. 2).

Intensity: Farmers surveyed in 2013 depicted a relatively slow invasion of Zone 1 cantons that began in 2005 but reached 100% of fields only in 2011 (Fig. 3A). In contrast, in Zone 2, the invasion was rapid with the snails first noted in 2008, but occurring in 100% of fields by 2011 (Fig. 3B). The invasion of Zone 3 cantons was similarly rapid with snails first noted in 2010 and present in 100% of fields by 2013 (Fig. 3C).

3.3. Damage and yield losses

About 80% of Ecuador's planted rice was exposed to the golden apple snail before 2011 with snails establishing only in areas of relatively minor rice production during 2012 (Figs. 2 and 3). The rapid pace of the invasion before 2011 was largely due to the concentration of Ecuador's rice production in a confined area along the Daule, Vince, Yaguachi, Babahoyo and Los Tintos Rivers (Fig. 1).

Based on reports from Daule of the levels of damage to fields during 2013, farmers took up to four years to adapt to manage snail damage. This was partly due to generally low snail densities and consequent lower intensities of damage at the time that snails first appeared on the farms, but also due to improved management of snails gained through experience of high densities at the peak of spread (Fig. S1). Farmer adaptation to snails occurred after the first year of peak snail densities on their farms and of substantial snail damage (i.e., up to 100%, but averaging 51%) with subsequent management reducing damage in succeeding years (Fig. S1).

Despite the large areas exposed and rapid spread of the snails (Fig. 4), as well as the relatively high levels of damage during the early years of invasion, yield losses were relatively contained. This was largely because of adaptations by farmers to treat and replant affected areas. Our estimates of yield losses depict initial losses during the years of maximum range expansion into new fields reaching a peak at 10.75 K tons in 2012 with residual effects for 2–3 years after (Fig. 5A). Until 2015, this represented an accumulated loss of 35.65 K tons of rice valued at $23.10 M. Because replanting reduces yield losses to low levels (2% in our model), productivity losses from damage to germinating seeds and to seedlings as well as lost inputs and labour were as high as losses to yield (Fig. 5B). This included seedling and related labour losses of $2.22 M at peak damage in 2012 ($9.61 M accumulated). We estimate total productivity losses between 2005 and 2015 at $32.71 M (Fig. 5B).

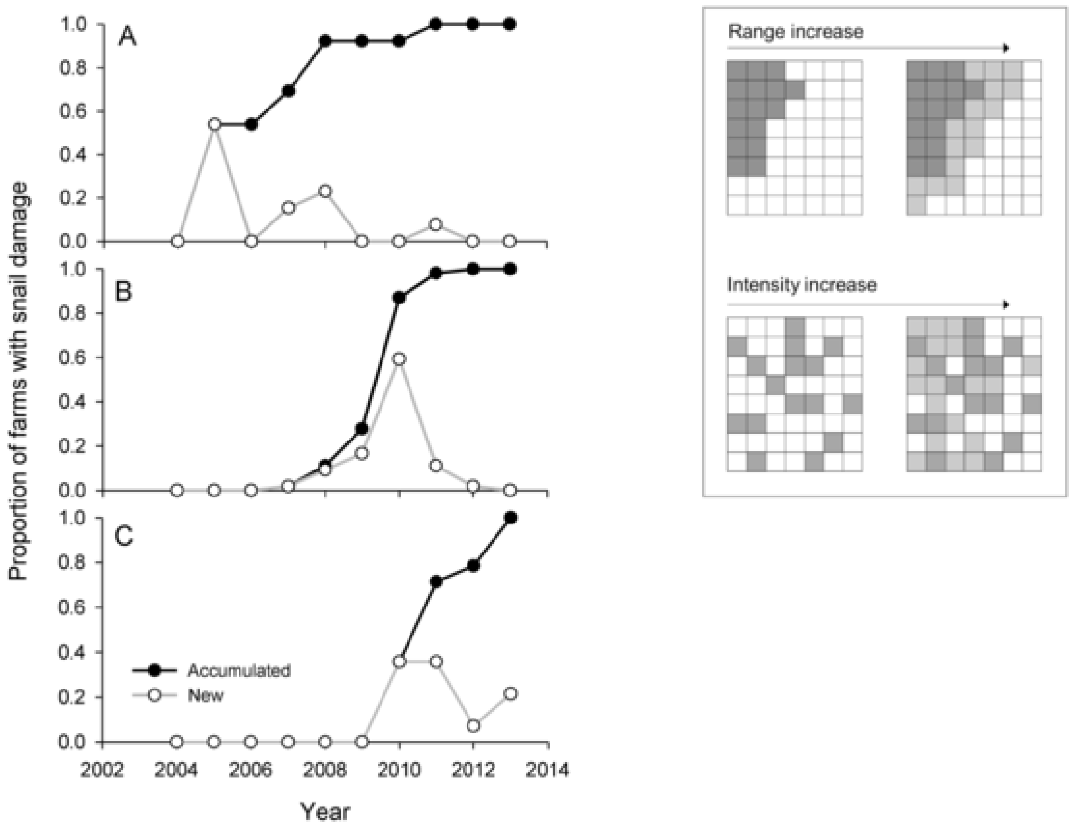

Fig. 3. The intensity of snail invasions. Graphs indicate the presence of snails and related damage as noted by rice farmers in A) El Triunfo and Naranjal, B) Duale and C) Babahoyo and Montalvo between 2002 and 2013. Solid symbols indicate the accumulated proportion of fields infested; open symbols indicate the proportion on fields newly infested. Inset differentiates between range increase and intensity increase.

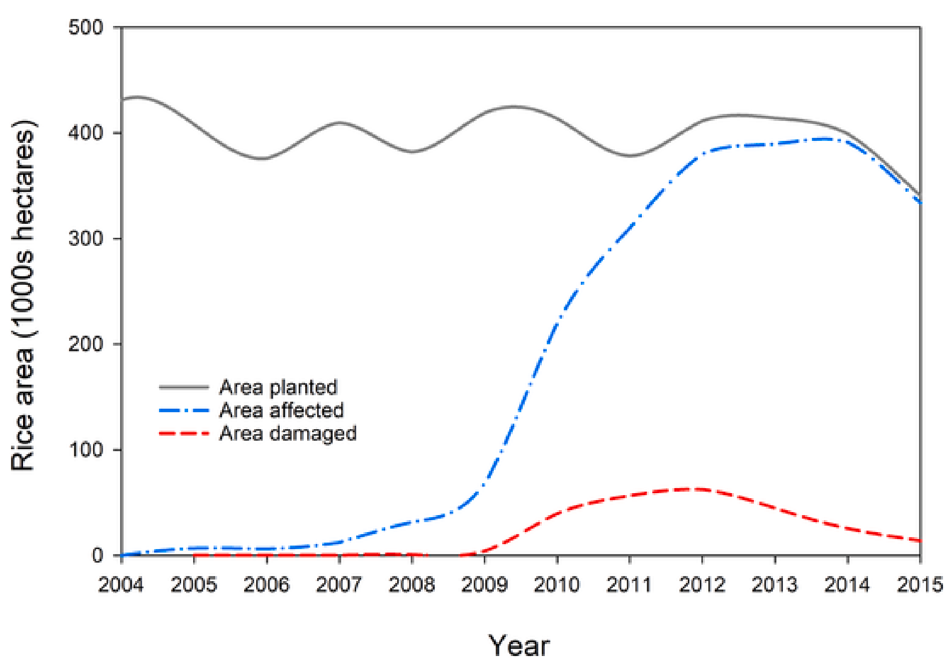

Fig. 4. Total area of rice planted, rice affected by apple snails and rice damaged by apple snails in Ecuador between 2004 and 2015.

3.4. Management costs

Management costs were mainly related to replacing damaged germinating seeds and seedlings and treating rice fields with insecticides and/or molluscicides to control the snails (Fig. 6A). Labour costs related to replanting were highest in the years of most rapid range expansion, reaching a peak of $7.67 M in 2012 (Fig. 6A); however, we estimate that costs related to pesticide purchases and applications have been considerably greater than replanting costs. During our interviews, 90% of farmers in lowland areas reported that they routinely used insecticides or molluscicides to control snail damage. Until 2012, and before its global ban, most farmers used Endosulfan to control the snails.

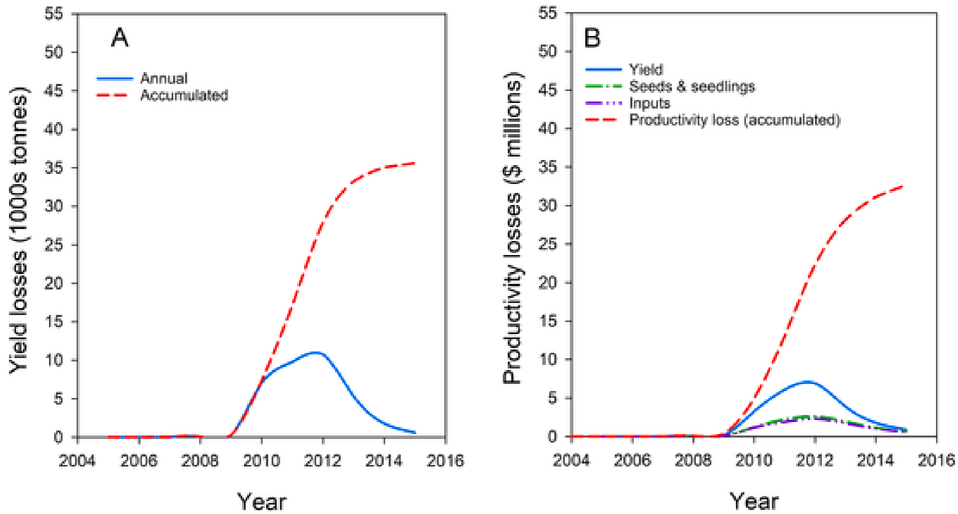

Fig. 5. Estimated (A) yield losses and (B) costs (2020 $ equivalents) due to lost productivity between 2004 and 2015. Costs are estimated based on average areas damaged in Zones 1 to 4 over the course of the invasion with 50% of yields lost in damaged areas that were not replanted and 10% in damaged areas that were replanted during the first year of peak densities, but 2% yield loss in subsequent years.

In 2013, 50% of surveyed farmers continued to apply Endosulfan. We estimate that after 2013, 81% of farmers used Metaldehyde to control the snails with the remainder using Niclosamide or available broad-spectrum insecticides. Farmers reported similar pesticide costs to control apple snails in transplanted and direct-seeded rice. We used a value of 75% of farmers applying molluscicides to calculate our lowest estimates of molluscicide costs during the early years of the snail invasion (≤ 5 years from initial establishment on farms). This application rate is based on observations from other regions where invasive apple snails have established in rice producing areas (Schneiker et al., 2016); however, evidence suggests higher proportions of farmers (≥ 90%) continued to apply molluscicides in many areas, particularly in the low-lying regions of Guayas and Los Ríos (Deknock et al., 2019). Based on treating 75–90% of snail-affected fields, we estimated the cost of molluscicide use at between $12.78 M and $16.94 M during the years following peak snail densities. The relatively high costs of pesticide applications depicted in Fig. 6A are largely due to farmers treating their entire fields and not only the damaged areas (based on information from the farmer surveys, and see Horgan et al., 2014a) because it is difficult for farmers to identify vulnerable areas within fields before they establish their crops. Our estimate of the accumulated costs of molluscicide-based control is $123.46 M between 2005 and 2015, assuming that 90% of farmers in affected areas treated their land at least once per rice crop (Fig. 6B).

4. Discussion

Our tracking, using government data, indicates a rapid spread of golden apple snail between 2005 and 2012 such that the snail occurred in almost 100% of Ecuador's coastal rice fields within a decade of first introduction. Although the snail spread quickly and farmers were unprepared for this new type of rice pest, our estimates of actual losses to rice yield were low (35.65 K tons until 2015 or < 1% of national yield during peak damage in 2012). Indeed, damage to seeds and seedlings, lost labour and lost inputs represented 47% of total productivity losses. The low yield losses were largely due to the rapid responses by farmers to the snails, either through their own trial-and-error methods (e.g., farmer experimentation using a range of snail management methods [Horgan et al., 2014a]) or with support from the Ecuadorean government that included open field days, the distribution of information leaflets, and talks and seminars at rice cooperatives. Yield losses from apple snails are also generally low because rice effectively compensates for snail damage and for low-density rice stands (Sanico et al., 2002; Horgan et al., 2014b). Records indicate that farmers experiencing damage in the years of peak densities quickly resorted to chemical control methods, particularly the use of Endosulfan, during the first years of invasion. Worrisome outcomes of pesticide use, including insect outbreaks and the poisoning of snail predators, caused the government to enforce a ban on Endosulfan and distribute Metaldehyde freely to farmers in the most snail-affected areas (Horgan et al., 2014a). Evidence suggests that following the first year of apparent snail damage to rice, farmers continued to apply molluscicides to their fields to avoid the build-up of snail populations (Horgan et al., 2014a; Deknock et al., 2019).

Our results indicate that sustained management actions, which cost the rice sector as much as $123.46 M before 2015, have represented the most expensive portion of snail-associated costs. Furthermore, increasing pesticide prices and increases in the costs of labour required to apply pesticides have meant that management costs continue to rise. Fluctuating rice prices over the years, and stagnating rice prices in recent years (Table S1), suggest that the continuing application of molluscicides, particularly as a prophylactic treatment (i.e., the application of molluscicides to puddled rice fields prior to seeding or transplanting and without monitoring snail densities) during land preparation, is economically unsustainable for rice producers. This does not include potential costs to the environment and the consequent loss of ecosystem services – particularly in bajos - or the costs to human health from wide-scale, heavy molluscicide use (Halwart, 1994; Naylor, 1996; Horgan et al., 2014a, 2018; Coelho and Caldeira, 2016; Gilioli et al., 2017; Martín et al., 2019). We also have not included possible health-related costs due to the transmission of rat lungworm (*Angiostrongylus cantonensis* [Chen]) to people that consume infected apple snails. Currently, the incidence of such infections in Ecuador is low, and reported infections have not been directly linked to the golden apple snail (Dorta-Contreras et al., 2011; Solórzano Álava et al., 2014; 2019; Zamora Giler et al., 2020).

4.1. Productivity losses

Accounts of the impact of apple snails on national rice sectors tend to report impacts as areas affected (i.e., the range of the snail: Cuong, 2006; Yahaya et al., 2017), areas damaged (Halwart, 1994), or by highlighting notable regions with different categories of damage (Suharto et al., 2006) without quantifying the resulting losses to rice production. Several studies have indicated impacts in terms of molluscicide purchases, molluscicides consumed, or fields treated (Adalla and Magsino,

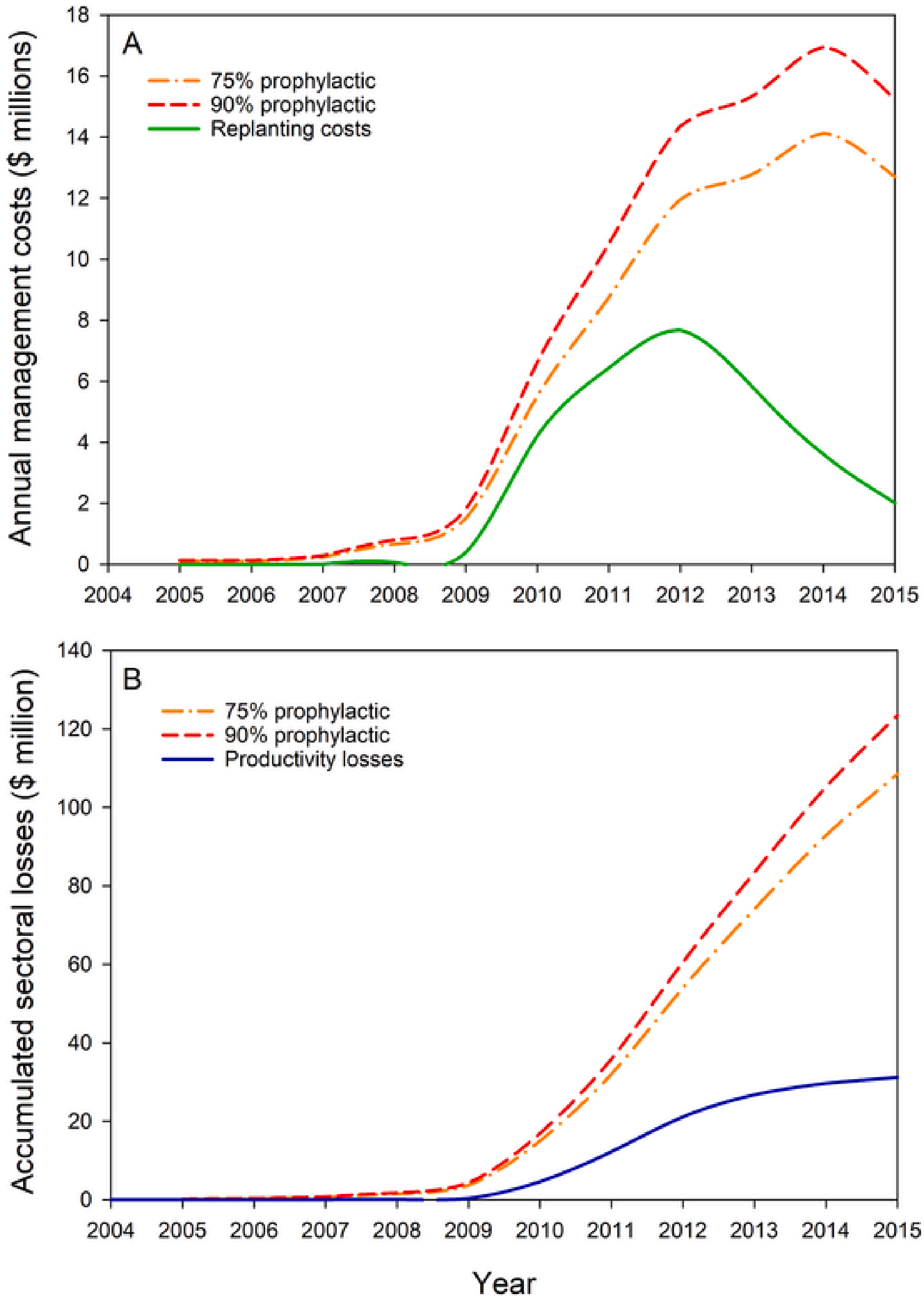

Fig. 6. (A) Annual expenditure on snail control using molluscicides (product purchase and application costs) and on the replanting of damaged rice areas. Estimates of costs of control based on applications to 90% and 75% of snail-affected areas are presented. Over 90% of farmers surveyed in 2013 used molluscicides to control the snails. (B) Accumulated costs of management and yield losses due to the snail invasion. Note that production losses had stabilized by 2015 but management costs continued to increase largely due to the increasing costs of pesticides and labour (Table S1). Estimates of accumulated costs are based on applications to 90% or 75% of affected areas.

2006; Wada, 2006). The lack of specific cost estimates in studies of snail impacts is partly because monitoring is usually conducted only after management actions have been taken. In our study, we captured information concerning rice production prior to snail establishment and after the snails had begun to cause damage. This information was mainly from surveyed farmers.

In Ecuador, the highest densities of snails (i.e., 100 adult snails/m^2) were experienced in 'bajos' and other low-lying, flood-prone production areas. This was largely due to the concentration of snails into shrinking bodies of water as the 'bajos' and rice ponds drained during the dry season (Horgan et al., 2014a). In most other cases, snails although still at relatively high densities (i.e., up to 10 adults/m^2) were more easily controlled during outbreaks. Initially, farmers experienced high levels of damage from the snails even when they had applied molluscicides, but replanting allowed farmers to recover yields (see also Halwart, 1994; Naylor, 1996). We estimated that at the peak of damage in 2012, apple snails had invaded most (≈94%) of Ecuador's rice producing area, and caused damage to about 50% of invaded rice fields. This estimate is high compared to estimates from other regions during apple snail outbreaks. For example, during the 1990s, recently invading apple snails damaged between 25 and 40% of rice in invaded areas in the Philippines (Naylor, 1996), up to 20% in Taiwan (Cheng and Kao, 2006) and the Dominican Republic (Rosario and Moquete, 2006), but < 2% in Japan (Wada, 2006). The relatively large area of rice damaged in 2011–2012 in Ecuador is probably due to the rapid spread of the snail after flooding in 2008 and the concentration of rice growing in low lying areas of the Guayas and Los Ríos Provinces where fields are interconnected by high densities of rivers, drains, and flooded ‘bajos’.

Despite the visual impact of snail outbreaks and the high proportion of fields with damage, yield losses from apple snails post introduction have been generally low. For example, even during the years soon after snail invasions, yield losses to damaged rice in Malaysia have been estimated at between 1 and 7% (Yahaya et al., 2017) and in the Philippines at between 0.7 and 1% (Naylor, 1996) following control measures and replanting. Previous detailed studies have indicated that at moderate densities of 1–5 adult snails/m^2, damage to unmanaged rice fields rarely causes more than 50% yield loss, and where controls are practiced, yield losses in snail-affected areas are typically maintained below 2% (Litsinger and Estano, 1993; Sanico et al., 2002; Sin, 2003; Horgan et al., 2014b; Yanes Figueroa et al., 2014). To our knowledge, the present study is one of only two studies (the other is by Naylor [1996]) to estimate yield losses from snails at a national scale. Previously, Naylor (1996) estimated potential yield losses in the Philippines during 1990 alone at about 270 K tons (assuming a density of 1 snail/m^2 and no management or replanting). By adopting control and replanting measures, production losses were reduced to between 70 and 100 K tons. Our estimates are consistent with those of Naylor (1996): using typical values of yield losses to damaged patches, we suggest that national yield losses were about 10.75 K tons at the peak of invasion in 2012 at a cost of $6.4 M in that year. Both Halwart (1994) and Naylor (1996) have emphasized the need to quantify productivity losses in terms of lost seed and seedlings and lost investments in crop management (i.e., losses of inputs and labour resulting from the need to replant damaged areas). Naylor (1996) estimated replanting costs in the Philippines at between $2.8 M and $10.3 M in 1990. Our estimates of replanting costs for Ecuador were as high as $7.67 M during the peak of the outbreak in 2012 with annual costs at about $2.01 M up to 10 years after the snail was first introduced.

The actual contribution of molluscicides to the maintenance of rice yields nationally is highly speculative. Attributing high efficacy to molluscicides and assuming that losses per damaged area would consistently be about 10% of yield if no molluscicides were used (but with replanting), then molluscicides prevented about $115 K of losses in 2012. However, by assuming higher losses from snail damage (50% of yield, perhaps due to area-wide effects of not controlling the snail), effective molluscicide applications potentially saved up to $10 M in yields in 2012 – or $4.9 M after pesticide-related costs. Although molluscicides reduced yield losses, alternative management strategies such as flood control - including the flooding of fields with sea water, traps and barriers, or cultural controls at the time of crop establishment (Horgan, 2017; 2018; Joshi and Parera, 2017) could have been implemented to reduce related soil and water contamination. Alternative molluscicides, based on plant extracts such as saponins might also have reduced the environmental impacts of apple snail control because these are less toxic to non-target organisms (Joshi et al., 2008; San Martín et al., 2008; Yang et al., 2017; Castillo-Ruiz et al., 2018; Horgan et al., 2018). Looking forward, alternatives to chemical snail control will need to be developed and adopted to increase the environmental and economic sustainability of Ecuador's rice sector.

4.2. Management costs

Our model indicates that the greatest losses to the rice sector were related to management of the snails. A large number of studies with widely different focal IAS suggest similar trends (Pimentel et al., 2000; Olson and Roy, 2002; Baxter et al., 2008; Wise et al., 2012; Glen et al., 2013; Alvarez, 2016). By 2015, management costs in Ecuador represented > ⅔ of the total costs of the snail invasion, and much of this was incurred after the years of peak damage. Molluscicide applications alone cost the rice sector over $15 M annually in the years after peak snail abundance (with total costs until 2015 estimated at over $82.16 M). We have not estimated costs beyond 2015 because we do not have more recent data; however, assuming that farmers continue to apply molluscicides to 75% of their fields (as in other tropical regions with invasive apple snails: Schneiker et al., 2016), annual molluscicide costs would have remained above $10 M until present. Furthermore, management costs have continued to increase over the years due to the increasing costs of pesticides and of labour. Because rice prices have not increased to the same degree, our estimates indicate a larger increase in losses due to management costs than from production losses during the sustained management phase. This has continued into recent years, suggesting that management costs will continue to represent the greatest losses to the sector. Because of the normally low yield losses from snail damage (i.e., ca 10% of yield per area damaged without molluscicides but with replanting), these management costs could be greater than the potential productivity losses if no management actions were taken or if farmers only replanted damaged crops – without prophylactic molluscicide use, particularly where damage to fields is restricted to small areas. In the Philippines, Naylor (1996) estimated that molluscicides, insecticides and hand-picking to control snails cost between $12.5 M and $17.2 M in 1990. These management costs were about equal to estimated yield losses. Cheng and Kao (2006) estimated that the cost of molluscicides each year between 1982 and 1990 was about $1 M to control 100 K ha of affected rice in Taiwan, presumably with highly targeted applications.

4.3. Policy recommendations

Our results suggest that, because of increasing pesticide and labour costs, but relatively stagnant rice prices, continued losses will be incurred to Ecuador's rice sector during the sustained management phase of the apple snail invasion. By 2015, the Ecuadorean government had reached a relatively stable situation, with snails largely controlled by pesticides, particularly where rice is double cropped. However, our model indicates that continued, largely-prophylactic molluscicide use is not economically sustainable. Government attention should now address possible chemical-free solutions to the snail problem. Cultural snail control methods at the time of crop establishment can effectively reduce snail damage to rice and have few added costs for farmers (i.e., delayed transplanting: Litsinger and Estano 1993, Sanico et al., 2002, Yanes Figueroa et al., 2014; low-density seedbeds: Yanes Figueroa et al., 2014; seedling broadcasting: Horgan et al., 2014b; and fertilizer or herbicide management: De La Cruz et al., 2001, Stuart et al., 2014, Xu et al., 2017). However, cultural controls during crop establishment can be unattractive for farmers wishing to transform from transplanting to direct-seeding in the face of increasing labour costs.

Alternatives to manual transplanting, such as machine transplanting, continue to be studied in detail and are gaining increased traction (Chen et al., 2019; Shan et al., 2020; Yang et al., 2020). In the long term, adoption of such transplanters is predicted to drastically reduce labour costs (Kim et al., 1999; Farooq et al., 2001). However, attention to such methods for snail-infested regions (which on a global scale are now more prevalent than snail-free rice producing regions) has been conspicuously overlooked. Currently, machine transplanting, like direct-seeding, in wet tropical regions depends on molluscicides to control apple snails. The negative impacts of these molluscicides on rice-associated biodiversity can be reduced by using plant-based products such as saponins (Joshi et al., 2004; 2008; San Martín et al., 2008; Attademo et al., 2016; Horgan et al., 2018). However, these products also represent an added cost for rice farmers. In contrast, rice crop establishment with machines that transplant older seedlings, including with soil plugs (Yang et al., 2020), and seedling broadcasting have been shown to dramatically reduce yield losses in snail-infested ponds without any additional pest management costs. Furthermore, because seedlings are broadcast with a soil plug, transplanting shock may be avoided, leading to more robust plants that better defend against snail damage and are more tolerant to a range of biotic stressors (Horgan et al., 2014b). We suggest that research to develop crop establishment methods for snail-infested paddy fields will be essential if farmers are to shift away from molluscicides.

The high densities of golden apple snail in Ecuador together with transborder trade in rice and in farming machinery increases the probability that the snail might spread to rice fields in neighbouring Colombia or Peru. Similarly, the invasion by apple snails of Myanmar's Ayeyarwady Delta and to the rice-growing regions of Pakistan increases the probability that the snails (both *P. maculata* and *P. canaliculata*) might spread to rice producing regions in Bangladesh and India. The governments of Columbia, Peru, Bangladesh and India, as countries at high-risk of apple snail invasion, will need to maintain vigilance against the introduction of these invasive apple snails to their rice-growing regions through effective quarantine practices (Cowie et al., 2009; EFSA (European Food Saftety Authority), 2012). These countries could also invest in preparedness by promoting crop establishment methods such as seedling broadcasting or the transplanting of older seedlings using machines (Horgan et al., 2014b; Horgan, 2018), to potentially save million in losses to their respective rice sectors should apple snails arrive from neighbouring countries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2021.105746.

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