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Economic impacts of invasive alien species on African smallholder livelihoods

Corin F. Pratt*, Kate L. Constantine, Sean T. Murphy

CABI, Bakeham Lane, Egham, Surrey TW20 9TY, UK

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ABSTRACT

In developing countries, invasive alien species (IAS) threaten smallholder farmer production and the food security of subsistence growers, but economic impacts are widely under-reported. Here, the economic impacts of IAS that threaten smallholder mixed maize farming in eastern Africa are presented. Maize is important for most smallholders and is commonly grown with horticultural crops and other cereals which collectively provide nutrition and income. These crops are also important for national economies. Estimates of the economic impacts of five major IAS: *Chilo partellus*, Maize Lethal Necrosis Disease, *Parthenium hysterophorus*, *Liriomyza* spp. and *Tuta absoluta* on mixed maize smallholders in six countries gave current combined annual losses of US$0.9–1.1 billion; and future annual losses (next 5–10 years) of US$1.0–1.2 billion.

1. Introduction

The diverse and vast scale of the negative impacts of many invasive alien species (IAS), namely a non-native organism causing economic or environmental harm or negatively affecting health (summarised from CBD, 2009), is increasingly well documented (Jackson, 2015; Mack et al., 2000; Nghiem et al., 2013; Pimentel, 2011). These species have largely become a global problem because of the accelerating rate of trade and transport, particularly since the end of the 20th century (Essl et al., 2011; Marini et al., 2011) and these factors are likely to drive further biological invasions (Levine and D'Antonio, 2003). Human enterprises and critical resources are affected, including trade, crop and livestock production, pastureland, forests, natural resources and biodiversity; as well as human and animal health (Mack et al., 2000; Mooney et al., 2005).

Despite the increasing knowledge of IAS impacts, most of the information to date is from studies of high-income countries with relatively little data available for developing countries (Nghiem et al., 2013; Peh, 2010). However, developing countries are particularly vulnerable to IAS impacts because the majority of people living in these countries are smallholders (land holdings of 2 ha or less) (Wiggins et al., 2010) and are almost totally dependent on agriculture and natural resources for their survival (Nghiem et al., 2013; Perrings, 2007; Wiggins et al., 2010), with IAS posing additional threats to nutrition and food security (Early et al., 2016). Smallholders typically grow a mixture of subsistence and cash crops and in some regions, households also harvest natural resources such as grasses and shrubs for animal fodder (Rai et al., 2012). In many developing regions, most crop production is by smallholders; small farms represent 80% of all farms in Sub-Saharan Africa (SSA) (approximately 33 million small farms) and in some countries contribute over 90% of national production (Livingston et al., 2011; Wiggins, 2009). Furthermore, almost 70% of the world's poor reside in rural areas (World Bank, 2015), with poverty now exacerbated by IAS which can affect many of the crops that they grow (Perrings, 2007).

An important dimension of impact, critical for policy and prioritization of actions, particularly for developing countries with limited resources, is that of economic costs associated with IAS. However, a major point arising from the unprecedented spread of IAS is that rural communities now face many IAS and yet the published studies to date on impacts on agriculture in developing countries are largely focussed on individual IAS; in addition, these studies relate more to impacts on yield rather than economic loss (Nghiem et al., 2013). Some authors have attempted to quantify IAS economic losses at a national or regional level but the studies are broad scale and mask the specific impacts on rural communities (e.g. Pimentel, 2011). Thus there is an urgent need to begin to address this gap in knowledge. One approach is to estimate economic impacts from existing published information detailing smallholder crop areas, production, values and distribution and yield losses from IAS in affected areas.

Here, a study is presented on the estimation of the economic losses caused by a representative group of damaging IAS that are currently known to be affecting smallholder agricultural production in mixed maize farming systems in six countries in eastern Africa: Ethiopia,

* Corresponding author.
E-mail address: c.pratt@cabi.org (C.F. Pratt).

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Kenya, Malawi, Rwanda, Tanzania and Uganda. The mixed maize farming system is chosen because it is one of the most common agricultural systems in SSA, particularly in the eastern region (Garrity et al., 2012). Maize (*Zea mays*) is frequently grown with several other crops by smallholders, and in particular, farmers may grow horticultural crops to provide nutrition and as cash crops to provide income (Maertens et al., 2012). Many IAS, across a diverse range of taxa, are present in the eastern African region and are having detrimental impacts on agriculture, and pose a major threat to smallholder farms in mixed maize farming systems (Nyambo et al., 2011; Perrings, 2005; UNEP, 2006). Five IAS that affect pre-harvest production are included in the study: three insects, one pathogen and a plant. These species were selected because they are spreading in the region – rapidly in some cases – causing serious damage to crops and were considered to be representative of the collective IAS problems that a typical maize farmer now faces in a growing season.

National economic loss figures are derived to illustrate the magnitude of the impacts on mixed maize smallholder production, but a case study of each of the IAS included is presented in the Supplementary information to provide specific distribution and impact information for each species. The estimates are for the current time and are based upon the latest available distribution data for the five species, with extrapolation where data is lacking. Estimates of the economic impacts for the 5–10 years following this, based on current rates of spread, are also included. This type of projection is rarely included in economic impact studies (Born et al., 2005), but is valuable for assessment of future risks. IAS management approaches were found to be highly variable and poorly reported with costs rarely quantified and as such were excluded from the main study, however, weeding of crop fields was universal in the study area and a representative example of the costs of weeding an IAS is given for *Parthenium hysterophorus*. In addition, the use of classical biological control to manage IAS is an approach that can benefit smallholders on a large scale, offering yield savings without direct costs to farmers. As an example, biological control savings in maize brought about by the release of the parasitoid *Cotesia flavipes* against the spotted stem borer, *Chilo partellus* were calculated.

1.1. The study farming system and the major invasive alien species

Maize is the most important staple crop for smallholder families in many countries in eastern Africa, and may also be sold in markets by these families to generate extra income (Salami et al., 2010; Smale et al., 2011). An estimated 22 million households rely on this crop across the six selected countries alone, with annual production exceeding 24.5 million tonnes in 2014 (FAO, 2015; plus see Table A in Supplementary information for production data). Mixed maize covers 10% of the land area of SSA and has a vast agricultural population estimated at 60 million (Livingston et al., 2011). The mixed maize farming system has high potential to contribute to food security and rural growth, but has more poverty than any other farming system in Africa (Garrity et al., 2012).

Other crops grown with maize include the common bean (='dry') (*Phaseolus vulgaris*) which is an essential subsistence crop and source of protein, important when there is a seasonally variable food supply, particularly for the poor, for whom it plays a strategic role in poverty alleviation (Katungi et al., 2009). However, many smallholders are now supplementing their incomes by engaging in broader horticultural activities where fruit and vegetables are grown for both domestic and export markets (English et al., 2004). These crops include pea (*Pisum sativum*) and French bean (a cultivar of the common bean and also known as green beans), both of which are high value, and tomato (*Solanum lycopersicum*) which is commonly traded on local markets.

The IAS assessed on maize were: *Chilo partellus*, the spotted stem borer, Maize Lethal Necrosis Disease (MLND) and *Parthenium hysterophorus*, parthenium. The IAS assessed on horticultural crops were: *Liriomyza* spp., vegetable leafminers on dry beans/peas as subsistence crops and green beans/peas as horticultural crops, and *Tuta absoluta*, the South American tomato leaf miner on tomatoes. Some key information on these species is included in Table 1 is no longer below, with full case studies provided in the Supplementary infromation. Images of the IAS can be found on the Invasive Species Compendium (www.cabi.org/isc).

2. Methods

Current economic impacts were estimated from published data on the present ranges and yield losses caused by the five species (see Supplementary information for further details) and from data on average crop production and farm gate prices taken from published sources and major databases for the period 2009–2013; after this period key datasets become incomplete (FAO, 2015). Projected economic impacts were also estimated for a 5–10 year period following 2016 to account for likely range expansions for each of the five species. For some of the species, expansion and economic impact into new countries where they are not currently recorded as present were also considered (see case studies in Supplementary information).

Economic impacts were estimated using the following relation:

$$YL_C = p_{IAS} \cdot p_{SH} \cdot yl_{IAS} \cdot P_C \cdot V_C$$

where $\boldsymbol{YL_C}$ is the annual economic value of smallholder yield losses in crop C to an IAS; $\boldsymbol{p_{IAS}}$ is the proportion of national crop production affected by an IAS; $\boldsymbol{p_{SH}}$ is the proportion of crop production affected by an IAS that is grown by smallholders; $\boldsymbol{yl_{IAS}}$ is the proportion of yield lost to an IAS in affected production areas; $\boldsymbol{P_C}$ is gross (pre loss to an IAS) national average annual production of crop C (tonnes); and $\boldsymbol{V_C}$ is the average value of crop C (US$ per tonne).

The major databases used for crop production and prices included FAOSTAT, the World Bank and Famine Early Warning Systems Network (FEWS NET). Where producer prices were absent from the FAOSTAT database, estimates were provided by the Prices Group, FAO Statistics Division.

For yield loss estimates, the need was to derive a typical representative level of loss that would occur as a result of the impact of each of the IAS across a country and year by year. However, for the IAS included in the study, reported yield losses tend to range from very low to very high values with fluctuations by season, area and year; this is generally a feature of many major IAS. Thus to achieve a representative estimate, first peer-reviewed data sources on yield loss for each IAS were prioritised to reduce bias from un-validated and extreme outlying data sources. Second, to illustrate the inherent variation that does occur in yield loss data, the most frequent values of yield loss in the data set were used, to generate a range with upper and lower bound figures. The values of these figures provide the typical range of losses and are used in this study to estimate "lower" and "upper" loss values for each of the IAS included.

The costs of weeding *P. hysterophorus* in maize were calculated by estimating the amount of time spent by smallholders carrying out this task at a standard labour rate per country. Biological control savings in maize brought about by the release of the parasitoid *C. flavipes* against *C. partellus* were calculated by comparing pre- and post-release yield loss estimates (please see Supplementary information for further details).

Where data were lacking for a country or region, extrapolations were made from published information from comparable regions; details are provided in the case studies (see Supplementary information). The estimated smallholder economic crop losses were also assessed in relation to the national agricultural gross domestic product (GDP) for each of the affected countries; GDP figures were obtained from the World Bank website (World Bank, 2016a, 2016b).

Table 1
Damage caused, main crops affected, distribution and future risk of focus IAS.

Invasive alien species	Key crops affected and damage caused by IAS	Presence in focus countries and agroecological zones affected	Future risk
Chilo partellus, spotted stem borer	Maize and sorghum. Larval leaf tissue feeding followed by growing point and stem tunnelling. Can result in plant stunting, grain weight reduction and dead heart.	Ethiopia, Kenya, Malawi, Tanzania, Uganda (from mid-twentieth century). Warm, drier, lower altitude regions (< 1500 m.a.s.l.) most at risk. Increases in altitudinal range observed in parts of eastern and southern Africa (> 2000 m.a.s.l. in some instances).	*C. partellus* likely to be the most significant borer threat in the preferred altitudinal range of the pest. Ongoing risk, but biological control providing significant yield savings. Climate change may result in higher altitude, valuable maize regions being threatened by *C. partellus*.
Maize Lethal Necrosis Disease, MLND	Maize. Disease causes maize ears to be small, deformed and set little or no seed with infected plants frequently barren. Results in high losses, up to total crop loss (De Groote et al., 2016).	Reported present in Ethiopia, Kenya, Rwanda, Tanzania, Uganda (relatively new arrival in eastern Africa i.e. 2011 in Kenya). Spreading quite rapidly in eastern Africa. Not restricted by altitude and potential to affect all maize growing regions (Gitonga and Snipes, 2014).	MLND is one of the most damaging new IAS in eastern Africa. Still spreading and reported high level losses which can result in complete crop loss.
Parthenium hysterophorus, parthenium	Various crops and pastureland (focus here on maize). Reduces crop yields and prevents germination through allelopathy and resource competition. Plant is toxic to cattle and has allergenic human and animal health impacts.	Well established in Ethiopia (mid-1970s) and Kenya (1973); established in Tanzania (2010) and Uganda (2008). Recent observations in Rwanda and Malawi (Arne Witt, pers. comm.). Spreading into important maize growing areas, with broadly overlapping ecological requirements.	Large areas of eastern Africa not currently affected by parthenium are favourable for the plant (McConnachie et al., 2011) with significant ecoclimatic overlap with major maize producing regions at low, mid and high altitudes.
Liriomyza spp., L. trifolii, L. huidobrensis *and L. sativae*, *Liriomyza* leaf miners	Attack a variety of crops of commercial value primarily in the Solanaceae, Fabaceae and Asteraceae. The larvae mine leaves, reducing plant productivity and plant growth. Mining damage reduces the value of the products or renders them unmarketable. In Kenya *L. trifolii* had significant impact on ornamentals and vegetables with heavy infestations resulting in many flower farm closures, job losses and loss of export opportunities (Foba et al., 2015).	Kenya (*L. trifolii* 1976; *L. huidobrensis*, found widespread in 2015), Tanzania (*L. trifolii*, *L. huidobrensis*, 2012) and Uganda (*L. sativae* dominant, *L. huidobrensis* restricted to higher altitudes). Highly probable *Liriomyza* presence in Rwanda. Initially occupied preferential altitudinal zones (*L. sativae* lowland; *L. trifolii* low-midland, *L. huidobrensis* highland), but now *L. huidobrensis*, the most aggressive of the three species, is displacing the other species at mid to low altitudes in Kenya (Foba et al., 2015).	Climate change in central, eastern and southern regions of Africa is likely to facilitate the range expansion of *L. huidobrensis* and *L. sativae* over the coming decades (Kroschel et al., 2015). The horticultural sector is at high risk.
Tuta absoluta, South American tomato leaf miner	Tomato and other Solanaceae. Larvae feed and develop inside the leaves, stem and fruit of tomatoes; photosynthetic ability reduced and susceptibility to secondary infection increased. Can cause total losses to important co-staple and high market value tomato crop.	Present in Ethiopia (2012/13), Kenya (2014), Tanzania (2015) and Uganda (2014). Invaded Africa relatively recently, currently spreading rapidly and threatening much of the continent (Pfeiffer et al., 2013). Tomato is grown widely across eastern Africa; *T. asboluta* does not appear to be affected by altitude.	The continued spread of *T. absoluta* is highly likely based on experience to date, with climatic suitability indices predicting high probability for continued invasion across SSA, with western, central and eastern areas favourable (Tonnang et al., 2015).

3. Results

3.1. Invasive alien species impact on smallholder farmer agricultural production

The economic losses to each crop by each IAS are variable but two of those on maize, *C. partellus* and MLND are currently contributing 72% of the total losses from all five IAS across the six countries (Table 2).

The estimated current annual economic losses to mixed maize smallholders caused by the five IAS range from close to US$0.9 to almost 1.1 billion, equating to between 1.8% and 2.2% of total agricultural GDP for the region (Table 3). Maize losses to *C. partellus* would be higher still without the parasitoid *Cotesia flavipes*, released as a biocontrol against this stem borer. Reductions in maize yield losses attributable to *C. flavipes* are estimated to have a combined annual value of $165.0–205.1 million to smallholders in the affected countries, with 10 year future savings worth $304.7–371.9 million.

From the estimates, Kenya and Ethiopia are experiencing the highest total national losses (IAS combined) but the totals are dependent on a number of factors; two of the most important are the area of a crop grown and the extent of invasion of each IAS. These influences can be removed by estimating the losses per unit tonne production for all the species affecting each crop in each country (Table 4). This shows that Uganda and Kenya, followed by Ethiopia have the highest losses to maize; and Kenya, the highest losses to both horticultural crops.

Assuming the continued range expansion of these highly invasive species based on published distribution data and trends in spread, estimates for the 5–10 year period following 2016 put the annual monetary losses at close to US$1.0 to 1.2 billion (Table 5). These figures do not include invasion of countries in which IAS were not reported as present in the published literature at the time of publication, but these countries may also be at risk.

4. Discussion

The quantification of impacts of IAS is a critical step towards the goal of reducing the negative consequences of invasions on natural and managed ecosystems (Pimentel, 2011). The lack of economic valuation of the costs and benefits of IAS control presents a significant barrier to the uptake of effective IAS prevention and management in countries; such data would provide essential support to instigate policy level action, although it is acknowledged that it is not always easy to

Table 2
Current average annual economic losses to smallholder agricultural production from individual IAS (per country and in total).

Invasive alien species	Crop	Eastern African country where IAS currently recorded as present	Estimated current annual production losses to smallholders (million US$)[a]	
			Lower estimate	*Upper estimate*
Chilo partellus, spotted stem borer	Maize	Ethiopia	61.3	73.2
		Kenya	42.8	51.0
		Malawi	104.3	139.1
		Tanzania	30.0	42.4
		Uganda	118.6	144.3
			357.0	450.0
Maize Lethal Necrosis Disease (MLND)	Maize	Ethiopia	131.2	152.5
		Kenya	123.6	144.6
		Rwanda	2.7	3.2
		Tanzania	19.9	22.8
		Uganda	13.8	16.1
			291.2	339.3
Parthenium hysterophorus, Parthenium	Maize	Ethiopia	46.6	71.4
		Kenya	3.8	7.7
		Tanzania	0.3	1.0
		Uganda	0.7	1.8
			51.4	81.9
Liriomyza spp., leaf-mining flies	Bean and pea (dry/ green)	Kenya	54.0	64.5
		Tanzania	49.8	59.3
		Uganda	21.3	25.3
			125.2	149.1
Tuta absoluta, tomato leaf-miner	Tomato	Ethiopia	2.6	2.9
		Kenya	45.9	52.4
		Tanzania	20.4	23.2
		Uganda	0.7	0.8
			69.6	79.4
Cumulative losses:			894.4	1099.7

[a] Adjusted to gross production pre-losses.

Table 3
Total current average annual economic losses to smallholder agricultural production from five IAS and estimated proportion of agricultural GDP[a] lost due to these IAS.

Country	Estimated total annual economic losses to smallholder production from five major IAS (million US$)		Estimated proportion of agricultural GDP lost to five major IAS	
	Lower estimate	*Upper estimate*	*Lower estimate (%)*	*Upper estimate (%)*
Ethiopia	241.7	300.1	1.41	1.75
Kenya	270.1	320.2	2.11	2.50
Malawi	104.3	139.1	6.95	9.27
Rwanda	2.7	3.2	0.13	0.15
Tanzania	120.4	148.8	1.04	1.29
Uganda	155.1	188.3	2.63	3.20
Total losses	894.4	1099.7	1.76	2.16

[a] Gross domestic product.

Table 4
Current average annual losses (US$) per unit tonne smallholder gross production of mixed maize crops from IAS.

Country	Crop US$ lost per unit tonne of crop					
	Maize IAS		Green and dry pea/ bean IAS		Tomato IAS	
	Lower estimate	*Upper estimate*	*Lower estimate*	*Upper estimate*	*Lower estimate*	*Upper estimate*
Ethiopia	43.32	53.82	–	–	50.6	58.80
Kenya	51.11	61.24	77.15	92.15	97.72	111.47
Malawi	29.05	38.74	–	–	–	–
Rwanda	5.46	6.38	–	–	–	–
Tanzania	10.99	14.49	48.35	57.61	59.88	68.29
Uganda	52.19	63.62	32.85	38.91	23.67	26.67

Table 5
Predicted annual economic losses under continued range expansion of five IAS in eastern Africa (5–10 year timescale) (per country and in total).

Invasive alien species	Crop	Eastern African country where IAS currently recorded as present	Estimated future annual production losses to smallholders (million US$)[a]	
			Lower estimate	*Upper estimate*
Chilo partellus, spotted stem borer[b]	Maize	Ethiopia	47.9	56.6
		Kenya	34.4	40.6
		Malawi	82.5	106.1
		Tanzania	26.5	37.1
		Uganda	92.1	108.8
			283.4	349.3
Maize Lethal Necrosis Disease (MLND)	Maize	Ethiopia	154.4	176.4
		Kenya	140.7	160.8
		Rwanda	5.1	6.0
		Tanzania	39.9	45.6
		Uganda	24.9	29.0
			365.0	417.8
Parthenium hysterophorus, parthenium	Maize	Ethiopia	106.0	141.3
		Kenya	19.1	28.7
		Tanzania	5.6	11.2
		Uganda	8.7	14.1
			139.4	195.3
Liriomyza spp., leaf-mining flies	Bean and pea (dry/ green)	Kenya	61.5	71.7
		Tanzania	57.1	66.6
		Uganda	25.1	29.3
			143.7	167.5
Tuta absoluta, tomato leaf-miner	Tomato	Ethiopia	3.4	3.8
		Kenya	59.8	66.5
		Tanzania	26.5	29.5
		Uganda	1.2	1.3
			91.0	101.1
Cumulative total losses:			$1022.3	$1231.0

[a] Adjusted to gross production pre-losses.
[b] Note: for *C. partellus* the values have reduced from current estimates (Table 2) due to biological control (see case study in Supplementary material for detail).

determine (Mwebaze et al., 2010; Wise et al., 2007). Currently, the movement – frequently due to increased trade and travel (Early et al., 2016; Essl et al., 2011; Hulme, 2009) – and influx of IAS goes unabated in many parts of the world, highlighting the need to enhance the implementation of comprehensive management interventions at national and international levels. Developing countries are disproportionately more vulnerable to biological invasions; this is particularly the case in the SSA region (Early et al., 2016; Paini et al., 2016), with increased IAS prevalence potentially intensifying smallholder dependence on pesticides, with associated health and environmental implications. Trade in high value crops is furthermore promoted as a route out of poverty, however, increases in international trade have exacerbated IAS spread, with frequency of introduction correlated with probability of IAS establishment (Hulme, 2009). Over time, trade between developing countries has increased, opening up new South-South trading opportunities, which in the context of IAS, connect bioclimatically similar ecosystems between which IAS can easily spread and become established (Perrings, 2005). Indeed, since international trade is recognised as a significant driver of biological invasions, consideration of geographic trade flows and bioclimatic similarity can contribute to development of models identifying areas at greater risk, with important policy implications for more effective, targeted IAS prevention and control (Dalmazzone and Giaccaria, 2014).

With the availability of resources to tackle IAS likely related to a country's GDP, the risk of establishment and spread of IAS could be expected to be significantly higher in poorer countries (Perrings, 2005). This outlook is supported by Early et al. (2016), who describe the current and increasing threat IAS pose to livelihoods in developing countries, particularly in Africa and the eastern hemisphere.

The estimates here of the scale of the current losses to smallholder production from five representative IAS signify a real threat to food security in the region. A summation of the estimated current average annual monetary losses to mixed maize smallholders ranges from close to US$0.9 to almost 1.1 billion, equating to between 1.8% and 2.2% of total agricultural GDP for the six countries in the region. Assuming current rates of spread of these highly invasive species over the next 5–10 years, the annual monetary losses could rise to between US$1.0 and 1.2 billion. These figures confirm the threat of IAS to food security in the region is real and growing. Although quantified in economic terms here, for subsistence farmers the yield losses to IAS directly increase the risks of malnutrition and hunger and it is important to view the losses in the context of these far-reaching impacts.

By using the most frequent yield loss values and excluding widely outlying data to give a focused range to generate the typical level of national losses suffered annually to a given IAS, extreme levels of loss are omitted. From the literature it is clear, however, that losses to IAS may vary significantly over years and by region. Most IAS are patchy in distribution resulting in some smallholders suffering up to total losses from any one IAS, putting intense pressure on income and food security, while other farmers, in different areas, may experience only minor damage. In this study, a complex of IAS impacts has been assessed at the farm level and losses may well not be additive as a crop may be lost to just one IAS. For example, in maize, dense infestations of parthenium can eventually lead to land abandonment, with huge socioeconomic ramifications (Fessehaie et al., 2005); and *T. absoluta* may eliminate an entire tomato crop, grown at expense and intended for sale and a small profit at market.

Horticulture is important for smallholders but the sector is particularly badly affected by IAS. For instance tomatoes can be grown year round, and aside from use in the home, can be sold on local domestic markets for a high price; tomatoes are seen as a very promising area for horticultural expansion but the sector across Africa is currently experiencing significant impacts from *T. absoluta* which puts the future of this crop in jeopardy (Gioe, 2006; Tefera and Tefera, 2013; Tonnang et al., 2015). Losses of up to 80% of the total harvest reportedly led to a three-fold increase in tomato prices in Tanzania in 2016 (Russell IPM, 2016). The same is apparent for highly lucrative fresh green bean and pea markets and the impacts of *Liriomyza* spp. EPPO regularly reports interceptions of infested produce destined for the European Union (EPPO, 2015) which can result in rejection of shipments and a cost to the farmer (Gitonga et al., 2010). Many news articles promote growing sugar snap and snow peas due to the suitability of climatic conditions and potential income benefits, but again the future of this market is threatened.

Parthenium infestations can result in livelihood impacts beyond smallholder crop yield losses, with school age children, for example, spending days weeding and missing key periods of education, limiting future prospects. In addition, extended exposure to this allergenic weed can cause skin and respiratory problems. These types of impact may be difficult to quantify economically, but cannot be ignored if the true costs of IAS are to be understood. Estimates (CABI, unpublished) of the current value of time invested by smallholders in weeding parthenium at a basic labour rate calculated for each affected study country give annual figures of US$0.2 million in Uganda; US$0.3 million in Tanzania; US$1.5 million in Kenya; and US$16.8 million in Ethiopia.

Pesticides are used by some smallholders, but the extent of use across the countries is very varied. Insecticides can be used against *C. partellus* and other stem borer species, however application can be challenging and this method is often prohibitively costly for resource-poor smallholders (Kalule et al., 2006), with the potential to harm natural enemies (Chinwada et al., 2001). The situation is similar for *Liriomyza* species and *Tuta absoluta*. Parthenium is susceptible to certain herbicides (Amare et al., 2015; Goodall et al., 2010), but the vast majority of smallholders growing maize lack the finance and equipment required for herbicide application (McConnachie et al., 2011; Tamado and Milberg, 2000), which must be carried out repeatedly for persistent control (Goodall et al., 2010). Any yield savings achieved through herbicide use would be countered to a degree by the cost of herbicides and equipment, with this approach better suited to large scale farming (Wise et al., 2007).

Data gaps in the published literature and the need for extrapolation in some cases led to a relatively conservative approach being adopted in the estimation of the economic impacts of the five IAS. Add to these figures losses from other IAS on the same and other staple and high value crops, livestock and pastoral costs, and costs for IAS management, and the true impact of IAS in eastern Africa is certain to be significantly higher. Invasive alien species also have impacts on important ecosystem services, exerting an ‘invisible tax’ with environmental and economic implications, and other costs difficult to account for in monetary terms (Pejchar and Mooney, 2009; Wise et al., 2007). These IAS threats are additional to those faced by farmers from damaging indigenous crop and livestock pests such as the maize stalk borer, *Busseola fusca*, the parasitic witchweeds, *Striga* spp., and diseases such as trypanosomiasis spread primarily by tstse flies, *Glossina* spp.

It is likely that changing and unpredictable climatic conditions will further challenge crop production and food security in Africa (Kroschel et al., 2015; Tonnang et al., 2015). Predictions of the distribution of *T. absoluta* under future climatic conditions suggest the species will spread in areas where it already occurs in Africa with a range expansion in tropical Africa and an increased number of generations per year, exerting higher levels of damage and associated yield loss increases (Tonnang et al., 2015). Both *L. huidobrensis* and *L. sativae* are predicted to expand their ranges in Africa with expansion into southern countries (Kroschel et al., 2015). *Chilo partellus* is also predicted to increase in abundance in higher altitude maize growing areas which include key production areas for the crop in eastern and south-eastern Africa (Kroschel et al., 2015).

IAS impacts affect millions of resource-poor smallholders. Against the backdrop of a growing world population, the depletion of natural resources and soil fertility, increasing levels of IAS introductions and likely climate change impacts on crop production and IAS distributions, it is clear that action is needed to improve the outlook for smallholders. At present IAS management approaches are commonly uncoordinated across affected regions and between countries, with unsatisfactory phytosanitary measures, poorly regulated movement of materials for trade, extensive disturbance and pathways of spread, an absence of early detection and rapid response measures to eradicate new infestations and a broad lack of knowledge of IAS impacts and management options. There is an urgent need for collaboration at national, regional and international levels, whereby effective monitoring, early warning and management is prioritised requiring a supportive political environment and the development of a long-term policy on IAS management in Africa (Boy and Witt, 2013; Nyambo et al., 2011). Improved awareness of potential IAS threats and likely pathways of introduction would be of value for the production of proactive management plans; the aim of which would be to control an IAS before it can become widely established and expensive or impossible to contain. The success of this approach would require improved monitoring and a clear chain of responsibility for responding to new IAS incursions. Where multi-national, government-supported approaches to IAS impact mitigation have been attempted, the benefits can be significant as exemplified by the *C. partellus* biocontrol programme which has brought millions of dollars in savings for cereal farmers, most of whom are small-scale subsistence growers (Midingoyi et al., 2016). Furthermore, although *P. hysterophorus* continues to spread in the study area, prospects for its management are enhanced significantly by the multi-agency biocontrol approach now being implemented in eastern and southern Africa (Rich and Izlar, 2015).

Invasive weeds can cause huge losses to agriculture and pastoralism, affecting communal land which can act as a reservoir for IAS. Individual smallholders are unlikely to invest in management of shared public land, but large scale integrated pest management approaches and biocontrol can benefit many and have a higher likelihood of success if implemented than management efforts by individuals. However, these strategies must be supported by consistent and reliable distribution and impact data – including economic assessments as presented here – to better understand the scale of IAS effects and inform how best to focus coordinated national and international responses. A consistent, broad-scale approach to IAS distribution and impact data collection is recommended to inform management techniques and coordination of responses. Economic impact evaluations using this type of data are valuable resources that can compel policymakers to act to limit IAS incursions and spread, thereby reducing negative impacts on livelihoods and the wider environment.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gfs.2017.01.011.

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