Introduction, Establishment, and Potential Geographic Range of *Carmenta* sp. nr *ithacae* (Lepidoptera: Sesiidae), a Biological Control Agent for *Parthenium hysterophorus* (Asteraceae) in Australia

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Introduction, Establishment, and Potential Geographic Range of *Carmenta* sp. nr *ithacae* (Lepidoptera: Sesiidae), a Biological Control Agent for *Parthenium hysterophorus* (Asteraceae) in Australia

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ABSTRACT Parthenium (*Parthenium hysterophorus* L.), a major weed causing economic, environmental, and human and animal health problems in Australia and several countries in Asia, Africa, and the Pacific, has been a target for biological control in Australia since the mid-1970s. Nine species of insects and two rust fungi have been introduced as biological control agents into Australia. These include *Carmenta* sp. nr *ithacae*, a root feeding agent from Mexico. The larvae of *C.* sp. nr *ithacae* bore through the stem-base into the root where they feed on the cortical tissue of the taproot. During 1998–2002, 2,816 larval-infested plants and 387 adults were released at 31 sites across Queensland, Australia. Evidence of field establishment was first observed in two of the release sites in central Queensland in 2004. Annual surveys at these sites and nonrelease sites during 2006–2011 showed wide variations in the incidence and abundance of *C.* sp. nr *ithacae* between years and sites. Surveys at three of the nine release sites in northern Queensland and 16 of the 22 release sites in central Queensland confirmed the field establishment of *C.* sp. nr *ithacae* in four release sites and four nonrelease sites, all in central Queensland. No field establishment was evident in the inland region or in northern Queensland. A CLIMEX model based on the native range distribution of *C.* sp. nr *ithacae* predicts that areas east of the dividing range along the coast are more suitable for field establishment than inland areas. Future efforts to redistribute this agent should be restricted to areas identified as climatically favorable by the CLIMEX model.

KEY WORDS *Parthenium hysterophorus*, *Carmenta ithacae*, Sesiidae, biological control, CLIMEX model

Parthenium (*Parthenium hysterophorus* L., Asteraceae), a native of tropical America, is a major weed causing severe economic, environmental, and human and animal health problems in Australia and several countries in Asia, Africa, and the Pacific (Dhileepan and Strathie 2009). Parthenium, a Weed of National Significance in Australia (http://www.weeds.org.au/WoNS/parthenium), occurs mainly in Queensland as a major weed in grazing areas, where it reduces beef production by as much as AU $16.5 million annually (Chippendale and Panetta 1994). Parthenium also affects crops, as well as roadside and riparian areas, and also acts as a reservoir host for insect pests and plant pathogens of crop plants (Dhileepan and Strathie 2009). Parthenium is a human health hazard, causing severe dermatitis and respiratory problems (McFadyen 1995)

Parthenium has been a target for classical biological control since the mid-1970s and, since then, nine species of insects and two rust fungi have been released (Dhileepan and Strathie 2009). All of them are aboveground herbivores and pathogens, except for the *Carmenta* sp. nr *ithacae* (Lepidoptera: Sesiidae), a root-feeding agent from Mexico. Root feeding agents cause significant reductions in plant populations and are more likely to contribute to the negative effects on the target weed than above ground herbivores (Blossey and Hunt-Joshi 2003). Cumulative or synergistic stress from root-feeding and above-ground agents has the potential to enhance the effectiveness of weed biological control programs (e.g., Blossey and Hunt-Joshi 2003, Simelane 2005, Seastedt et al. 2007). Hence, for parthenium, the specialist root-herbivore is a valuable addition to the suite of already released above-ground weed biological control agents.

Carmenta ithacae (Beutenmüller) *sensu stricto* has a wide native range in Canada and the United States

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(Arizona, Colorado, Kansas, Missouri, North Carolina, northern Florida, New Mexico, New York, Manitoba, Mississippi, Texas, and Wisconsin). Its recorded host plants in the United States are *Helenium autumnale* L. and *Heliopsis helianthoides* (L.) Sweet (Asteraceae) (Eichlin and Duckworth 1988). A morphologically similar *Carmenta* species occurs on *P. hysterophorus* and the related perennial species *Parthenium confertum* Gray in Mexico (Nuevo Leon, Tamaulipas, and Veracruz) (McClay et al. 1995, Withers et al. 1999). Specimens from this population were identified by T.D. Eichlin as *C. ithacae.* However, because of its distinct host range we believe this to be a separate species, and hence refer to it as *C.* sp. nr *ithacae* (Withers et al. 1999).

Carmenta spp. are mostly host specific and some have been used or proposed as biological control agents for other weeds (Forno et al. 1991, Cordo et al. 1995a, Paynter 2005, Ostermeyer and Grace 2007). Studies in Australia using *C.* sp. nr *ithacae* collected on *P. hysterophorus* from Mexico confirmed that this specialist insect herbivore does not pose a risk to any nontarget plants, and hence the moth was approved for field release (McFadyen and Withers 1997, Withers et al. 1999). Field releases of *C.* sp. nr *ithacae* commenced in September 1998 and continued till February 2002. We report the field establishment and potential geographic range of *C.* sp. nr *ithacae* in Australia.

Materials and Methods

Study System. Parthenium, native to the Gulf of Mexico and central South America, is an annual herb with an extensive root system and an erect shoot that becomes woody with aging. Young plants initially develop into a rosette with a short stem and numerous large leaves close to the ground. As it matures, the plant develops many branches at its upper half, and may eventually reach a height of >2 m. A fully-grown plant can produce >15,000 flower heads in its lifetime, with each head bearing four or five seeds. With substantial rainfall and warm temperature, parthenium can germinate and grow at any time of the year.

Carmenta sp. nr *ithacae* is a common and widespread insect on parthenium in Mexico (McClay et al. 1995). A laboratory colony of the agent was established at the quarantine facility in Sherwood, Brisbane, using larvae and pupae collected from the vicinity of Monterrey, Nuevo Leon, Mexico (25.67°; −100.30°) in April 1996 and January–February 1997. Larvae fed and developed on roots of all growth stages of parthenium. The moth was approved for field release in Australia in 1998.

Mass Rearing. The insect was mass reared in climate-controlled glasshouses (20–30°C, and a photoperiod of 12:12 [L:D] h) in Sherwood, Brisbane (−27.53°; 152.97°) and at the Tropical Weeds Research Centre in Charters Towers (−20.09°; 146.27°). Ten pairs of newly emerged adults were transferred into insect-proof oviposition cages (188 by 91.5 by 60 cm) with 20 parthenium plants at the preflowering or flowering stage. Adults mate mostly in the morning (9:00 to 11:00 a.m.), and oviposition takes place from noon to early afternoon of the same day. Mating and oviposition only occurred under bright light, and hence two supplementary overhead incandescent lights (250 W each) were provided above the oviposition cages especially on cloudy days and during the winter season. The plants in the oviposition cages were checked daily for egg laying and plants with eggs (>20 eggs) were transferred to a glasshouse and replaced with fresh parthenium plants. Two weeks after initial signs of larval establishment (wilting of leaf axils and presence of frass), 80% of plants were transferred to a growth tunnel, to be used in field releases. The remaining larval-infested plants were placed in rearing cages (90 by 60 by 90 cm) and emerging adults were used in mass-rearing.

Field Release. Insects reared at the Tropical Weeds Research Centre were field released in northern Queensland as potted parthenium plants infested with larvae and pupae. Occasionally, newly emerged adults also were field released. The potted plants were placed on grazing properties at Cardigan (50 km southeast of Charters Towers), Felspar (107 km northwest of Charters Towers), Granite (30 km northeast of Charters Towers), Gainsford (40 km north of Charters Towers), Hillgrove (50 km north of Charters Towers), Lassie Creek (100 km north of Charters Towers), Lochlea (220 km northwest of Charters Towers), Plain Creek (190 km south of Charters Towers), and Sellheim (30 km north of Charters Towers) from December 1999 to July 2000 (Table 1). At each site, pots with *C.* sp. nr *ithacae* larvae infested plants were suspended by rope from nearby trees and Tangle-Trap insect trap coating (Tanglefoot Company, Grand Rapids, MI) was applied on the rope to prevent predation by ants. The pots were hand watered at weekly intervals. At Cardigan Station, emergence of adults, as evident from empty protruding pupal cases, was recorded at weekly intervals.

In central Queensland, parthenium plants infested with *C.* sp. nr *ithacae* larvae and pupae from Brisbane were planted at 24 sites surrounding the towns of Mackay, Nebo, Clermont, Emerald, Rockhampton, Bauhinia, and Injune, from 1999 to 2002 (Table 1). At these sites, plants were removed from the pot and planted among the naturally-growing parthenium plants in the field. Sites at Morebridge (50 km east of Clermont), Hillside (10 km north of Clermont), Delargum (100 km north of Taroom), and Wycarbah (35 km west of Rockhampton) were maintained as irrigated field-nurseries, where parthenium infestations were fenced to prevent cattle grazing and received irrigation manually during dry periods.

Field Monitoring. From 1998 to 2002, all the release sites were revisited annually (February to May) to monitor any signs of establishment. Since 2004, release sites in northern (Felspar, Cardigan and Plain Creek) and central (Cobbadah, 22 km northwest of Injune; Delargum; Hillside; Hutton Creek, 27 km north of Injune; Mooleyamber Creek, 78 km south of Rolleston; Morebridge; Mt. Hay, 37 km southwest of Rockhamp-

Table 1. Release efforts and establishment status for the *C.* sp. nr *ithacae* in Queensland, Australia

Region	Site or property	Latitude	Longitude	No. released		No of releases	Release years	Establishment status
				Plants with larvae	Adults			
Greenvale	Lochlea Station	S 18.8338	E 144.6243	10		1	1999	No
	Lassie Creek Station	S 19.3456	E 145.8369	4		1	1999	No
	Hillgrove Station	S 196281	E 145.8771	10		1	1999	No
	Gainsford Station	S 19.8118	E 146.0237	4	70	2	1999	No
	Granite Station	S 19.8951	E 146.2539	6		1	1999	No
	Sellheim	S 19.9006	E 146.1754	26	39	2	2000	No
	Felspar property	S 19.8087	E 145.2523	42	39	1	2000	No
Charters Towers	Cardigan station	S 20.2219	E 146.6485	10	30	3	1999 and 2000	No
	Plain Creek	S 21.4911	E 146.6421	234	108	4	1999 and 2000	No
Nebo Shire	Landsborough station	S 21.5549	E 148.4579	180		1	2001	No
	Kemmis creek	S 21.6074	E 148.3772	40		1	2000	No
	Oxford Downs	S 21.8373	E 148.9334	35		1	1999	No
Mackay	Lotus Creek	S 22.3539	E 149.1009	25		1	2001	No
	Kilcummin bore	S 22.3781	E 147.5669	30		1	1999	No
	Carfax	S 22.5882	E 148.3487	65		2	1998 and 1999	Yes
Clermont	Morebridge	S 22.6467	E 147.9334	40		1	2000	No
	Hillside	S 22.7453	E 147.5237	130		2	2000 and 2001	No
	Coll's nursery	S 22.8228	E 147.6581	62		2	1998 and 2000	No
Emerald	Lucknow	S 23.5268	E 148.1611	100		3	1998 and 2001	No
Rockhampton	Long Island reserve	S 23.2452	E 150.4051	167		2	2000 and 2001	Yes
	Wycarbah	S 23.5334	E 150.2352	278		6	1998 and 1999	Yes
	Mt Hay	S 23.5774	E 150.1901	28		1	1999	Yes
Bauhinia	Rolleston	S 24.5173	E 148.5851	127		3	1998 and 1999	No
	Leonora Hills	S 24.6518	E 148.0859	50		1	2000	No
	Delargum	S 24.7732	E 149.4925	513		8	1999, 2000, 2001 and 2002	No
	Nayanda	S 24.9033	E 148.3167	40		1	2000	No
	Mooleyamber creek	S 25.1898	E 148.5638	30		1	2000	No
Injune	Oak wells	S 25.4616	E 148.1530	40		1	2000	No
	Hutton Creek	S 25.6905	E 148.5187	90		2	2001 and 2002	No
	Womblebank	S 25.7539	E 148.0236	180	30	3	1998, 1999, and 2001	No
	Cobbada	S 25.7769	E 148.3589	220	56	6	2000, 2001, and 2002	No

ton; Oak wells, 60 km northwest of Injune and Wycarbah) Queensland areas (Table 1) were surveyed annually in autumn (April and May) at the end of the parthenium growing season. During 2006–2011, at each release site, five 0.25-m^2 plots were randomly sampled for the presence (percentage of infested plants) and abundance (number of immatures per plant) of *C.* sp. nr *ithacae* and for an assessment of the weed density. Plants with damage symptoms were brought to Brisbane and the identity of emerging adults was checked. In addition, other release sites (Long Island, 20 km north of Rockhampton; Carfax, 200 km southwest of Mackay; Kemmis Creek, 94 km southwest of Mackay; Landsborough, 80 km west of Mackay; Lotus Creek, 103 km south of Mackay; and Oxford Downs, 70 km southwest of Mackay; Table 1) and nonrelease sites (Gracemere, 8 km southwest of Rockhampton; Carfax yards, 197 km southwest of Mackay; Overflow, 105 km south of Mackay; and North Wycarbah, 34 km west of Rockhampton) in central Queensland also were sampled in January and March 2009, March 2010, and April 2011.

CLIMEX Model. CLIMEX, a tool for modeling species' responses to climate, has been commonly used to predict the spread of biological control agents (Sutherst et al. 2007). CLIMEX uses a database of monthly average weather records (rainfall, daily minimum and maximum air temperature, relative humidity) from ≈2,400 meteorological stations worldwide (675 meteorological stations in Australia), as well as spatially interpolated climate data on grids, known as 'Climate Surfaces' at a spatial resolution of 10 min. CLIMEX calculates an integrated climate index to describe the climatic suitability of areas likely to be climatically suitable for plants and poikilothermal animals. The CLIMEX model uses an Annual Growth Index (GI_A) to describe the potential for population growth during favorable climate conditions, and four stress indices (cold, wet, hot, and dry) and their interactions to describe the probability that the population can survive during unfavorable conditions. The growth and stress indices are calculated weekly, and combined into an overall annual index of climatic suitability, the Ecoclimatic Index (EI), scaled from 0 to 100. The suitability of an area is expressed in terms of its EI, with areas having an EI value of >30 considered favorable for the insect and those with <10 being less likely to sustain a population over a long period.

In this study, CLIMEX version three was used to predict the potential distribution of *C.* sp. nr *ithacae* in Australia on the basis of records from its native geographic range on *Parthenium* spp. in Mexico only. In Mexico, *C.* sp. nr *ithacae* was collected on *P. hysterophorus* in the states of Nuevo León (Apodaca, Cadereyta, Linares, Los Sabinos, and Monterrey); Tamaulipas (Ciudad Victoria); and Veracruz (Atongo, Cardel, Jalapa, Los Alamos, Paso del Toro, Rinconada,

Table 2. The parameters used to develop a CLIMEX model for *C.* sp. nr *ithacae* from its distribution records in Mexico

Parameter group	Parameter	Value
Temperature	Limiting low temp (DV0)	18
	Lower optimal temp (DV1)	20
	Upper optimal temp (DV2)	32
	Limiting high temp (DV3)	38
Moisture	Limiting low moisture (SM0)	0.1
	Lower optimal moisture (SM1)	0.3
	Upper optimal moisture (SM2)	1
	Limiting high moisture (SM3)	1.5
Cold stress	Cold stress temp threshold (TTCS)	8
	Cold stress temp rate (THCS)	−0.0005
	Cold stress degree-day threshold (DTCS)	8
	Cold stress degree-day rate (DHCS)	−0.001
Heat stress	Heat stress temp threshold (TTHS)	38
	Heat stress temp rate (THHS)	0.01
Dry stress	Dry stress threshold (SMDS)	0.1
	Dry stress rate (HDS)	−0.01
Wet stress	Wet stress threshold (SMW)	1.5
	Wet stress rate (SHWS)	0.01
Degree-days per generation	PDD	1000

and Veracruz) (A.S.M., unpublished data). The climate profile of *C.* sp. nr *ithacae* was determined by recursively testing various sets of parameter values until the model's distribution matched its recorded distribution on *Parthenium* spp. in Mexico. The estimated parameters (Table 2) were then used to predict its potential distribution in Australia.

Data Analysis. Two-way analysis of variance (ANOVA) was used to compare presence (proportion of plants with damage) and abundance (number of larvae per plant) of *C.* sp. nr *ithacae* across two sites, Wycarbah and Mt Hay. The analysis was restricted to the two sites, as the establishment of *C.* sp. nr *ithacae* was first noticed in 2004 and since then has been monitored continuously in these two sites. The number of adults emerged per infested plant across six sites with *C.* sp. nr *ithacae* established were compared using one-way ANOVA. Nonlinear regression analysis was used to study the relationships between parthenium density and the incidence (proportion of plants with damage), between parthenium density and abundance (number of larvae per plant) of *C.* sp. nr *ithacae*, between the total summer rainfall (November to March) and proportion of plants with *C.* sp. nr *ithacae;* and between the number of *C.* sp. nr *ithacae* adults emerged per plant and plant vigor (basal stem diameter). All results in the text are presented as means ± SE.

Results

Life Cycle. Under glasshouse conditions (20–30°C and a photoperiod of 12:12 [L:D] h) adult moths lived for 3–12 d and laid 64–235 eggs in their lifetime. Females constituted 44% of all adults emerged ($n = 446$) in the glasshouse. Newly emerged adults mated on the day they eclosed and the females laid eggs singly on leaves and stems soon after mating. Eggs hatched in 12 ± 0.39 d ($n = 12$, range: 10–14), and the neonates entered the stem through leaf axils and tunnelled down to feed on the cortical tissue of the taproot and crown. After 5–6 wk, the late instars pupated in the root or stem-base in silk cocoons. Adults emerged after 11 ± 0.4 d ($n = 12$, range: 10–12) from the clearly visible pupal case protruding from the stem at or above the soil level. There was no evidence of diapause in the glasshouse. Under glasshouse conditions, the mean number of adults produced per plant was 4.5 ± 0.51 ($n = 81$; range: 2–10), and the total duration of life cycle (egg to adult) was around 10 wk.

Field Release. In total, 2,816 potted plants infested with larvae and 372 adult moths were released in 30 sites across Queensland during 1998–2002 (Table 1). This translates to a field release of >12,000 adult moths (4.5 adults per plant × 2,816 plants). Regular field observations on the number of adults emerged per plant (as evident from empty pupal cases protruding from the stem base) at the Cardigan site in northern Queensland indicated that the mean emergence was 4.2 adults per plant.

During early stages of field releases (1998–2000), the moth was recovered from the field sites that received irrigation (i.e., Morebridge and Hillside sites near Clermont and Wycarbah near Rockhampton), but not in sufficient numbers to indicate sustained establishment. At Morebridge, after field release of larval-infested plants in February 1999, larvae were found in June 1999, but neither larvae nor adults were found at a subsequent visit in April 2001. At Hillside, also an irrigated site near Clermont, neither larvae nor adults were found in June 2001, after field releases of larval-infested plants in September 2000 and April 2001. At Wycarbah, after field release of larval-infested plants in March 1999, April 1999, and June 1999, both larvae and adults were recovered in 2001. Neither larvae nor adults were found during early stages of field releases in any of the release sites in northern Queensland.

Field Monitoring. Sustained field incidence was recorded in four (Wycarbah, Mt. Hay, Long Island, and Carfax) of the 13 release sites surveyed (Table 1), all in central Queensland. At two of the release sites (Wycarbah and Mt. Hay), persistence of established populations was confirmed during 2004–2009. During this period, the incidence of *C.* sp. nr *ithacae* at these sites ranged from 30 to 70% (Fig. 1), and did not differ significantly between years ($F_{3,37} = 0.48$, $P = 0.69$) or sites ($F_{1,37} = 0.15$, $P = 0.71$). The mean number of larvae recovered per plant did not differ significantly between years (2006 = 0.43 ± 0.11; 2007 = 0.51 ± 0.09; 2008 = 0.62 ± 0.12; 2009 = 0.24 ± 0.12; $F_{3,37} = 2.08$, $P = 0.12$) or sites (Wycarbah = 0.36 ± 0.07; Mt Hay = 0.53 ± 0.08; $F_{1,37} = 2.62$, $P = 0.11$). The proportion of plants infested with *C.* sp. nr *ithacae* ($R^2 = 0.06$; $F = 1.68$; $P = 0.21$) and the number of larvae recovered per plant ($R^2 = 0.24$; $F = 1.92$; $P = 0.22$) were not dependent on the density of parthenium (plants per m^2). The failure to find *C.* sp. nr *ithacae* at either release sites in 2010 and 2011 was possibly because of summer floods (Fig. 1). This hypothesis is supported by the

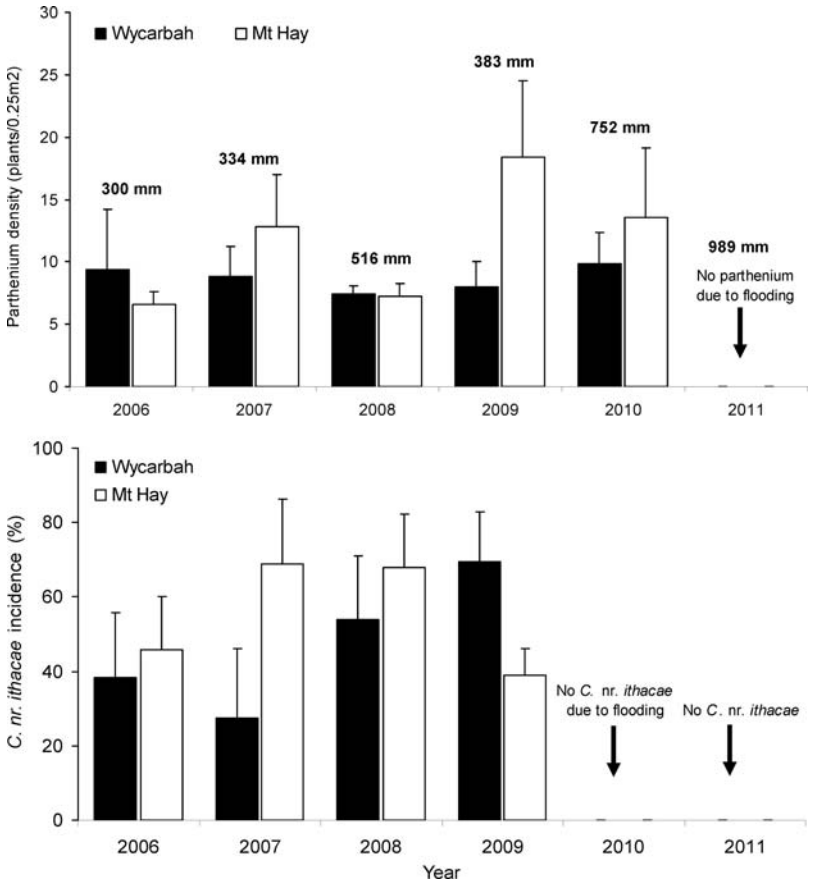

Fig. 1. Variations in the percent infestation (Mean ± SEM) of parthenium and its biological control agent *C.* sp. nr *ithacae* at two release sites, Wycarbah (solid bars) and Mt Hay (empty bars) in Queensland, Australia during 2006–2011. Values above the parthenium incidence bars for each year represent the total summer (November to March) rainfall at Gracemere weather station close to both release sites.

negative relationship between the total summer (November to March) rainfall and incidence of the insect (Fig. 2).

Field establishment of *C.* sp. nr *ithacae* was confirmed in three nonrelease sites, Gracemere (≈20 km from the release site at Long Island), North Wycarbah

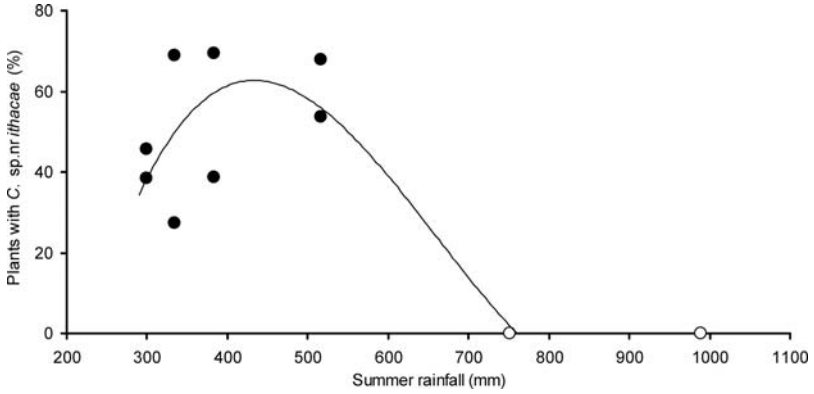

Fig. 2. Relationship between total summer (November to March) rainfall (x) and proportion of plants with *C.* sp. nr *ithacae* (y) ($y = -287.4 + 1.93x - 0.0033x^2 + 0.000002\,x^3$; $R^2 = 0.819$) at two release and establishment sites (Wycarbah and Mt Hay) in Queensland, Australia. Solid (●) and empty (○) circles represent rainfall levels with and without *C.* sp. nr *ithacae* field incidence, respectively.

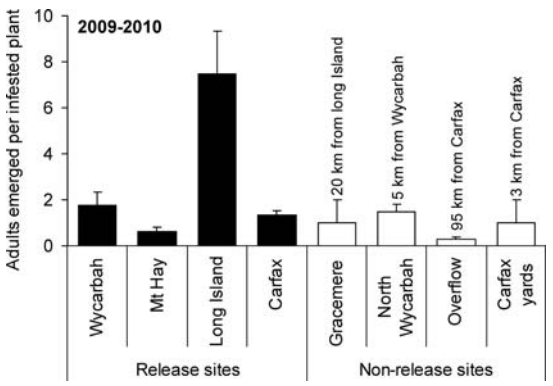

Fig. 3. Number of *C.* sp. nr *ithacae* adults emerged per infested parthenium plants (Mean ± SEM) at release (solid bars) and nonrelease sites (empty bars) in Queensland, Australia.

(≈5 km from the Wycarbah release site), and Overflow (≈95 km from the Carfax release site) in January and March 2009 (Fig. 3). Field establishment also was confirmed along a roadside parthenium infestation 3 km from the release site at Carfax in April 2010 (Fig. 3). In 2011, although no *C.* sp. nr *ithacae* incidence was observed in any of the release sites, the insect was recovered from a nonrelease site near Carfax, confirming the continued persistence of the agent in the field. The number of adults emerged per infested plant varied widely between sites (Fig. 3) with a suggestion of a decline with increasing summer rainfall (Fig. 2). More data in high rainfall years are needed to confirm this. The number of adults emerged per plant increased with the increase in the basal stem diameter (Fig. 4). No establishment was evident in other release sites sampled in northern (Cardigan, Plain Creek, and Felspar) and central (Cobbadah, Delargum, Hillside, Hutton Creek, Kemmis Creek, Landsborough, Lotus Creek, Moleyamber Creek, Morebridge, Oak Wells, and Oxford Downs) Queensland (Table 1).

CLIMEX Model. The CLIMEX model (Table 2), based on the native range of the moth in Mexico, suggest that areas along the coast in the northern and central Queensland are more suitable than inland areas (Fig. 5). In Australia, the current distribution of *C.* sp. nr *ithacae* is restricted to eight sites, all near coastal areas of central Queensland, with no evidence of field establishment in the inland regions or in northern Queensland (Fig. 5). Areas in the southwest and central inland regions in Queensland with substantial parthenium infestations appear less suitable for *C.* sp. nr *ithacae.* Similarly, only limited areas in northern Queensland, where parthenium is becoming a major problem, appear climatically suitable for survival of *C.* sp. nr *ithacae.*

Discussion

Biological control insects introduced against parthenium before *C.* sp. nr *ithacae* were either leaf (*Bucculatrix parthenica* Bradley, *Zygogramma bicolorata* Pallister); stem and shoot (*Conotrachelus albocinereus* Fielder, *Epiblema strenuana* Walker, *Listronotus setosipennis* Hustache, *Platphalonidia mystica* Razowski & Becker); seed (*Smicronyx lutulentus* Dietz); or sap (*Stobaera concinna* Stål) feeders (Dhileepan and Strathie 2009). Because the suite of agents did not include any obligatory root-feeding insects, *C.* sp. nr *ithacae* was prioritized and introduced to complement the complex of existing agents. *Carmenta* sp. nr *ithacae*, with root-feeding larvae, is the only root-feeding agent to be released as a biological control agent against parthenium in Australia (or elsewhere).

Carmenta sp. nr *ithacae* has never been reared previously under laboratory conditions and only limited information was available on its life cycle (A.S.M., unpublished data). Mating under glasshouse conditions proved to be a problem for laboratory rearing in Australia, which was overcome by providing additional light sources to adults in the morning, which resulted in successful mating. Mass-rearing of the moth continued throughout the year, and there was no evidence of obligatory diapause under glasshouse conditions. This possibly was because of the favorable temperature and light conditions maintained in the glasshouse. However, field releases were made only from early spring to late autumn, coinciding with the prevalence of parthenium in the field. Occasional field releases were made in winter months in northern Queensland (Table 1), when green parthenium was available in the field. Even though release efforts were directed both in the northern and central Queensland area, the number of adults and larval-infested plants released and frequency of field releases were greater in central Queensland than in northern Queensland (Table 1). Unlike in central Queensland where field releases were continued over 3 yr (1999–2002), field releases in northern Queensland were made only over 1 yr (1999–2000), with a limited number of releases in each site.

Of the nine insect species released so far as biological control agents against parthenium in Australia, *C.* sp. nr *ithacae* is the sixth agent to become established in the field. Although adults were recovered from many of the release sites within a year after initial releases, consistent field recoveries were made at only two of the release sites in central Queensland since 2004. Field establishment of *C.* sp. nr *ithacae* in two of the release sites near coastal areas in central Queensland possibly was because of release of more larval-infested plants, more frequently and over a 3-yr period. In addition, both these sites received irrigation to keep the parthenium green throughout the year, which also could have helped the establishment of the agent. However, in spite of irrigation and larger, more frequent releases (Table 1), field establishment has not been achieved in any of the release sites in the inland region. *Carmenta* sp. nr *ithacae* is widespread in the range of *P. hysterophorus* in Mexico. Attack rates at individual field sites in the vicinity of Monterrey, Mexico, in April 1996 ranged from 10 to 72%, with a mean of 2.16 larvae or pupae per infested plant (maximum 11 larvae) (A.S.M., unpublished data). In Aus-

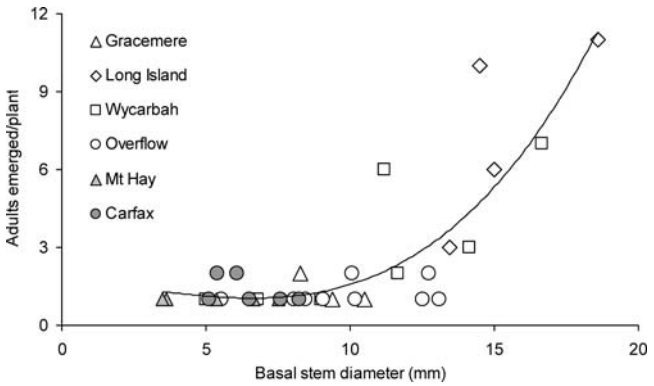

Fig. 4. Relationship between basal stem diameter (x) of parthenium plants and number of *C.* sp. nr *ithacae* adults emerged (y) in 2009 at five release sites (regression for the data from all sites combined, $y = 4.41 - 1.012x + 0.073x^2$; $R^2 = 0.727$) in Queensland, Australia.

tralia, in contrast, the agent is not yet widespread, but in areas where they are known to be established, adult recovery was ≈0.4 adult per plant. Annual sampling since 2006 at Wycarbah and Mt Hay, the two established sites, indicated that the incidence (proportion of plants damaged) and abundance (number of larvae per plant) of *C.* sp. nr *ithacae* remained high during 2006–2009. However, there was no evidence of *C.* sp. nr *ithacae* at both sites in 2010 and 2011, although the agent was found at some nonrelease sites. High summer rainfall (>700 mm) resulting in flooding could have affected the root-boring larvae. A positive relationship between the basal stem width and the number of larvae per plant, suggests that this agent prefers larger plants in the field. This agrees with field observations in Mexico (A.S.M., unpublished data). Preferences for larger and more vigorous plants are known in other *Carmenta* spp. (Cordo et al. 1995b), root-feeding insects (Smith and Story 2003), and other parthenium biological control insects (Dhileepan, 2004).

So far, no information on the phenology of *C.* sp. nr *ithacae* under Australian field conditions is available, as field sampling was restricted to once a year, because of the remoteness of release sites. Sampling of parthenium plants surrounding the established sites also suggests that the agent is spreading only 1–2 km per year from its release and establishment site. *Carmenta mimosa* Eichlin and Passoa, an agent released against *M. pigra* in Australia, also exhibited a slow spread rate (Ostermeyer 2000). At release sites where establishment is yet to be confirmed, populations may be too low to detect during the annual sampling. Populations of many weed biological control agents often remain at low densities for some time before reaching detectable levels (e.g., Dhileepan et al. 1996, Mo et al. 2000).

In its native range (e.g., Mexico) *C.* sp. nr *ithacae* is widespread, along the Gulf coastal plain, from ≈19° N to 26° 30′ N. In Australia, coastal areas of central and southeastern Queensland are identified as climatically most suitable areas for *C.* sp. nr *ithacae* (Fig. 5). The restriction of field establishment of *C.* sp. nr *ithacae* to release sites near the coast, with none in inland areas, possibly because of cold stress, support the validity of the CLIMEX model. Lack of any evidence of establishment in northern Queensland, although some of the release sites there appear climatically suitable for the insect, possibly was because of limited release efforts in this region. Had the CLIMEX model been developed before the initiation of the release program, the release efforts in the inland region would have been redirected to climatically more suitable areas along the coast. This highlights the need to develop CLIMEX models for biological control agents before release efforts are made (Rafter et al. 2008).

Occurrence of all *C.* sp. nr *ithacae* establishment sites within the climatically suitable areas identified in the CLIMEX model highlights that the model based on the distribution records of *C.* sp. nr *ithacae* on parthenium in Mexico is robust and valid. In contrast, a model based on the recorded distribution records of *C. ithacae* in Canada, the United States, and Mexico, on all host plants, would have predicted a much wider geographic range covering the entire parthenium infestation in Australia, similar to the ragweed borer *Epiblema strenuana* Walker, an introduced parthenium biological control agent in Australia. *Epiblema strenuana*, which has a wide native range distribution similar to *C. ithacae* (e.g., Canada, the United States, and Mexico) occurs throughout Queensland and New South Wales where host plants occur (McFadyen 1992, Dhileepan and Strathie 2009). However, predictions based on climatic models need to be treated with caution because the best climatic match is no guarantee of successful establishment of biological control agents, although some biological control agents have thrived outside their predicted climatic range (McFadyen 1998).

Parthenium is a major weed in many countries in Asia, Africa, and the Pacific. Biological control efforts against parthenium are in progress in South Africa and Ethiopia, whereas in India it is planned to import new agents to complement *Z. bicolorata* that was released in the mid-1980s. *Carmenta* sp. nr *ithacae*, a highly host-specific insect, is a safe and suitable biological

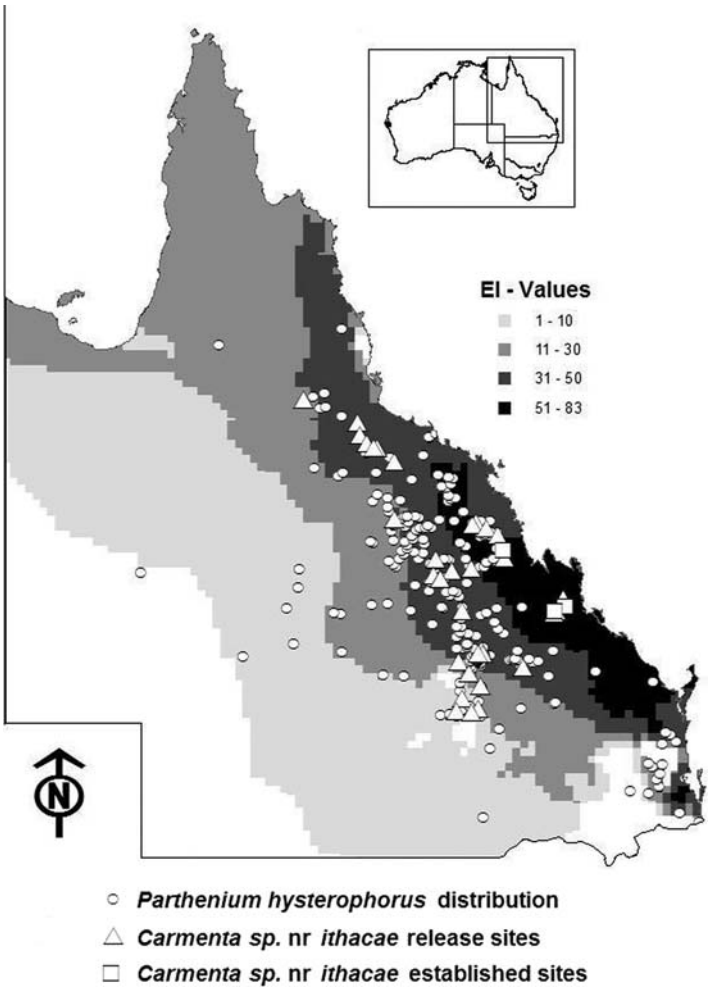

Fig. 5. Climatic suitability of Queensland, Australia for *C.* sp. nr *ithacae* by interpolation of the Eco-climatic Index (EI) derived from a CLIMEX model (Table 2). Higher EI values indicate a more suitable climate. Parthenium infestations (○) and *C.* sp. nr *ithacae* release (Δ) and established (□) sites.

control agent worth consideration for introduction in these countries where parthenium is a major weed.

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References Cited

Blossey, B., and T. R. Hunt-Joshi. 2003. Belowground herbivory by insects: Influence on plants and aboveground herbivores. Annu. Rev. Entomol. 48: 521–547.

Chippendale, J. F., and F. D. Panetta. 1994. The cost of parthenium weed to the Qld cattle industry. Plant Prot. Q. 9: 73–76.

Cordo, H. A., C. J. DeLoach, and R. Ferrer. 1995a. Host range of the Argentine root borer *Carmenta haematica* (Ureta) (Lepidoptera: Sesiidae), a potential biocontrol agent for snakeweeds (*Gutierrezia* spp.) in the United States. Biol. Control 5: 1–10.

Cordo, H. A., C. J. DeLoach, R. Ferrer, and J. Briano. 1995b. Bionomics of *Carmenta haematica* (Ureta) (Lepidoptera: Sesiidae) which attacks snakeweeds (*Gutierrezia* spp.) in Argentina. Biol. Control 5: 11–24.

Dhileepan, K. 2004. The applicability of the plant vigor and resource regulation hypotheses in explaining *Epiblema* gall moth-*Parthenium* weed interactions. Entomol. Exp. Appl. 113: 63–70.

Dhileepan, K., and L. Strathie. 2009. *Parthenium hysterophorus* L. (Asteraceae), pp. 272–316. *In* R. Muniappan, G.V.P. Reddy, and A. Raman (eds.), Biological control of tropical weeds using arthropods. Cambridge University Press, Cambridge, United Kingdom.

Dhileepan, K., B. Madigan, M. Vitelli, R.E.C. McFadyen, K. Webster, and M. Trevino. 1996. A new initiative in the biological control of parthenium, pp. 309–312. *In* R.C.H. Shepherd (ed.), Proceedings of the Eleventh Australian Weeds Conference, 30 September–3 October 1996. Weed Science Society of Victoria, Melbourne, Australia.

Eichlin, T. D., and W. D. Duckworth. 1988. Sesioidea: Sesiidae, pp. 1–176. *In* R. B. Dominick, D. C. Ferguson, J. G. Franclemont, R. W. Hodges, E. G. Munroe, and J. A. Powell (eds.), The moths of America north of Mexico, fascicle 5.1. The Wedge Entomological Research Foundation, Washington, DC.

Forno, I. W., R. C. Kassulke, and M. D. Day. 1991. Life cycle and host testing procedures for *Carmenta mimosa* Eichlin and Passoa (Lepidoptera: Sesiidae), a biological control agent for *Mimosa pigra* L. (Mimosaceae) in Australia. Biol. Control 1: 309–315.

McClay, A. S., W. A. Palmer, F. D. Bennett, and K. R. Pullen. 1995. Phytophagous arthropods associated with *Parthenium hysterophorus* (Asteraceae) in North America. Environ. Entomol. 24: 796–809.

McFadyen, R.E.C. 1992. Biological control against parthenium weed in Australia. Crop Prot. 11: 400–407.

McFadyen, R.E.C. 1995. Parthenium weed and human health in Qld. Aust. Fam. Physician 24: 1455–1459.

McFadyen, R.E.C. 1998. Biological control of weeds. Annu. Rev. Entomol. 43: 369–393.

McFadyen, R.E.C., and T. M. Withers. 1997. Report on biology and host-specificity of *Carmenta ithacae* (Lep: Sesiidae) for the biological control of parthenium weed (*Parthenium hysterophorus*). Internal Report, Queensland Department of Natural Resources, Australia.

Mo, J. H., M. Trevino, and W. A. Palmer. 2000. Establishment and distribution of the rubber vine moth, *Euclasta whalleyi* Popescu-Gorj and Constantinescu (Lepidoptera: Pyralidae), following its release in Australia. Aust. J. Entomol. 39: 344–350.

Ostermeyer, N. 2000. Population density and distribution of the biological control agent *Carmenta mimosa* on *Mimosa pigra* in the Adelaide and Finniss River catchments of the Northern Territory. Plant Prot. Q. 15: 46–50.

Ostermeyer, N., and B. S. Grace. 2007. Establishment, distribution, and abundance of *Mimosa pigra* biological control agents in northern Australia: implications for biological control. BioControl 52: 703–720.

Paynter, Q. 2005. Evaluating the impact of a biological control agent *Carmenta mimosa* on the woody wetland weed *Mimosa pigra* in Australia. J. Appl. Ecol. 42: 1054–1062.

Rafter, M. A., A. J. Wilson, K.A.D. Wilmot Senaratne, and K. Dhileepan. 2008. Modelling climatic similarities in native and introduced ranges of cat's claw creeper *Macfadyena unguis-cati* (Bignoniaceae) to prioritise areas for exploration and release of biological control agents. Biol. Control 44: 169–179.

Seastedt, T. R., D. G. Knochel, and S. A. Shosky. 2007. Interactions and effects of multiple biological control insects on diffuse and spotted knapweed in the Front Range of Colorado. Biol. Control 42: 345–354.

Simelane, D. O. 2005. Biological control of *Lantana camara* in South Africa: targeting a different niche with a root-feeding agent, *Longitarsus* sp. BioControl 50: 375–387.

Smith, L., and J. M. Story. 2003. Plant size preference of *Agapeta zoegana* L. (Lepidoptera: Tortricidae), a root-feeding biological control agent of spotted knapweed. Biol. Control 26: 270–278.

Sutherst, R. W., G. F. Maywald, and D. Kriticos. 2007. CLIMEX version 3 users guide. Hearne Scientific Software Pty Ltd., Melbourne, Australia.

Withers, T., R.E.C. McFadyen, and J. Marohasy. 1999. Importation protocols and risk assessment of weed biological control agents in Australia: the example of *Carmenta sp.* nr *ithacae*, pp. 195–214. *In* P. A. Follett and J. J. Duan (eds.), Nontarget effects of biological control. Kluwer, Boston, MA.

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