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Climatic-requirements models of cat's claw creeper *Macfadyena unguis-cati* (Bignoniaceae) to prioritise areas for exploration and release of biological control agents

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Abstract

Climate matching software (CLIMEX) was used to prioritise areas to explore for biological control agents in the native range of cat's claw creeper *Macfadyena unguis-cati* (Bignoniaceae), and to prioritise areas to release the agents in the introduced ranges of the plant. The native distribution of cat's claw creeper was used to predict the potential range of climatically suitable habitats for cat's claw creeper in its introduced ranges. A Composite Match Index (CMI) of cat's claw creeper was determined with the '*Match Climates'* function in order to match the ranges in Australia and South Africa where the plant is introduced with its native range in South and Central America. This information was used to determine which areas might yield climatically-adapted agents. Locations in northern Argentina had CMI values which best matched sites with cat's claw creeper infestations in Australia and South Africa. None of the sites from where three currently prioritised biological control agents for cat's claw creeper were collected had CMI values higher than 0.8. The analysis showed that central and eastern Argentina, south Brazil, Uruguay and parts of Bolivia and Paraguay should be prioritised for exploration for new biological control agents for cat's claw creeper to be used in Australia and South Africa.

Keywords: Predictive models; CLIMEX; Biological control; Agent prioritisation; Agent selection

1. Introduction

Classical biological control of weeds involves the importation and release of exotic natural enemies (i.e. insects, mites and pathogens) with the expectation that they will become established and give permanent control (McFadyen, 1998). Many invasive plants targeted for biological control have a wide geographic distribution even in their native range (Williamson and Fitter, 1996; Alpert et al., 2000; Heger and Trepl, 2003).

Success or failure of weed biological control agents may be determined by climatic factors which determine whether an agent species can survive and proliferate in its country of introduction (McClay, 1996; Broughton, 2000; McEvoy and Coombs, 1999). Biological control agents for weeds with wide climatic tolerances need to be chosen carefully because specialist herbivores and plant pathogens that have restricted distributions in their native range may have narrow climatic tolerances which will limit their ability to control the weed over its whole distribution (Dhileepan et al., 2005; McClay and Hughes, 2007). Selection of biocontrol agents that are adapted to the areas of intended release requires a thorough analysis of the climates in the source and release sites (McFadyen, 1991; Marohasy, 1995; Hoelmer and Kirk, 2005; Goolsby et al., 2006; Zalucki and van Klinken, 2006).

Climate matching has been used widely to predict the potential establishment and distribution of invasive plants in their introduced ranges (McFadyen and Skarratt, 1996; Holt and Boose, 2000; Kriticos et al., 2003a,b,c, 2005; Goolsby, 2004; Dunlop et al., 2006; Scott and Batchelor, 2006; Raimundo et al., 2007), to identify climatically

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suitable areas in the introduced ranges for biological control agent release (Mo et al., 2000; Byrne et al., 2002; Lockett and Palmer, 2003, 2004; Wood et al., 2004; Senaratne et al., 2006; Palmer and Senaratne, 2007; Palmer et al., 2007) and, sometimes, to identify areas in the native range to explore for agents that are climatically adapted to the intended areas of release (Scott, 1992; Julien et al., 1995; Marohasy, 1995; Goolsby et al., 2003; Dhileepan et al., 2006; Senaratne et al., 2006).

In this study we used climate matching software (CLIMEX) as a tool in the targeted classical biological control of cat's claw creeper *Macfadyena unguis-cati* (L.) Gentry (Bignoniaceae), an invasive liana currently under biocontrol investigation in Australia and South Africa. CLIMEX was used to (1) predict the potential distribution of cat's claw creeper in its introduced ranges of Australia and South Africa, (2) prioritise areas in the native range for the exploration of new biological control agents, and (3) identify potential release sites in Australia and South Africa that have similar climates to the source locations of biocontrol agents.

2. Methods

2.1. The study system

Cat's claw creeper is a climbing woody vine. Its geographic distribution spans over 6000 km in its native range, from Mexico through Central America and tropical South America to north-eastern Argentina (Everett, 1980; Howard, 1989) (Fig. 1). Cat's claw creeper is an invasive weed in Australia, South Africa, India, Mauritius, China, New Caledonia and Hawaii and Florida in the USA (Dhileepan et al., 2005; Henderson, 1997; Holm et al., 1991; Meyer, 2000; Sparks, 1999). In Australia, it is a major environmental weed in the states of Queensland (Batianoff and Butler,

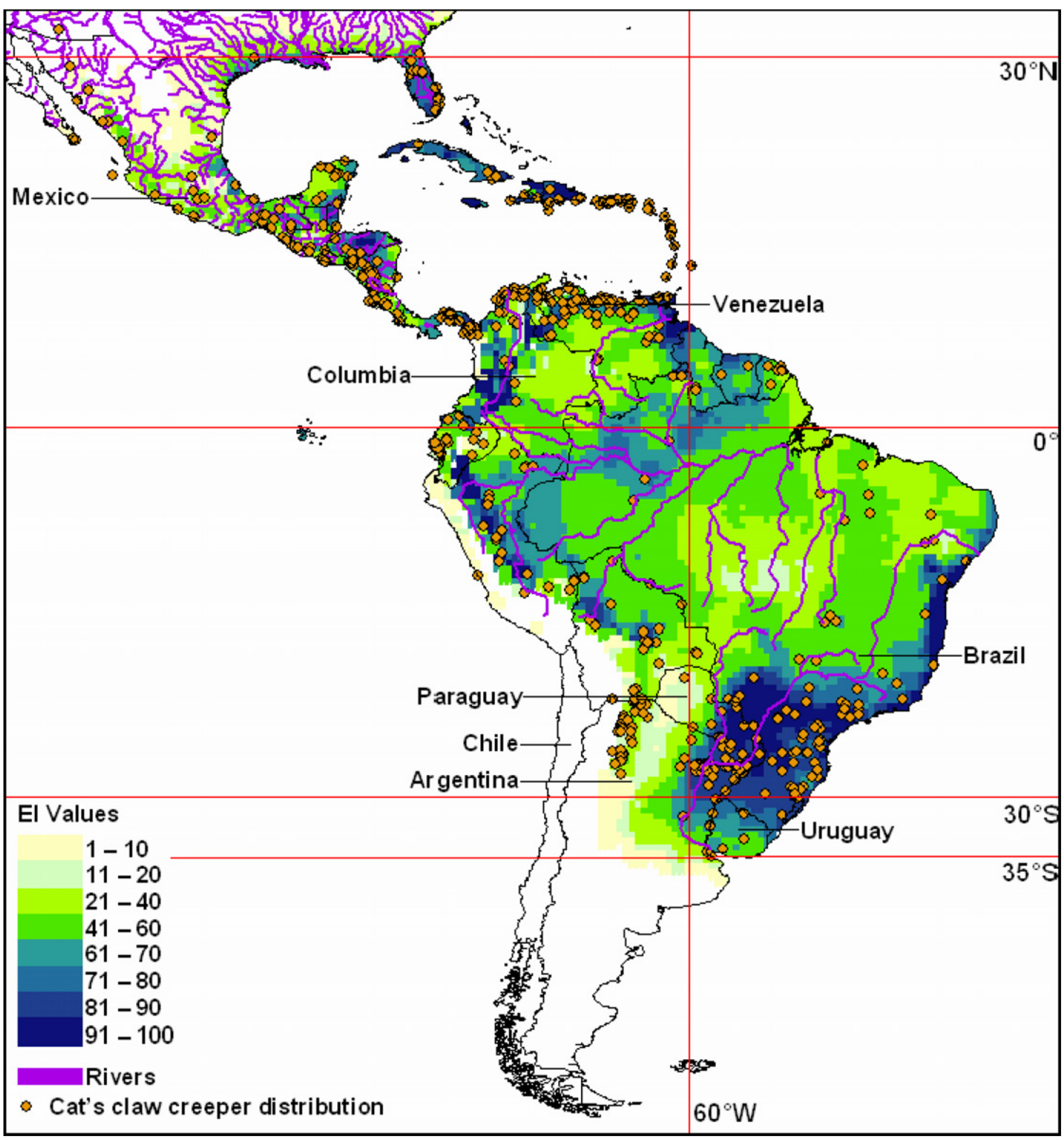

Fig. 1. The current distribution of *Macfadyena unguis-cati* in its native range of South and Central America (orange dots) and the potential distribution of *M. unguis-cati* as predicted by the CLIMEX model (major catchment locations in purple, country borders in black, latitude and longitude in red).

2003) and New South Wales (Quirico, 1992) where it poses a significant threat to biodiversity in riparian and rainforest communities. Plant genotypic studies suggest that the invasive haplotypes in Australia and South Africa are similar to those in the southern parts of the native range of cat's claw creeper, Peru, Bolivia, Paraguay and Argentina (Sigg et al., 2006). The seeds of cat's claw creeper are capable of hydrochory and the plant can also regenerate from underground tubers and broken stems. Costs, logistical constraints and the need for reapplication of treatments associated with mechanical or chemical controls for this weed are such that biological control is regarded as the most desirable option for long term management (Vivian-Smith and Panetta, 2004; Dhileepan et al., 2005).

Surveys in Brazil, Argentina, Paraguay, Venezuela and Trinidad have identified nine species of insects as potential biological control agents for cat's claw creeper (Sparks, 1999). A leaf-feeding beetle, *Charidotis auroguttata* (Boheman) (Chrysomelidae: Coleoptera) was the first agent to be introduced into South Africa (Sparks, 1999), but this agent was not approved for release in Australia due to its perceived non-target risk to a native plant (Dhileepan et al., 2005). Subsequently, the leaf-sucking tingids, *Carvalhotingis visenda* (Drake & Hambleton) and *Carvalhotingis hollandi* Drake (Hemiptera: Tingidae), and the leaf tying moth *Hypocosmia pyrochroma* (Jones) (Lepidoptera: Pyralidae) were prioritised for host specificity tests in both South Africa (Williams, 2003a, 2003b) and Australia (Snow et al., 2006; Treviño et al., 2006). *C. visenda* and *H. pyrochroma* have been approved for release in Australia (Dhileepan et al., 2007a, 2007b).

2.2. Distribution records

The distribution of cat's claw creeper in its native and introduced ranges was compiled based on Sparks (1999), herbaria records (Missouri Botanic Gardens; Instituto Nacional de Biodiversidad, Costa Rica; Queensland Herbarium, Australia's virtual herbarium), plant databases (i.e. TROPICOS-VAST; http://www.invasivespeciesinfo.gov/databases/tpdb.shtml; http://plants.usda.gov; etc.), Government Departments (Queensland Department of Natural Resources & Water; Queensland Parks and Wildlife; New South Wales Department of Environment and Conservation); research organisations (Institute of Systematic Botany, The University of South Florida; Florida Exotic Pest Plant Council; Plant Protection Research Institute, South Africa); local governments (New South Wales North Coast Weed Advisory Committee); and community groups (Mary River Catchment Coordinating Committee; Gympie Landcare; Northern Rivers Catchment Management Authority).

2.3. CLIMEX

CLIMEX is a tool for modelling species' response to climate (Sutherst et al., 2004) and has been commonly used to predict the spread of weeds, pests and biological control agents. In this study two functions of the CLIMEX package were used to: (i) predict the potential geographic distribution of cat's claw creeper based on climate ('*Compare Locations*'); and (ii) compare the climates of the native and introduced ranges of cat's claw creeper to prioritise locations for agent exploration and release ('*Match Climates*'). The '*Compare Locations*' function uses an inferential approach to determine the climatic requirements of species. The assumption of this model is that the climate conditions that a species can tolerate can be inferred from its known distribution (Sutherst et al., 2004). The '*Match Climates*' function simply compares climatic similarity of selected locations (Sutherst, 2003).

2.4. Potential distribution of cat's claw creeper (Compare Locations)

The '*Compare Locations*' function was used to develop a model of the potential distribution of cat's claw creeper based on distribution data from its native range (see Sutherst, 2003; Sutherst et al., 2004; and Kriticos et al., 2005 for the mechanics of this approach). The values of the CLIMEX parameters were inferred by considering the climatic factors that are most likely to limit the native distribution of cat's claw creeper (Table 1). The model was validated using the distribution of cat's claw creeper in its introduced ranges (Australia and South Africa).

The Ecoclimatic Index (EI), which represents the likelihood of a species being able to persist in an area, is mapped in Figs. 1–3. The EI is a value between 0 and 100, with higher values reflecting a greater likelihood of species persisting and '0' indicating climatic conditions under which the organism in question cannot survive. The EI is based on two growth indices; temperature and moisture; and four stress indices; cold stress, heat stress, dry stress and wet stress. Priority areas for exploration and release of biological control agents are those with the highest EI value in both introduced and native distributions.

2.5. Climate matching (Match Climates)

The '*Match Climates*' function uses long-term meteorological data for each of the selected 'Away' locations which is then compared with the climate of the 'Home' location (Sutherst and Maywald, 1985; Sutherst et al., 2004). Similarity of the 'Home' and 'Away' locations is measured by the Composite Match Index (CMI), a value between zero and one, with higher values relating to a greater match between locations. CMI values are calculated using the following variables: maximum, minimum and average temperatures, total rainfall and rainfall pattern and relative humidity, all of which are monthly averages. Variables may be weighted between zero and one, with one giving full consideration of the variable and zero to exclude it. For the climate matching performed in this study, a weight of one was assigned for maximum and minimum temperatures,

Table 1
The indices and parameters used to develop a model of the potential distribution and spread of *Macfadyena unguis-cati* from its current native distribution

Index	CLIMEX Parameter	Value
Temperature	DV0 limiting low temperature	10
	DV1 lower optimal temperature	18
	DV2 upper optimal temperature	31
	DV3 limiting high temperature	34
Moisture	SM0 limiting low moisture	0.15
	SM1 lower optimal moisture	0.4
	SM2 upper optimal moisture	1.5
	SM3 limiting high moisture	1.7
Cold stress	TTCS cold stress temperature threshold	9
	THCS cold stress temperature rate	−0.0005
	DTCS cold stress degree-day threshold	20
	DHCS cold stress degree-day rate	0.0002
Heat stress	TTHS heat stress temperature threshold	34
	THHS heat stress temperature rate	0.00005
Dry stress	SMDS dry stress threshold	0.15
	HDS dry stress rate	−0.003
Wet stress	SMWS wet stress threshold	1.75
	HWS wet stress rate	0.006
Degree-days	PDD	1800

rainfall total and rainfall pattern (the default setting in CLIMEX). Relative humidity, soil moisture and average temperature were not used as their inclusion further constricted the CMI between locations. To determine locations that should be prioritised to explore for biological control agents in the native range a CMI value of 0.8 was used. This value is conventionally used to indicate significant climatic similarity between two locations (Sutherst, 2003).

The climate at four Australian sites (Bundaberg, Gympie and Brisbane in Queensland and Coffs Harbour in New South Wales; Fig. 2) and two South African sites (Pretoria and Pietermaritzburg; Fig. 3) were compared to the climate in the native range of cat's claw creeper. There were dense infestations of cat's claw creeper at all of the selected 'away' sites making them potentially suitable areas for release of biological control agents.

'Match Climates' was used to compare locations where biological control agents originated with areas in Australia and South Africa, to identify potential areas for release. The insects included were: *C. visenda* and *C. hollandi* from near Curitiba, Brazil; *H. pyrochroma* from Posadas, Argentina; and *C. auroguttata* from Caracas, Venezuela.

2.6. Model output

All maps produced a 10 minute grid using interpolated climate data (CRU TS 1.2) (Mitchell et al., 2003). Grid data is advantageous because the entire landmass is included in the application rather than only locations where weather stations are situated. Unless otherwise stated, the CMI values referred to in this paper are taken from the grid data.

3. Results and discussion

3.1. Current and potential distribution of cat's claw creeper (Compare Locations)

The current native distribution of cat's claw creeper in South and Central America (1579 records) spans over 6000 km from a latitude of approximately 30°N to 35°S (Fig. 1), covering several climatic zones such as wet tropics, temperate and tropical savannah. Cat's claw creeper occurs across all of Central America, the Venezuelan and Columbian coasts, Uruguay, northeast Argentina and southern Paraguay and Brazil in South America, while there are no records of its occurrence in the Amazon rainforest of central and northwest Brazil.

The model developed from the current native distribution of cat's claw creeper indicated that cold stress accounts for the plant's southernmost distribution of 35°S and dry stress limited its ability to survive in much of North America (Fig. 1; Table 1). Cold and dry conditions probably exclude cat's claw creeper from the Andes mountain range, which runs along the west Chilean border.

In Australia the current distribution of cat's claw creeper is concentrated in southeast Queensland but it is also found as far north as Cooktown and as far south as Forbes in the state of New South Wales (Fig. 2). The model predicts the current distribution could extend further north along the east coast of Queensland including the tropical rainforests in Far North Queensland, and further south in New South Wales (Fig. 2). In Queensland, cold and dry inland conditions limit cat's claw creeper but EI values of over 50 exist in a thick band along the coast between an approximate latitude of 34°S and 19°S. All inland cat's claw creeper infestations with an EI of 1–10 are located in riparian microclimates (Fig. 2). Cat's claw creeper has been recorded in riparian areas in Mexico, in areas with low EI values (<10). Microclimatic effects of riparian habitats, such as protection from frost (eliminating cold stress) and increased soil moisture (negating dry stress), would enable species to exist in areas where the macroclimate is unfavourable (Kriticos et al. 2003c).

In South Africa, cat's claw creeper is currently distributed predominantly in North West, Limpopo, Gauteng and Mpumalanga provinces, with a few sites in the Kwazulu-natal province especially around Pietermaritzburg (Fig. 3). The model predicts that cat's claw creeper could spread along much of the southern coastline near Pietermaritzburg and Durban, between latitudes 33°S and 26°S (indicated in blue) but would be excluded by cold stress from much of the central and western areas of the country (Fig. 3).

3.2. Prioritising sites for exploration in the native range (Match Climates)

Climate matches of the four Australian locations with the native range of cat's claw creeper in South and Central

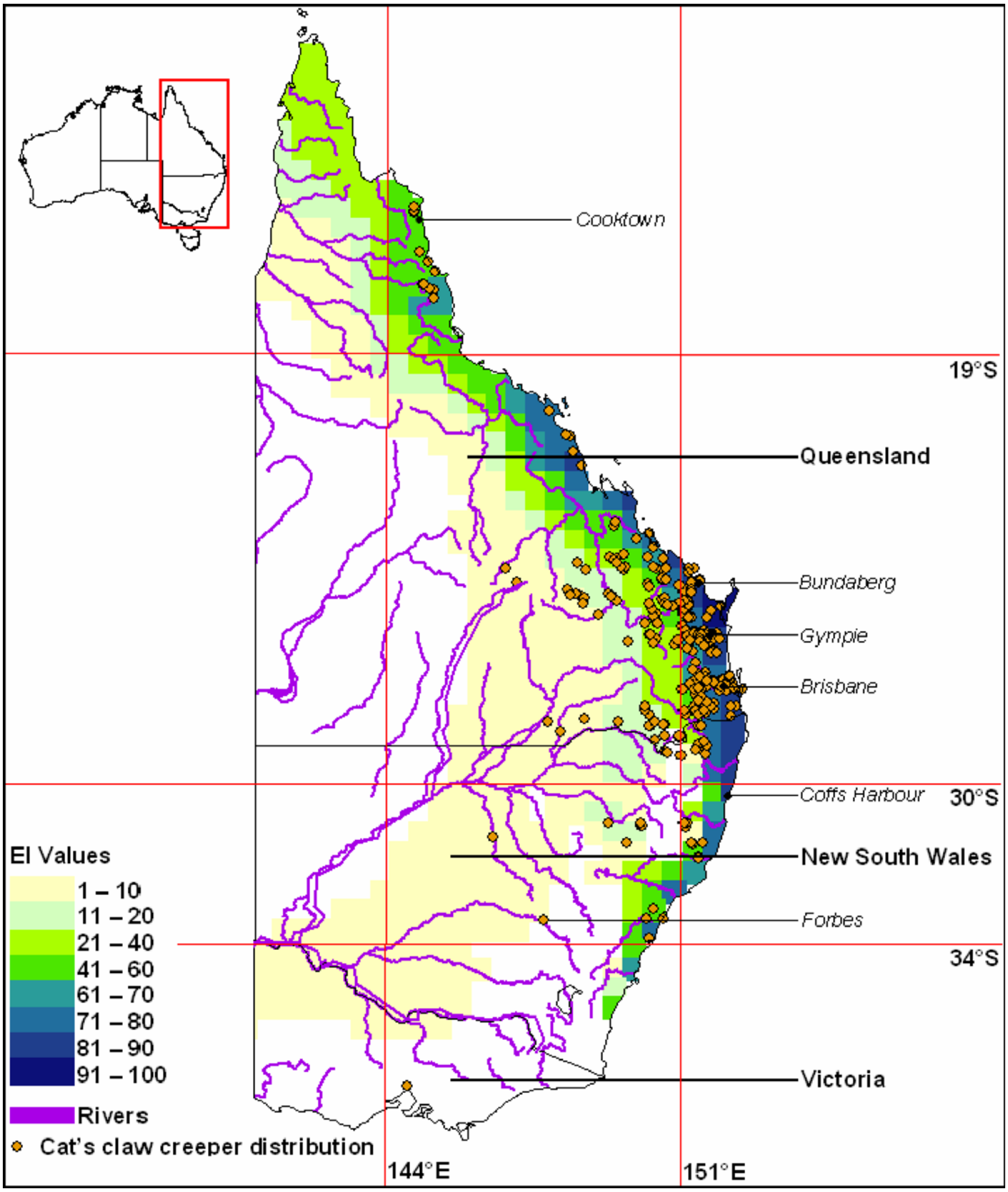

Fig. 2. The current distribution of *Macfadyena unguis-cati* in Australia (orange dots), and the potential distribution of *M. unguis-cati* as predicted by the CLIMEX model (major catchment locations in purple, state borders in black, latitude and longitude in red).

America revealed that all four Australian locations share their highest CMI values (0.61–0.8) between latitudes 17°S and 36°S (Fig. 4). No Australian location tested had CMI values greater than 0.8 and many of the same locations featured in the list of the highest CMI values, with only their order changing in response to subtle climatic differences.

Gympie, closely followed by Bundaberg, was shown to have the greatest geographic spread of CMI values between 0.61 and 0.8 (Fig. 4B and A). For Brisbane, the distribution of CMI values between 0.61 and 0.8 was restricted to areas in north-eastern Argentina, central Paraguay and parts of Bolivia and Brazil (Fig. 4C). For Coffs Harbour, the distribution of CMI values between 0.61 and 0.7 was confined to southern Brazil below 26°S, the whole of Uruguay, east Paraguay and north-eastern Argentina around Posada (Fig. 4D). The use of CMI values to prioritise areas for future exploration suggests that exploration in northern Argentina should yield climatically suitable agents for southeast Queensland (Fig. 4A, B and C). For northern New South Wales, agents from sites situated east of northern Argentina such as Uruguay, east Paraguay and southern Brazil (Fig. 4D) should be more appropriate.

The South African cities of Pretoria and Pietermaritzburg had similar but more constricted distributions of CMI values in South and Central America (Fig. 4E and

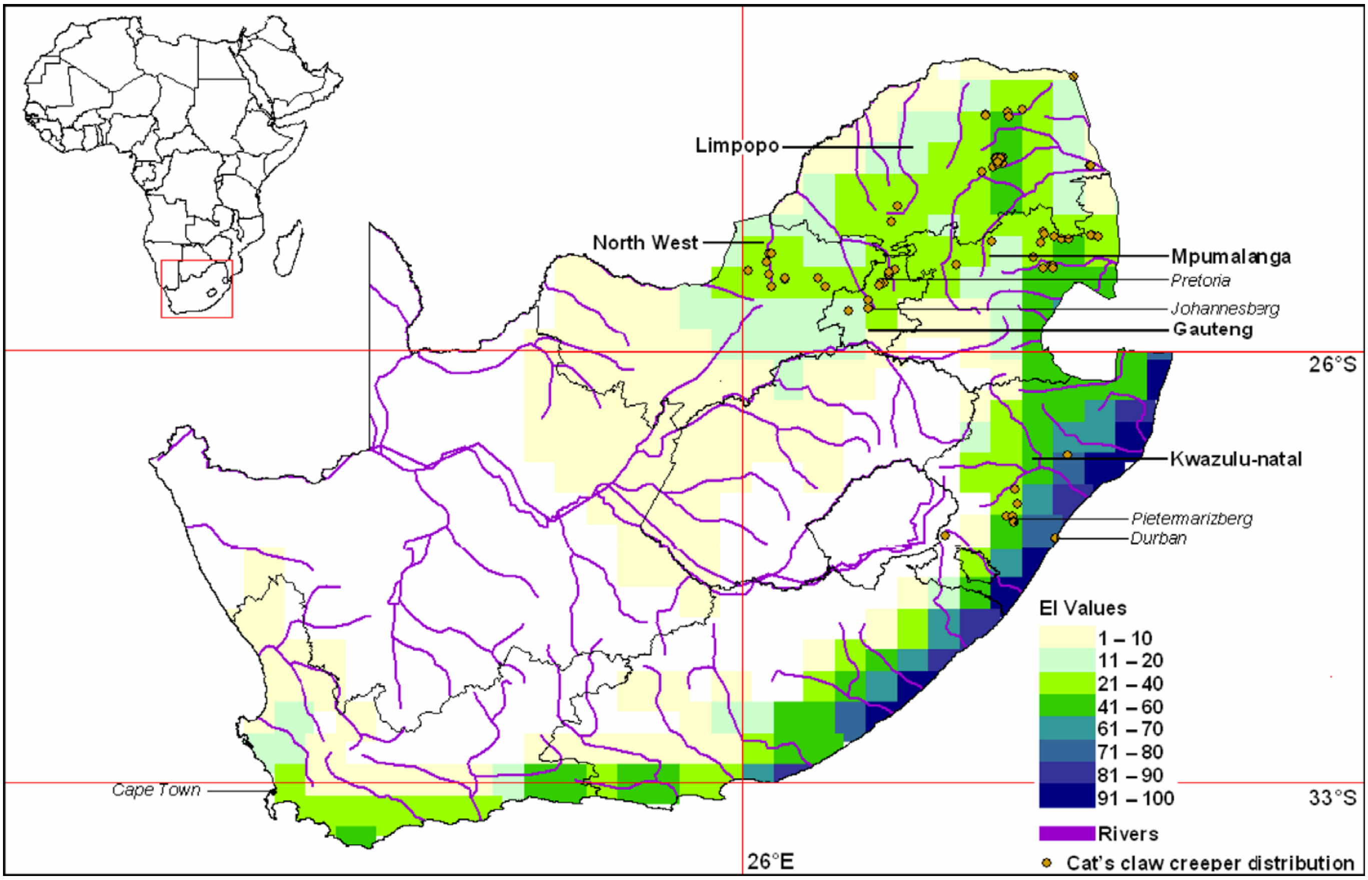

Fig. 3. The current distribution of *Macfadyena unguis-cati* in South Africa (orange dots) and the potential distribution of *M. unguis-cati* as predicted by the CLIMEX model (major catchment locations in purple, province borders in black, latitude and longitude in red).

F). As with the Australian cities, the highest CMI values for Pretoria and Pietermaritzburg were ⩽0.8 but there was no overlap in the locations with CMI values of 0.8 for these two cities. The highest CMI values (0.61–0.8) for Pretoria occurred predominantly in central northern Argentina. For Pietermaritzburg, the highest CMI values were also in central northern Argentina, but unlike Pretoria, the area covered was greater and these values also occurred in eastern Brazil. Releases intended for Pretoria and Pietermaritzburg in South Africa, should prioritise agents from localities in central and northern Argentina (Fig. 4E and F).

3.3. Prioritising release sites of current biocontrol agents (Match Climates)

The South American cities of Caracas (Venezuela), Curitiba (Brazil) and Posadas (Argentina) had CMI values between 0.5 and 0.8 for Australia, although the Caracas (Venezuela) and Curitiba (Brazil) climate matches did exhibit small patches above 0.81 (Fig. 5A and B). Caracas (Venezuela), had the greatest distribution of high CMI values, with values between 0.61 and 0.8 lining the east coast of Australia between the latitudes 39°S and 16°S, covering areas of current heavy cat's claw creeper infestation (Fig. 5A). This suggests that *C. auroguttata* collected from Caracas (Venezuela) should be climatically suitable for use in Australia (Fig. 5A). However, this agent has already failed Australian host testing and is no longer considered a potential agent (Dhileepan et al., 2005).

The distribution of CMI values between 0.61 and 0.8 for Curitiba (Brazil), when matched to Australia, also lined the east coast but formed a narrower band than the range observed for Caracas (Fig. 5B). Based on the *'Match Climate'* results *C. visenda* and *C. hollandi*, collected from Curitiba (Brazil), should be climatically suitable for areas with cat's claw creeper infestation in both Queensland and New South Wales (Fig. 5B).

The climate match between Australia and Posadas (Argentina) had the most limited distribution, which ranged between the latitudes 25°S to 36°S (Fig. 5C). A very thin band of CMI 0.7–0.8 exists from Bundaberg to Coffs Harbour, which is in the midst of the current heaviest infestations of cat's claw creeper (Fig. 5C). The distribution of CMI values for Posadas were more similar to those of Curitiba (Brazil), than Caracas (Venezuela), reflecting the closer geographical proximity of Posadas and Curitiba. Climate matching indicates that coastal areas where heaviest cat's claw creeper infestations currently occur are more suitable for *H. pyrochroma* from Posadas (Argentina) (Fig. 5C), but the potential range of this agent is not necessarily limited to the coastal fringe.

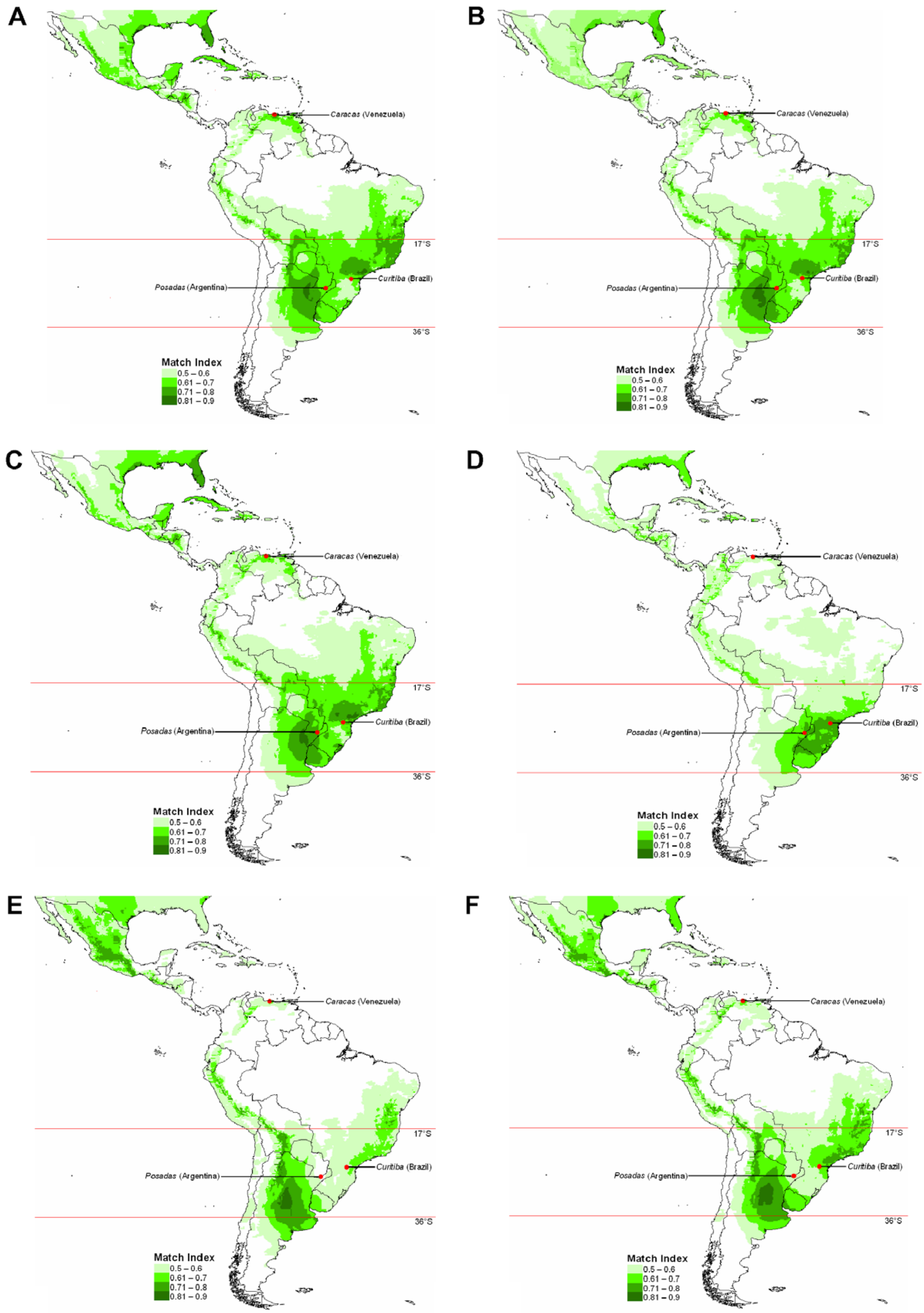

Fig. 4. Climate match, using the 'Match Climates' function, between the native range of *Macfadyena unguis-cati* and four Australian cities; Bundaberg (A), Gympie (B), Brisbane (C) and Coffs Harbour (D) and two South African cities; Pretoria (E) and Pietermaritzburg (F) (green shading indicates CMI values, country borders in black, latitude and longitude in red).

The climate match between Caracas (Venezuela) and South Africa showed CMI values between 0.61 and 0.8 were spread along the east coast and border and the area around Pretoria, with a thin band of CMI values >0.8

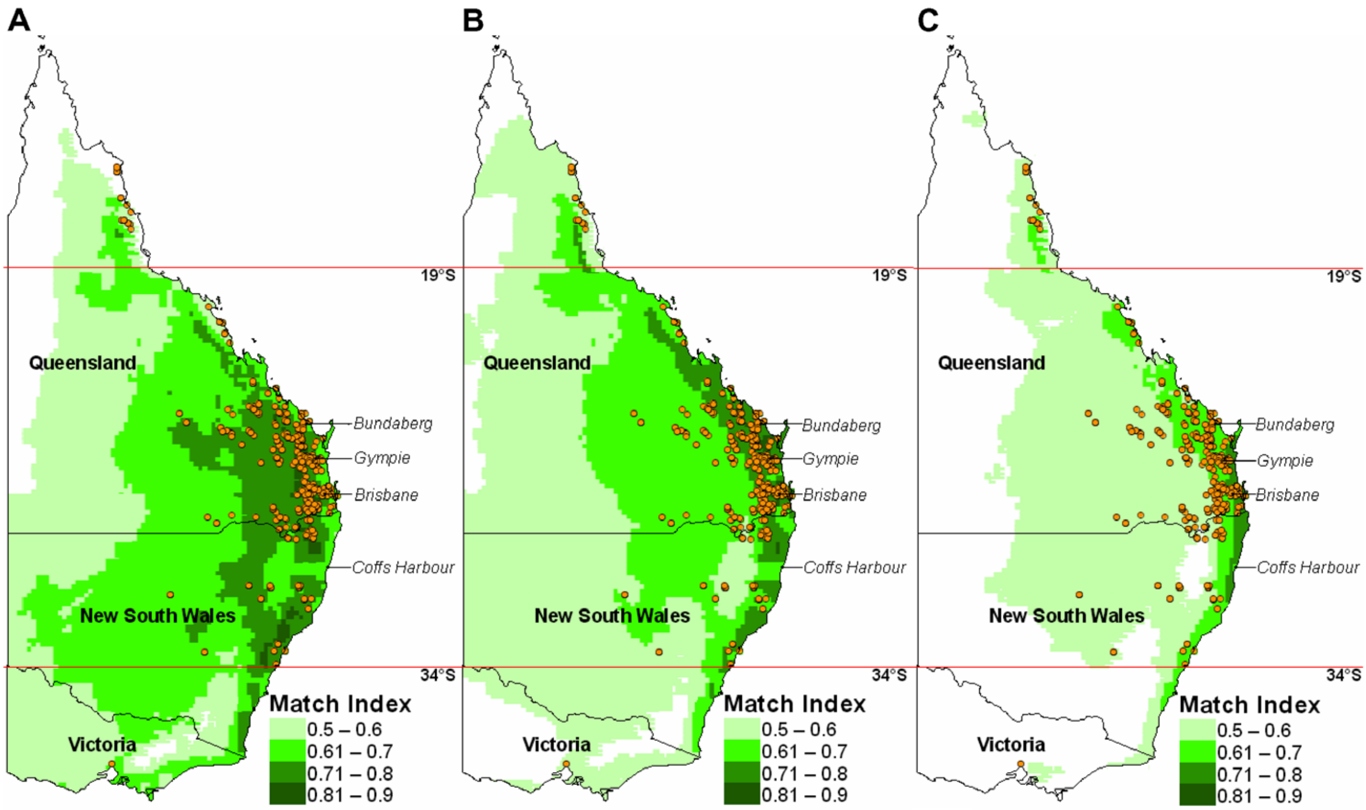

Fig. 5. Climate match between Australia and the three cities from the native range of *Macfadyena unguis-cati* where biological control agents have been collected; (A) Caracas, Venezuela, (B) Curitiba, Brazil and (C) Posadas, Argentina (green shading indicates CMI values, state borders in black, latitude and longitude in red).

along the east coast near Pietermaritzburg (Fig. 6A). A climate match between Curitiba (Brazil) and South Africa demonstrated limited CMI values between 0.61 and 0.8 to the east and southern coast of the country (Fig. 6B). CMI values between 0.61 and 0.7 generated for Posadas (Argentina) were restricted to the southeast coast of South Africa in a very narrow band (Fig. 6C). Climate matches for South Africa indicated that the *C. visenda* and *C. hollandi*. from Curitiba (Brazil) may be climatically suitable biological control agents for cat's claw creeper along the south-eastern coastline of South Africa, but *H. pyrochroma* from Posadas (Argentina), would have limited potential in South Africa (Fig. 6B and C). *Charidotis auroguttata* collected from Caracas, Venezuela, was released in South Africa (Sparks, 1999), but did not establish for unknown reasons (H. Williams, personnel communication).

None of the current biological control agents from Curitiba (*C. visenda* and *C. hollandi*) or Posadas (*H. pyrochroma*) have CMI values over 0.61 that cover all of the current distribution of cat's claw creeper in South Africa (Fig. 6B and C). Therefore the '*Match Climates*' data for South Africa suggest that another biological control agent will be necessary to control cat's claw creeper in this part of its introduced range. Collection of known agents, as well as exploration for new agents, from areas prioritised by climate matching (i.e. Argentina) are being planned collaboratively between researchers in Australia and South Africa.

The failure of *C. auroguttata* collected from Caracas (Venezuela) with very high CMI values, to become established in South Africa, highlight the need for interpreting the '*Match Climates*' CLIMEX data with caution. The highest CMI value between two locations does not necessarily demonstrate biological significance (Sutherst, 2003). In spite of the limitations, '*Match Climates*' is the only predictive tool currently available to assist in decisions on native range explorations and release of biological control agents in introduced ranges (Sutherst, 2003; Kriticos and Randall, 2001). Future models that describe the full native range of potential agents not just a climate match of one known location may specify completely different more informed potential distributions.

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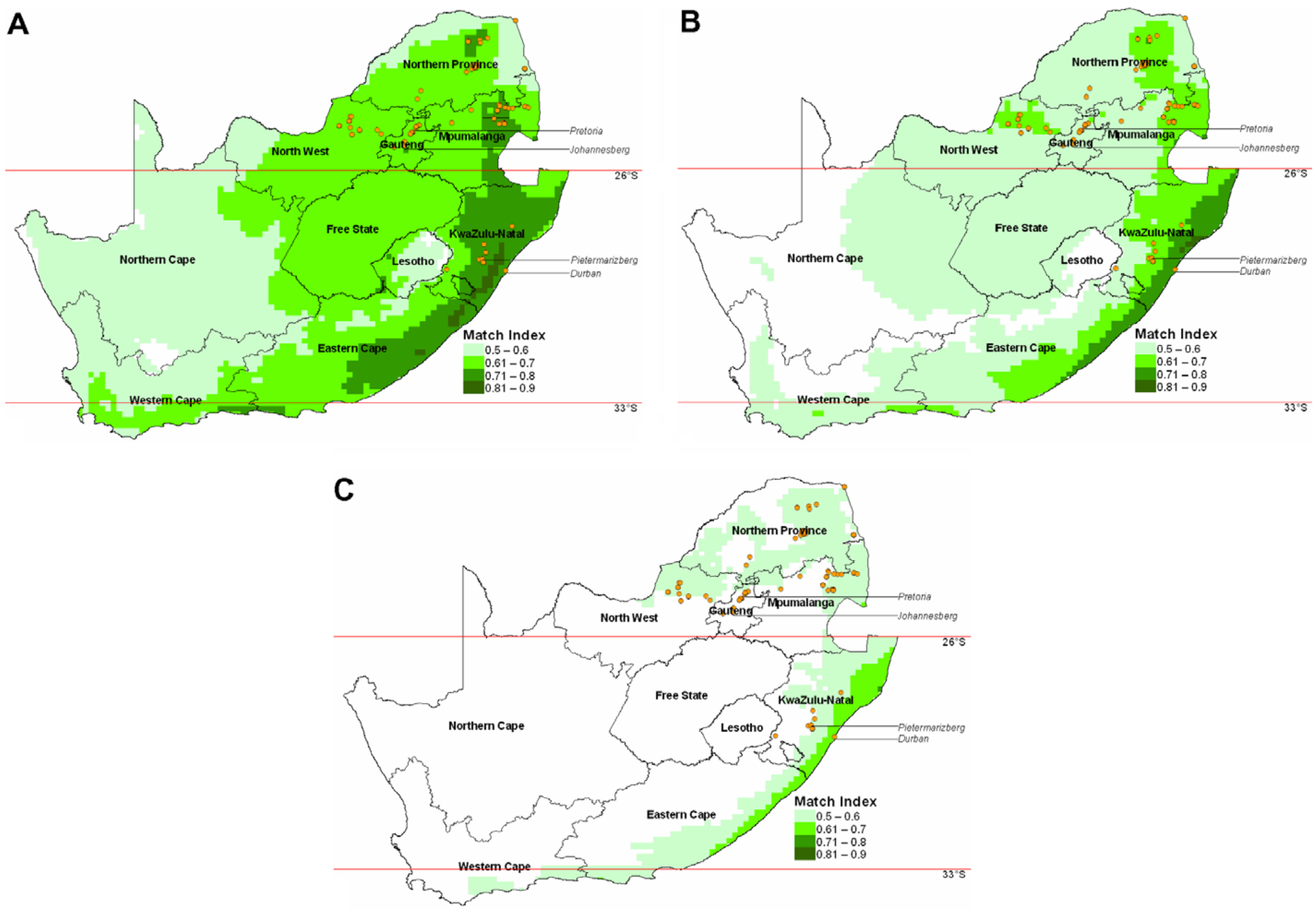

Fig. 6. Climate match between South Africa and the three cities from the native range of *Macfadyena unguis-cati* where biological control agents have been collected; (A) Caracas, Venezuela, (B) Curitiba, Brazil and (C) Posadas, Argentina (green shading indicates CMI values, province borders in black, latitude and longitude in red).

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