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Towards estimating the economic cost of invasive alien species to African crop and livestock production

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Abstract

Background: Invasive alien species (IAS) cause significant economic losses in all parts of the world. Although IAS are widespread in Africa and cause serious negative impacts on livelihoods as a result of yield losses and increased labour costs associated with IAS management, few data on the impacts are available in the literature and the magnitude and extent of the costs are largely unknown. We estimated the cost of IAS to agriculture, the most important economic sector in Africa.

Methods: Data on the monetary costs of IAS to mainland Africa as well as information about the presence and abundance of the most important IAS were collected through literature review and an online survey among a wide variety of stakeholders. Using this and additional data from publicly available sources we estimated yield losses and management costs due to IAS in agriculture for individual countries and the entire continent. Where the data allowed, the costs for selected IAS or crops were estimated separately. The estimates were extrapolated using production and distribution data and/or matching of agro-ecological zones.

Results: The total estimated annual cost of IAS to agriculture in Africa is USD 65.58 Bn. Management costs (comprising mainly labour costs associated with weeding), crop yield losses and reductions in livestock derived income constitute the majority of the estimated cost (55.42, 44.31 and 0.26 percent, respectively). The IAS causing the highest yield losses was *Spodoptera frugiperda* (USD 9.4 Bn).

Conclusions: This study reveals the extent and scale of the economic impacts of IAS in the agricultural sector in one of the least studied continents. Although the cost estimate presented here is significant, IAS also cause major costs to other sectors which could not be assessed due to data deficit. The results highlight the need for pre-emptive management options, such as prevention and early detection and rapid response to reduce huge potential future costs, as well as measures that contribute to large-scale control of widely established IAS at little cost to farmers and other affected land users, to reduce losses and improve livelihoods.

Keywords: Economic impact, Labour costs, Livestock derived income, Management, Pests and diseases, Weeds, Yield loss

Introduction

Invasive alien species (IAS) are harmful species that have been introduced to a new region through human activities and that have become widespread, causing significant

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economic, ecological and societal impacts. For example, the cassava mealybug (*Phenacoccus manihoti* Mat.-Ferr) caused yield losses of up to ca. 80% across Africa prior to the introduction and subsequent establishment of the biological control agent *Apoanagyrus* (*Epidinocarsis*) *lopezi* De Santis (Nwanze 1982; Zeddies et al. 2001). Similarly, the recent invasions by tomato leaf miner (*Phthorimaea absoluta* Meyrick) and fall armyworm (*Spodoptera frugiperda* J.E. Smith) significantly reduced tomato and maize yields, respectively (Day et al. 2017; Rwomushana et al. 2019). Invasive plants have contributed to increased weeding costs in arable and grazing land (Le Maitre et al. 2002; Pratt et al. 2017), exacerbated water loss (Le Maitre et al. 2002), increased human and animal health risks (Adkins et al. 2018), and have contributed to social conflicts (Little 2019). These numerous effects on both agriculture and the environment demonstrate the need to mitigate and manage these IAS impacts. However, without information on the economic cost of these species, it is difficult to convince decision makers of the need to act to control IAS.

Assessments of the financial impacts of IAS in various countries have highlighted extensive economic costs. For example, Pimentel et al. (2001) estimated that the annual cost of IAS to the USA, United Kingdom, Australia, South Africa, India and Brazil was ca. USD 314 Bn. Similarly, significant costs have been estimated for other parts of the world, including Canada (Colautti et al. 2006), Europe (Kettunen et al. 2009), and China (Xu et al. 2006). Countries in sub-Saharan Africa are among the most vulnerable to the effects of invasions and the resulting impacts (Paini et al. 2016). Yet, relatively few studies of economic impacts of IAS in Africa have been conducted (Diagne et al. 2021) and these have had either a regional (Bekele et al. 2018; Pratt et al. 2017), national (Bokonon-Ganta et al. 2002; van Wilgen et al. 2020) or sub-national focus (Currie et al. 2009; Hosking and Preez 1999; Kettunen 2002; Ngorima and Shackleton 2019; Nkambule et al. 2017; Shackleton et al. 2017a, b; Shiferaw et al. 2019; Wise et al. 2007). Moreover, studies of economic costs of IAS often focus on a particular species or sector and rarely on an entire country, region or continent. Only two estimates have been made for the whole of Africa: the impact of eleven invasive insect and mite species in agricultural food systems was estimated to in excess of USD 1 Bn per year (Sileshi et al. 2019) and an estimate of yield loss based on published literature (Diagne et al. 2021) that highlighted the lack of data. The study by Sileshi et al. (2019) also highlighted information gaps in the availability of crop loss estimates and management costs in most countries, and noted that loss estimates are not made for all host species affected by invasive insects and mites. The small number of studies, limited scope of each and the geographic bias in data from Africa (Diagne et al. 2021) indicate that the data in the literature are insufficient for making a comprehensive estimate at the continental scale and costing the negative impacts of IAS therefore remains a challenge (Jeschke et al. 2014).

Previous studies estimating the economic impacts of IAS have used a variety of different approaches. In some studies, the costs of a few species have been estimated in detail, sometimes followed by an interpolation of the costs for other species (Aukema et al. 2011). Williams et al. (2010) calculated the costs of IAS management as a fraction of the total pest management in greenhouses. In addition, Pimentel et al. (2001) based their estimate of yield losses on the proportion of IAS in different sectors of the economy. The number of IAS and the total number of damaging species in an area were counted and the percentage IAS calculated. This percentage was applied to estimates of monetary losses in different sectors, such as agriculture and forestry. As an alternative approach, Kettunen et al. (2009) based their analysis of monetary IAS costs in Europe on information for 61 species and 14 species groups, which were broken down into the cost of damage and cost of control. The authors applied a conservative extrapolation to give a more comprehensive representation of the costs incurred in Europe, using data from areas affected by IAS to extrapolate to areas that could be affected by the same species. The authors also converted country level estimates to estimates per unit area, which were applied to regions for which no data were available. Williams et al. (2010) used a combination of species focused and crop level approaches for their estimation of IAS costs to Great Britain.

For one of the most recent IAS in Africa, *S. frugiperda*, estimations of potential impact were made based on data from household surveys in Ghana and Zambia that were extrapolated across ten other maize-producing countries based on agroecological zones (Day et al. 2017). The authors highlighted the potential for this method and the impact this species may have as it spreads throughout Africa. Such extrapolations may be applied more broadly to better estimate the costs of IAS to Africa. Similarly, Pratt et al. (2017) estimated the costs of a selection of IAS to smallholder farmers in mixed maize systems and expressed this as a proportion of national crop production affected by IAS, the proportion of yield lost to an IAS and the gross production weight multiplied by the average value of the crop. Given the uneven distribution of data among African countries and across habitats and IAS, it is clear that a combination of methods needs to be adopted to develop an estimate of IAS costs for the entire continent.

There is currently no estimate of IAS costs for all of Africa that includes both management and yield loss across a broad range of species, yet such estimate would help to inform policy and prioritisation of resources. Therefore, this study aimed to estimate the current annual direct economic cost of IAS to mainland Africa, specifically for the most economically important sector, agriculture. We used a combination of methods employed by others, including a focus on the IAS that are likely to have the largest economic impact, indicated by the geographic distribution, number of records in databases of IAS and the number of crops or habitats affected, an assessment of the cost of weeding IAS as a fraction of total weeding costs and extrapolation of data to data-deficient countries based on habitat and climate matching. We collated data from the literature and gathered new data through a questionnaire survey of stakeholders across Africa to estimate yield losses and management costs.

Methods

Data collection

Prioritisation of damaging invasive alien species in Africa

A list of the IAS occurring in agricultural systems in Africa was compiled using GRIIS (Global Register of Introduced and Invasive Species; http://www.griis.org, accessed on 11 March 2020), the Global Invasive Species Database (http://www.iucngisd.org/gisd, accessed on 3 December 2019) and the CABI Invasive Species Compendium (ISC; http://www.cabi.org/isc, accessed on 30 March 2020) and amended based on feedback from IAS experts, which resulted in addition of a few recent, impactful pests. Only species which were introduced from outside of mainland Africa were considered and we excluded marine species. These IAS were ranked according to the number of main crops or habitat types (e.g. forestry or grasslands) listed in the ISC, multiplied by the mean of the number of countries where specified as invasive on GRIIS list and number of countries recorded in the ISC. The top species for each main crop or habitat type were retained for assessment of their impacts and the final species were determined by the availability of data.

Literature search

As part of the literature review, data collection within different categories of impact was undertaken using two methods. First, an analysis of the literature for impacts related to invasive species of importance was conducted. Searches were undertaken in CABDirect (https://www.cabdirect.org/) and Google Scholar using "species name"; the geographic location of records was refined to only those from Africa. Then, searches using keywords relating to management costs (labour, eradication, economic costs, pesticide, insecticide, herbicide, biological control), yield loss (yield, carrying capacity, ha, USD, percentage loss) were undertaken to identify relevant sources of information. Data concerning the economic and other impacts were extracted from the shortlisted papers, separated into monetary costs related to yield, management and the cost of research, environmental and socio-economic impacts, along with percentage yield losses related to species affecting agriculture.

Questionnaire survey

There were large gaps and geographic biases in the data gathered from the literature. Therefore, a survey was designed to gather expert stakeholder knowledge of IAS impacts in Africa. The survey comprised of four sections (see Additional file 1). The first section focused on background data on the sector in which the respondent is active in, and associated data needed to analyse the responses, such as currency and area sizes. The second section aimed to quantify, in monetary terms (and percentages where applicable), the losses incurred as a result of a group of IAS, or specific species, including yield losses, management costs, lost income, etc. The final section aimed to capture the costs of research related to IAS impacts or management. In addition to economic information, the respondents were asked to select two IAS and assess their non-monetary environmental and societal impacts based on the Environmental Impact Classification of Alien Taxa (EICAT) and Socio-Economic Impact Classification of Alien Taxa (SEICAT) schemes (Bacher et al. 2018; Blackburn et al. 2014; Hawkins et al. 2015). The introductory text of the survey explained to participants that the data collected through the survey would be used for research purposes only and that the data would be aggregated, anonymised and analysed and published in a peer reviewed journal. Participants consented by continuing and completing the survey.

The survey was encoded in onlinesurveys.ac.uk and the link was sent to over 1000 stakeholders. The stakeholder list consisted of national contact points of the African National Plant Protection Organisations (NPPOs), protected area managers and rangers, and people who had attended CABI-led workshops about IAS in Africa previously. The survey was also sent to scientists who had published a peer-reviewed paper relating to one or more of the shortlisted invasive species since 2010. The survey link was further distributed via the following groups and mailing lists: The Forestry Research Network for Sub-Saharan Africa (FORNESSA), Forest Invasive Species Network for Africa (FISNA), Aliens-L, the "forpath" and "forent" lists of the International Union of Forest Research Organisations (IUFRO) and African Association of Insect Scientists (AAIS). The survey was also shared with additional respondents recommended by survey participants. Respondents were given four weeks to complete the survey. Two reminders were sent during this period and the deadline extended by 1 week.

In total 110 survey responses were received, from 30 countries, including six countries from which no data on impact of IAS were found in the literature. The majority of responses were received from those working in government (48) or university/research (58). Fifty-five respondents specified they had several years of experience working with/managing the species they were reporting on, 50 specified that although they were not a species expert, they were confident separating IAS from non-invasive species, four specified that they were not confident in separating IAS from native species; one person didn't respond to this question.

Confidence in the data

The level of confidence was assessed for data obtained through literature searches and survey responses using a similar methodology developed by (Kumschick et al. 2012). Levels corresponded to the following: (1) Low: mentioned in paper without evidence, no reference, speculation or expert judgement; (2) Medium: evidence in literature, observational; (3) High: demonstrated evidence in peer-reviewed literature, experimental. In addition to questions about their confidence in the evidence they provided, survey respondents were asked to rank their knowledge of IAS as follows: (1) I have several years of experience working with/managing and identifying the species I am reporting on; (2) Although not a species expert, I am confident separating IAS from non-invasive species; (3) I am not confident in separating IAS from native species for the sector I am reporting on. The average rating by respondents was 1.53 ($\pm$0.05 (SE)), indicating a high level of self-assessed expertise. For maize and tomato, expert loss estimates with a confidence score of <1 were not used in the analysis. Due to a paucity of data, all expert loss estimates were considered for other crops.

Data analysis

The methods employed needed to match the data available, therefore a simple model was used for which data was most available. The calculations of impact in this paper were based on the equations of Parker et al. (1999)

$$I = R \times A \times E$$

where impact is defined as I, and R = range, A = average abundance per unit area within the stated range, and E = the effect of the species.

We estimated the annual cost of IAS in 2019 USD using a conversion rates obtained from https://www.exchangerates.org.uk/, and where necessary values found in literature were adjusted for inflation to 2019 USD using the online tool at www.inflationtool.com (Inflationtool.com 2020).

Table 1 Selected main crops in African agriculture and representative IAS for which yield loss estimates were made

Crop type	Crop	Representative IAS
Cereals	Maize	*Spodoptera frugiperda* J. E. Smith *Chilo partellus* C. Swinhoe
Stored products	Maize	*Prostephanus truncatus* Horn
Root crops	Cassava	*Phenacoccus manihoti* Matile-Ferrero
Fruit	Mango, citrus	*Bactrocera dorsalis* Hendel
	Banana, including plantains	Banana bunchy top virus
Vegetables	Tomato	*Phthorimaea absoluta* Meyrick

Yield loss

Representative IAS were selected for at least one crop of the main crop types in African agriculture (Table 1). The ISC, GRIIS and GISD provided information about the presence of each species at the country level. In the ISC, information on distribution within the country is sometimes added to a record and only those listed as "present", i.e. occurring in a particular country or area (without details on range), or "present widespread", i.e. occurring practically throughout the country or area where conditions are suitable, were considered.

Production data from 2012–2018 for the relevant crops (value and quantity) were downloaded for every African country from FAOSTAT (Food and Agriculture Organization of the United Nations 2017). For each focal IAS, we extracted production value and quantity data for countries where the species was present. For each country with available production value data, we inflation-adjusted the annual production values and calculated the average annual production for this period. For countries where only production quantity data was available, we estimated the value of the annual production based on the median price per tonne for the relevant crop across all other countries where the IAS was present. For each year, the median was calculated and applied to the annual production values. The resulting value was inflation adjusted and an average taken for each country over all years. To estimate annual production values for countries for which no production value or quantity data for the relevant crops were available, we used data on the production quantity of relevant crops in the year 2000, obtained from EARTHSTAT (Monfreda et al. 2008) and looked for countries which had similar production quantity to our countries of interest. We then used the annual FAOSTAT production values of those countries as a proxy. When the production quantity data were similar to multiple countries, we used the average FAOSTAT production value of these countries as an estimate for our country of interest. These annual data were then inflation adjusted and averaged across years for each country. If an IAS arrived during the 2012–2018 period, production values were used from the years after the species was first recorded as present within that country. This was done specifically for *P. absoluta* and *S. frugiperda*, which have recently spread across Africa. Although it may take years before a species establishes everywhere in a country, we assumed that species established throughout the growing area of that crop when it was first recorded. While this is a strong assumption, it is the best possible given the available data. We aimed to overcome this serious shortcoming in the data by excluding countries where the species occurrence was listed as localised in the ISC. It is likely that *Spodoptera frugiperda* and *Phthorimaea absoluta*, the two most costly species, are present where the hosts (tomato, maize) are grown.

Yield loss figures and abundance estimates associated with a particular IAS or crop were collated from literature sources and survey results. Although unrealistic due to differences in climate suitability, data availability forced us to assume that crop losses are the same throughout all crop growing areas. High, mean and low loss figures were derived from literature or survey data: the upper and lower limits were taken as the high and low estimates, and the mid-point as the mean estimate. If data for a country from the literature and from surveys were available, only the loss values from the literature were used because data from peer-reviewed literature was considered more reliable than survey data. For both, a certainty estimate was calculated. If multiple high certainty data points were available from the survey, we used a mean of the yield loss estimates. If the yield loss was only reported in the literature data, then this value was used. The yield loss for each country was calculated as:

$$Yield\ loss(USD) = \frac{V}{1 - (F_L \times F_A)} - V$$

where V is the average crop production values (2012–2018) in USD, F_L is the fraction yield loss due to the IAS, and F_A is the fraction of crop affected by the IAS. These calculations were carried out using the lower, mean and upper estimate of yield loss.

If there was data available on pest abundance for countries from literature or survey information, these were used. However, estimates were extrapolated to countries where no yield loss IAS or abundance data was available, based on similarity of the agroecological zones (AEZ). The spatial dataset Agro-ecological Zones of Africa (Sebastian 2009) was used to calculate the percentage area of each AEZ type per country. European Space Agency Climate Change Initiative (ESA CCI) Landcover (European Space Agency 2017) crop data (classes 10, 20 and 30) were used to refine the percentage areas so that country matches were based on the similarity of agricultural areas only. A matrix of AEZ similarities (1-dissimilarity, based on Bray–Curtis dissimilarity) of all country combinations was built using the vegdist() function in the vegan package (Oksanen et al. 2020) in R (R Core Team 2019). This was performed for agricultural areas and all land areas. The matrix was used each time loss estimate information needed to be extrapolated to fill gaps where no data was available. In each case, data was extrapolated from the highest matching country with data, first by agricultural land AEZ similarity, and if no suitable matches were found then by total land AEZ similarity.

In addition to the species-based yield losses, we calculated yield losses for selected crops, based on survey responses where respondents indicated the percentage of total yield losses caused by IAS. The calculations were similar to the species-level calculation, whereby the entire country was affected ($F_A = 1$) and were based on the percentage yield losses and gross production statistics for each crop or corresponding crop type in FAOSTAT and extrapolation was based on the similarity of AEZ as described above. As it was unclear which IAS caused the yield loss at crop level and what contribution that species had made to the estimated loss, the crop-level estimates were not included in our total loss estimates to avoid double counting.

Loss of livestock derived income

To shortlist the main invasive alien weeds associated with pasture and livestock systems in Africa, IAS listed in the ISC as affecting “Managed grasslands (grazing systems)” were shortlisted. This list was further restricted to those that had a very high impact on livestock on grazing land (Van Wilgen et al. 2008), and that were present in more than 10 countries according to the merged ISC and GRIIS lists. The reduction in livestock derived income caused by these species was then calculated as:

$$\text{Reduced livestock derived income (USD)} = \text{H} \times \text{A} \times \text{I}$$

where H is the area of grazing land within a country (ha), A is the affected area (fraction of the surface) and I is the estimated financial impact per unit area.

The total grazing area was calculated for each country using the Global Agricultural Lands: Pastures, 2000, dataset (Ramankutty et al. 2010). The area affected was based on CLIMEX models of environmental suitability for selected invasive weeds: *Chromolaena odorata* (L.) R.M.King & H.Rob. (Kriticos et al., 2005), *Lantana camara* L. (Taylor et al., 2012), *Prosopis juliflora* (Sw.)

DC. (D.J. Kriticos unpublished data), *Parthenium hysterophorus* L. (Kriticos et al. 2015a, b), *Tithonia diversifolia* (Hemsl.) A.Gray (D.J. Kriticos unpublished data) and *Opuntia stricta* (Haw.) Haw. (Witt et al. 2020).

The financial impact on carrying capacity per unit area was estimated using literature on the impacts of weeds, livestock densities and livestock market values. Van Wilgen et al. (2008) ranked the impact of invasive alien plants on carrying capacities in South Africa based on expert opinion. The same method was used in this study where it was assumed that all species included in the calculations had a 'very high' impact on carrying capacity and, in-line with Van Wilgen et al. (2008), reduce carrying capacity by 80% when very abundant, 20–50% when abundant and 5% when occasional. For example, *P. hysterophorus* impact was regarded as very high based on a study by McFadyen (1992) in Queensland Australia, who found that dense invasions reduced cattle stocking rates by up to 80%. For each weed, we applied impact estimates of Van Wilgen et al. (2008) to the area with each level of abundance as in the CLIMEX models, assuming that the area indicated as suitable by the CLIMEX models is currently invaded: (1) the area environmentally unsuitable for a species was omitted from the analysis, (2) we assumed a 5% reduction in carrying capacities in areas where CLIMEX models indicated a suitability of between 1–30 for the target species, and 3) a 35% reduction in carrying capacities in areas where CLIMEX models indicated a suitability of between 30–100. This was done for countries where the species are recorded as present in the ISC, GRIIS lists and GISD. A final category where plants were invasive was defined based on data from published surveys (Witt et al. 2018). For this category the proportion of land estimated to be affected by the species was taken directly from literature sources and multiplied by the 'abundant' area, because invasive stands are more likely to be found within areas where CLIMEX models predict suitability to be > 30 (Kriticos et al. 2015a, b). The area of the third category was then reduced by subtracting the area estimated to be affected by the invasive species. We applied an 80% reduction in carrying capacity to the area where the species was invasive.

The effect of the reduction in grazing on the number of livestock per unit area was calculated by multiplying the reduction in carrying capacity for each abundance category by the pasture area of each category. The total reduction in grazing area was multiplied by the number of livestock units per ha (FAOSTAT, average of 2012–2018 data for cattle and sheep for each country) to give the total reduction in livestock number. Calculating the effect of the change in carrying capacity on income from livestock was done by multiplying the average inflation adjusted value of each livestock head (value of meat, milk and wool divided by the number of livestock heads per country for 2012–2018; FAOSTAT), by the total reduction in livestock number. Where there was no value for livestock production in a country the median price per head of livestock per ha from all other countries was applied. To avoid double counting of IAS impacts, all impact on livestock derived income was attributed to the species which had the greatest impact in that country (Van Wilgen et al. 2008).

Weeding cost

Calculations were made for five crop types: maize, other cereals, root crops, vegetables and legumes. Calculations for other crop types were not possible due to the paucity of data concerning weeding efforts or weed community composition. The formula applied to each crop type per country was:

$$\text{Weeding cost (USD)} = \text{H} \times \text{A} \times \text{F} \times \text{L},$$

where H is the harvested area, A is the fraction of the area managed (in percentage; we assumed that the entire crop area is weeded), F is the fraction of weeds that are IAS and L is the labour cost per unit area (in USD).

The harvested area was obtained from the Spatial Production Allocation Model (SPAM) datasets for the distribution of twenty crop types in 2017 (https://www.mapspam.info/data/), which accounts for multiple cropping seasons where applicable. Data was not available for 2017 for countries north of the Sahara; for those 2010 data was used. For 2010, some crop categories were unavailable and these were excluded from the calculations. Western Sahara and Djibouti were omitted, as SPAM does not provide data. Equatorial Guinea was omitted because the data appear to be very deficient in SPAM, leading to many zero values.

The abundance of IAS as a fraction of all the weeds in arable fields in Africa was based on a literature review of weed species found in different cropping systems (in Google Scholar using search terms *crop name* + weed community composition). Few studies on weed community composition were found, with relatively small differences among the crop types in terms of the fraction of alien species. The studies reported three measures for abundance of a species (number of plants per species, relative abundance as percentage of total vegetation cover and the Oosting scale). It is impossible to combine or convert these measures to make the values comparable, but the abundance of alien species was higher than native species in all but one study. On average, the abundance estimate values were 45% higher for alien than for native weeds and we assumed that on average 55% (± 5) of the species in each crop type is alien.

Table 2 Average annual person days spent on weeding one ha of five crop types in African countries, as reported in peer-reviewed journal articles

	Average	SE	No. studies
Cereals (excl. maize)	50.0	11.3	10
Legumes	54.2	8.1	18
Maize	54.6	8.3	24
Root crops	92.0	18.9	5
Vegetables	82.7	12.1	20

Indicated are the mean, standard error of the mean and the number of studies on which the values are based

Table 3 The absolute and relative contribution of labour, yield loss, lost livestock derived income and research to the annual cost of IAS to African agriculture in billions USD

	USD	Percentage
Yield loss	29.06	44.31
Weeding cost	36.34	55.42
Lost livestock derived income	0.17	0.26
Research costs	0.00	0.00
Total	65.58	

The number of person days spent weeding in different crop types in African countries was obtained from a literature search. There is a lot of variation among estimates for each country and crop, with root and vegetable crops requiring more time than maize, cereals and legumes (Table 2). Upscaling each crop or country would seem unreliable because of the small number of studies per crop and country. Few studies were found that reported data that could be converted into person days per year per ha. Consequently, we only estimated the time spent weeding for crop types for which more than five studies had been undertaken in different African countries.

The agricultural labour cost was based on the minimum wage for each country (https://wageindicator.org/salary/minimum-wage). Some countries have minimum wages per hour, week or month and in order to convert such indications to the cost per day, such values were corrected for the number of working days per month (assuming four weeks per month) or the number of hours per working day (assuming eight hours per day) and multiplied with the minimum wage in local currency.

Research costs

Participants in the survey were asked to estimate the direct cost their organization spends on invasive species research per annum (including project work, meetings, initiatives, answering queries and giving advice etc.) and the numbers of person days spent. The midpoints of the provided ranges were used for the calculations. Where more than one species was named, the costs were split evenly between the species listed. For each species, the direct costs were summed. Labour costs were monetised based on mid-level lecturer or research worker wages costs from (https://www.paylab.com/).

Non-monetary impacts

We used the EICAT and SEICAT frameworks (Bacher et al. 2018; Blackburn et al. 2014; Hawkins et al. 2015) to obtain an assessment of ecological and societal impacts of IAS in the questionnaire survey. Eighty-three respondents provided EICAT and SEICAT impact scores for a total of 29 species, including three, four and nine aquatic, crop weed and woody plant species, respectively, and seven insect species, three fungi and two viruses. Scores for a single vertebrate species (Indian house crow, *Corvus splendens* Vieillot) were excluded from the analysis. The scores were converted to numerical scores (one to six for least to maximum impact) and "data deficient" scores were excluded. Differences in the average scores given for the impact types (societal impacts: safety, assets, health, relations; ecological impacts: competition, predation, hybridisation, disease transmission, parasitism, toxicity, herbivory, IAS interactions) and species groups were analysed with generalised linear mixed models using the glmmTMB() function [package glmmTMB, version 0.2.3; (Brooks et al. 2017)] in R (R Core Team 2019), with an assumed truncated Poisson distribution. If a significant difference among the impact types or species groups was found, differences between factor levels were analysed using the lsmeans() function [package lsmeans, version 2.30–0; (Lenth 2016)] with the Tukey method to adjust P values for multiple comparisons. Significance was assessed at the 0.05 level.

Results

Losses by sector

The total estimate of IAS costs to Africa is USD 65.58 Bn per year (Table 3). The labour cost of weeding constitutes the largest fraction of the estimated costs (55.42%), followed by the value of yield loss. The value of the lost livestock derived income and research costs are a very small fraction of the total estimate. The combined weeding cost for the five crop types is USD 36.34 Bn per year (Table 3). Almost three quarters of that amount (72%) is attributed to weeding in cereals, other than maize, and legumes. Weeding in maize and root crops each roughly account for half of the remainder, and weeding vegetables represents a small fraction of the estimate (3.3%).

Table 4 Summary of estimated costs by country

Country	Annual weeding costs	Reduced livestock derived income	*Spodoptera frugiperda*	*Prostephanus truncatus*	*Chilo partellus*	*Phenacoccus manihoti*	*Phthorimaea absoluta*	BBTV	*Bactrocera dorsalis*	Total
Algeria	608	2	–	–	–	–	–	–	–	611
Angola	1066	1	368	–	–	–	2	96	185	1717
Benin	452	0	376	–	–	–	36	0	18	883
Botswana	26	0	1	–	1	–	2	–	0	31
Burkina Faso	874	1	186	–	–	–	12	–	2	1075
Burundi	6	0	11	–	–	192	5	92	204	510
Côte d'Ivoire	1212	1	211	–	–	495	–	–	64	1984
Cameroon	725	0	2237	–	363	79	24	17	1	3446
Central African Republic	125	1	137	–	–	21	–	1	18	304
Chad	1052	2	51	–	–	–	–	–	21	1126
Congo, Republic of	272	0	12	–	–	1163	1	24	100	1573
Congo, Democratic Republic of	3166	0	418	–	–	0	–	16	451	4053
Djibouti	–	0	–	–	–	–	–	–	–	0
Egypt	520	9	–	–	–	–	967	–	–	1496
Equatorial Guinea	–	–	–	–	–	–	0	2	14	16
Eritrea	32	3	16	–	10	–	–	–	16	78
Ethiopia	442	22	209	–	427	–	17	–	80	1197
Gabon	148	0	9	–	–	0	–	0	1	159
Gambia, The	21	1	4	–	–	0	–	–	13	40
Ghana	703	0	277	14	–	0	–	–	94	1088
Guinea	427	0	37	–	–	0	–	–	35	500
Guinea–Bissau	0	0	4	1	–	3	–	–	24	33
Kenya	917	33	719	41	304	155	222	–	184	2576
Lesotho	69	–	–	–	8	–	8	–	–	85
Liberia	12	–	–	–	–	0	–	–	21	34
Libya	178	0	–	–	–	–	–	–	–	178
Malawi	457	1	31	59	127	1231	119	204	–	2288
Mali	1099	3	252	–	–	2	–	–	421	1776
Mauritania	5	0	–	–	–	–	–	–	13	18
Morocco	1442	5	–	–	–	–	211	–	–	1658
Mozambique	868	3	421	30	71	1587	58	36	107	3212
Namibia	365	1	9	–	–	–	5	–	13	392
Niger	2477	1	5	–	–	5	–	–	34	2522
Nigeria	10194	2	500	–	–	238	1854	79	2202	15069

Table 4 (continued)

Country	Annual weeding costs	Reduced livestock derived income	*Spodoptera frugiperda*	*Prostephanus truncatus*	*Chilo partellus*	*Phenacoccus manihoti*	*Phthorimaea absoluta*	BBTV	*Bactrocera dorsalis*	Total
Rwanda	13	1	17	6	–	59	–	0	47	143
South Sudan	174	15	26	–	–	–	–	–	–	214
Senegal	589	0	25	3	–	7	284	–	42	950
Sierra Leone	115	0	0	–	–	0	–	–	94	210
Somalia	16	5	16	–	9	–	–	–	–	46
South Africa	2275	33	1082	–	599	–	–	–	–	3989
Sudan	542	7	5	–	7	–	–	–	256	816
Eswatini	9	1	–	–	7	–	–	–	54	70
Tanzania	1268	4	644	64	144	613	175	–	526	3438
Togo	303	0	13	13	–	3	–	–	1	334
Tunisia	228	1	–	–	–	–	118	–	–	348
Uganda	391	5	609	30	233	0	1	–	371	1639
Zambia	375	4	307	9	217	399	29	0	10	1350
Zimbabwe	89	1	144	11	65	0	–	–	80	390
Total	36,342	173	9394	382	2592	6254	4149	568	5820	65,573

In millions USD. For the yield losses by individual species, the values are the middle estimates, based on literature and survey responses. A dash indicates that no estimate was made, whereas a zero indicates a small estimate

Table 5 Yield loss value caused by individual IAS in billions USD. Numbers in brackets indicate high and low estimates

Host	IAS	Literature only	Literature + survey
Maize	*Spodoptera frugiperda*	6.9 (–)	9.4 (7.7–12.1)
	Prostephanus truncatus	0.2 (0.1–0.3)	0.3 (0.2–0.5)
	Chilo partellus	2.6 (2.1–3.1)	2.6 (2.1–3.1)
Cassava	*Phenacoccus manihoti*	0.0 (0.0–0.0)	6.3 (5.5–7.3)
Tomato	*Phthorimaea absoluta*	4.8 (3.6–6.7)	4.1 (3.2–5.6)
Banana	BBTV	0.2 (–)	0.6 (0.5–0.6)
Mangoes (and citrus in survey)	*Bactrocera dorsalis*	3.5 (1.7–10.6)	5.8 (4.4–10.0)
Total		18.2	29.1

The average annual cost of IAS (excluding research costs) per country was USD 1.366 Bn, but there were large differences among countries: the estimates for Botswana, Djibouti, Equatorial Guinea, Gambia, Guinea-Bissau, Liberia, Mauritania and Somalia were less than USD 50 Mn, whereas Nigeria stands out with an estimate of over USD 15 Bn (Table 4). Nigeria also has the highest nominal GDP and the largest population of the African countries. The research costs were excluded from the country averages, because the data are incomplete and are very unevenly distributed across the continent. Some of the differences in the estimates were due to the size of the arable land and grazing land, the production value of different crops and the presence of specific pests, which were the basis of our calculations. Significant positive relationships were found between the country estimates and nominal GDP (2018), agricultural GDP (2017), population size and land area, even when Nigeria was excluded from the analyses (Spearman rank correlations: $P < 0.001$).

IAS were estimated to cause losses in livestock derived income worth USD 172.6 Mn annually. *Prosopis juliflora* and *Chromolaena odorata* were the most common species causing the highest costs (in 28 and 10 countries, respectively), whereas *Lantana camara* was estimated to cause the highest cost in five and *Parthenium hysterophorus* and *Opuntia stricta* in single countries. Consequently, *P. juliflora* and *C. odorata* accounted for a large fraction of the total loss (90.1 and 2.9%, respectively).

Losses caused by individual IAS

When considering literature sources only, the cost of yield loss was highest due to *S. frugiperda* in maize, followed by *P. absoluta* in tomato, *B. dorsalis* in mangoes and *Chilo partellus* in maize. Banana bunchy top virus (BBTV) and the storage pest *Prostephanus truncatus* were estimated to cause comparatively little yield loss (Table 5). No estimate could be made for *P. manihoti* based on literature. For all species, except *S. frugiperda* and BBTV, low and high estimates were calculated and these were on average 32.3% and 80.2% smaller and larger, respectively, than the middle estimates for the same species. This indicates that there were some studies with really high comparative losses, but the middle estimates were closer to the lower loss value. There was substantial variation in the range of the estimates, which appears largely due to differences between the high, medium and low loss estimates for *B. dorsalis*.

Table 6 Summary of the data sources used for the species calculations and the number of countries for which the estimates were based on extrapolation

Species/Crop	Literature	Survey	Extrapolated countries
Spodoptera frugiperda	3	11	27 (7.97)
Prostephanus truncatus	6	4	4 (8.90)
Chilo partellus	5	0	12 (7.18)
Phthorimaea absoluta	3	4	15 (6.77)
Phenacoccus manihoti	2	3	22 (6.6)
BBTV	1	5	9 (7.70)
Bactrocera dorsalis	1	3	33 (6.1)

Numbers in brackets indicate the mean agro-ecological match score (out of 10). The score is an indication of the similarity of agro-ecological zones in the countries for which extrapolations were made and in the closest matching country, on which the extrapolation was based

The survey responses complemented the data in the published literature. The number of data points increased for certain species (Table 6), but not the geographic coverage: data in literature concerned 32 countries and our survey yielded responses from 33 countries. On average, the survey results provided extra yield loss data for an extra 3.86 countries. The survey responses especially added more recent information about the distribution and impact of selected IAS.

When survey results were considered, the medium total estimate was in most cases larger than when only literature sources were used. This was as a result of the roughly double estimates for most species and the estimates for *P. manihoti* that were now included. The estimates for *P. absoluta* were smaller when the survey responses were included than when the estimate was only based on literature, whereas the opposite trend was found for the other IAS.

Table 7 Summary of the costs per crop in billions USD, based on expert knowledge as gathered through the survey

Crop	Yield loss
Maize	9.8 (30)
Rice	3.8 (9)
Sorghum	1.7 (11)
Vegetables (fresh nes)	3.7 (15)
Cassava	21.8 (14)
Tomato	10.1 (13)
Fruit (oranges, lemon, limes, grapefruit, citrus nes)	14.6 (4)
Mango	3.7 (1)
Banana	7.1 (13)
Plantains	5.9 (4)
Total	82.2

Respondents indicated the fraction of yield loss caused by IAS; n indicates the number of estimates obtained from the survey responses that were used in the calculation. For maize and tomato, expert loss estimates with a confidence score of < 1 were filtered out of the analysis. Due to a lack of data, all expert loss estimates were considered for other crops. Terms in brackets in the first column indicate the categories in FAOstat that were used as basis for the crop yield estimates

Respondents to the survey also indicated the percentage yield loss due to IAS for individual crops, without identifying the IAS. The crop-level costs calculated based on these responses (Table 7) were similar to the estimates based on the individual pests (Table 5), especially when the range of the latter estimates is considered. However, especially the estimates for bananas and cassava were clearly larger when based on the percentage loss due to all IAS combined compared to the mean species-based estimates.

Research costs

Seventy-nine of the 110 respondents reported the annual number of staff days spent on individual IAS and 63 respondents provided estimates of direct costs associated with research. Together, the responses indicated that USD 1.9 Mn was spent on research in 2019, with 40% of that amount being direct costs and the remainder staff costs. Most funding was related to *Spodoptera frugiperda, Eichhornia crassipes, Lantana camara* and *Phthorimaea absoluta*, which accounted for 51.6% of the estimated research cost (Fig. 1).

Non-monetary impact

Societal impact scores for all organism groups were provided by survey respondents. On average, the impact on assets (2.5: between Minor and Moderate; Fig. 2) was higher than the impact on health and relationships (both 1.6: between Minimal concern and Minor), with the average impact on safety in between (2.1: Minor; $P<0.05$). There were no differences in the average impact score for the different species groups and there was no difference in the impact of species groups on the impact types (both $P>0.05$).

Ecological impact scores were also given for all organism groups. Ecological impact scores for bio-fouling, trampling, digging and flammability were excluded from the analysis. Across all species groups, the impact through competition received the highest score (3.6: in between Moderate and Major; Fig. 2) and herbivory and hybridisation the lowest (2.0 and 1.9: Minor), with all other impact types in between. There were no differences in the average impact scores for the species groups.

Discussion

The total estimated economic cost of IAS to agriculture in Africa is USD 65.58 Bn per year, which represents on average 13.0% of the national agricultural GDP of individual countries, but there are large differences: the cost to Algeria, Djibouti, Somalia and Mauritania represents less than 1%, and the cost to Zambia, Niger, Malawi and Mozambique more than 25% of their respective agricultural GDP. The cost to the Democratic Republic of the Congo, which is dominated by weeding costs, corresponds to an estimated 148% of the agricultural GDP. This comparison indicates the scale of invasive species impacts on African economies, despite the fact that this cost estimate only focuses on agriculture, when IAS also affect the environment, water resources trade, infrastructure, aquaculture, human and animal health, transport and tourism (Kettunen et al. 2008; Williams et al. 2010). The current available data enabled an estimate of the costs of IAS on agriculture, but a paucity of data for other key sectors such as plantation forestry and aquaculture, means that the estimate could be improved further. This aligns with findings in Diagne et al. (2021) whose estimate was dominated by agricultural costs.

This estimate of the total cost of IAS is based on available literature and survey results and it provides an improved estimate for a data-deficient continent (Diagne et al. 2021). We have added to the knowledge base of the costs of IAS by: including survey data from across the continent, including from countries where no data were found in the literature, by extrapolating species costs from one AEZ to similar AEZs across the continent, by the inclusion of the cost of reduced livestock derived income; and by the inclusion of research and labour costs, which are generally not included in estimates of the costs of IAS. Lost livestock derived income is of particular importance within the African context, where capital is often held as livestock (Ouma et al. 2003). In addition, labour costs are critical within African agriculture, as

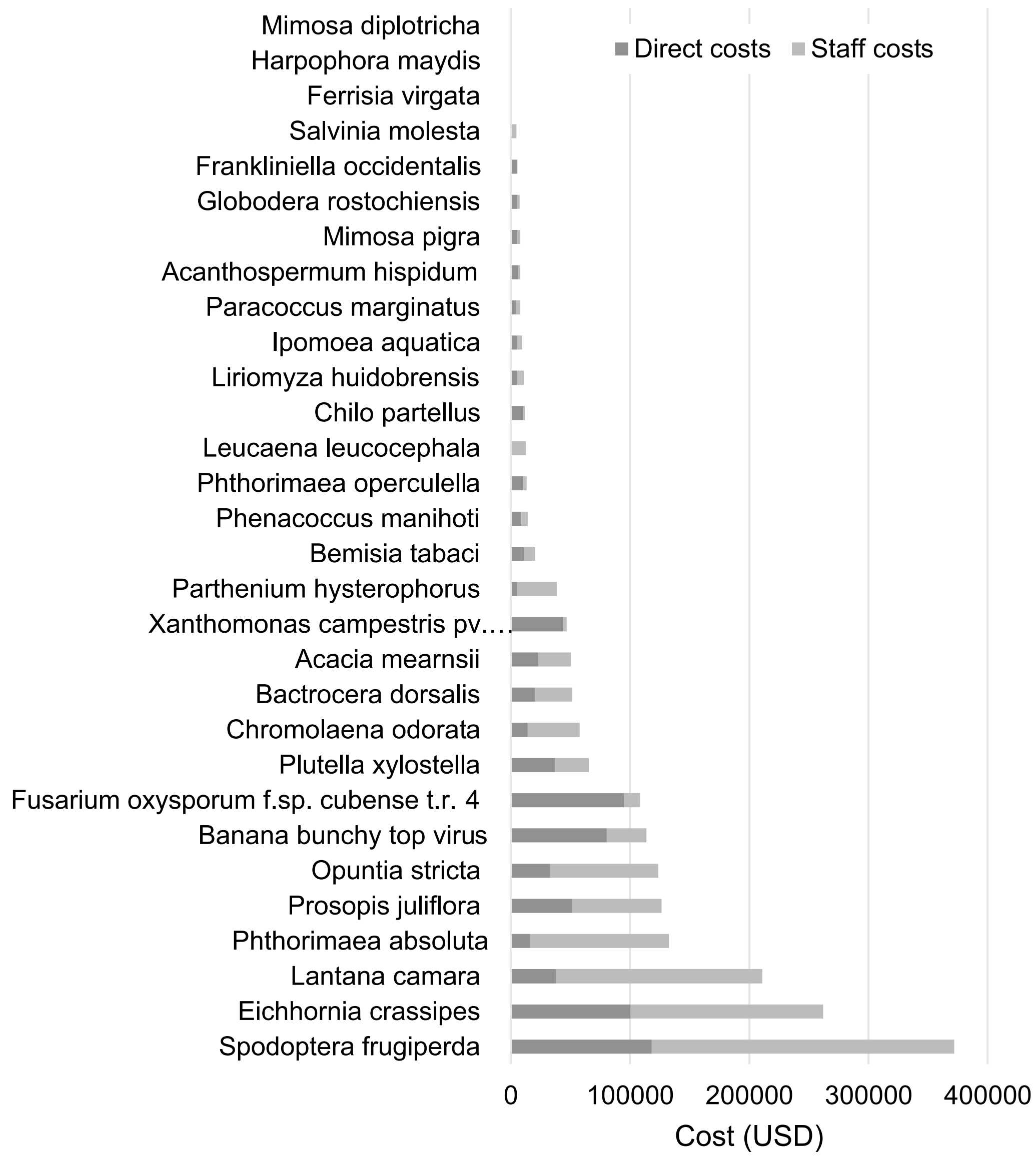

Fig. 1 Research costs related to different IAS in 2019. Data are based on survey responses and are separated into direct and staff costs

land preparation, weeding and pest control are generally undertaken manually, but labour is often not seen as a cost. Therefore, inclusion of weeding costs of IAS provides a closer estimation of the actual costs of IAS to the agricultural sector.

Taken together, our results indicate that IAS have major impacts on people's livelihoods, because women and children spend a lot of time weeding IAS, because crop yields are significantly reduced and because degradation of grassland habitats by IAS reduces livestock carrying capacity, which affects people's income and capital. The results of the survey further illustrate the extent of non-monetary ecological and societal impacts caused by IAS across the continent. Hence, there is an urgent need for measures to mitigate current and prevent future IAS impacts.

Weeding costs

A significant part of our estimate is the labour cost for weeding of IAS in cropping systems, which corresponds to the finding in McFadyen (1998) who stated that manual weeding makes up 60% of all pre-harvest costs in the developing world. These costs are generally not monetised in many calculations of the cost of managing crop pests, including IAS, and so it is difficult to put our estimate in relation to other studies. However, the

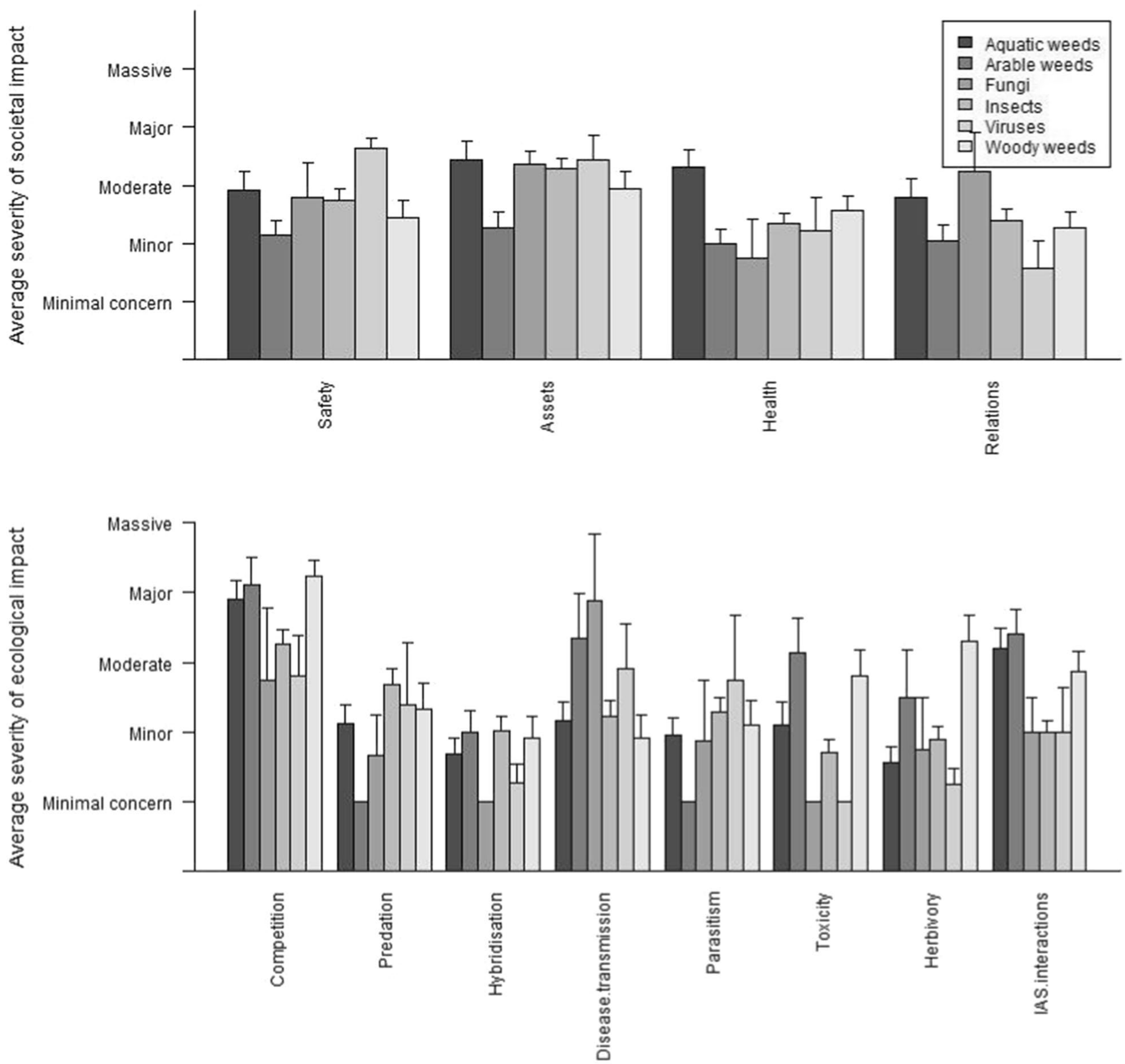

Fig. 2 Non-monetary impacts of IAS in Africa. Bars indicate means across responses for each impact type x species group combination. Error bars indicate one standard error measure

cost of the time spent weeding represents a lost opportunity to spend time on some other activity or job i.e. it is an opportunity cost. Hence, the cost can realistically be as high as our estimate, but it should not be concluded that people are being paid that amount as salaries, so it is not money spent as part of the formal economy. There are also additional hidden costs to weeding, as weeding is primarily undertaken by women and children (SOFA Team and Doss 2011). When the weeding burden is reduced for women, they spend more time on child-care, income-generating and community activities (Grassi et al. 2015). In addition, 69% of children in sub-Saharan farming households are removed from school during the peak weeding season, with consequential effects on their education (Gianessi 2009). While the costs included in this estimate therefore represent a true, or even undervalued, cost of weeding to an economy, it should be recognised that in some situations, if a farmer is unable to weed their fields, they may not hire labour for that purpose, but rather leave the field un-weeded. In those cases, the economic cost of weeding would be reduced, though it is likely that the yield loss due to the presence of the weeds would increase. A further consideration is whether it is correct to assume a proportion of weeding costs can be attributed to the presence of IAS. Based on studies that reported the weed community composition in African cropping systems, we assumed that IAS represent on average 55% of the weeds in agricultural fields. It can be argued that the cost of weeding is the same, whether or not the weed is an IAS, and that if an invasive weed was not present, a native weed is likely to be present instead, which will require weeding. Despite the challenges in establishing the actual cost of weeding IAS to the African economy in terms of money paid, the economic cost remains the value of the time taken to weed the IAS, and therefore this value is included in our estimate.

Yield loss and costs by species

A further key part of our estimate is that of crop yield loss due to IAS. This formed the foundation of the estimate of losses caused by specific IAS for the key crops, and is the most robust section of the total cost estimate, as most of the available data quantified the direct effects of IAS on crops i.e. the yield loss. As double counting of costs caused to individual crop species was a risk in calculating this cost estimate, we followed a similar approach to that taken by Aukema et al. (2011) and focused on key species affecting specific crops or crop groups. For example, for tomato we calculated the costs caused by *P. absoluta* and did not capture costs potentially caused by other tomato pests. This eliminated the risk that yield losses incurred were attributed to more than one IAS, which would have caused an overestimate of the total costs. This approach is justified by a comparison of the costs described in Tables 5 and 7, where it can be seen that while the costs calculated for *P. absoluta* at USD 4.1 Bn are lower than those calculated for tomato as crop, regardless of IAS, at USD 10.1 Bn, the costs attributed to *S. frugiperda* (USD 9.4 Bn) are comparable to those calculated for maize (USD 9.8 Bn). This indicates that through the focus on key pests per crop species we have estimated the main costs caused by IAS for key crops, while eliminating the risk of double counting our estimates.

A further comparison of our species estimates is enabled by data from Diagne et al. (2021). Their cost estimates for *S. frugiperda* and *P. absoluta* are USD 2.9 Bn and USD 1.15 Bn respectively, as compared to our estimates of USD 6.9 Bn and USD 4.8 Bn from literature only (Table 5). This difference is explained by the exclusion of costs based on extrapolation of data from the Diagne et al. (2021) estimate, whereas extrapolation of costs across the continent to provide a more comprehensive assessment of costs forms an important part of this current estimate.

The decisions about which species to use as the key species was based on the literature as well as feedback from country IAS experts as to which species were currently having the greatest impact. This may have led to a focus on only the highest priority IAS affecting agriculture and meant that some IAS causing environmental damage have been missed in this cost estimate. Despite the robustness of the yield loss estimates, it is worth noting that costs related to chemical pesticide use have not been included and would increase our estimate significantly. Costs include the pesticides themselves, the labour associated with pesticide application and the required equipment. However, data on these costs were not available for inclusion.

Reductions in livestock-based income

Livestock keeping is central to the culture and economy of large parts of Africa, a continent where grasslands are widespread, and assessing the impact of IAS on these grasslands is important when creating an overview of the costs to agriculture. Although capital is held as livestock, we only estimated income based on livestock; our estimate was based on the number of livestock held and this IAS impact is comparable to crop yield losses for farming. Although in our study the impact of IAS on livestock derived income is small compared to the other estimates, the impacts of IAS on livestock numbers and thus on capital on the household or community level can be significant (Linders et al. 2020). Estimating the impacts of weeds on grasslands, and how this reduced the carrying capacity, was limited by the availability of distribution and impact data for the IAS, which restricted the number of species for which we were able to estimate impacts across the continent, and was further complicated by the frequent co-occurrence of species that makes it impossible to attribute impacts to a single species and introduces the risk of double counting of costs. In order to avoid the latter, we decided to only consider the value for the costliest species for each country and our estimate is to be considered as conservative. This is even more so, since other weed species impact on the quality of grazing land, but our results appear to confirm the important impact of *L. camara* on grazing land [Swarbrick et al. 1995, in CABI (2015)] and fodder availability (Shackleton et al. 2017a, b) and of *P. juliflora* on income from livestock (Linders et al. 2020).

Survey results

Estimating IAS losses using survey responses doubled the cost estimate based on literature alone. This was due to a combination of responses from countries that are underrepresented in the literature and additional estimates for almost all pests, and highlights the need for more information on IAS impacts in Africa. For species that have been present in Africa for less than 10 years (*Spodoptera frugiperda, Phthorimaea absoluta),* it is possible that current research, that was reported through the survey, has not yet been published, and therefore the costs found in the literature do not present the current economic cost of these species. Research into species that are newly invasive in an area commonly focuses on the biology, potential yield loss and possible control methods for that species, rather than the economic impact. For example, only one of the top ten studies on *S. frugiperda* in Africa quantified the potential economic loss caused by the species (Abrahams et al. 2017). Furthermore, the longer a species has been present the better or more cost-effective the management interventions become. However, if a resurgence of damage caused by a species occurs, e.g. *P. manihoti* damage has increased over the past five years in certain areas (Bisimwa et al. 2019; Fening et al. 2014), this may not be widely reported in the literature yet, and only reported through the survey results. In addition, the value of the crop affected by the IAS will have an effect on the economic losses reported. For example, *P. absoluta* is a serious pest of tomato, a key cash crop for much of Africa, so any yield loss caused by the species has serious economic and financial consequences for the farmers involved (Aigbedion-Atalor et al. 2019). These costs are likely to have been reported by survey respondents, as the broad-scale impact being experienced by farmers were widely reported in the media and through agricultural websites, but there is limited reporting of these costs in the literature so far (Rwomushana et al. 2019).

There is a possibility that survey respondents gave information on the species they work on and unintentionally overestimated the loss in the absence of rigorous data. Perception data is unlikely to be as accurate as field measurements, but we have no reason to believe that higher estimates following inclusion of survey results as basis for the calculations were due to systematic overestimation. We assessed this by comparing loss and abundance data obtained from literature and the survey for *P. absoluta* and *S. frugiperda*. While it is true that the loss estimates were higher in the survey results for *S. frugiperda* (0.54 ± 0.10 vs. 0.27 ± 0.05; mean ± SE per country), there was also more variation that allowed us to generate low, mid and high estimates, which was in most cases absent from the literature. Moreover, the estimates for abundance of the pest were much lower and more differentiated than what could be deducted from the literature (0.63 ± 0.10 vs. 1.00 ± 0.00). A similar pattern was found for *P. absoluta*: the loss estimates were higher in the survey results (0.66 ± 0.09 vs. 0.49 ± 0.05), and the estimates for abundance of the pest were much lower and more differentiated than in the literature (0.54 ± 0.10 vs. 1.00 ± 0.00). However, when loss was calculated based on these values (loss caused * abundance), we found no such obvious difference between literature and survey results (for example: in *S. frugiperda* 0.27 ± 0.05 vs. 0.32 ± 0.08; in *P. absoluta*: 0.49 ± 0.05 vs. 0.41 ± 0.10). Thus, the difference in the estimates (Table 5) came from the extrapolation, where values for loss for data deficient countries were adopted from countries with the most similar agro-ecological zones. When survey results were included, the extrapolation was based on more countries than the small sample for which only literature data were available (for *S. frugiperda*: four vs 12 countries, for *P. absoluta*: three vs. seven countries). Hence, the higher estimated costs when survey data were used appear to be the result of the more robust data obtained by conducting the survey, which clearly increased the number of countries for which data are available and increased detail, and not due to a difference in survey and literature data.

Extrapolation to agro-ecological zones

There were considerable gaps in the data to enable estimations of costs for all countries on the continent, which were addressed by extrapolating data based on AEZ, climate modelling and land use. Climate and environmental suitability modelling and crop cover were used by Day et al. (2017) and Early et al. (2018) following the arrival of *S. frugiperda* in Africa to predict areas of suitability and potential distribution of the moth. These models were further used to estimate potential economic costs of *S. frugiperda* to maize farmers. The approach was also used by Rwomushana et al. (2019) to extrapolate the calculated costs of *P. absoluta* from Zambia and Kenya to 10 other African countries with similar AEZs. The estimation of reduction in livestock derived income, was also guided by climatic modelling. Adoption of a modelling approach enabled prediction of economic costs rather than leaving gaps in the data that would lead to an underestimation of the costs of IAS.

Ecosystem services and other non-monetary costs

The impacts of IAS on ecosystem services and biodiversity are significant with varying estimates, although the total costs can be in of tens of billions of USD according to Pimentel et al. (2005). Despite the seeming importance of IAS, few studies have sought to estimate the impact of invasive species on the delivery of holistic ecosystem services in Africa. The few studies that have been done have either focused on a single ecosystem service such as surface water supplies (Le Maitre et al. 2000), or a single species like black wattle (*Acacia mearnsii* De Wild.) (De Wit et al. 2001) or *P. juliflora* (Shiferaw et al. 2019). Other studies have identified the effect of IAS on ecosystem services (Sutton et al. 2016; Van Wilgen et al. 2008), but have not monetized the costs of these reductions in ecosystem services, though it is apparent there are costs due to, for example, a reduction in livestock carrying capacity. Kashe et al. (2020) analysed the effects of *P. juliflora* and *Salvinia molesta* on ecosystem services in Botswana, noting the negative welfare effects on those providing tourism services, and riparian communities. They stated the need to monetize these negative effects. However, it is notoriously hard to monetize ecosystem service effects, and therefore we used the SEICAT and EICAT (Bacher et al. 2018; Hawkins et al. 2015) methods to provide an indication of the effects of IAS on ecosystem services. The overall lower average scores for the societal impact as compared to the ecological impact of IAS suggest that, even with the use of methods that focus on changes in people's activities, there is still a lack of realisation of the long-term societal consequences caused by IAS, and a disconnection between the direct effects of IAS and their wider ecosystem effects on people's livelihoods. Unfortunately, it is impossible to make inferences about the conditions or causes that affect the non-monetary impacts of IAS based on the survey results. Hence, the perceptions about non-monetary costs that we report provide valuable data on the level of societal or ecological impacts that are experienced and should be included in any future studies of the economic costs of IAS.

Research costs

Research costs are a negligible part of the total cost estimate. This is a consequence of the small number of survey respondents who provided information about research expenditure, and the small figure likely reflects the generally low level of research into IAS across the continent, apart from in South Africa, as evidenced by the low level of articles in peer-reviewed journals and grey literature (Diagne et al. 2021). The estimated USD1.9 Mn is a small amount compared to the €132 Mn spent on IAS research by the European Union between 1995 and 2010 (USD 10.7 Mn per annum) (Scalera 2010). The reasons for this difference include the limited research capacity and the lack of financial resources. Another reason could be a lack of awareness of the effects and costs that IAS have, and therefore there is little pressure to allocate scarce resources to this field of research. This is in line with the findings of García-Llorente et al. (2011) who stated that willingness to pay for management of IAS was influenced by knowledge and perception of IAS, as well as an individual's interest in nature and socio-demographic characteristics. The estimates of country costs presented here may help to change perceptions and increase the focus on IAS and the need to provide additional funding for research to reduce the costs of these species to each country's GDP.

Conclusions

The substantial cost of IAS revealed by our study, even if incomplete, highlights the need to develop and implement management that is effective against the targeted species, safe for the environment and people, and adapted to the local circumstances. The results reveal comparatively small investments in research on IAS. Yet, measures are needed that prevent new species from arriving and established species from spreading, and that reduce management costs for widely present and impactful species through methods such as biocontrol. The knowledge of how much IAS cost African countries provides policy makers with the evidence needed to enable prioritisation of management measures for IAS, thereby reducing costs in the long term. We recommend that benefit:cost analyses are undertaken to guide the limited available resources to research into and implementation of management options that most effectively mitigate the impacts of IAS. In addition, our study provides evidence of the need for country and regional quarantine and phytosanitary measures to prevent the entry and spread of new IAS, preventing additional, potentially huge costs as new IAS spread across the continent.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-021-00038-7.

Additional file 1. The questionnaire survey used to collect information about monetary and non-monetary costs of invasive alien species in Africa.

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Authors' contributions
The authors designed the study together and all contributed to data collection. RE, BT and FW led the writing of the manuscript with critical input of all authors.

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Availability of data and materials
The datasets supporting the conclusions of this article are available from https://doi.org/10.34857/0069674.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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