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INVASION NOTE

Lack of human-assisted dispersal means *Pueraria montana* var. *lobata* (kudzu vine) could still be eradicated from South Africa

Sjirk Geerts · Bongani V. Mashele · Vernon Visser · John R. U. Wilson

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Abstract The legume, *Pueraria montana* var. *lobata* (kudzu vine) is one of the worst plant invaders globally. Here we present the first study of *P. montana* in South Africa. We found only seven *P. montana* populations covering an estimated condensed area of 74 hectares during the height of the growing season. Based on a species distribution model, it appears that large parts of the globe are suitable, including parts of the eastern escarpment of South Africa (where most populations occur). South African populations of *P. montana* appear to have a similar ecology to populations in the USA: high growth rates, low seed germination, no natural long-distance dispersal, little herbivory and vigorous post-fire resprouting. In contrast to the USA, most South African populations do flower and flowers are capable of producing seed in the absence of pollinators. However, *P. montana* appears to have never been widely planted in South Africa, and the incursion was for many years restricted to a single introduction site. The comparison between the invasions of *P. montana* in the USA and South Africa highlights the often overriding importance of human-assisted dispersal and cultivation in creating widespread invasions, and should serve as a warning to people who have proposed to utilize the species in Africa.

Keywords Africa · Alien invasive weed · Climate models · Fabaceae · Legume · Pollination

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Introduction

One of the best predictors of plant invasiveness is whether a species is invasive elsewhere (see for ex. Herron et al. 2007). Information from one region, in which a species has an established history of invasion, can be used to inform predictions in another region (Pauchard et al. 2004; Diez et al. 2012), and in particular be used to motivate for initiating an eradication attempt (Anderson 2005). Efforts to predict invasiveness can also be based on plant traits (see for ex. van Kleunen et al. 2010), mutualisms (see for ex. Geerts and Pauw 2009), taxonomy (see for ex. Diez et al. 2009) and climate (see for ex. Pheloung et al. 1999). Of these, climate is one of the best predictors, with invasive alien species that have major impacts in one region currently prioritized for control in climatically similar regions where these species start to naturalize (Pauchard et al. 2004; Pheloung et al. 1999). But this begs the question, why is there a substantial difference in observed invasiveness between regions?

Here we explore the case of *Pueraria montana,* one of the world's most damaging invasive species (Forseth and Innis 2004; Friedman 2010). It was introduced to the USA in 1876 and subsequently widely planted as an ornamental, for erosion control, soil stabilisation and as high-nitrogen forage (reviewed in Forseth and Innis 2004). It is a now a widespread invader in the USA, but without data on planting locations it is difficult to assess the importance of direct human dispersal versus natural dispersal, in stimulating these invasions.

Here, for the first time, an invasion of *P. montana* in South Africa is investigated, and we attempt to explain whether the current narrow distribution is due to residence time, climatic conditions, biological factors or some aspect of introduction dynamics. Specifically, we (1) disentangle the introduction history and control of *P. montana* in South Africa, (2) model the worldwide climatic suitability for *P. montana*, (3) map the current and potential distribution in South Africa, and (4) compare the ecology and mechanisms of spread in South Africa and the USA.

Methods

Study species

Pueraria montana (Lour.) Merr. var. *lobata (Willd.) Maesen & S. M. Almeida ex Sanjappa & Predeep* (Fabaceae) is a perennial, climbing vine with deciduous foliage. It grows best in high-light forest-edge areas and can achieve growth rates of 10–30 m per season. Due to its large underground root tubers, plants can rapidly regrow after fires. Flowers are of a typical legume form and borne in compact racemes. The low seed production in the introduced ranges is attributed to a lack of suitable pollinators and insect predation on seeds (reviewed in Forseth and Innis 2004). Natural seed dispersal may be by wind, animals, water and potentially by birds (Burrows 1989), although birds have not been observed and are unlikely (Burrows pers. comm. 2013; pers. obs.). Although vervet monkeys, baboons and guinea fowls were observed at *P. montana* populations in South Africa, no utilisation or seed dispersal by these animals were observed. Despite the range of dispersal vectors, natural seed dispersal distance is generally less than 6 m (Abramovitz 1983; Forseth and Innis 2004). However, long-distance dispersal along corridors such as roads does happen (Pappert et al. 2000).

Introduction history and current distribution in South Africa

A list of all *P. montana* records was compiled from the Southern African Plant Invaders Atlas (SAPIA) (accessed April 2012 (Henderson 1998)), a database of herbarium records (PRECIS 2012), an online spotter network (www.ispot.org.za) and responses to pamphlet distribution to local foresters, conservation officers, botanists and conservationists (Fig. S1). Localities were visited between 2011 and 2014. Current and previous landowners and foresters were interviewed for information on historical control efforts.

All *P. montana* populations were mapped by walking around the perimeter of each clump. We systematically surveyed one population at the start of the growing season, mapped all sprouting rootstocks, and compared this to a map of the patch perimeter obtained later in the season. Based on the quality of the fit between the two methods (Fig. S2), mapping the perimeter of a patch appears to be a reliable measure of sprouting rootstocks and was subsequently used for all other populations. In the area where *P. montana* was first introduced and the most abundant (Barberton, Kaapsehoop and Rosehaugh near Schagen, Nelspruit, Mpumalanga), we did roadside sampling by car of all tarred regional and main gravel roads in the area (excluding those purely in suburbs), for a total distance of 428 km.

Potential *P. montana* distribution in South Africa based on climate

We obtained *P. montana* occurrence records from the Global Biodiversity Information Facility (GBIF 2008; gbif.org/species) and included additional occurrences for South Africa (this study) and Switzerland (Gigon et al. 2014). After data cleaning we were left with 509 occurrences. We used Maxent in the dismo R package to build species distribution models (SDMs) using the aforementioned presence records and 10,000 pseudo-absence records. We selected pseudo-absence records based on the frequency of records of species closely related to *P. montana* (Table S1) within 10' grid cells (Merow et al. 2013). We selected nine environmental variables from the WORLDCLIM dataset as predictors, basing our selection on variables thought to be ecologically important for *P. montana* and also excluding any highly correlated pairs of environmental variables (Table S2; Merow et al. 2013). We ran Maxent and used the randomly selected subset of 70 % of the data for model calibration, and the remaining 30 % for model evaluation using the area under the receiver operating characteristic curve (AUC) and the continuous Boyce Index (Hirzel et al. 2006). We masked areas for which the model is extrapolating into novel environmental space (see supplementary material for detailed methods).

Ecology and mechanisms of spread: pollination, reproduction, seed germination, herbivory and vegetative reproduction

Floral visitors were observed at one site (Rosehaugh population, Sudwala Road; −25.37653°; 30.71592°) and nectar measured (n = 20 flowers) to infer potential pollinators. To establish the ability of *P. montana* to produce fruit autonomously, inflorescences were haphazardly selected and bagged with fine-mesh gauze bags when in bud phase to exclude all visitors (n = 16 plants; 18 inflorescences and 457 flowers). As a control, an adjacent inflorescence was tagged and left open to receive pollinator visits (n = 19 plants; 31 inflorescences and 1268 flowers). Seed viability of naturally produced seeds was tested by germinating them under controlled conditions. Forty haphazardly selected leaves and 78 flowers were examined for herbivore damage. To determine the importance of vegetative reproduction, runner survival was determined under controlled greenhouse conditions. Runners were cut to contain one node, and be 20 cm long and either have no roots (n = 26), contain a few small roots but not rooted in the soil (n = 15) and starting to root in the soil (n = 19). Anecdotal evidence during detailed mapping of all populations, suggests the study population to be representative in herbivory and pollinators (see supplementary material for detailed methods).

Australian weed risk assessment for *P. montana* in South Africa

To assess the potential invasiveness of *P. montana* in South Africa we used the Australian weed risk assessment protocol developed by Pheloung et al. (1999) and the Hawaii Pacific weed risk assessment. This was adapted to South African conditions, by using the predictions of the species distribution model in answering question 2.01 of the protocol (is the species suited to South African climates?).

Statistical analyses

Cutting growth results were analysed with a Chi square test. Generalized linear models with binomial errors were used to compare pods and seeds produced between pollinator-excluded and open inflorescences. Open inflorescences had more (43 %) flowers per inflorescences than bagged branches. We therefore include plant effect and number of flowers as covariates in the analysis. The data on the survivorship of runner fragments were analysed with a Chi square test. All statistical analyses were conducted in R (R Development Core Team 2015).

Results

Introduction history and current distribution in South Africa

Pueraria montana was introduced in the 1920s from Argentina as nutritious fodder for cattle (Chris Dunshea pers. comm., 23rd August 2013) (Fig. 1). It was introduced to one farm only, on which growth and spread was initially limited by heavy grazing. However, the population slowly expanded onto the adjacent riverbank and roadside. Road upgrades (from gravel to tar) during 1975 and 1976, resulted in further spread as road building equipment and forestry trucks inadvertently transported *P. montana* material (Fig. 1; Chris Dunshea pers. comm.). Subsequent spread by roadside mowing equipment has also been reported (Ndlovu 2011). Substantial efforts were made to control *P. montana* during the 1970s and early 1980s, but the project failed (Zimmermann 2011, pers. comm.). From 1982 to 2006, *P. montana* was sporadically and unsuccessfully controlled by local farmers with Triclopyr and grazing by fenced-in goats. Fire as a control method also proved unsuccessful. The first formal record of *Pueraria montana* as invasive in South Africa was only in 1984 (Henderson 1998), with the first published record a few years later (Burrows 1989).

We found seven *P. montana* populations in three provinces covering 74 hectares in total (Table S3; Fig. 2 inset). Most populations occur in the Mpumalanga Province (Fig. 2), with the largest populations in the Schagen district (Rosehaugh) at the initial introduction site (Fig. 2). Currently *P. montana* occurs mostly in forestry plantations (Fig. S3a), road embankments and riparian zones (Fig. S3b), but also in disturbed shrublands and abandoned pastures.

Potential *P. montana* distribution in South Africa based on climate

The SDM model exhibited high predictive accuracy (AUC = 0.91 ± 0.13 95 % CI; continuous Boyce Index = 0.99 ± 0.0002 95 % CI) and predicts *P. montana* occurrence across much of Southeast Asia (the species' native range), Japan, the Koreas, the eastern seaboard of Australia, New Zealand, much of the southeastern USA, southern Brazil, southern Europe and parts of central Africa (Fig. S4). We found that precipitation of the warmest quarter (BIO18) had the largest influence on *P. montana* occurrence, followed by mean diurnal temperature range (BIO2) and temperature seasonality (BIO4) (Table S4). *P. montana* is most likely to occur in regions with high summer rainfall, low diurnal variation in temperature, and intermediate seasonal

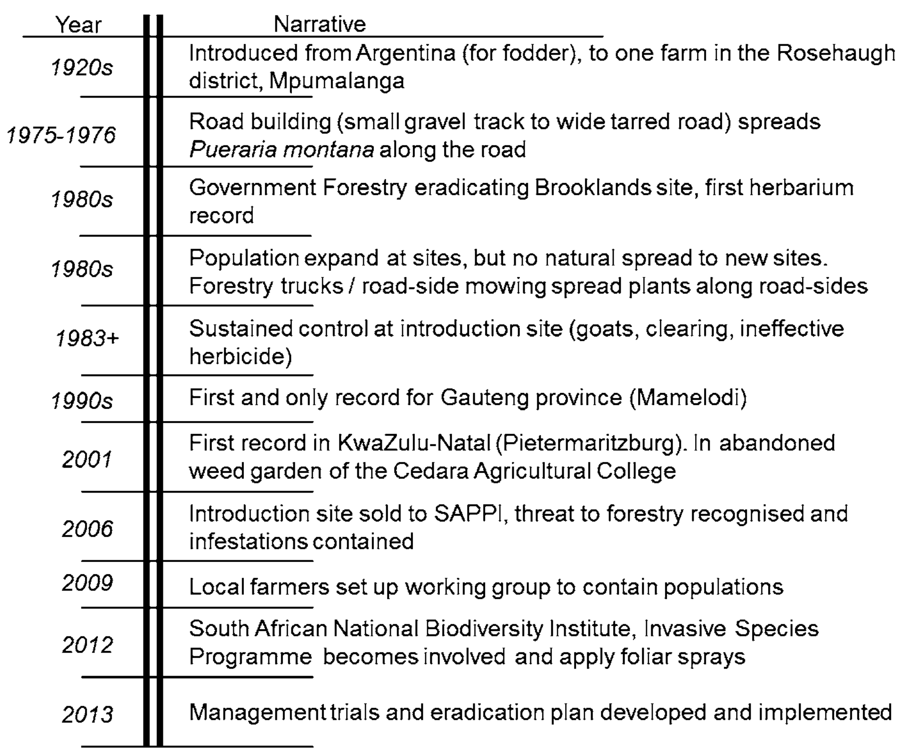

Fig. 1 A narrative of *Pueraria montana* history in South Africa highlighting the limited introduction effort and human assisted spread

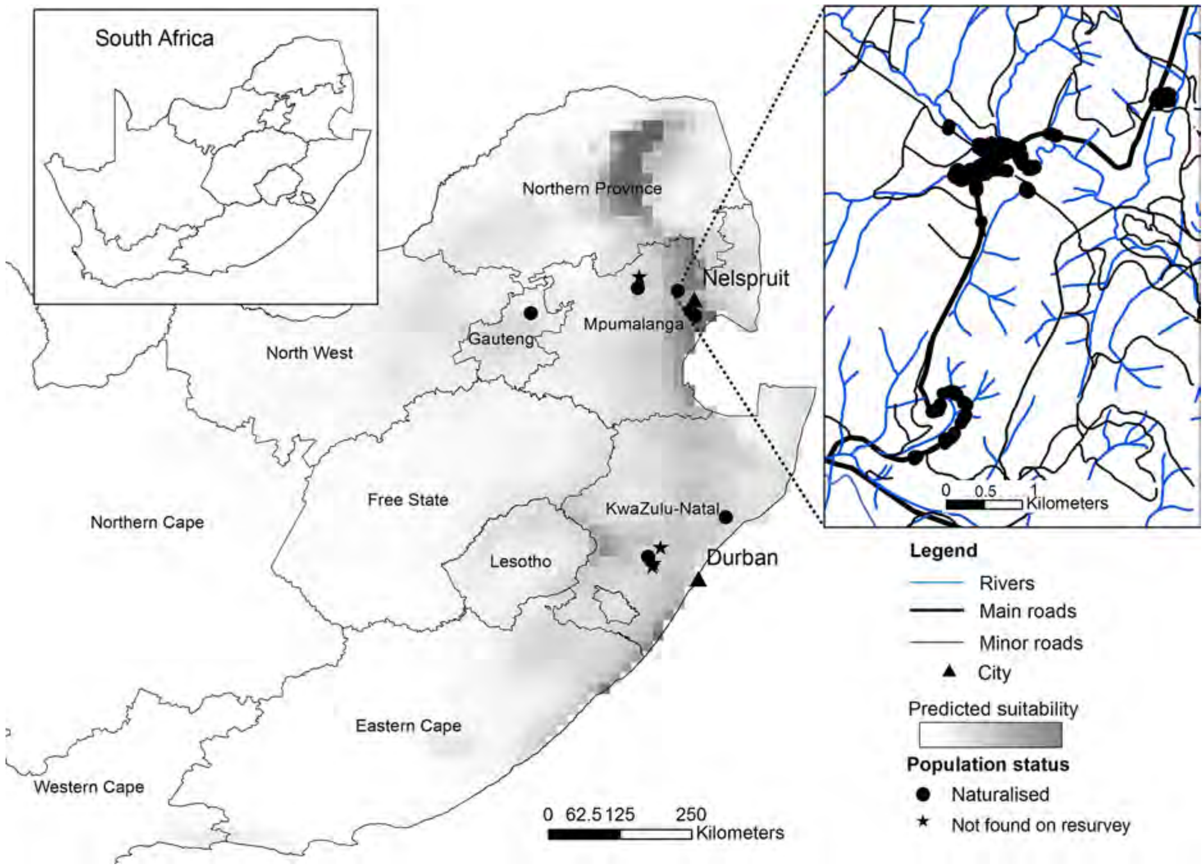

Fig. 2 Distribution of *Pueraria montana* in South Africa. The predicted climatic suitability for *P. montana* is shown (see "Methods" for details), with *darker grey* indicating higher suitability. Inset shows the introduction site at Rosehaugh near Schagen (Nelspruit, Mpumalanga), with subsequent spread along roadsides in all four directions

variation in temperature (Fig. S5). In South Africa climatic suitability for *P. montana* is moderate across much of the eastern escarpment and parts of the KwaZulu-Natal province, with the remainder of the country unsuitable (Fig. 2, Fig. S6).

Ecology and mechanisms of spread: pollination, reproduction, seed germination, herbivory and vegetative reproduction

The typical legume flowers (Fig. S3 c) of *P. montana* are visited by honeybees (*Apis mellifera scutellata*) and carpenter bees (*Xylocopa* spp.). A total of 480 flower-pollinator interactions were observed, with honeybees the most frequent visitors (3.6 visits per flower per hour). This corresponds with the low nectar volume of 0.1 µl (range 0–1.5 µl), and a concentration of 24.5 % (range 23–32 %) sucrose.

Pollinator-excluded inflorescences produced fewer pods ($t = 9.4$, $df = 13$, $p < 0.01$; mean in pollinator-excluded 5.3, mean in naturally pollinated 29.7); and fewer seeds per pod ($z = 3.5$, $p < 0.01$; mean of 2.1 in pollinator-excluded versus 3.6 in naturally pollinated flowers) than control inflorescences.

Only 9 % (4–16 %; 95 % CI) of seeds in the germination trials germinated. This low germination rate is substantiated by the absence of seedlings in the field. No evidence was found that animals consume or disperse seeds. Little leaf damage was observed (Fig. S3 e) with an average of 10 % (range 0–50 %) leaf surface lost due to herbivory by the blister beetle, *Mylabris oculata* (Fig. S3 f). Flowers are damaged at the base (26 % of flowers) by an unidentified leaf-dwelling larva.

After 10 weeks, the survival rate for runners was 4 % for cuttings with no roots, 7 % for those with only a few roots, and 11 % for those with many roots, with no significant difference between the treatments (Chi square test, $\chi^2 = 5.2$, df = 4, $p = 0.27$).

Australian weed risk assessment for *P. montana* in South Africa

A score of 26 (Table S5) in the Australian Weed Risk assessment suggests that *P. montana* would fail a pre-border evaluation (Hawaii-Pacific Weed Risk Assessment 2012; Pheloung et al. 1999).

Discussion

Here we argue that *Pueraria montana* is not a widespread invasive plant in South Africa due to a lack of introduction effort, human dissemination and seemingly limited natural dispersal. We show that the global potential distribution of *P. montana* includes many areas of the world. The eastern parts of South Africa are only moderately suitable, with largely similar climatic conditions to the native range, while the remainder of the country has an unsuitable climate. Based on the climatic suitability and invasiveness elsewhere, *P. montana* has the potential to become one of the most serious invaders of the summer rainfall regions in South Africa, including some of the most agriculturally productive and highest conservation value areas of the country (e.g. Kruger National Park). The evidence provided here suggests that there is a barrier to recruitment and that humans are the most important dispersers, which should drive management practices in non-invaded climatically suitable areas of South Africa.

In contrast to the USA, where the enormous increase in area was driven by human introduction and cultivation of seedlings at hundreds of sites (Forseth and Innis 2004), in South Africa there were no concerted efforts to cultivate and spread *P. montana* plants. Where plants are found, they are generally occurring on roadsides, in line with findings from the USA that road building and roadside mowing are important mediators for spread (Kartzinel et al. 2015). However, as survival of runners in this study was low, even this mode of spread is unlikely unless large quantities of plant material are moved around. There are several potential biotic dispersal agents in the region, e.g. primates and birds, but the current distribution is only really consistent with limited natural spread and spread along roads by construction vehicles.

In contrast to the USA, where flowering is rarely observed (Kidd 2002), in South Africa most populations produce flowers, and flowers are frequently visited by native pollinators. Although largely reliant on pollinators for seed production, *P. montana* in South Africa can also produce seeds in the absence of pollinators (4.6 % of pollinator-excluded flowers produced pods in South Africa, while none are produced in the USA). Similarly, only 3.3 % of naturally-pollinated flowers in the USA produced pods (Abramovitz 1983), while 72 % did so in South Africa. Despite this, seed viability in South Africa is low at nine percent, but still within the usual range for non-scarified seeds (Susko et al. 2001). Similar to other Fabaceae species, impermeable seeds of *P. montana* might ensure seed longevity in the soil (Baskin and Baskin 1998; Susko et al. 2001), but no studies have determined the longevity or the size of soil seed banks (Forseth and Innis 2004). With the relative low levels of seed production, the apparent lack of natural dispersal, and the absence of seedlings in the field, seeds seem to currently be of little importance for *P. montana* dispersal in South Africa.

In terms of management, several classical biological control agents have been tested in the USA, but no effective, host-specific agents have been found to date (Frye et al. 2007), and, unless eradication can be ruled out, it does at present not seem to be the most promising option for control in South Africa. Fire can be effective in some circumstances, but it will damage native vegetation, and stimulate *P. montana* resprouting and seed germination (Susko et al. 2001). Therefore, for South Africa we suggest initial control through grazing by goats (Terrill et al. 2003) in riparian populations, whilst focused chemical and mechanical control should attempt to extirpate all other populations. Subsequent physical removal of roots in riparian areas is labour intensive and time consuming, but the only method to ensure eradication. Throughout, close monitoring of current populations is suggested, with emphasis also on searching for new populations. Such a proactive approach against potentially invasive species was until recently rarely undertaken in South Africa (but see Geerts et al. 2013a, b; Wilson et al. 2013), but is recommended for *P. montana*.

This study will serve as an important basis for future work on *P. montana* in South Africa and Africa, which should focus on the following: niche shift and niche conservatism relative to its native range (Callen and Miller 2015); differences in soil chemical properties between South Africa, the USA and the native range; symbiotic relationships with nitrogen-fixing bacteria and the benefit for germination and growth; a genetic analysis to disentangle population relatedness and dispersal sequences in South Africa as these have proven useful to guide management practices (Kartzinel et al. 2015); seed bank size and seed bank longevity; and lastly the influence of the introduction pathway (including molecular analyses), which for South Africa was via Argentina, whilst the USA plants came directly from the native range. These questions should be addressed simultaneously with control, since eradication is critical and should receive priority.

A major concern is that despite the plethora of information on the invasiveness of *P. montana*, there is still a demand for *P. montana*. One such example is a request from tropical Africa for half a tonne of *P. montana* seeds to be grown for fodder (David Orr pers. comm. 2013). This is reason for concern, since plant species are not restricted by country borders, and species introduced in one country are able to spread (aided or unaided) into neighbouring countries. This is particularly concerning in Africa where most countries have limited resources to counter the threat of invasive alien species and little environmental legislation exists or is enforced. More generally, it highlights that impact is largely a function of usage, e.g. biofuel crops and fodder species that are initially dependant on human assistance for establishment and dispersal, but once established could become major invasive species. Potential future examples could include the alien fodder crop, *Cytisus proliferus* (Tree lucerne) advocated as an ideal fodder species for the drier parts of Africa. Closely scrutinising and allowing for monitoring these species via permit systems will go a long way to ensure institutional memory and prevent abandoned plantations or fodder crops from becoming major invaders.

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Lack of human assisted dispersal means *Pueraria montana var. lobata* (kudzu vine) could still be eradicated from South Africa

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Supplementary methods

Potential P. montana distribution in South Africa based on climate

We obtained *P. montana* occurrence records from the Global Biodiversity Information Facility (GBIF; gbif.org/species) and included additional occurrences for South Africa (this study) and Switzerland (Gigon et al. 2014). We cleaned these occurrence data by removing records in the sea or moving them to the nearest location on land. We also checked for outliers in relation to environmental factors (see below) and manually inspected locality descriptions for these records. We removed outlier records that had no locality description, and geo-referenced records that were obviously incorrect based on their locality descriptions. We also removed all duplicate records within 10' grid cells. After data cleaning we were left with 506 occurrences for *P. montana*. These records included both the native and non-native ranges, which provide better predictions than using native-range records alone.

We used Maxent in the dismo R package to build species distribution models (SDMs), using the aforementioned presence records and 10 000 pseudo-absence records. We selected pseudo-absence records based on the frequency of records of species closely-related to *P. montana* (Table S1) within 10' grid cells (Merow et al. 2013). The Webber et al. (2011) approach of using Koeppen-Geiger climate zones to delimit pseudo-absence selection was also used, but we found that this approach actually performed slightly worse (AUC = 0.94 versus 0.97). We selected nine environmental variables from the WORLDCLIM dataset as predictors, basing our selection on variables thought to be ecologically important for *P. montana* and also excluding any highly correlated pairs of environmental variables (Table S2; Merow et al. 2013). We ran Maxent using only linear, quadratic and hinge features to reduce the chances of model overfitting and the generation of biologically implausible response curves

(Merow et al., 2013). We used the raw output from Maxent to predict the potential distribution of *P. montana* based on climatic suitability. This output can be interpreted as the "relative likelihood of presence" (Renner et al., 2015) or the "relative occurrence rate" (Merow et al., 2013). Using the raw output of Maxent is preferable to trying to estimate the probability of occurrence (from the logistic output of Maxent), because this relies on knowing the prevalence (the proportion of localities where the species occurs) of the species in question (Merow et al., 2013).

We used a randomly-selected subset of 70% of the data for model calibration, and the remaining 30% for model evaluation using the area under the receiver operating characteristic curve (AUC) and the continuous Boyce Index (Hirzel, 2006). This process was repeated 100 times in order to account for variability in model performance arising from the selection of calibration and evaluation data. The SDM fitted using records of *P. montana* from across the globe exhibited high predictive accuracy (AUC = 0.97 ± 0.15 95% CI).

The value of the regularization coefficient in Maxent (β) can have a major impact on model predictions. We therefore explored a range of values for β and selected the best model based on the maximization of the AUC (Merow et al. 2013).

We used the methods described by Zurell et al. (2012) to delimit geographical areas for which the model is extrapolating into novel environmental space. These methods rely on dividing the reference data into five bins (the default number) "where each bin holds a unique combination of environmental predictor values" and doing the same for the prediction data. Any bins of the prediction data that do not overlap with those of the reference data are defined as novel environmental space. The advantage of this approach is that novel environmental space is defined not only by the range of individual environmental predictors, but also represents new environmental space in terms of the combinations of the various environmental predictors.

Ecology and mechanisms of spread: pollination, reproduction, seed germination, herbivory and vegetative reproduction

To determine whether local pollinators are visiting *P. montana* flowers, we observed pollinators at one site (Rosehaugh population, Sudwala Road; -25.37653; 30.71592) during optimal pollinator weather conditions (minimal wind and no precipitation; 21st January 2012, 8.30-9.30 and 10.00-11.00). Although the observation time was short, similar frequencies were seen while mapping populations. Detailed observations of the behaviour of flower visitors were made from a distance of ~5 m aided by close-focusing 8 x 40 binoculars. All flower visitors and their contact with anthers and/or stigma were recorded. Nectar volume was measured with 5 µl capillary tubes and concentration determined with a Bellingham and Stanley 0-50% handheld refractometer (n = 20 flowers).

To establish the dependence of *P. montana* on local pollinators and the ability to produce seed and fruit autonomously, pollinators were experimentally excluded from inflorescences. Mature fruits were collected before pod opening and seed release. Fruit set was quantified as the proportion of flowers that developed into mature fruits, since flowers that do not produce a fruit abscise and leave a scar on the stem. The pods are borne in clusters (Fig. S3d). Anecdotal evidence during detailed mapping of all populations, suggests the study population to be representative in pollinators.

Seeds were germinated on Whatman filter paper in petri dishes (n = 10) with 10 seeds per dish. Seeds were kept under a constant temperature of 25°C ± 2°C degree and a 16h:8h, light: dark cycle. Seed germination was determined after 6 weeks. No scarification was attempted since most populations occur in forestry areas, rocky roadsides or river beds that rarely burn.

After field collection, cuttings were immediately transferred to pots with a 50:50 compost: soil ratio. Cuttings were watered twice weekly and housed under shade cloth in the Lowveld National Botanical Garden. Mortality was scored after 10 weeks.

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Merow C., Smith M. J. & Silander J. A. (2013) A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. Ecography 36, 1058-69.

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Supplementary tables

Table S1 Genera used as pseudo-absence records for species distribution modelling. All records were sourced from the Global Biodiversity Information Facility and subjected to the same data cleaning procedures as for *P. montana* (see methods). Genera were selected based on their close evolutionary relationships with *Pueraria* (Li et al., 2013).

Genus	No. of records
Amphicarpaea	440
Bituminaria	566
Cullen	3500
Glycine	2838
Hoita	127
Neonotonia	238
Orbexilum	33
Otholobium	339
Pediomelum	322
Phylacium	13
Psoralea	774
Pueraria (all species excluding *P. montana*)	491
Rupertia	30
Teramnus	289

Li, H., Wang, W., Lin, L., Zhu, X., Li, J., Zhu, X., & Chen, Z. (2013). Diversification of the phaseoloid legumes: effects of climate change, range expansion and habit shift. *Frontiers in Plant Science,* 4: 1-8.

Table S2 Environmental variables included as predictors of *P. montana* occurrence for species distribution modelling.

Variable	Bioclim number
Mean annual temperature	BIO1
Mean diurnal temperature range	BIO2
Temperature seasonality	BIO4
Maximum temperature of the warmest month	BIO5
Mean temperature of the wettest quarter	BIO8
Mean temperature of the driest quarter	BIO9
Precipitation seasonality	BIO15
Precipitation of the warmest quarter	BIO18
Precipitation of the coldest quarter	BIO19

Table S3 Known records of *Pueraria montana* in South Africa. All historical records from PRECIS (National Herbarium Pretoria (PRE) Computerized Information System), iSpot and SAPIA (Southern African Plant Invaders Atlas), were re-visited.

Locality	Population identify confirmed	Record origin	Year recorded	Source	QDGC	Coordinates Lat / Long	Date visited	Size of population (hectares)	Detailed description	Notes
Alkmaar	No	SAPIA 872	07/1984	Lesley Henderson	2530BD	Not available	2012-2014	N/A	SAPIA: Between Alkmaar and Rooiuitsig	Not found on resurvey
Brooklands State Forest	Yes	SAPIA 871	04/1985	Herbarium specimen (PRE)	2530AA	-25.30347 30.09562	2014/2015	<2	The population is in the plantations	Treated for the last two years
Tzaneen	No	SAPIA 18014	05/1998	Working for Water (WfW)	2330CC	Not available	2012-2014	N/A	Tzaneen, watercourse	Not found on resurvey
Crammond /Albert Falls	No	SAPIA 49733	11/2001	J. Goodall	2930CB	- 29.35982 30.45846	2010 and 2012	N/A	Clan SAPPI Plantation Crammond /Albert Falls	Not found on resurvey
Cedara	Yes	SAPIA 49734	11/2001	J. Goodall	2930CB	- 29.50819 30.25840	2012	<1	Pietermaritzburg. In abandoned weed garden of the Cedara Agricultural College	Initial control done in February 2015
Near Edendale	No	SAPIA 49722	10/2002	G.R. Nichols	2930CB	- 29.65824 30.32509	2012	N/A	Growing in a disturbed site where there is illegal dumping	Potential misidentified *Lablab* species.

Locality	Population identify confirmed	Record origin	Year recorded	Source	QDGC	Coordinates Lat / Long	Date visited	Size of population (hectares)	Detailed description	Notes
Pietermaritzburg Botanical Gardens	No	SAPIA 49721	10/2002	G.R. Nichols.	2930CB	-29.60822 30.34176	2012	N/A	Pietermaritzburg, just above Botanical Gardens	Not found in, or above gardens but potential misidentified as *Dioscorea dregeana*
Mamelodi	Yes	SAPIA 49378	02/2003	Lesley Henderson	2528CB	- 25.696944 28.419444	2013	1	Next to brick yard	Population is monitored.
R539 Rosehaugh to Rietvallei	Yes	SAPIA 63866 63865 63864 63863 63498	01/2008	J. Burrows	2530BC	- 25.34275 30.724528	2011-2014	36	All along the Sudwala Road Fig. 3 B	Treated for the last three years
Queens river bridge/Barberton	Yes	N/A	2012	J. Brink pers. com.	2530DB	-25.73963 30.99798	2015	<1	Both sides of Queens river bridge	Treated for the last two years
Eshowe	Yes	N/A	2014	Sharon Louw KZN Wildlife	2831CD	- 28.88963 31.47734	2014	<5	Along Kangela Street, also accessible off Rynhoud Street	Discovered in 1999. Some initial clearing done by uMlalazi Local Municipality. South African National Biodiversity Institute clearing from 2015
Kaapsehoop stream	Yes	Walter Mabatha	2014	Walter Mabatha	2530DB	-25.66242 30.92000	2014	<28 ha		Treated for the last two years

Locality	Population identify confirmed	Record origin	Year recorded	Source	QDGC	Coordinates Lat / Long	Date visited	Size of population (hectares)	Detailed description	Notes
Groot Dwarsrivier	No	PRE0659724-0	1985	PRECIS Sawyer B.	2530AA	-25.12500 30.12500	2012-2014	N/A		Not found on resurvey

Table S4 Environmental variable importance in predicting the occurrence of *P. montana* using Maxent. Importance is measured in one of two ways: (1) “Percent contribution”, which is determined by the increase in gain (a measure of model performance) that each variable contributes to the model; (2) “Permutation importance”, which is a jackknife approach (i.e., one variable is excluded at a time and the change in model performance is measured) (Baldwin, 2009).

Variable	Percent contribution	Permutation importance
Precipitation of the warmest quarter (BIO18)	70.3	80.3
Mean diurnal temperature range (BIO2)	13.2	5.1
Temperature seasonality (BIO4)	11.3	8.3
Mean annual temperature (BIO1)	2.5	0.5
Precipitation seasonality (BIO15)	1.5	1.2
Mean temperature of the wettest quarter (BIO8)	1.1	4.2
Precipitation of the coldest quarter (BIO19)	0.1	0.3
Mean temperature of the driest quarter (BIO9)	0.0	0.1
Maximum temperature of the warmest month (BIO5)	0.0	0.0

Baldwin, R. A. (2009). Use of maximum entropy modeling in wildlife research. *Entropy*, 11, 854-866.

Table S5 Risk assessment for *P. montana*. We assessed the potential invasiveness in South Africa using the Australian weed risk assessment protocol of Pheloung et al. (1999). An assessment from Hawaii (Hawaii Pacific weed risk assessment (HPWRA)) was adapted to South African conditions. In answering question 2.01 of the protocol (i.e. is the species suited to South African climates?) we used the predictions of the species distribution model of this study. For question 4.02, allopathic potential has been shown (Rashid *et al.* 2010). For question 6.04, partly self-compatibility has been shown in this study. For question 6.05, *P. montana* is pollinated by generalist pollinators (this study). For question 7.05, propagules water dispersed; even though occurring along rivers these populations originated from adjacent populations and searches along rivers showed no evidence of dispersal by water (this study). Other references at http://www.hear.org/species/pueraria_montana/

Question	Answer
Is the species highly domesticated?	No
Species suited to South African climates	Yes
Quality of climate match data	High (this study)
Broad climate suitability (environmental versatility)	No
Native or naturalized in regions with tropical or subtropical climates	Yes
Does the species have a history of repeated introductions outside its natural range?	Yes
Naturalised beyond native range	Yes
Garden/amenity/disturbance weed	Yes
Weed of agriculture/horticulture/forestry	Yes
Environmental weed	Yes
Congeneric weed	Yes
Produces spines, thorns or burrs	No
Allelopathic	Yes
Parasitic	No
Unpalatable to grazing animals	No
Toxic to animals	No
Host for recognised pests and pathogens	Yes
Causes allergies or is otherwise toxic to humans	No
Creates a fire hazard in natural ecosystems	
Is a shade tolerant plant at some stage of its life cycle	Yes
Tolerates a wide range of soil conditions (or limestone conditions if not a volcanic island)	Yes
Climbing or smothering growth habit	Yes
Forms dense thickets	Yes
Aquatic	No
Grass	No
Nitrogen fixing woody plant	Yes
Geophyte	Yes
Evidence of substantial reproductive failure in native habitat	No
Produces viable seed	Yes
Hybridizes naturally	
Self-fertilisation	Yes
Requires specialist pollinators	No
Reproduction by vegetative propagation	Yes
Minimum generative time (years)	3 years
Propagules likely to be dispersed unintentionally	Yes

Propagules dispersed intentionally by people	Yes
Propagules likely to disperse as a produce contaminant	No
Propagules adapted to wind dispersal	No
Propagules water dispersed	No
Propagules bird dispersed	No
Propagules dispersed by other animals (internally)	No
Propagules survive passage through the gut	Yes
Prolific seed production	No
Evidence that a persistent propagule bank is formed (>1 yr)	Yes
Well controlled by herbicides	No
Tolerates or benefits from mutilation, cultivation or fire	Yes
Effective natural enemies present in South Africa (e.g. introduced bio control agents)	No

Pheloung P. C., Williams P. A. & Halloy S. R. (1999) A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *Journal of Environmental Management* **57**, 239-51.

Rashid M. H., Asaeda T. & Uddin M. N. (2010) The allelopathic potential of kudzu (*Pueraria montana*). *Weed Science* **58**, 47-55.

Supplementary figure legends

Figure S1 Pamphlet distributed amongst local foresters, conservation officers, botanist and conservationists requesting *Pueraria montana* localities and information.

Figure S2 To determine whether mapping sprouting rootstocks is a reliable measure of patch perimeter, we systematically surveyed one population at the start of the growing season and compared this to a map obtained later in the season. The blue line is a track of the above-ground population of 5.7 hectares surveyed in January 2012 within a eucalyptus plantation. The black dots are growing points mapped during August 2013 (the apparent linear nature of the growing points is an artefact of how the area was surveyed, by walking up and down forestry rows). The black line encompasses the entire area surveyed in August 2013 and consisted of tar and gravel road surrounding the population, preventing further spread. Growing points were only found where vegetation was mapped the previous season, meaning that the mapping of vegetation at this site provided a very accurate indication of where rhizomes will be. The site was sprayed by herbicide and burnt, and so the lack of increase from 2012 to 2013 is not surprising.
Google Earth 6.0.1 2010. Sudwala pass 25°20'05.6" S 30°44'42.4" E <http://www.google.com/earth/index.html> [Viewed 19 May 2015].

Figure S3 (a) *Pueraria montana* (kudzu vine) invasion of a eucalyptus forestry plantation close to the initial introduction site in Mpumalanga Province of South Africa; (b) *P. montana* smothering native and alien riparian vegetation at the site of initial introduction; (c) The typical legume flowers of *P. montana* attract honeybees and carpenter bees; (d) Pods are borne in clusters, but seeds are of little importance in spread in South Africa; (e) Some particularly badly damaged leaves through herbivory, this seemingly does not restrict growth; (f) The blister beetle *Mylabris oculata*, might be partly responsible for leaf herbivory as well as damage to the flowers.

Figure S4 Predicted global distribution of *Pueraria montana* based on occurrences in both its native and alien ranges (see methods for further details). (a) Occurrences indicated by black dots. (b) Projected presence (black) or absence (grey) of *P. montana* using the 95th percentile relative likelihood of presence (of all occurrences) as a threshold. (c) Projected relative likelihood of presence of *P. montana* (Maxent raw output). Darker shading indicates a higher relative likelihood of presence. For (b) and (c) areas masked in light grey indicate novel environmental space, i.e. where the model would be extrapolating.

Figure S5 Response curves of environmental predictors for a Maxent model of *P. montana* relative likelihood of presence. Temperature variables are all measured in degrees Celsius and precipitation variables in mm. Rug lines on the lower x-axes represent values at which *P. montana* occurrences are found, and rug lines on the upper x-axes represent values for pseudo-absences.

Figure S6 Predicted distribution of *Pueraria montana* in South Africa. (a) Projected presence (black) or absence (grey) of *P. montana* using the 95th percentile relative likelihood of presence (of all occurrences) as a threshhold. (b) Projected relative likelihood of presence of *P. montana* (Maxent raw output). For (a) and (b) occurrences are indicated by open circles and areas masked in light grey indicate novel environmental space, i.e. where the model would be extrapolating.

INVASIVE PLANT ALERT

Have you seen this plant?

Kudzu vine

Scientific name: *Pueraria montana* var *lobata* (family: Fabaceae)

Environmental Affairs
Agriculture, Forestry and Fisheries
Water Affairs

WORKING FOR WATER

EXPANDED PUBLIC WORKS PROGRAMME
CONTRIBUTING TO A NATION AT WORK

SANBI
Biodiversity for Life

Pueraria montana var *lobata* (Willd.) Ohwi (kudzu vine) was probably introduced into South Africa as an ornamental and for erosion control. The earliest record at the Pretoria National Herbarium is of a specimen collected in Mpumalanga at Brookland State Forest in 1985, but the species has since spread to Schagen valley between Sudwala and Rosehaugh. It has been recorded in Limpopo and KwaZulu-Natal, and a Gauteng population was verified to be kudzu at Mamelodi.

Kudzu vine forms dense mats over the ground, debris, shrubs, and trees by twining around objects. It invades forest margins and gaps, riverbanks, and moist areas. It smothers desirable plants and causes them to collapse. Kudzu vine is a legume, and can thus fix nitrogen and enhance soil fertility. This may also affect indigenous species. It is very drought tolerant, which makes it even more aggressive. In the United States, kudzu vine has taken over many areas, especially in the southern parts of the country, and control of kudzu vine runs to billions of dollars. Farmers need to be aware of kudzu vine as it can be mistaken for soybean when it is still young and it can be an alternate host for soybean rust.

The EDRR programme will attempt to control this species before it spreads any further.

Description

Pueraria montana var *lobata* is a perennial, long-running, hairy vine that can climb up to 18 m high, is somewhat woody, with tuberous roots, and have leaf stalks and stems covered with rusty-brown hairs. Leaves are light green, finely hairy, and 3-foliolate; leaflets with margins entire or shallowly lobed, 70–150 mm long, abruptly sharp-pointed but not bristle-tipped. Flowers are reddish-purple, fragrant, in spikes up to 300 mm long. Pods flattened, clustered, 50–130 mm, covered with long rust-brown hairs. Flowering time: January–April.

What you can do to help

Report sightings of kudzu vine and other invasive species.

Where possible please provide us with

The locality: report sightings of these plants to the Early Detection and Rapid Response Programme (EDRR) team. We will need to know its locality (the exact locality, supply any landmarks or GPS information if possible).
The infestation size: provide an estimate of the number of plants per hectare/site.

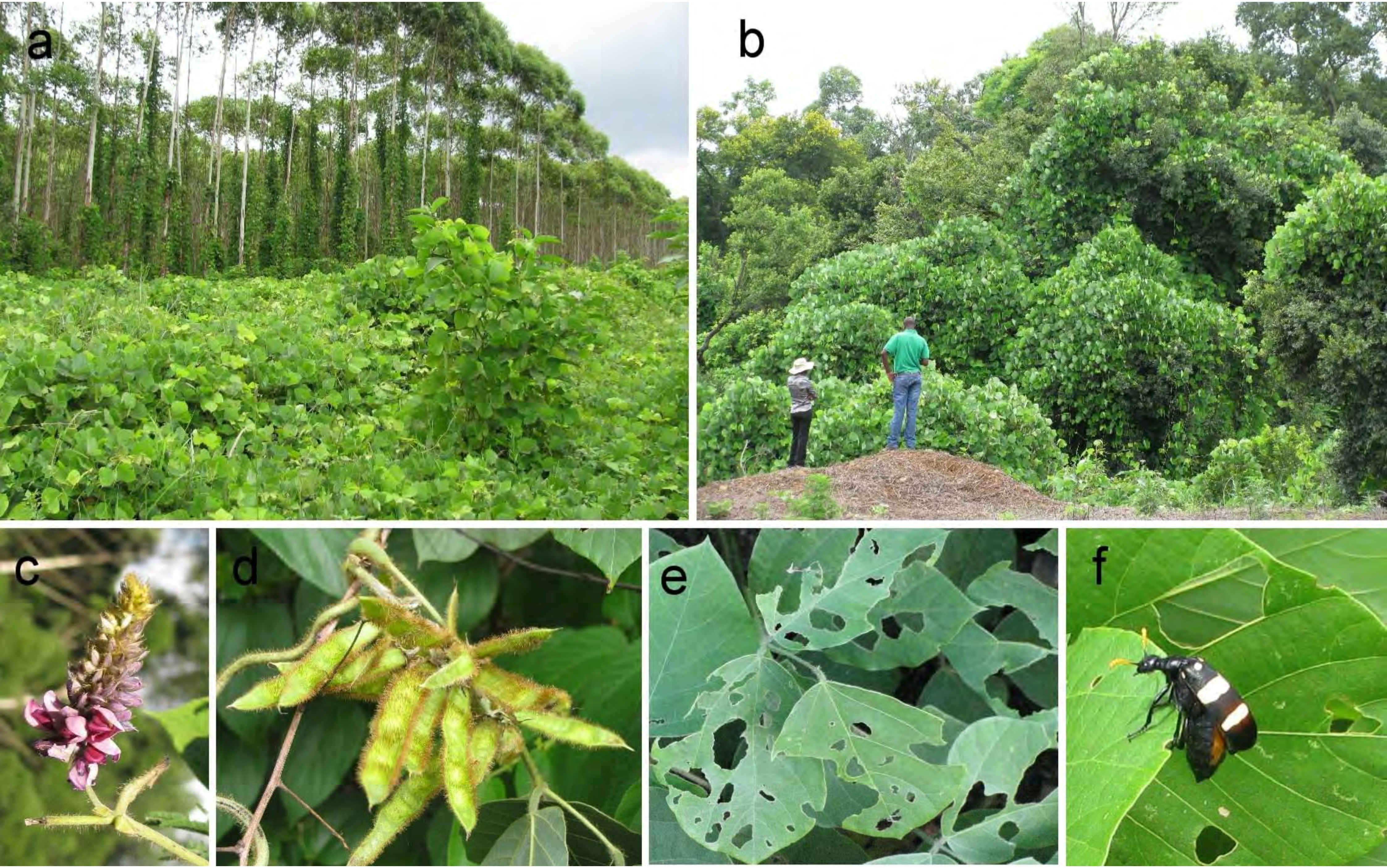
Contact us:

alienplants@sanbi.org.za
Mr Bongani Vincent Mashele, Mpumalanga Province Regional Coordinator, tel 013 752 6504 or e-mail: b.mashele@sanbi.org.za
Mr Phetole Manyama, Deputy National Coordinator (Northern Regions)
Tel 012 843 5000/5024 or e-mail: p.manyama@sanbi.org.za

The South African National Biodiversity Institute (SANBI) has a legal mandate to promote the conservation of South Africa's biodiversity and also to monitor and report on invasive alien species. Therefore, in addition to the work done by the Department of Agriculture, Forestry and Fisheries, the Agricultural Research Council and others, SANBI, in partnership with these organisations, has developed a programme of Early Detection and Rapid Response for Invasive Alien Plants with initial funding from the Working for Water Programme (DEA). This initiative seeks to reduce the incidence of plant invasions in South Africa through early detection and identification of emerging alien plants. Once the identity of the potential invasive plant has been verified, risk assessment and response planning are undertaken to ensure that the recommended control methods are implemented.

SANBI Publications. 2012.


8/23/2013
269 m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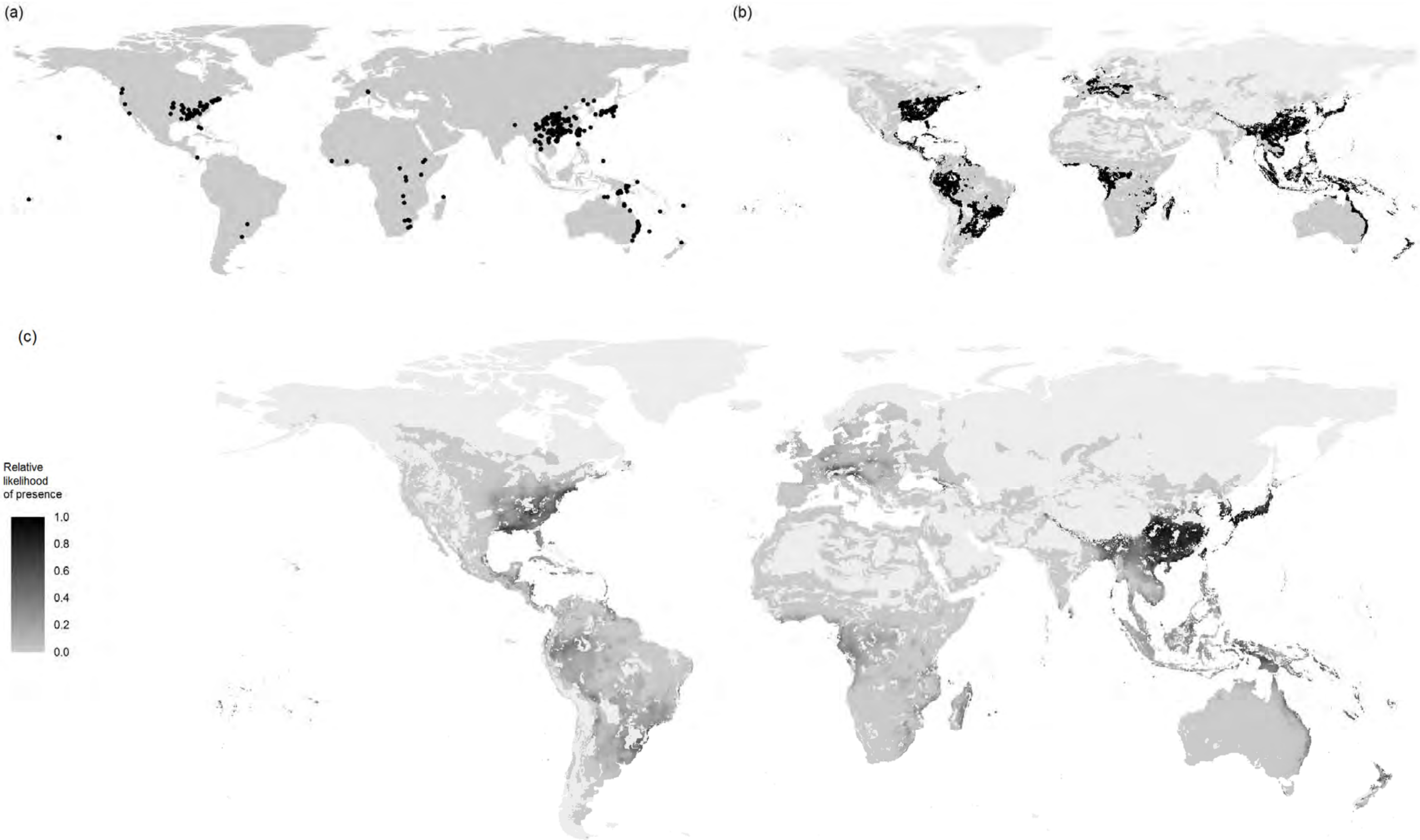
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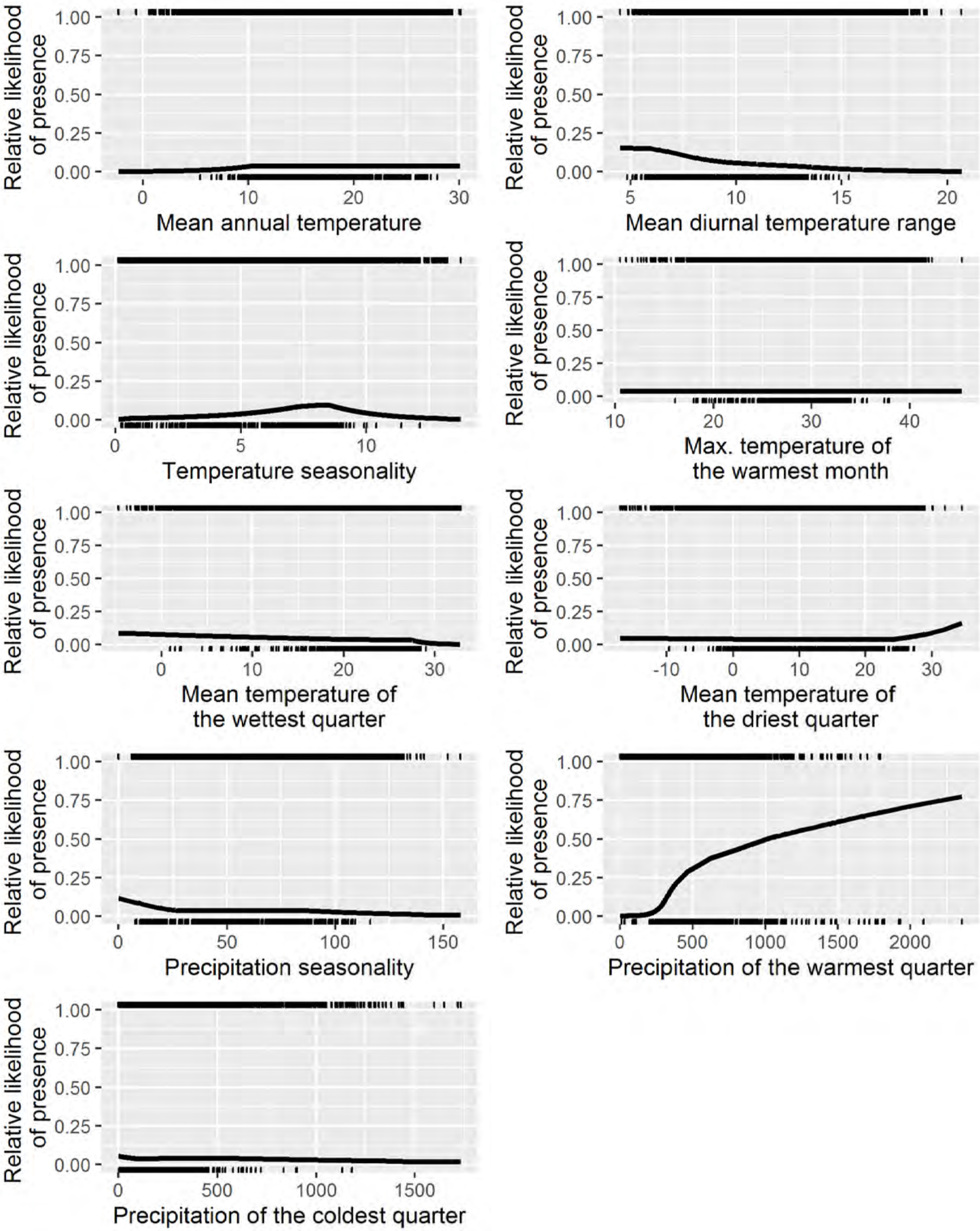
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Mean annual temperature
Mean diurnal temperature range
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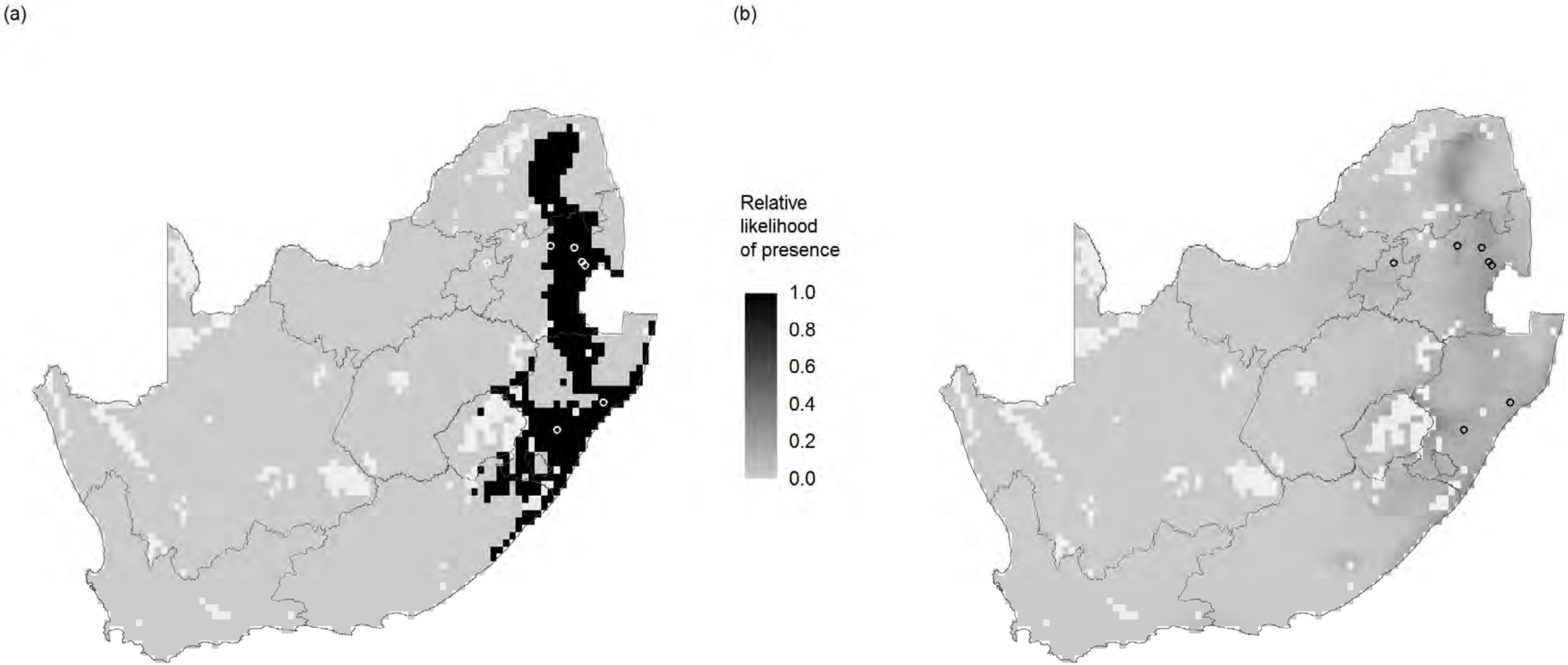
Mean temperature of the wettest quarter
Mean temperature of the driest quarter
Precipitation seasonality
Precipitation of the warmest quarter
Precipitation of the coldest quarter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Relative likelihood of presence
1.0
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