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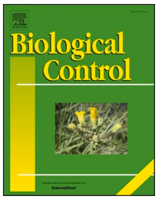

Potential distribution of *Acerophagus papayae*, a parasitoid of the papaya mealybug (*Paracoccus marginatus*), across Africa

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HIGHLIGHTS

- Data for parasitoid biocontrol of *Paraccocus marginatus* in areas at risk of invasion.
- West Africa showed high suitability for both pest and parasitoid.
- Large areas of east and central Africa were suitable for pest but not for parasitoid.
- Annual precipitation and minimum temperatures most affected parasitoid suitability.

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ABSTRACT

The papaya mealybug, *Paracoccus marginatus*, is a highly polyphagous invasive pest that affects at least 133 economically important crops, and causes economic losses worldwide. *Acerophagus papayae* (Noyes and Schauff), a parasitic wasp, has proven to be a successful biocontrol agent, but its use in Africa is limited. Here, we use a predictive correlative model to explore the potential distribution of *A. papayae* and relate it to data showing the potential distribution of *P. marginatus*, to highlight potentially suitable areas for biological control of *P. marginatus*, for its current distribution, as well as its potential future distribution.

The resulting model performed well with a test AUC of 0.89. Areas that were highly suitable for *P. marginatus* and were also suitable for *A. papayae* were highest across West Africa. Whilst there were areas which were suitable for both species in both East Africa and Central Africa, there were large areas of cropping land which were highly suitable for *P. marginatus* although not suitable for *A. papayae*. Across Northern and Southern Africa, there were limited cropping areas which were suitable for *P. marginatus* and where there was suitability, it was only moderate. Across these areas, there was limited suitability for *A. papayae*.

Our results offer refined information on the potential suitability for *A. papayae* across Africa with the aim to help guide decisions on the areas where use of *A. papayae* could be used effectively as a part of an integrated pest management programme against *P. marginatus*.

1. Introduction

The papaya mealybug, *Paracoccus marginatus* Williams & Granara de Willink (Hemiptera: Pseudococcidae, is a polyphagous pest which affects at least 133 economically important crops (Chellappan et al., 2013). *Paracoccus marginatus* feed on the sap of plants, leading to stunted growth, leaf yellowing, fruit deformation, and in severe infestations, plant death. Additionally, the mealybug excretes honeydew, which promotes the growth of sooty mould, further reducing photosynthesis and overall plant health, exacerbating the yield losses. Crop losses due to *P. marginatus* can have severe economic impacts. In Kenya, for example, the estimated papaya yield loss due to papaya mealybug was estimated to be 57 %, with an associated annual economic loss of 3,009 USD per ha at the farm level, and 29.8 million USD at the national level (Kansiime

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et al., 2020). A similar level of losses due to *P. marginatus* have been reported in Bangladesh reaching a loss of USD 700 per ha (Khan et al., 2014Khan et al., 2015) and in Ghana where yield losses of up to 65 % have been reported (Goergen et al., 2011).

Thought to be native to Mexico and Central America, *Paracoccus marginatus*, has spread rapidly and is present over much of Asia (Muniappan et al., 2009). It was first found in Africa in 2009 when it was detected in Ghana (Cham et al., 2011). Since then it has spread further in West Africa into Benin, Togo, Nigeria, Senegal, Mauritania, Burkina Faso, Gabon, Cameroon, and Sierra Leone (Goergen et al., 2011). It has also spread to East Africa into Tanzania (IITA, 2015), Kenya (Macharia et al., 2017), South Sudan (Gama et al., 2020) and Uganda (IPPC, 2022). The pest is also found in Mozambique in Southern Africa (Ahmed et al. 2015). Whilst it has not been officially reported in other African countries, a recent study by Finch et al. (2021) highlighted, based on climatic predictors, the substantial potential for the expansion of *P. marginatus* into other cropping areas in Africa**.** A quarter of the top papaya producing countries are in Africa and in 2021, African countries produced 11 % of the world's total papaya production (FAOSTAT, 2023). Thus, uncontrolled populations, and further expansion of *P. marginatus* into African countries would have significant ramifications to sustainable papaya production.

Traditionally, chemical pesticides are the primary management strategy for control of crop pests. Mealybugs, however, are covered in a waxy coating which significantly impacts the efficacy of traditionally used pesticides such as Cypermethrin or Dimethoate (Meyerdirk et al., 2004; Tanwar et al., 2010). As a result of this reduced efficacy, multiple pesticide applications are required, which can have knock-on effects on human health (Tanwar et al., 2010). Further to this, increased pesticide applications can lead to pesticide resistance, and can adversely affect the natural enemies of the papaya mealybug, resulting in a resurgence and multiplication of papaya mealybug populations (Browning, 1992; Noyes and Schauff, 2003). It can also lead to the accumulation of chemical residue within the crop, affecting the farmer's ability to export them (European Food Safety Authority, 2010). As such, alternative pest control strategies for *P. marginatus* are needed.

One of the most important biocontrol agents for *P. marginatus* is *Acerophagus papayae* Noyes and Schauff (Hymenoptera: Encyrtidae), a parasitic wasp native to Mexico. This parasitoid has been successfully used to control papaya mealybug populations in Guam, Palau, Sri Lanka, Mexico, Puerto Rico, Dominican Republic, India, Sri Lanka (Muthulingam and Vinobaba, 2021) and Florida (Amarasekare et al., 2009). In Africa, this parasitoid has been used successfully in West Africa (Goergen et al., 2011) and most recently, releases along the coast of Kenya suggest its ability to become established in this area, and to effectively reduce populations of *P. marginatus* (Opisa et al., 2024). Further, studies in India have shown the speed at which the release of *A. papayae* can be effective; 5.7 million individuals were released throughout Tamil Nadu, at an estimated density of 250 parasitoids per hectare (Myrick et al., 2014). Within a month, the parasitoids had become established and the *P. marginatus* populations were declining. Five months later, complete suppression of the pest was seen in papaya and mulberry, and 97 % control in cassava was achieved (Kalyanasundaram et al., 2010; Sakthivel, 2013). Other success stories on biocontrol of papaya mealybug have been reported in Sri Lanka (Galanihe et al., 2010). Whilst the initial cost of such a biocontrol programme can be large, the full economic benefits of such programmes are substantial. In India, whilst the biocontrol programme costs USD 200,000 in the first year, with another USD 100,000 being spent in the next three years (Myrick et al., 2014), the net economic benefit of biocontrol of *P. marginatus* with *A. papayae* was estimated to range between USD 524 million to USD 1.34 billion (Myrick et al., 2014). Further, an economic impact analysis on the adoption of classical biocontrol of *P. marginatus* in Ghana showed that, between 2011 and 2013, the intervention yielded an aggregate level total economic surplus of GHS 6.10 million (Roughly, USD 414,342) (Offei et al., 2015).

Given the substantial initial costs for parasitoid release, information on the potential suitability for *A. papayae* across Africa could help guide decisions on the areas where use of *A. papayae* could be used effectively as a part of an integrated pest management programme against *P. marginatus*. This could be utilised not only in areas where the pest is currently found, but also for areas potentially suitable for future invasion. In this study we use a statistical species distribution model to predict climatically suitable locations for *A. papayae* across Africa and overlay these results with previous results showing the potential distribution of *P. marginatus*.

2. Materials and methods

2.1. Current distribution of *Acerophagus papayae*

We collected all available locational information on the distribution of *A. papayae*, from both its native range, as well as it's invaded global range. Data were pooled from several publications (Amarasekare et al., 2012; Ayyamperumal et al., 2018; Geetha et al., 2020; Le et al., 2023; Mastoi et al., 2016; Muniappan et al., 2006; Muthulingam et al., 2021; Sandeep et al., 2016), as well as a minority of unpublished sources. For papers with location information but without coordinate data, we georeferenced the points based on the location names. We cleaned all datasets, removing duplicate points and those that were outside of country boundaries. In total, 360 records for *A. papayae* were collected from 13 different countries. These records were filtered so that there was only one record in each climatic grid-cell (each grid cell had a resolution of 10 arc-minutes). This resulted in a final dataset consisting of 144 records.

2.2. Environmental variables

Based on the life-history and environmental requirements of *A. papayae* (Villanueva-Jimenez et al. 2015), we selected the following climatic variables: maximum temperature of the warmest month; minimum temperature of the coldest month; annual precipitation; precipitation of wettest month.

These variables were downloaded from the WorldClim database v1.4 (Hijmans et al., 2005) at a 10 arc-minute resolution. We checked for collinearity between the variables using a matrix of Pearson's rank correlation coefficients for all possible pairs of variables, however no variable pairs had a collinearity greater than 0.7, which is considered the threshold for collinearity (Dormann et al., 2013). We also conducted a Mantel test with 9999 permutations to test for spatial autocorrelation in the variables (R package: *ecospat*, Di Cola et al. 2017).

2.3. Models and data analyses

We used the Maximum Entropy Species Distribution Model version 3.4.1 (hereafter 'MaxEnt') (Phillips et al., 2006) to model the potential distribution of *A. papayae*. MaxEnt is a machine learning algorithm that compares the environmental conditions at known occurrence points (where the species has been observed) with those at background points (randomly selected locations from the study area where the species' presence or absence is not known). By contrasting these, MaxEnt identifies the environmental conditions that are more likely to be associated with the species' presence, allowing it to predict the species' potential distribution across the landscape. MaxEnt was chosen as it is effective when modelling using presence-only data and is widely used for modelling the potential distribution of invasive species and biocontrol agents (Fischbein et al. 2019; Müller et al. 2019).

Background points for the MaxEnt model were generated within the same Köppen-Geiger climatic zones as the known occurrence points. This ensured that the environmental conditions of the background points were ecologically comparable to those of the species' occurrences, thereby enhancing the accuracy of the distribution predictions.

Cross-validation datasets were partitioned using a spatially explicit block method; occurrence localities were divided into four bins based on the lines of latitude and longitude that divide the occurrences as equally as possible, each model was then run 4 times, with each run using 3 blocks for training and 1 block for testing. This has been shown to be a robust method for estimating the predictive performance of models (Roberts et al., 2017). To optimize model performance, improve generalization and prevent overfitting MaxEnt models were run with various regularisation multipliers (0.5, 1, 1.5, 2, 2.5, 3, 3.5) and feature class combinations (L, LQ, H, LQH, LQHP; where L = linear, Q = quadratic, H = hinge and P = product). For this we used the R package '*ENMeval*' (Kass et al., 2021). We used area under the receiver-operator curve (AUC) to assess the accuracy of the model. AUC scores range from 0 to 1, with a value of 0.5 indicating a model that is no better than random, and a value of 1 indicating a predictive accuracy of 100 % (Elith et al., 2011). We also calculated the 10th percentile omission rate to look for evidence of overfitting.

We applied a maximum training sensitivity plus specificity logistic threshold to the model results to define the potential suitability for *A. papayae*; values derived from the models above that threshold were designated as suitable, while values at or below that threshold were designated as unsuitable. This threshold selection method has been proven to produce consistent results among different datasets (Liu et al., 2016).

2.4. Comparison with suitability for P. marginatus

Spatial information on the suitability of *P. marginatus* was extracted from Finch et al. (2021) and suitability was classified into two categories; moderately suitable areas as designated by an Ecoclimatic Index (EI) 0.1–0.3) and highly suitable areas (EI = 0.3—1) (Sutherst et al., 2018). This was then intersected with our binary model results for *A. papayae* (described above) to highlight which areas suitable to *P. marginatus* were also suitable for *A. papayae* and which were not. We then applied a crop mask so that only areas where suitable crops were grown were included in our analysis. The crop mask included spatial data on cropping areas for a number of economically important crop hosts of *P. marginatus*, including avocado, bean, cashew, cassava, cherry, citrus, cocoa, coconut, cotton, cowpea, eggplant, maize, mango, okra, papaya, pea, pepper, pigeonpea, pineapple, potato, pumpkin, rubber, sunflower, sweet potato and tomato. This data was obtained from EARTHSTAT (Monfreda et al., 2008). This follows the methodology in Finch et al. (2021). Finally, for each country in Africa we calculated the percentages of cropping areas suitable, both moderately and highly, for *P. marginatus* which were suitable and not suitable for *A. papayae*.

3. Results

3.1. Model fit

The MaxEnt model performed well with a mean AUC_{test} value and standard deviation of 0.89 ± 0.006. There was minimal evidence of overfitting with a 10th percentile omission rate of 0.11. The predicted distribution of *A. papayae* was largely affected by annual precipitation and the minimum temperature of the coldest month, with a percentage contribution of 59.8 % and 36.4 %, respectively. Precipitation of wettest month and maximum temperature of warmest month were less important, with a 2.4 % and a 1.3 % contribution, respectively.

3.2. Potential distribution across East Africa

Across East Africa, the percentage of cropland that was highly suitable and suitable for *P. marginatus*, and also suitable for *A. papayae* was 21.8 % and 3.47 %, respectively. These areas were mainly situated along the coastline from southern Somalia, through Kenya and Tanzania to the north of Mozambique, as well as large parts of South Sudan (Fig. 1). Areas that were highly suitable and suitable for *P. marginatus*, yet were unsuitable for *A. papayae*, represented 37.4 and 37.33 % of all cropping areas, respectively. These were mainly situated in the western regions of Uganda, Tanzania and Mozambique (Fig. 1).

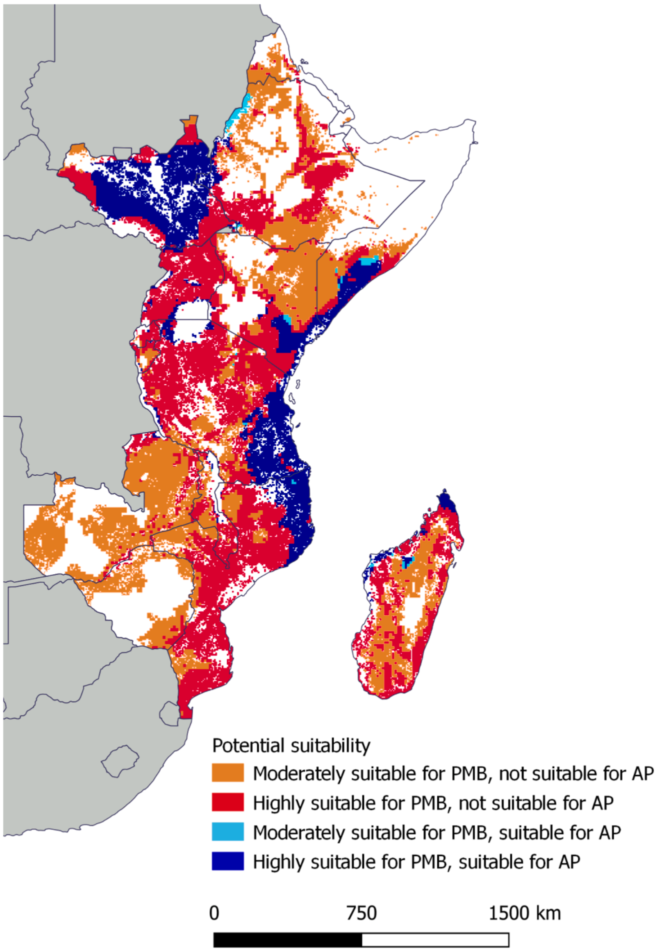

Fig. 1. Modelled climate suitability *Paracoccus marginatus* (PMB) and *Acerophagus papayae* (AP) across cropping areas of Eastern Africa.

Whilst the total cropping area suitable for *P. marginatus* and *A. papayae* was low across East Africa, there was a wide variability between the different countries (Fig. 2). South Sudan and Somalia had the highest alignment of cropping areas that are suitable for both species with 69.1 % and 34.9 %, respectively, whilst Burundi, Ethiopia, Malawi, Rwanda, Malawi, Eritrea, Zambia, Djibouti and Zimbabwe had the lowest alignment, all with under 5 %. When we consider cropping areas which are highly suitable for *P. marginatus* and not suitable for *A. papayae*, Uganda and Rwanda all have the highest percentages with over 85 % (Fig. 2).

3.3. Potential distribution across West Africa

Countries in Western Africa generally had the highest levels of cropland that was suitable for both *P. marginatus* and *A. papayae* (40.1 %). These areas were distributed mainly along the southern coastal countries in West Africa from Nigeria to Côte d'Ivoire (Fig. 3). Across all of West Africa, whilst 59.8 % of cropland was suitable for *P. marginatus* but not suitable for *A. papayae*, only 14.9 % was highly suitable for *P. marginatus*, with the remaining only being moderately suitable.

As aforementioned, countries on the southern coast of West Africa, specifically Ghana, Benin and Togo, had the highest level of alignment between suitability for *P. marginatus* and *A. papayae*, as all had over 90 % of cropping areas suitable, or highly suitable, for both species.

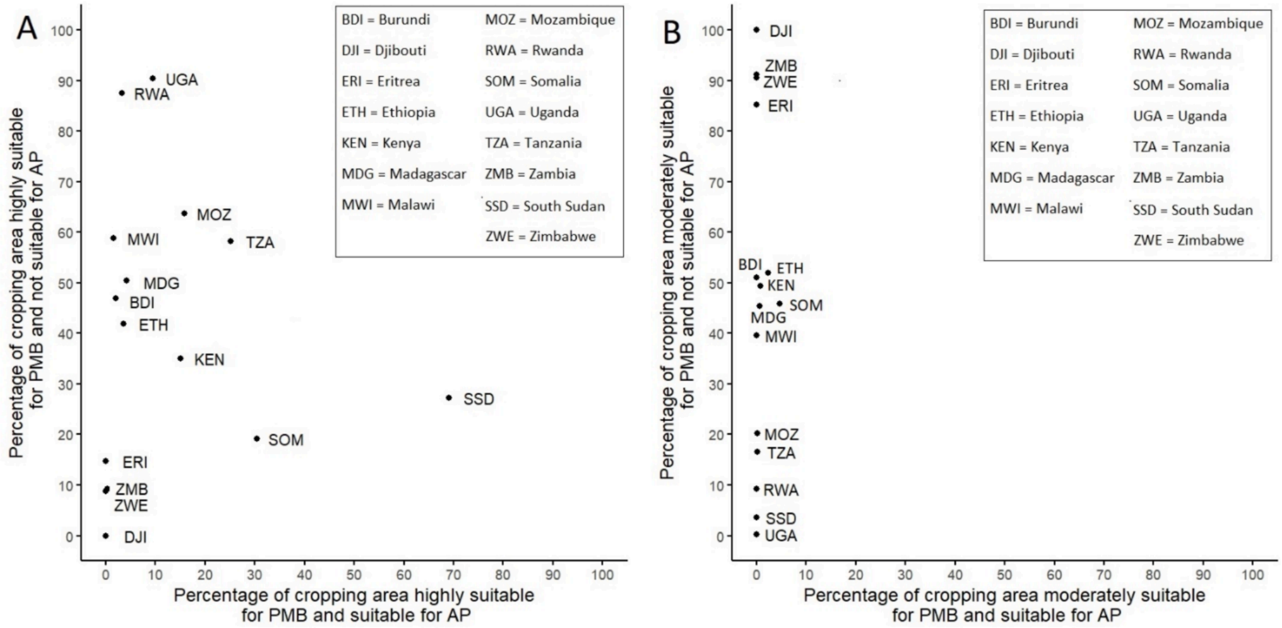

Fig. 2. Percentages of cropping areas in East African countries which were a) highly suitable for *P. marginatus* (PMB) and which were suitable and unsuitable for *A. papayae* (AP) and b) those which were suitable for *P. marginatus* and which were suitable and unsuitable for *A. papayae*.

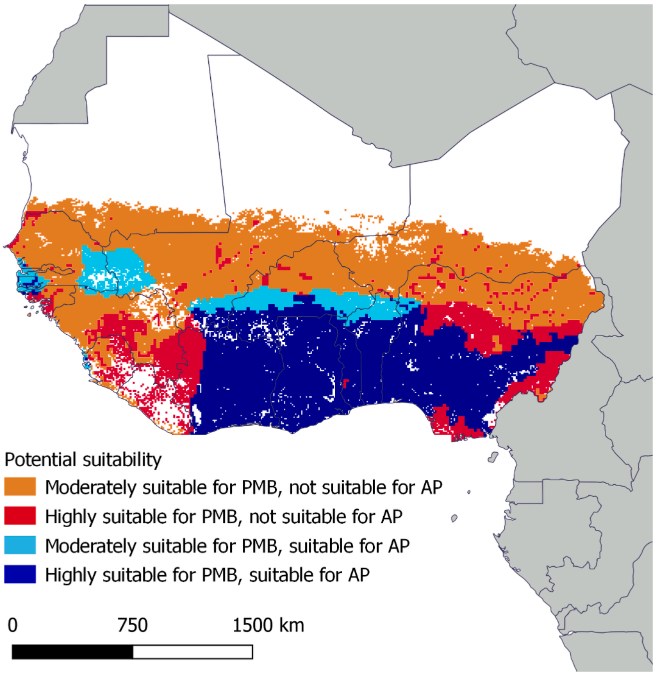

Fig. 3. Modelled climate suitability *Paracoccus marginatus* (PMB) and *Acerophagus papayae* (AP) across cropping areas of West Africa.

Conversely, Guinea, Guinea-Bissau, Liberia, Mauritania, and Sierra Leone all had the lowest alignment in suitability for the two species, with over 90 % of cropping areas in these countries being suitable, for *P. marginatus* yet not for *A. papayae*. Only four countries had over 30 % of their cropping areas modelled as being highly suitable for *P. marginatus* and not suitable for *A. papayae*; Guinea, Guinea Bissau, Sierra Leone and Liberia (Fig. 4).

3.4. Potential distribution across southern Africa

Across Southern Africa, the amount of cropping areas that are suitable, to any degree, for *P. marginatus* was not extensive. What little area there was, was predominately only moderately suitable for *P. marginatus*, and was distributed in the north and north east of the Southern Africa countries (Fig. 5). In these areas, there is no suitability for *A. papayae* (Fig. 6).

3.5. Potential distribution across Central Africa

The percentage of cropland which were suitable for both *P. marginatus* and *A. papayae* was generally relatively low in central African countries (12.6 % across the whole region), with the majority of these areas being highly suitable for *P. marginatus* (9.99 %). 87.4 % of cropland which was suitable for *P. marginatus*, was not suitable for *A. papayae*. This was split fairly equally between those areas highly suitable for *P. marginatus*, and those moderately suitable for *P. marginatus* (Fig. 7).

At a country level, Gabon and the Republic of Congo, had the greatest alignment of cropping areas highly suitable for *P. marginatus and suitable for A. papayae*, all with over 30 %. Angola, Central Africa Republic, Democratic republic of Congo, Equatorial Guinea, and Chad had the lowest alignment in suitable areas, all with over 80 % of cropping areas suitable, either highly or moderately, for *P. marginatus* yet not suitable for *A. papayae* (Fig. 8).

3.6. Potential distribution across north Africa

There were very few cropping areas in North Africa that were suitable for *P. marginatus.* Only Egypt and Sudan had more than 10,000 km^2 of cropland which was suitable in any way for *P. marginatus* and all of it was not suitable for *A. papayae*. The majority of these areas, close to 100 % in both countries, were only moderately suitable for *P. marginatus* (Fig. 9 and Fig. 10).

4. Discussion

Paracoccus marginatus is an invasive pest with a high economic cost

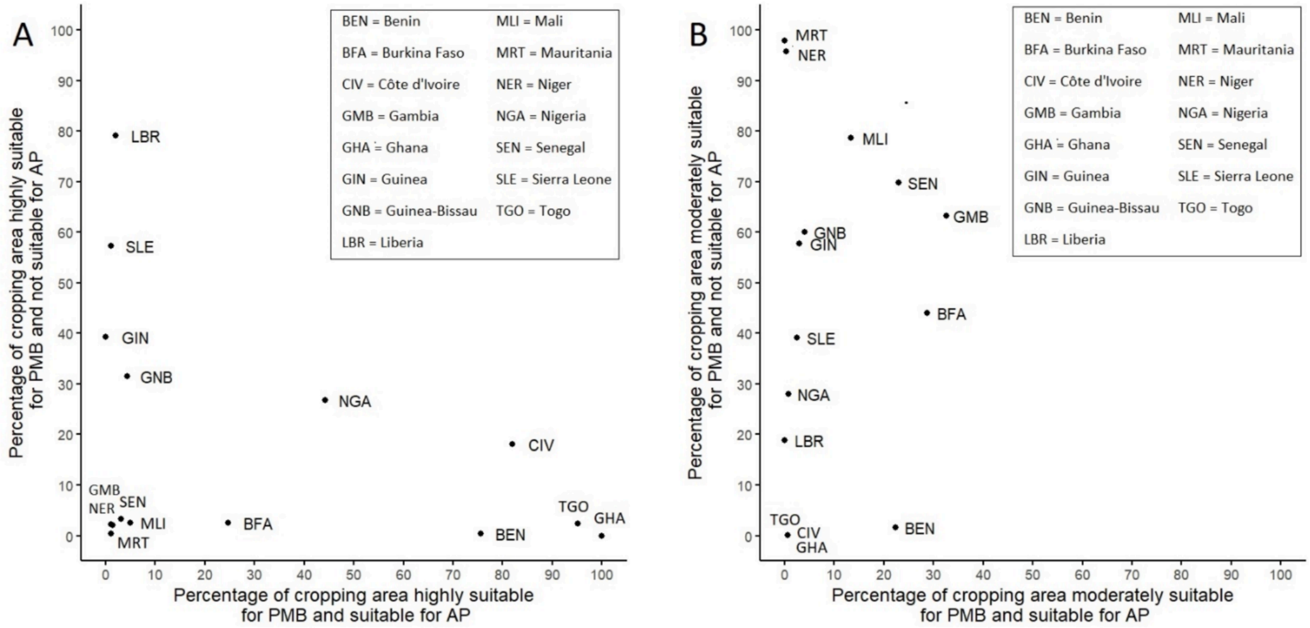

Fig. 4. Percentages of cropping areas in West African countries which were a) highly suitable for *P. marginatus* (PMB) and which were suitable and unsuitable for *A. papayae* (AP) and b) those which were suitable for *P. marginatus* and which were suitable and unsuitable for *A. papayae.*

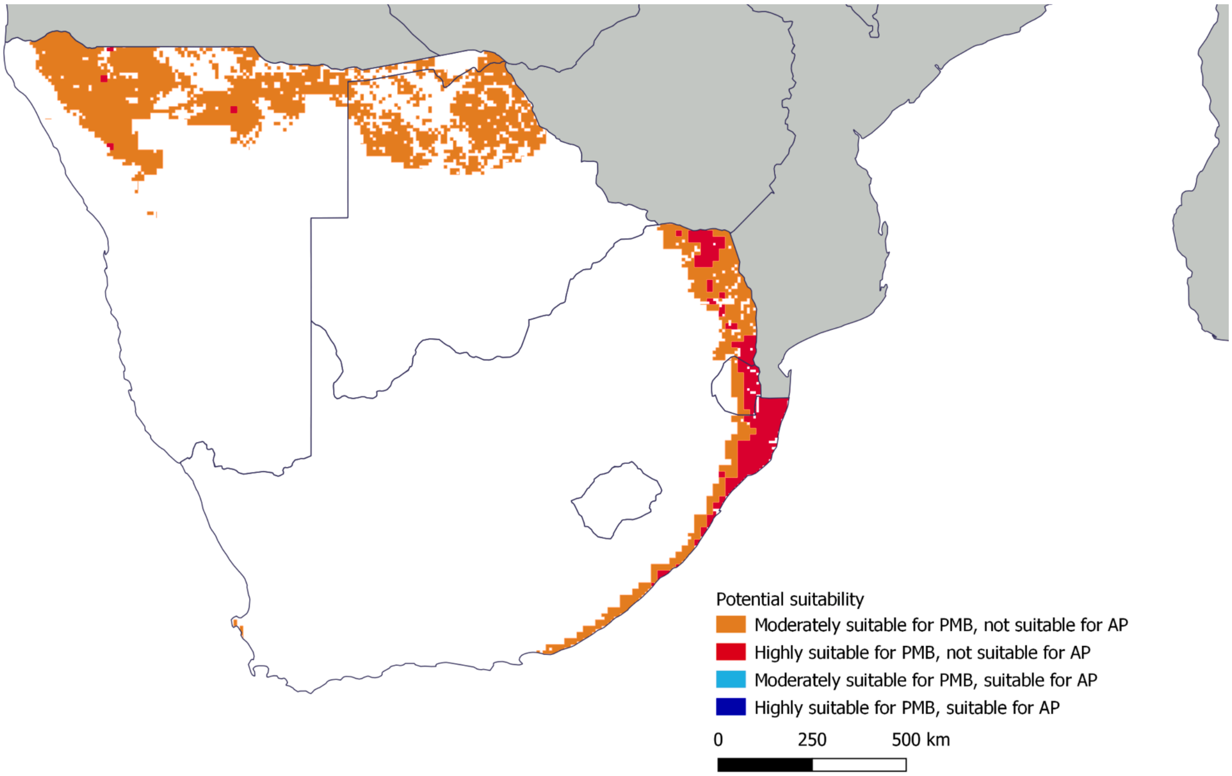

Fig. 5. Modelled climate suitability *Paracoccus marginatus* (PMB) and *Acerophagus papayae* (AP) across cropping areas of Southern Africa.

and the ability to spread rapidly and infest multiple types of crops. *Acerophagus papayae*, a parasitoid of *P. marginatus*, has been successfully used to control papaya mealybug populations in numerous countries globally, including Guam, Palau, Sri Lanka, Mexico, Puerto Rico, Dominican Republic, India, Sri Lanka (Muthulingam and Vinobaba, 2021), Florida (Amarasekare et al., 2009), West Africa (Goergen et al., 2011) and Kenya (Opisa et al., 2024). In order to inform management strategies across the whole of Africa, we have pooled data from 14 countries to model the potential distribution of *A. papayae* and highlight areas which have the greatest potential for use of biocontrol.

Paracoccus marginatus has been found recorded along the coastal regions of Kenya and Tanzania (IITA, 2015; Macharia et al., 2017), and in the Cabo Delgado region and the Nampula area of north-eastern Mozambique (Massamby et al., 2016). Our results, in general, show good suitability for *A. papayae* across these areas, suggesting that *A. papayae* is able to survive. This is supported by a recent study which

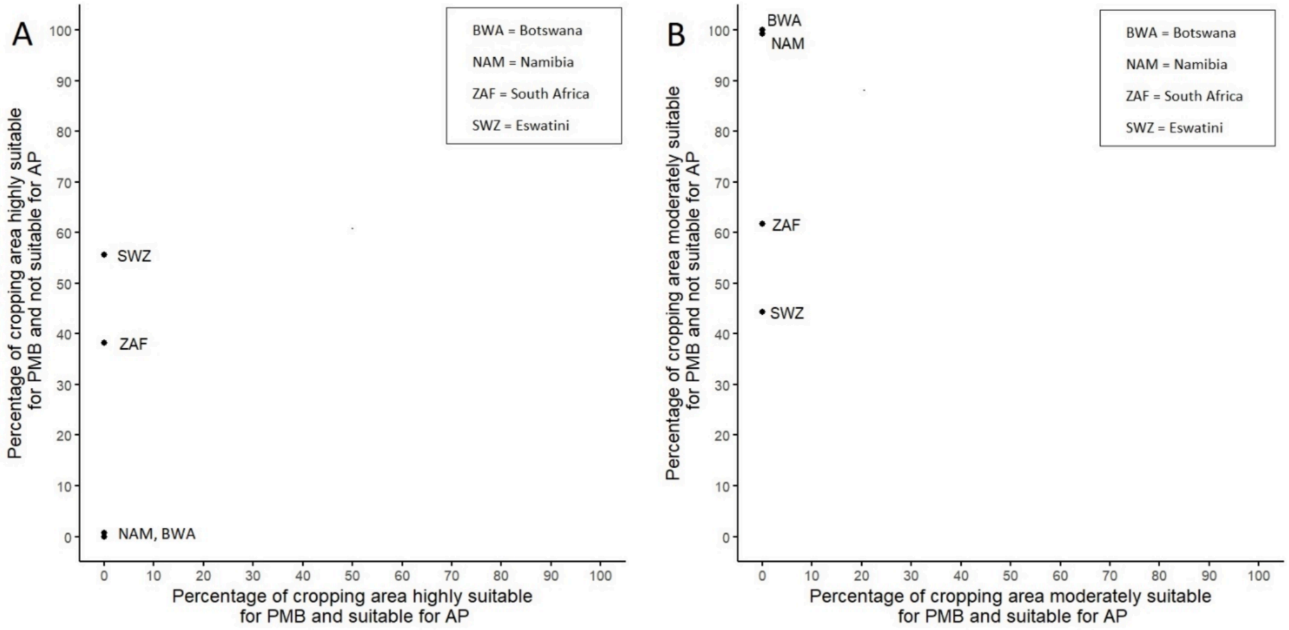

Fig. 6. Percentages of cropping areas in Southern African countries which were a) highly suitable for *P. marginatus* (PMB) and which were suitable and unsuitable for *A. papayae* (AP) and b) those which were suitable for *P. marginatus* and which were suitable and unsuitable for *A. papayae*.

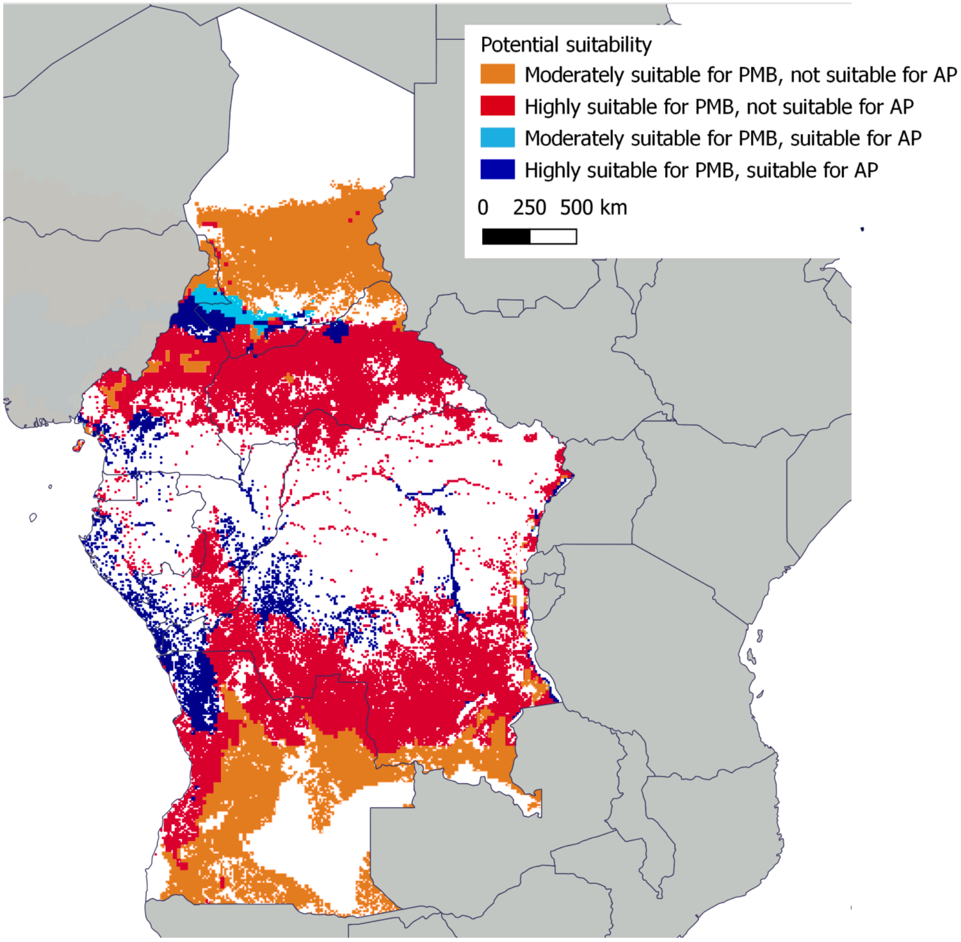

Fig. 7. Modelled climate suitability *Paracoccus marginatus* (PMB) and *Acerophagus papayae* (AP) across cropping areas of Central Africa.

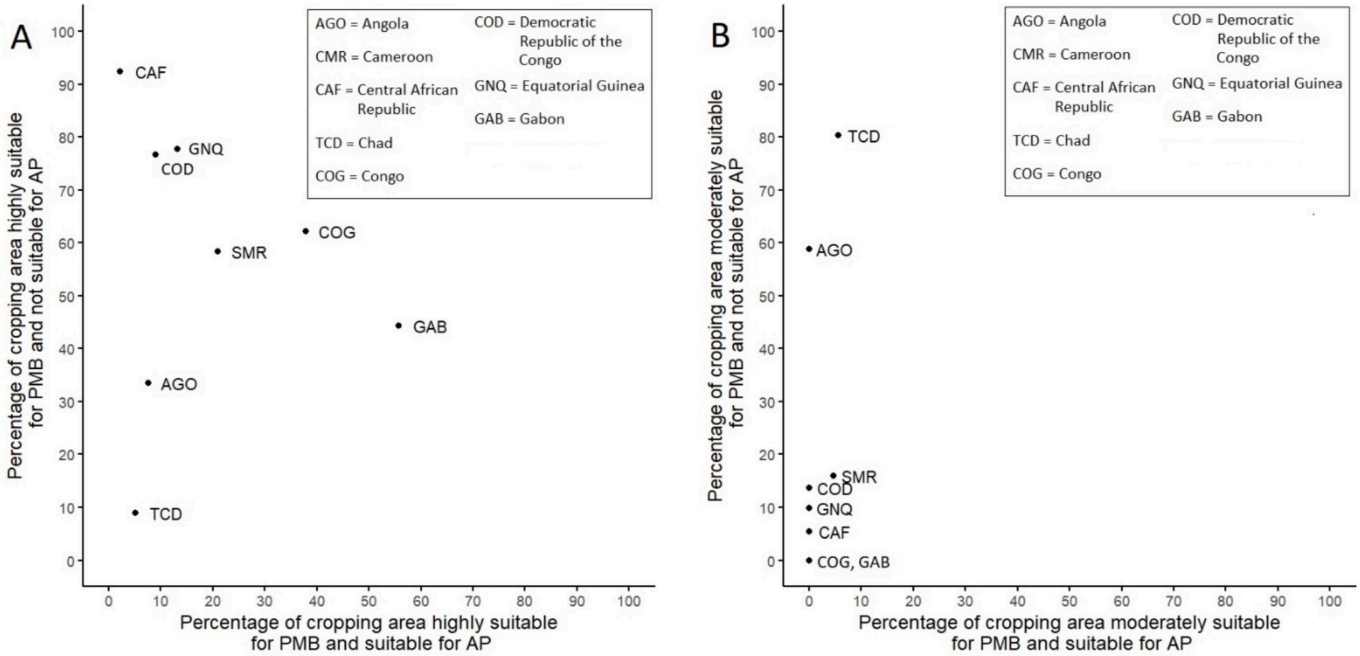

Fig. 8. Percentages of cropping areas in Central African countries which were a) highly suitable for *P. marginatus* (PMB) and which were suitable and unsuitable for *A. papayae* (AP) and b) those which were suitable for *P. marginatus* and which were suitable and unsuitable for *A. papayae*.

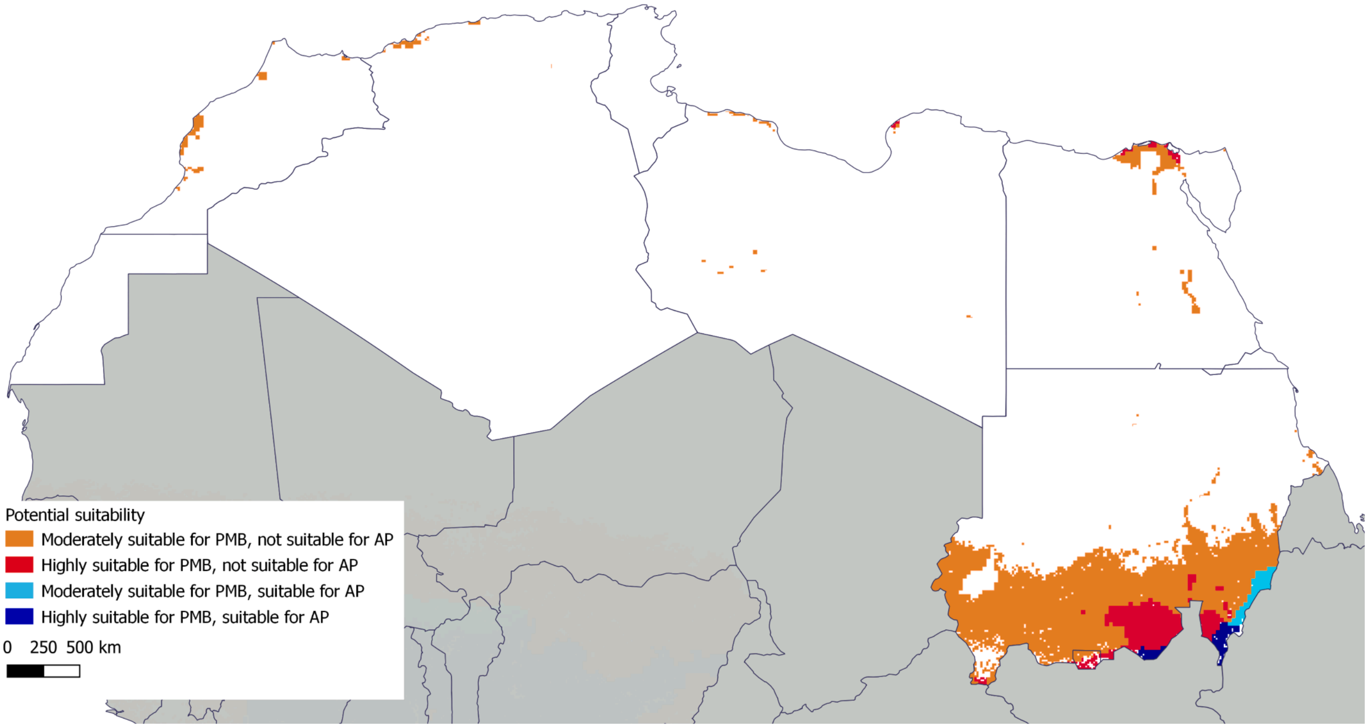

Fig. 9. Modelled climate suitability *Paracoccus marginatus* (PMB) and *Acerophagus papayae* (AP) across cropping areas of North Africa.

highlighted the utility of the release of *A. papayae* as a way of controlling *P. marginatus* populations in the south-coastal regions of Kenya (Opisa et al., 2024). Whilst populations of *P. marginatus* have not been officially recorded in other areas of East Africa, areas of high suitability for *P. marginatus* extend to the south coast of Somalia, to non coastal areas of Tanzania, to central and southern Mozambique and to Uganda, and South Sudan. Of these areas, our results suggest generally good suitability for *A. papayae* across South Sudan andsouthern Somalia. There is no suitability in the other areas, suggesting that if *P. marginatus* were to invade, other control methods, besides release of *A. papayae*, would have to be explored. Small experimental releases in low to no suitability areas, however, would help us to validate these assumptions.

In West Africa, *P. marginatus* has been found extensively throughout Ghana, Benin, Togo (Goergen et al., 2014), and Côte d'Ivoire and our model suggests that these countries are suitable for *A. papayae.* Indeed, *A. papayae* has already been successfully used as a biocontrol method in

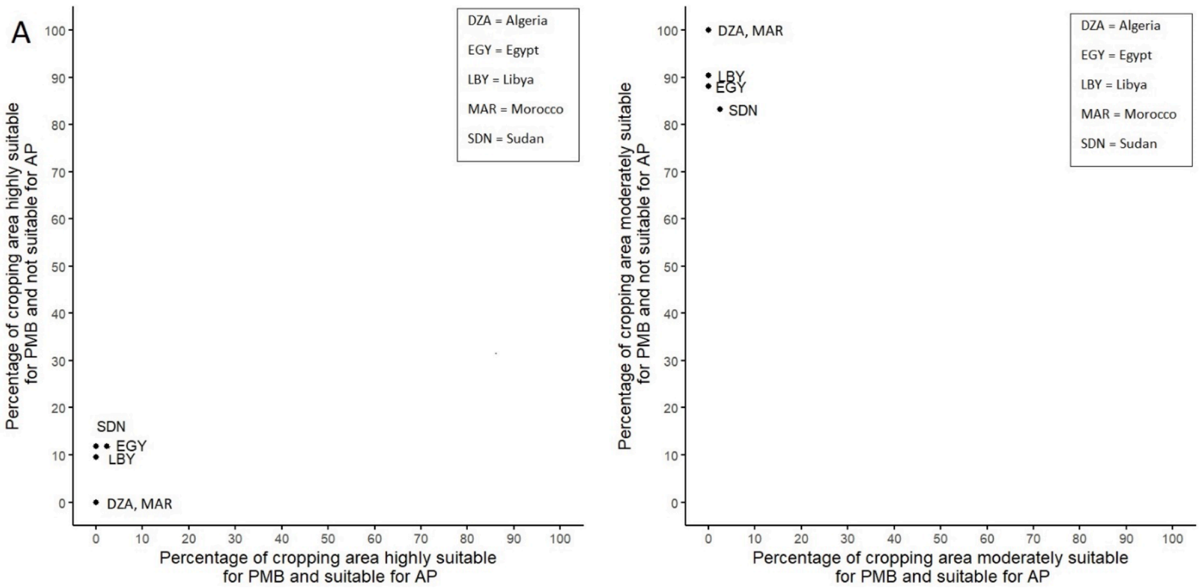

Fig. 10. Percentages of cropping areas in Northern African countries which were a) highly suitable for *P. marginatus* (PMB) and which were suitable and unsuitable for *A. papayae* (AP) and b) those which were suitable for *P. marginatus* and which were suitable and unsuitable for *A. papayae*.

Benin and Ghana (Goergen et al., 2014). *Paracoccus marginatus* has also been recorded in the southern parts of Nigeria (Goergen et al., 2014), although results from our model suggest that the more northern areas are also suitable for this species. Whilst the areas of Nigeria where *P. marginatus* have currently been recorded are also suitable for *A. papayae*, our model suggests that for any potential expansion of *P. marginatus towards the north of the country*, use of *A. papayae* as a biocontrol agent may not be suitable. *Paracoccus marginatus* has also been recorded in Liberia, Sierra Leone, Burkina Faso, Mauritania (Goergen et al., 2014). Whilst we could not find exact information as to the extent of these invasions, our results suggest that the southern and central regions of Burkina Faso, are also suitable for AP, potentially making it a viable control method in these areas. Given its proximity to other countries where *P. marginatus* has been recorded, and the high suitability for this species, western Guinea, Sierra Leone and Liberia are also at potential risk of invasion. Suitability for *A. Papayae* was low in these areas, suggesting any potential spread may require alternative management strategies.

In central Africa, *P. marginatus* has been recorded in Central Cameroon and in Gabon (Goergen et al., 2014). Across Gabon there was little suitable crop for *P. marginatus,* but of this 55 % was suitable for *P. marginatus* and *A. papayae*. Parts of northern Cameroon were also suitable for *P. marginatus* and *A. papayae*, however our results suggest that if *P. marginatus* spread into the southern regions of the country, large areas would not be suitable for *A. papayae*. Whilst the spread of *P. marginatus* into other countries in central Africa is currently unknown, our results suggest that the coastal region of the Republic of Congo and along the north coastal regions of Angola are suitable both the *P. marginatus* and *A. papayae*.

Whilst results from our study can give an indication of areas which may be suitable for *A. papayae*, it is important to note that environmental suitability is not the only factor affecting the survival of populations of *A. papayae* and their utility as a biocontrol agent. One major factor is the population density of the host species. This is specifically important for *A. papayae* as there are no other recorded hosts for this parasitoid, so populations would be completely dependent on *P. marginatus* (Noyes and Schauff, 2003), and thus areas where the population density of *P. marginatus* is low might be less suitable for release of *A. papayae* as a biocontrol agent, even if environmental conditions are favourable.

Even if *A. papayae* were able to become established in an area, there are other factors which would affect how effective it would be at controlling populations of *P. marginatus*. The plant hosts of *P. marginatus*, for example, have been shown to significantly affect various life metrics of *A. papayae*; *A. papayae* individuals lived the longest, had more offspring in general, as well as more female offspring when they were able to parasitise *P. marginatus* which had fed on papaya and cotton than when they were fed on potato (Nisha and Kennedy, 2016). The host plant species has also been shown to affect the survival probability of *A. papayae*; survival probability was highest in papaya (99 %) and cotton (71.6 %) than on tapioca (39.8 %) and hibiscus (41 %) (Nisha et al., 2015). Thus, the type of plant infected by *P. marginatus* should be considered when weighing up whether biocontrol using *A. papayae* is an appropriate choice of control method.

Instar stage of the *P. marginatus* is also an important consideration for control using *A. papayae*. Parasitism rates are higher in 2nd and 3rd instars than in adults (Mastoi et al., 2018), however the size of the emerging parasitoid, often used as a signifier of fitness, was larger in 3rd instars and adult *P. marginatus* than in 2nd instars (Mastoi et al., 2018). Instar stage also affected the sex ratio of the emerging *A. papayae*; there was a strong male biased sex ratio in *A. papayae* emerging from host parasitised as 2nd instars compared to those from later stages which had a stronger female biased sex ratio (Mastoi et al., 2018). Thus, releasing *A. papayae* when the field is dominated by 2nd and 3rd *P. marginatus* instars might increase effectiveness and sustainability of biocontrol programs.

In this study we have modelled the potential distribution of *A. papayae* across Africa and shown that areas that were highly suitable for *P. marginatus* and were also suitable for *A. papayae* were highest across West Africa. Whilst there were areas in East and Central Africa that were suitable for both species, there were large areas which were highly suitable for *P. marginatus* although not suitable for *A. papayae*. This knowledge on the suitability for this parasitoid can be used to guide decisions on the best integrated pest management programme against *P. marginatus*, helping to ascertain the best course of action to preserve yields.

CRediT authorship contribution statement

Elizabeth A. Finch: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Kris A.G. Wyckhuys: Writing – review & editing, Data curation, Conceptualization. **Ivan Rwomushana:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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