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Improved surveillance for early detection of a potential invasive species: the alien Rose-ringed Parakeet *Psittacula krameri* in Australia

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Abstract

The Rose-ringed parakeet *Psittacula krameri* is the most widely introduced parrot in the world, and is an important agricultural pest and competitor with native wildlife. In Australia, it is classified as an '*extreme threat*', yet captive individuals frequently escape into the wild. The distribution and frequency of incursions are currently unknown, as are the potential impacts of the species in Australia. This lack of critical ecological information greatly limits effective biosecurity surveillance and decision-making efforts.

We compiled a unique dataset, which combined passive surveillance sources from government and online resources, for all available information on parakeet detections at-large in Australia. We investigated whether geographic variables successfully predicted parakeet incursions, and used species distribution models to assess the potential distribution and economic impacts on agricultural assets.

We recorded 864 incursions for the period 1999-2013; mostly escaped birds reported to missing animal websites. Escapes were reported most frequently within, or around, large cities. Incursions were best predicted by factors related to human presence and activity, such as global human footprint and intensive land uses. We recommend surveillance of high (predicted) establishment areas adjacent to cities where a feral parakeet population could most affect horticultural production.

Novel passive surveillance datasets combined with species distribution models can be used to identify the regions where potential invasive species are most likely to establish. Subsequently, active surveillance can be targeted to the areas of highest predicted potential risk. We recommend an integrated approach that includes outreach programs involving local communities, as well as traditional biosecurity surveillance, for detecting new incursions.

Key-words: biosecurity; economic impact; online resources; pet trade; propagule pressure; species distribution modelling

Introduction

One of the greatest difficulties for managing invasive species is that once the invader has established (and spread), control can be extremely costly and difficult (Myers et al. 2000; Pluess et al. 2012a). Landowners and biosecurity agencies invest considerable resources mitigating the damages of invasive pests, yet, control techniques are often economically or environmentally unsustainable, or simply ineffective (Bomford and Sinclair 2002; Tracey et al. 2007). Preventing the establishment (or introduction) of invasive species is usually considered the most cost-effective management option (Keller et al. 2007). Early detection of new invasions is a pivotal element of any prevention strategy (Myers et al. 2000; Leung et al. 2005). However, surveillance can be costly, and complicated by uncertainty in establishment areas and the impacts the parakeets may cause. In this study we used the case of the introduction of the Rose-ringed parakeet *Psittacula krameri* (Scopoli, 1769), hereafter parakeet, in Australia to demonstrate how passive surveillance and currently available analytical techniques can be directly applied to improve early detection programs and predict the distribution of new (potential) invasive species.

Invasive pest birds pose major threats to agricultural and natural systems, causing damage of over AU$300 million per year in Australia and US$1.9 billion per year in the United States (Pimentel et al. 2005; Gong et al. 2010). In addition to the 27 alien bird species already established across Australia (Evans et al. 2014), new alien species are regularly detected (Henderson et al. 2011). Currently, the parakeet is an emerging pest of major interest in Australia due to its extensive history as an invasive species elsewhere. The parakeet is the most widely introduced parrot species in the world (Lever 2005), and is regarded as one of the worst agricultural pest birds in Asia (Dhindsa and Saini 1994), and a potential threat to Europe (Strubbe and Matthysen 2009a; Vilà et al. 2009; Kumschick and Nentwig 2010). In its area of natural distribution they inflict heavy damage on important grain crops, oil-seeds, fruits and vegetable crops (see Table S1 in Online Resource 1). A feral parakeet population established in Australia would represent a particular risk for agricultural production, as the parakeet is known for being a pest of multiple commodities currently grown in Australia; such as cereals, vegetables, citrus fruit and grapes (Dhindsa and Saini 1994; Fletcher and Askew 2007; Tayleur 2010).

Previous risk assessments have identified a high species-climate matching with Australia and have scored the bird with a 'serious' or 'extreme' risk of establishment if introduced (Bomford 2003; DAFWA 2007; Latitude 42 2011). For these reasons, the parakeet has been classified by Australian authorities as an '*extreme threat species*' (VPC 2007). Accordingly, the general policy position for the species is that it '*should not be allowed to enter or be kept in Australia*' (VPC 2007). Yet, the parakeet is one of the most popular pet species in the domestic bird market (Australian Birdkeeper 2011-2013; The Avicultural Society of Australia Inc. 2011-2013) and is widely available at a relatively low price (The United Bird Societies of South Australia Inc. 2003-2013; The Avicultural Society of Australia Inc. 2012-2014). The species is considered suitable for live import (Department of Environment 2001), and trade and keeping of parakeets is legal throughout Australia, with few restrictions (Wilson 2011). Despite its high potential to become a pest, little is known about current occurrence of parakeet incursions in the wild or the potential impacts of its establishment. This lack of information is clearly an obstacle for effective monitoring and control strategies. The main objective of this study was to explicitly address this knowledge gap and provide critical procedures to inform decisions on how to better prioritize management, and resources to prevent the establishment of this emergent invasive alien species.

A major knowledge gap, regarding the status of the parakeet at large, is the lack of information on the number and distribution of incursion events. This information is critical because propagule pressure (defined here as the total number of individuals of an alien species released into a defined location) is one of the strongest correlates of establishment success (Lockwood et al. 2005; Lockwood et al. 2009). However, most parakeet incursions (as well as other emerging invasive species) do not leave readily identifiable traces, and are therefore never reported, or recorded. To date, we found published information for only 96 parakeet incursion events reported to biosecurity agencies (Henderson and Bomford 2011), and six escapes from zoos (Cassey and Hogg 2015). However, given that the bird is so common in captivity, we strongly believed that this was a highly inaccurate record of Australia-wide incursions. In this study, we used public online resources as a novel tool for passive surveillance to provide information on the number and distribution of parakeet incursions. In the last decade different internet citizen initiatives have been developed, particularly through social networks, with the aim of reuniting missing companion animals with their owners, and a set of these exist that provide information for missing birds.

A second problem, is that previous risk assessments, used to identify areas of suitable habitat for the parakeet in Australia, were based on simple climatic niche models (DAFWA 2007; Bomford 2008). This type of approach can result in a considerable mismatch between the suitable habitat area and the locations where the species is more likely to occur, because it fails to account for the association of the parakeet with human-modified habitats, either as a source of new incursions (Chiron et al. 2009) or as a habitat where the species can persist (Strubbe and Matthysen 2009b; Strubbe et al. 2015). Here we attempted to overcome this challenge by including, in our analysis, the relationship of the parakeet with human-modified habitats. First we used information on parakeet introductions to predict the spatial distribution of the relative probability of incursions (an incursion risk surface) occurring in mainland Australia as a function of human impact variables and socio-economic variables related to the distribution of pet ownership; because accidental escapes is the major pathway of introduction of the parakeet in Australia (Henderson et al. 2011). Second we developed an environmental matching model by creating a predictive parakeet habitat model using global presence data as a function of environmental variables and the distribution of human-modified habitats (Strubbe et al. 2015). We combined the incursion risk surface with the environmental matching model to predict the potential establishment area of the parakeet in Australia. Finally, we assessed the spatial variation of potential impacts on agricultural commodities, in order to identify the locations where surveillance, monitoring and control can be best employed, hence contributing to the most cost-efficient preventative management action.

Methods

Study species

The parakeet is a long-tailed, grass green, red-beaked parrot, 37 to 43 cm in length (including the tail). Males have a narrow black and pink collar that is absent in females and immature birds. Four subspecies are currently distinguished: *krameri* and *parvirostris* are distributed across sub-Saharan Africa, while Asian subspecies *borealis* and *manillensis* are present in the Indian subcontinent (Juniper and Parr 1998). In addition to the natural varieties imported to Australia, many artificial colour bred mutations have become common in captivity (Aus Birdkeeper 2011-2013; Avi Soc Aus 2011-2013).

Data collection

We collected all available information on parakeet incursion events in Australia from: (i) State and Territory government departments responsible for implementing biosecurity; (ii) the Atlas of Australian Birds; (iii) reports to citizen science initiatives; (iii) escape events from public institutions; and (iv) reports to missing animal internet pages (see Table S2 in

Online Resource 1; and Online Resource 2 for the complete list of references and the corresponding internet links).

We obtained data on the distribution of the parakeet overseas from the Global Biodiversity Inventory Facility (GBIF; http://www.gbif.org) and eBird (http://ebird.org/ebird/data/download). To increase sample size, and to confirm the status of the GBIF observations, we used literature reviews on naturalised species (Lever 2005) and recent publications on feral parakeet populations (Nebot 1999; Eguchi and Amano 2004; Butler 2005; Fletcher and Askew 2007; Strubbe and Matthysen 2009a). Species distribution models (SDMs) tend to under-predict the potential distribution of introduced species when trained only with data on the native distribution because the realized niche of the native range can underestimate the full potential climate niche of a species (Broennimann and Guisan 2008). We have dealt with this issue by using distribution data from both the native and introduced populations. Introduced populations were only included if breeding, or established status, for the species was confirmed. Our final dataset included 13,616 unique locations from 56 countries, of these 36.8% were locations of introduced populations and 63.2% were native populations.

We used a set of environmental variables, which were previously reported to provide the most accurate bird distributions with the least collinearity (Barbet-Massin and Jetz 2014). Bioclimatic variables were obtained from the WorldClim dataset (version 1.4; Hijmans et al. 2005; http://www.worldclim.org/). The dataset contains information for 19 bioclimatic variables, averaged over 1950-2000. We selected six bioclimatic variables: annual mean temperature (bio1), mean diurnal range (bio2), temperature seasonality (bio4), mean temperature of the driest quarter (bio 9), annual precipitation (bio12) and precipitation of the warmest quarter (bio18). Climate moisture index (MI; Vörösmarty et al. 2005) was obtained from Data Basin (http://databasin.org/datasets/).

Human impact was measured using the Human Influence Index (HII) from the Global Human Footprint project (Sanderson et al. 2002; Wildlife Conservation Society - WCS and Center for International Earth Science Information Network - CIESIN - Columbia University 2005). Data on human population density (number of humans/km^2) was extracted from the Gridded Population of the World database (Balk & Yetman 2003). We obtained information on land use from the Australian Bureau of Agricultural and Resource Economics and Sciences website (ABARES; http://www.agriculture.gov.au/abares). We obtained data on average personal income and age structure of the population from the Australian Bureau of Statistics (ABS; http://www.abs.gov.au/). We refer the reader to Online Resource 1 for the complete details on data extraction, the list of references and the corresponding links. All data manipulation and analyses were conducted in the R software environment for statistical computing and graphics version 3.03 (R Core Team 2015). Datasets were manipulated with the R- packages ‘raster’ (Hijmans et al. 2014) and ‘dismo’ (Hijmans et al. 2013).

We conducted an extensive and systematic review of the economic impacts of the parakeet overseas, and identified the agricultural commodities known (and reported) to be damaged by the parakeet. We searched publications in peer-refereed journals in Web of Science and Google Scholar from 1964 to the present using the following keywords: *Psittacula krameri*; Indian Ringneck; Rose-ringed Parakeet; Ring-necked Parakeet. This search yielded over 2,380 references, which were refined using terms for economic consequences: impacts; damage; management. We complemented the review using Juniper and Parr, (1998); Collar, (1997); Lever, (1987; 2005); and references therein. Most information of parakeet impacts on agricultural commodities is from the native range, particularly the Indian sub-continent, where the damage has been identified and quantified more extensively (see Table S1 in Online Resource 1). Impacts on agricultural commodities in the introduced range have been identified but information is mostly anecdotal (Butler 2003; Dubois 2007; Fletcher and

Askew 2007; Kumschick and Nentwig 2010; Tayleur 2010; Strubbe et al. 2011; Menchetti and Mori 2014; and references therein). We assumed that these commodities would be similarly threatened if an introduced parakeet population were to become successfully established in Australia. We collected information on the distribution of the economic value of these commodities from the ABS database (see Online Resource 2).

Analysis

Parakeet incursion risk surface in Australia and environmental matching

We used generalised linear models (GLMs) to identify the relevant putative factors associated with the risk of parakeet incursions in Australia. Parakeet incursion events were included as presence data, and because no absence data were available, a total of 50,000 random points were generated to be used as background pseudo-absence data (Phillips et al. 2009). Given that the chance of incursion, or of detecting an incursion, in the desert is arguably close to zero, we used the HII GIS raster layer to place the random points within a buffer around towns, cities and major roads, and created using the HII layer as a mask. We used the lower scores of the HII (HII < 4) to identify and exclude the areas of the Australian mainland without significant human impact (Sanderson *et al.* 2002), then we used this layer to place the background points, and as a mask for the rest of the layers of the predictors. The buffer covered 61% of the surface of Australia. GLMs were fitted using the R-package ‘dismo. The occurrence of parakeet incursions was modelled with a binomial error distribution and a logit link function. To balance model fit and predictive performance all of the models were calculated using 10-fold cross-validation and the procedures were run 50 times to ensure stable estimates of model evaluation statistics. To avoid problems with model fitting, due to collinearity, we checked for highly-correlated pairs of variables (Pearson’s $r \leq |0.7|$). Collinearity amongst the different variables was low (see Table S3 in Online Resource 1).

We used the R-package ‘MuMIn’ (Barton 2013) to fit all possible combinations of explanatory variables to identify the most likely models, and to calculate Akaike Information Criterion (AIC) values that were used to rank and weight models (Anderson and Burnham 2002). For the models with ΔAIC < 4 of the best model we calculated the model-averaged estimates and standard deviations. The distribution of the values of the model-averaged estimates and standard deviations for all the variables are presented as coefficient plots. We generated the parakeet incursion risk surface using R-package ‘dismo’ following the recommendations in Hijmans *et al.* (2013). The GLMs produced relative probabilities of an incursion event occurring in a grid cell.

For the environmental matching model, the data on the distribution of the parakeet overseas was used as presence data and we generated 100,000 random background points to be used as pseudo-absence data to accurately sample the environments available to parakeets. We used GLMs to predict the potential spatial distribution of parakeet in Australia. We fitted the models with the environmental variables (the six bioclimatic variables plus MI) and HII as predictor variables with the same specifications as before (binomial error distribution, logit link function, 10 fold cross-validation and 50 runs).

Because the geographic data for the predictors were available at different native resolutions all the datasets were reprojected to the lowest native resolution available, using bilinear interpolation for continuous variables and nearest neighbour for categorical variables. For the parakeet incursion risk surface we reprojected the predictors at 5km grid cells. This resolution matches the scale to which the moderator data was collected (i.e., suburb level) and captures accurately spatial heterogeneity of where birds are most likely to escape captivity. For the environmental matching model we reprojected the variables at 60km grid cells. Climatic covariates do not vary too much over a 60 km area, so the resolution is appropriate and the map reflects the realistic range limits for the birds.

For evaluating the performance of our model we fitted null models without any covariates and compared the AIC with our full models. This is a null model for predicting incursion events based uniquely on the mean relative probability of incursion, and a null model for the environmental matching based on the mean relative probability of matching. If the covariate models have predictive power, then their AICs should be substantially lower than the null model.

The predictive model of the parakeet incursion risk surface and the environmental matching model were combined using the function 'overlay' in the R-package 'raster' (Hijmans et al. 2014) to calculate the grid cells where high probability of incursion matched highly suitable habitat. This provided us with an estimate of the potential establishment area of the parakeet in Australia. For the combination the environmental matching layer was reprojected to match the incursion surface layer resolution.

Spatial variation in potential impacts

Finally, we considered two possible scenarios for the potential distribution of the economic impact. First, we considered a low risk scenario, where the parakeet does not spread beyond the introduction areas, given that it is predicted to be released in suitable habitat. This scenario combined the potential establishment area of the parakeet with the distribution of the value of agricultural commodities produced in Australia, as identified in the literature review to be potentially threatened by the parakeet. Second, we explored a high risk scenario, where the parakeet spreads beyond the predicted release areas by combining only the environmental matching model and the distribution of the value of agricultural commodities. Both scenarios were created using the function 'overlay' as before.

Results

Status of the parakeet in Australia

For the period 1999-2013 we recorded 861 parakeet incursion events in Australia, involving at least 1,151 individuals. Most of these events were concentrated in the period 2011-2013 (Fig. 1), largely due to an increase in the number of incursions reported to the Australian Rescue and Rehoming Resource. Information obtained from missing pet websites represented 74% of our final dataset (Fig. S1a in Online Resource 3). The majority of these reports corresponded to lost birds (67%) (Fig. S1b in Online Resource 3). The other sources of information (combined) represented 26% of all events; with being government agencies being the second most frequent source of information for parakeet incursions. The majority of parakeet incursions were reported from urban or peri-urban areas. Most of these incursions were concentrated within or around six Australian major metropolitan areas, and particularly along the east coast (Fig. 2). The Brisbane area accounted for c. 40% of all incursion events in Australia.

Potential distribution and impacts of the parakeet in Australia

<u>Parakeet incursion risk surface in Australia and environmental matching</u>

The performance of the incursion risk surface model was very high (median AIC [5^{th}; 95^{th} percentile] = 2,102.8 [2,056.2; 2,149.5]; compared to the null model AIC = 7,860.7). Parakeet incursions were positively related to the degree of human impact on the landscape as measured through the HII, and to intensive land use (residential settlement, commercial or industrial uses), and negatively related to land used for agricultural production (Fig. 3; Table S4 in Online Resource 1). These results supported our initial hypothesis that the majority of incursion reports come from urban and peri-urban areas (e.g., residential suburbs and parks), where parakeets have either escaped, or are more frequently sighted. Alternately, we found no relation between parakeet incursions and socio-economic factors; although average personal income appeared to be marginally significant (Fig. 3; Table S4 in Online Resource 1). The projection of the predicted distribution of parakeet incursions, according to our model, revealed that the area of parakeet incursions is unevenly distributed, but overlaps with the location of the major capital cities and the areas with greater urban development (Fig. S2). Likewise, the performance of the model for the environmental matching between parakeet native and introduced distribution to Australia was very high (median AIC [5^{th}; 95^{th} percentile] = 21,649.8 [21,554; 21,722.8]; compared to null model AIC = 65,667). The environmental matching model revealed that the areas of Australia more suitable for the parakeet's persistence are in the tropical north, whereas the arid and uninhabited interior, and largely the north, are predicted as less suitable. However, when human-modified habitats are included the predicted probabilities by the model are very low everywhere except in the main urban areas (Fig. 4a; Table S5 in Online Resource 1). The combination of the environmental matching model and the predicted distribution of incursions provided an explicit prediction for where the future establishment (i.e., breeding and recruitment) of the parakeet in Australia is most likely to occur. These areas are located within the suitable habitat distribution but mostly restricted to the urbanized areas (Fig. 4b-f).

Spatial variation in potential impacts

When contrasting our models with the distribution of the economic value of the agriculture commodities at greatest potential risk from parakeets (Fig. S3 in Online Resource 3), under the low risk scenario, the distribution of the parakeet reveals little overlap with the distribution of the most highly valued commodities. Under the high risk scenario the distribution overlaps the distribution of the agriculture commodities in the areas of suitable habitat, particularly the rural areas in the south western and south eastern corners of the continent (Fig. S4 in Online Resource 3).

Discussion

Our study provides first-hand information for the propagule pressure (incursion events) of an alien species introduced via accidental escape from widespread captivity. We have confirmed that the number of parakeet incursions in Australia had been considerably underestimated, by a factor of almost 10 (Henderson and Bomford 2011; Cassey and Hogg 2015). There is no evidence that the difference in the numbers between our dataset and previous records is associated with parakeets escaping more often, or more recently. Instead, we suggest that the disparity is mostly due to data becoming more accessible via the increased popularity of online internet resources. Parakeet incursions were reported to missing animal web pages much more frequently than to all other sources combined. We believe these online resources can be a useful tool for passive surveillance and early detection of other alien species, especially birds, but also amphibians, reptiles or mammals introduced via the pet trade (Derraik and Phillips 2009; Kikillus et al. 2012; García-Díaz and Cassey 2014).

We found that the parakeets were more likely to be reported at large in areas with a high degree of human impact on the landscape, i.e., urban and peri-urban areas in suitable habitat, from where the parakeets are more likely to escape. However, besides previous breeding observations in Western Australia (Susan Campbell, Department of Agriculture and Food, Western Australia; pers. comm.), the parakeet has not established any feral populations in Australia, despite the high frequency of incursions reported here. We suggest two non-mutually exclusive explanations for the lack of established parakeet populations in Australian cities, to date. First, most incursions involve only one or two individuals. According to ecological theory, a reduced initial population is very vulnerable to extinction by environmental and demographic stochasticity, and has little probability of surviving the founder event (Cassey et al. 2014). Propagule pressure has been shown to be an important predictor of the establishment of alien birds in Australia (Duncan et al. 2001). Second, these birds usually disappear shortly after being reported. From descriptions provided in the reports, we deduced that many of these birds are captive bred animals; therefore they are highly dependent on humans for food and shelter (Clubb, 1998; Engebretson, 2006). Consequently, it might be assumed that these animals have reduced skills for surviving on their own, and the probability of starting a self-sustaining population is particularly low (Carrete and Tella 2008).

We found no evidence that parakeet incursions are related to communities with a higher proportion of elderly, families with children, or higher average personal income areas. Previous studies have shown that bird-keeping is a symbol of higher socio-economic status among increasingly urban societies (Jepson and Ladle 2005), and that demand for pets increases as societies progressively achieve higher living standards (Chiron et al. 2010). We suggest two possible explanations for this detour from the general trend. First, the parakeet is one of the least expensive species of the medium sized parrots regularly found in the pet trade (Bird Soc SA 2003-2013; Avi Soc Aus 2012-2014), and second bird keepers in Australia are likely range across the socio-economic spectrum (Animal Health Aliance 2013). Therefore, the keeping of parakeets could be distributed more evenly across the population and less concentrated in particular population groups.

Risk assessments based on SDMs, which use only environmental envelopes, have a major limitation for predicting potential distribution. By not considering other major drivers of establishment, such as propagule pressure (Lockwood et al. 2005) and the use of human modified habitats (McKinney 2006), predictions could lead to identifying suitable areas where the species will never be introduced (Bellard et al. 2013). Previously predictive models for the potential distribution of the parakeet in Australia (DAFWA 2007; Henderson & Bomford 2011b), using CLIMATCH (BRS 2006) as a modelling algorithm, predicted a wider distribution of the parakeet in Australia, including the vast interior of the continent, where it is very unlikely that the species would be ever released. We used a GLM based approach that allowed us to include important variables, other than climatic variables, such as HII. Previous studies have found evidence that establishment success is correlated with measures of human activity (Strubbe and Matthysen 2009b; Chiron et al. 2009). Recently human modified habitats has been shown to accurately predict the invasion risk of the parakeet in Europe (Strubbe et al. 2015). Human activity is suggested to enhance establishment by providing the necessary resources for their survival and by increasing introduction effort (Pithon 1998; Strubbe and Matthysen 2009b). Likewise, parakeets introduced in arid environments, such as Australia, are found to be strongly dependent of human altered habitats (Eason et al. 2009). This association is suggested to be related to the distribution of water and food resources, and trees in arid zones.

We suggest that surveillance and control efforts should be focused on those areas where incursions occur most frequently, because these are the areas where propagule pressure is greatest. We also highlight the importance of considering human-mediated processes (e.g., pet trade and bird-keeping), in order to fully understand potential species distribution (Leung and Mandrak 2007). By including information on the predicted distribution of incursions and excluding the areas, where there is very low likelihood that the species will occur, we have improved our ability to predict the areas that should be preferably monitored. This information will allow for a better management of monitoring efforts in areas with greatest likelihood of parakeet establishment.

Finally, by using the distribution of the economic value of potentially affected agricultural commodities we have further refined the recommendation of surveillance activity to areas at greater risk of economic damage, and adjacent areas to the commodities most likely to support breeding populations. Under our low risk scenario, we think it is likely that a feral parakeet population could affect horticultural production adjacent to urban areas: in the UK the parakeet has come into conflict with growers of stone, berry fruit and grapes in the urban/rural fringe, causing damages estimated in thousands of pounds annually (Fletcher and Askew 2007; Tayleur 2010). While these damages might seem unimportant from an economic perspective, initially, they would still likely generate complaints from the growers. Moreover, under the high risk scenario, if the birds are allowed to establish in the cities, they may expand along natural and artificial corridors, such as rivers or highways and eventually affect high value crops in rural areas. This trend has been documented in Europe where the species is now well established (Fletcher and Askew 2007; Strubbe et al. 2010). Therefore, the potential impact of the parakeet in Australia appears to be largely dependent on the management of their populations at large: if allowed to establish and spread we should expect the species to establish over all suitable habitats, as it has happened elsewhere, resulting in the predicted high-risk scenario. However, if their populations are destructively managed, like in the case of Western Australia, we should expect the low risk scenario and minimal impact.

Management options

Preventing the arrival, introduction, or establishment of a new species is commonly suggested as the most cost-effective and efficient strategy for dealing with alien species and helping mitigate their impacts (Myers et al. 2000; Leung et al. 2002; Keller et al. 2007). Recently released alien species are easiest to remove as close to detection as possible, before they can disperse (Pluess et al. 2012a; Pluess et al. 2012b). Given the high potential for parakeets to establish in Australia, and become agricultural pests, we have advocated for intervention, particularly when any breeding activity is detected, or when multiple birds are congregating at a particular location. This relies on early reporting and follow-up detection.

It was previously recommended that '*Australia's biosecurity system will be most effective if resources are targeted to those areas of greatest return from a risk management perspective*' (Beale et al. 2008; Pp 26). Yet, our analyses have revealed that the vast majority of reports do not make it to the agencies with legislative responsibility for early intervention. We suggest that there currently exists a disconnection between onshore biosecurity agencies and the broader community. It is vital that government agencies responsible for biosecurity surveillance become 'more flexible' in the way they collect and use information; particularly when they are faced with increasingly limited and scarce resources. Our analyses have shown that there exist alternative data sources, where information can be directly or indirectly obtained. More specifically, we have used missing pet websites as a novel resource to obtain information on the numbers and localization of newly escaped companion animals, and this constitutes a useful source of information to better understand bird incursions generally.

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Figure captions

Fig. 1. Frequency of parakeet incursion events for the period 1999-2013. Abbreviations are: Zoos, Zoos and Aquarium Association; Missing pets, Australian Rescue and Rehoming Resource; Citizen science, Atlas of Living Australia, Eremaea E-bird and Birding-Aus; Biosecurity, Biosecurity and quarantine government agencies; and Atlas, Birdlife's Atlas of Australian Birds.

Fig. 2. Distribution of parakeet incursion events in Australia for the period 1999-2013 (60x60 km cell resolution). Brisbane area accounted for 40.6% of all incursion events, followed by Perth (24%), Sydney (19.5%), Melbourne (9.7%) and Adelaide (3%).

Fig. 3. Coefficient plot of the generalised linear model for risk of parakeet incursions events in Australia. Positive regression estimates represent higher frequency of incursions.

Fig. 4. (a) Distribution of suitable habitat for the persistence of the parakeet in Australia (60x60 km cell resolution). Environmental matching model fitted with six bioclimatic variables, MI and HII. (b-f) Insets for the distribution of potential establishment area of the parakeet (5x5km cell resolution) for (b) Sydney, (c) Melbourne, (d) Brisbane, (e) Adelaide, and (f) Perth. Predictive maps created by the combination of the environmental matching model (Fig. 4a) and the incursion risk surface (Fig. S2) projections.

Figure 1

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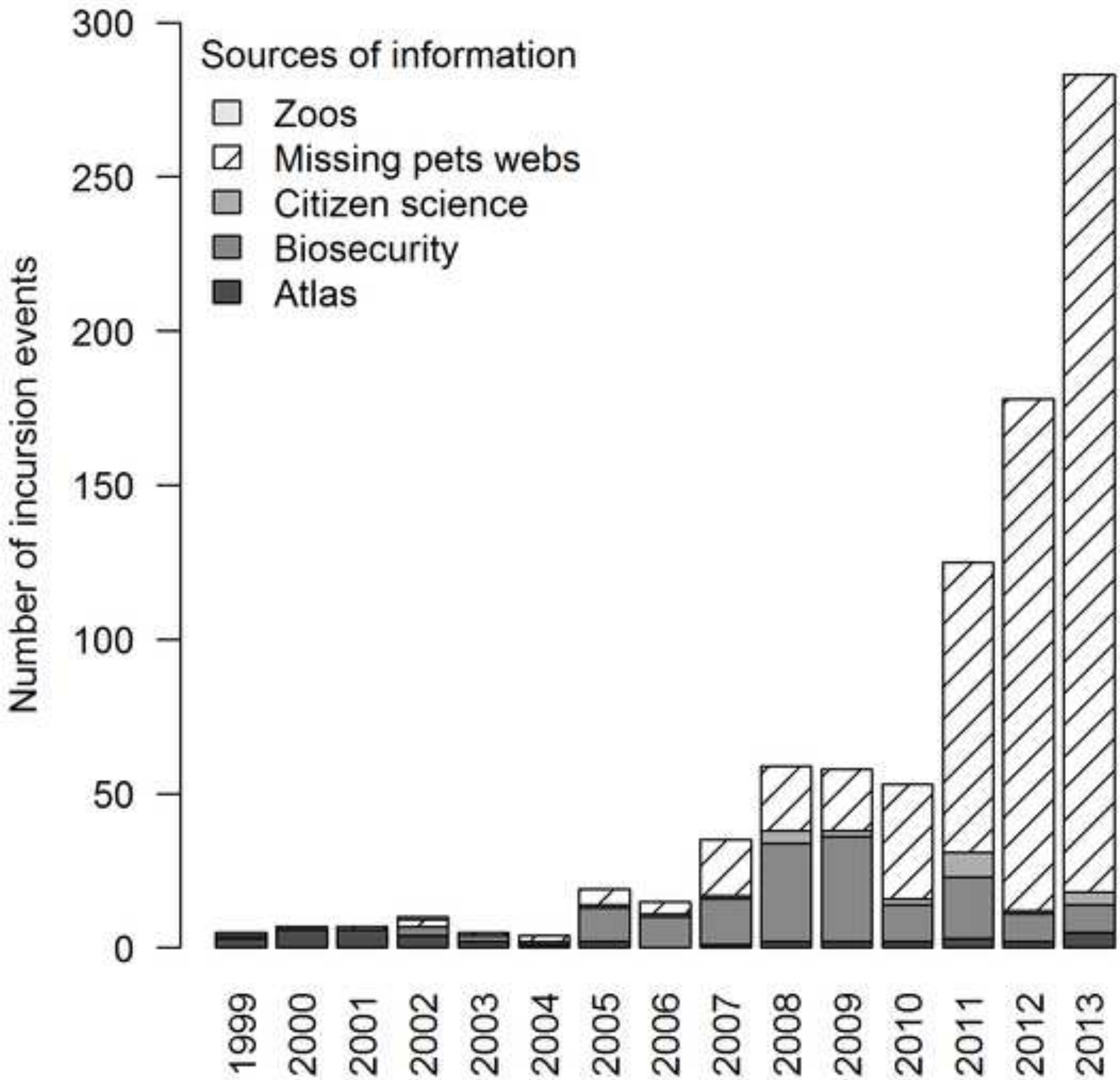

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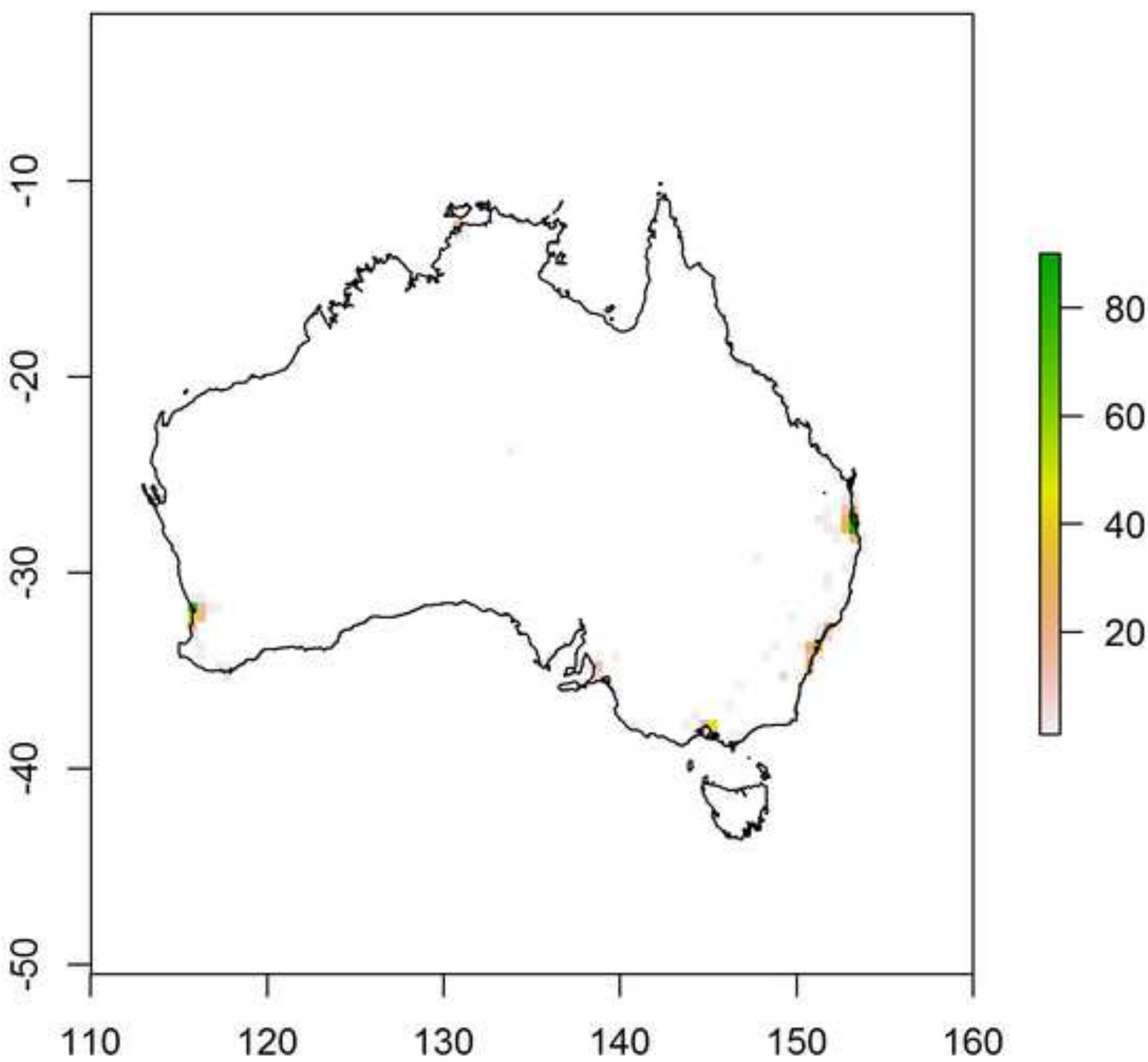

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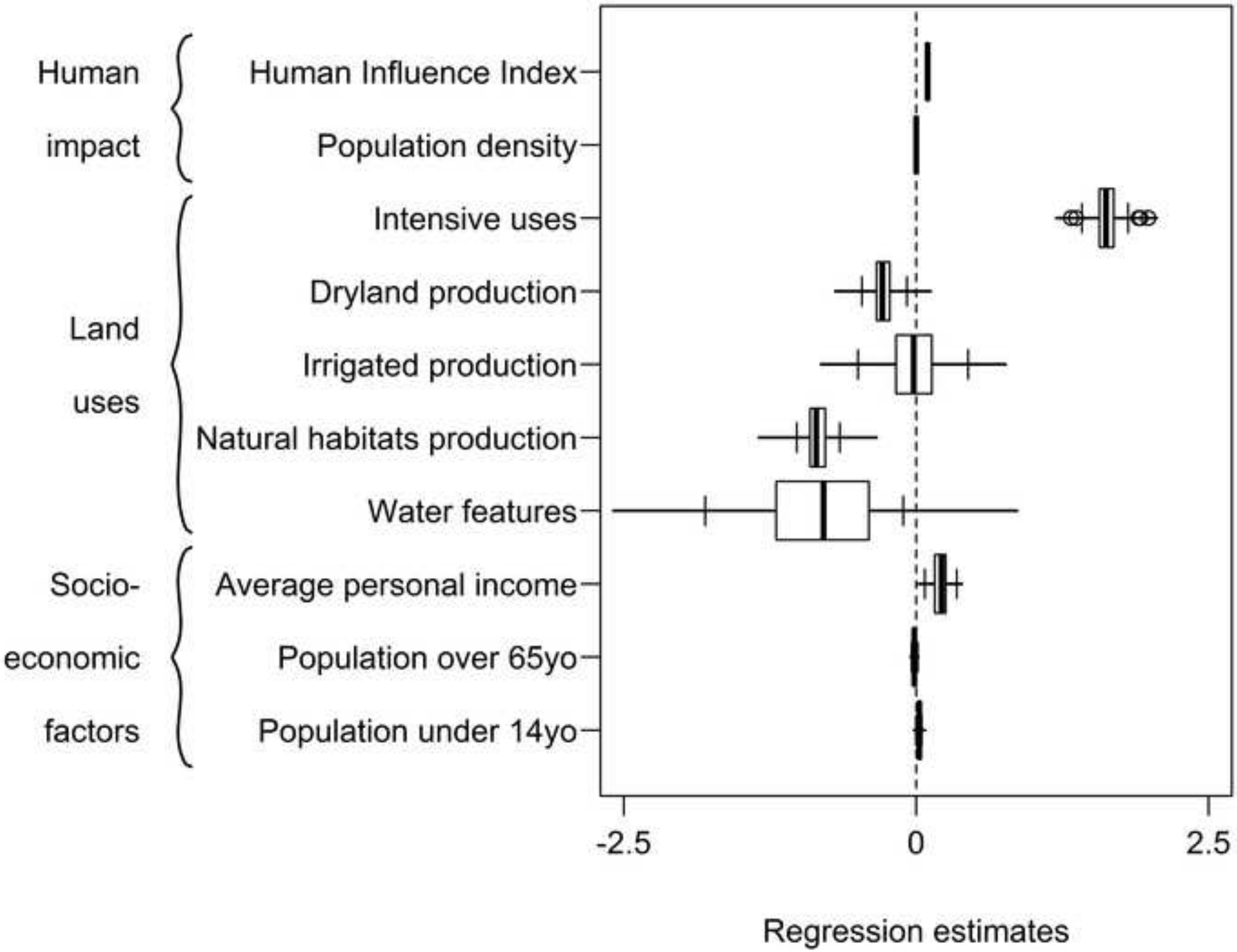

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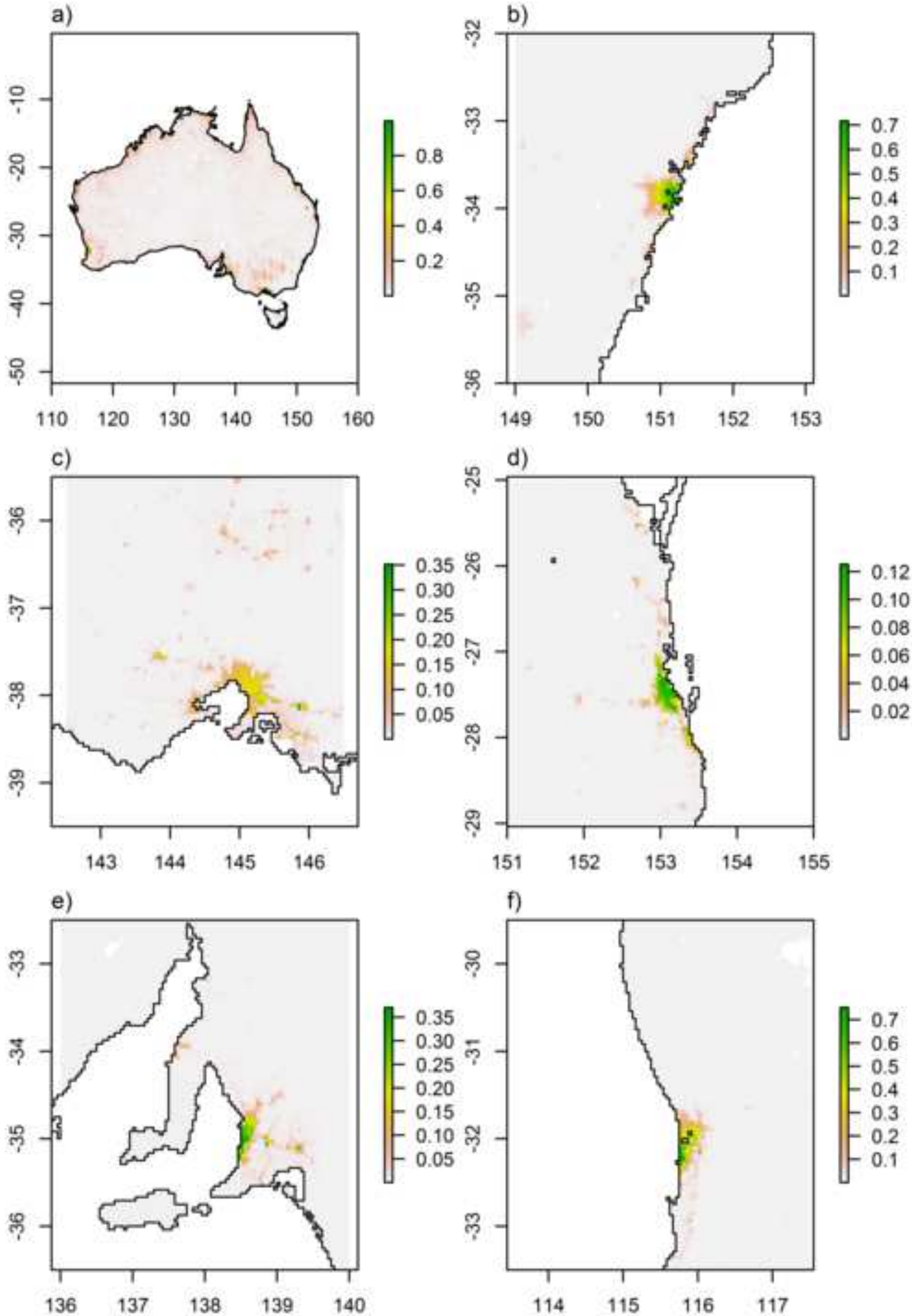

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