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REVIEW

Biological control of cat's claw creeper (*Dolichandra unguis-cati*; Bignoniaceae): Current status and future prospects

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Abstract

Cat's claw creeper (*Dolichandra unguis-cati*), native to tropical South America, is a major invasive species and a target for biological control in Australia, South Africa and some South Pacific Island countries. Native range surveys in Argentina, Brazil, Paraguay and Venezuela have identified eight insects and four fungal pathogens as potential agents. Five leaf-feeding insects a tortoise beetle *Charidotis auroguttata*, two tingids *Carvalhotingis visenda* and *C. hollandi*, a leaf-tying moth *Hypocosmia pyrochroma* and a leaf-mining beetle *Hedwigiella jureceki*, have been tested and all were released in South Africa. Four of these have become established but are not widespread and cause only limited damage. In Australia, only three of these, *C. visenda*, *H. pyrochroma* and *H. jureceki* were released, while *C. auroguttata* was not approved due to perceived non-target risks. All agents have become widely established, except for *H. pyrochroma* which is restricted to riparian corridors in southeast Queensland. In South Africa, an accidentally introduced leaf-spot pathogen, *Neoramulariopsis unguis-cati*, causes necrotic lesions and premature abscission of leaves in cat's claw creeper infestations, resulting in widespread defoliation. Based on its impact and field-host specificity in its native range and in South Africa, the pathogen has been prioritised for evaluation as a potential additional agent in Australia. The current priority is to seek approval for the introduction of this leaf-spot pathogen into Australia. Future research should focus on the gall-inducing rust *Uropyxis rickiana* and the seed-feeding weevil *Apteromechus notatus* as prospective agents.

KEYWORDS
Australia, cat's claw creeper, invasive liana, South Africa, weed biocontrol

1 | INTRODUCTION

Dolichandra unguis-cati (L.) L.G. Lohmann (Bignoniaceae), commonly known as the cat's claw creeper, is a perennial climbing vine that is native to tropical and subtropical South America. Cat's claw creeper is regarded as an invasive species in many countries in Africa (Kenya, Mauritius, Malawi, South Africa, Tanzania and Zimbabwe), Asia (China and India), Oceania (Australia, Hawaii, New Caledonia, New Zealand and Vanuatu), North America (Florida and Texas, USA) and the Caribbean (Cuba) (King & Dhileepan, 2009; Rojas-Sandoval, 2023).

Available information on the impacts and management of cat's claw creeper is largely limited to Australia and South Africa where there have been long-term programs to manage the vine. In Australia it is ranked as a major invasive species in Queensland (Batianoff & Butler, 2003; Osunkoya et al., 2020) and New South Wales (NSW) (Downey et al., 2010). Although major infestations of the weed currently occur in the coastal and subcoastal areas of southeast Queensland and northern NSW, cat's claw creeper has the potential to spread throughout eastern Australia (Dhileepan, 2012). In South Africa, major cat's claw creeper infestations occur in the Gauteng, Kwazulu-Natal, Limpopo, Mpumalanga and Northwest Provinces (King et al., 2011). Cat's claw creeper is still considered to be in the early stages of invasion in South Africa, but at the current rate of dispersal the vine has the potential to spread over much of South Africa's eastern and southern coastal areas (Henderson & Wilson, 2017; Rafter etal., 2008). Cat's claw creeper is listed as a Category 1 species by the Florida Exotic Pest Plant Council, and is invasive in Texas (PPQ, 2019). In Vanuatu, a cat's claw creeper has been found on three islands (Day & Bule, 2016). However, information on the distribution, infestation levels, and impact of cat's claw creeper in other countries where it is regarded as invasive, is lacking.

Extensive infestations of cat's claw creeper in both Australia and South Africa occur along roadsides and riparian corridors and in natural forests, cultivated orchards and forestry plantations (Downey & Turnbull, 2007; Vivian-Smith & Panetta, 2004; Williams, 2002). In riparian corridors and natural forests, vine smother standing vegetation, including large trees, causing canopy collapse (Sparks, 1999). The vine grows along the ground in areas with no standing structures or vegetation, preventing germination and growth of desirable understory vegetation. Combined, these impacts pose a significant threat to local biodiversity and ecosystem functioning (Downey & Turnbull, 2007).

The management objectives for cat's claw creeper are focused on lowering the rate of shoot growth to limit the vine's ability to climb and smother native vegetation as well as to reduce tuber biomass. Chemical control options for managing weeds are available but are often not used because of the sensitive ecosystems in which weeds occur. Mechanical control of above-ground growth provides only temporary relief, as regeneration from subterranean tubers is rapid and continues over many years. Biological control is the most desirable management option for cat's claw creeper. A biological control program was initiated in South Africa in 1996 (Sparks, 1999) and based on this program, Australia commenced its own in 2001 (King & Dhileepan, 2009). More recently, based on research conducted in Australia, a biological control program for the cat's claw creeper in Vanuatu has been started (Anon, 2018).

Biological control programs are long-term projects spanning many decades, including native range surveys (3–5 years), host-specificity testing of prioritized agents (3–4 years for each agent), rearing and release of approved agents (3–5 years for each agent) and monitoring the establishment, dispersal and the impact of released agents (>5 years). Progress with the cat's claw creeper biological control programs in South Africa (King et al., 2011) and Australia (Dhileepan, 2012) has been reviewed. These early reviews focused primarily on host specificity testing and release of potential agents. Since then, additional agents have been introduced in both countries and further progress has been made by monitoring their establishment, dispersal, and impact. A later review of biological control of invasive lianas in South Africa in 2021 (King et al., 2021) also included updates on cat's claw creeper biologial control, but no recent review has been published for Australia. Thus the aim of this paper is to provide an update on the recent progress made in Australia and, for the first time, to collate information about cat's claw creeper and its biological control agents from Australia and South Africa. This will provide a valuable resource for other countries or regions where the cat's claw creeper is an invasive species and where biological control is yet to be implemented. The recommendations from this review are anticipated to aid the selection and release of suitable agents for other countries (e.g., South Pacific Islands) impacted by cat's claw creeper.

2 | CATS CLAW CREEPER

The cat's claw creeper is a woody liana that prefers tropical and subtropical climates. The liana climbs on supporting structures, such as fences and other vegetation, including tall trees (Figure 1). In the absence of any supporting structures, the vine prostrates along the ground forming a dense mat of roots and numerous underground tubers in the soil. The liana produces trumpet-shaped yellow flowers in late spring or in early summer. The flowers develop into linear flat pods, containing winged oblong seeds that are dispersed primarily by wind and water and remain viable for up to a year (Vivian-Smith & Panetta, 2004). The liana reproduces both sexually using seeds and vegetatively from underground tubers and creeping stems trailing along the ground. Although the dispersal mechanism of cat's claw creeper is mainly through seeds, the mechanism of its persistence is through its underground tuber bank (Osunkoya et al., 2009).

Wide morphological and genetic variations in cat's claw creeper populations exist in the native range (Prentis et al., 2009; Sigg et al., 2006). In Australia, there are two forms of the weed with significant morphological, phenological and genetic differences; a long-pod (LP) form with bigger leaves, longer fruit pods and infrequent flower pulses; and a short-pod (SP) form with smaller leaves, shorter pods and annual flowering pulses (Shortus & Dhileepan, 2010). The SP form exhibits higher phenotypic plasticity (Boyne et al., 2013; Buru et al., 2019), produces polyembryonic seeds with rapid and higher germination rates (Buru et al., 2014; Buru, Dhileepan, Osunkoya, & Scharaschkin, 2016) and produces more biomass (Buru, Dhileepan, Osunkoya, & Firn, 2016; Taylor & Dhileepan, 2012) relative to the LP form, highlighting the greater invasion potential of the SP form. In South Africa, only the SP form of cat's claw creeper occurs.

3 | BIOLOGICAL CONTROL

3.1 | Native range surveys

Cat's claw creeper is native to Central America, tropical and subtropical South America and the Caribbean (Dhileepan, 2012). A climex

FIGURE 1 Cat's claw creeper (short-pod form) infestation smothering native vegetation in southeast Queensland, Australia.

model predicted areas covering northern Argentina, Southern Brazil and Southern Paraguay, to be climatically suitable to source potential biological control agents for both Australia and South Africa (Rafter et al., 2008). Genetic studies have highlighted that the majority (>96%) of introduced haplotypes of cat's claw creeper in Australia are the SP form (with smaller leaves, shorter fruit pods, and annual flowering pulses) which matched a single haplotype from Paraguay (Prentis et al., 2009; Sigg et al., 2006). The remaining LP specimens in Australia (with larger leaves, longer fruit pods, and infrequent flowering pulses) could not be matched with any of the haplotypes from the native range (Prentis et al., 2009; Sigg et al., 2006). Therefore, based on herbaria records, climatic suitability (Rafter et al., 2008) and genetic studies (Prentis et al., 2009), native range surveys for both LP and SP forms of cat's claw creeper were conducted, primarily targeting Argentina, Brazil and Paraguay from 1996 to 2016. Other *Dolichandra* species and members of Bignoniaceae co-occurring with cat's claw creepers were also surveyed, to ascertain the field-host range of prospective agents.

Native range surveys identified six leaf-feeding insects and two seed-feeding insects, and four pathogens as potential biological control agents (Table 1). Under field conditions, all agents have been reported on cat's claw creeper only (Williams et al., 2008). This was further confirmed by observations of their field-host range in the native range, where the respective agents were found only on the cat's claw creeper. However, in host specificity tests under quarantine conditions, the seed feeding *Clydonopteron pomponius* Druce fed on the mature fruits of *Tecoma stans* (L.) Jess. Ex. Kunth (Bignoniaceae) (Madire, 2010). A yet to be identified gall midge (Cecidomyiidae) and a shoot tip feeding sawfly (Pergidae) have also been recorded (Williams et al., 2008). No insects were recorded to feed on the subterranean tubers. Native range surveys focusing on fungal pathogens identified several damaging leaf-spots and two rust pathogens, that attack leaves and leaves and stems of the vine, respectively, and one leaf-spot and one rust pathogen were subsequently described as new species (Colmán, 2014; Colmán et al., 2020; Da Silva et al., 2012; Hernández & Hennen, 2003). Cat's claw creeper is susceptible to leaf herbivory (Raghu et al., 2006; Raghu & Dhileepan, 2005) and multiple defoliation events are needed (St Pierre, 2007) to manage weed effectively. Hence, prospective agents targeting leaves were initially prioritized for detailed host-specificity testing.

3.2 | Agents tested/released

3.2.1 | *Charidotis auroguttata* Boheman

The tortoise beetle *C. auroguttata* (Coleoptera; Chrysomelidae), the first agent tested against the cat's claw creeper, is native to Argentina, Brazil, Paraguay, Trinidad and Venezuela (Sparks, 1999). In the native range, *C. auroguttata* was found on both the LP and SP forms. Both adults and larvae feed on leaves and cause premature leaf abscission and shoot dieback (Sparks, 1999). The life cycle (egg to adult) of *C. auroguttata* is completed within 7–8 weeks (Dhileepan et al., 2005; Williams, 2002). The adults are long-lived (more than 1 year) and the beetle is believed to overwinter as adults in the native range.

Charidotis auroguttata was imported from Venezuela to South Africa in 1996 for host-specificity tests. No-choice larval survival and adult and larval choice tests have confirmed the host

TABLE 1 Specialist phytophagous insects and plant pathogens associated with cat's claw creeper in the native range.

Species	Order/Family	Common name	Plant part affected	Reported native range
Phytophagous insects				
Charidotis auroguttata Boheman	Coleoptera: Chrysomelidae	Tortoise beetle	Adults and larvae feed on leaves	Argentina, Bolivia, Brazil, Mexico, Paraguay and Venezuela
Hedwigiella jureceki (Obenberger)	Coleoptera: Chrysomelidae	Leaf-mining jewel beetle	Adults and larvae feed on leaves	Argentina, Brazil and Paraguay
Apteromechus notatus (Hustache)	Coleoptera: Curculionidae	Seed-feeding weevil	Adults and larvae feed on developing seeds	Argentina, Brazil and Paraguay
Carvalhotingis visenda (Drake & Hambleton)	Hemiptera: Tingidae	Leaf sucking tingid	Adults and nymphs feed on leaves	Argentina, Brazil and Paraguay
Carvalhotingis hollandi (Drake)	Hemiptera: Tingidae	Leaf sucking tingid	Adults and nymphs feed on leaves	Argentina, Brazil, Paraguay
Hypocosmia pyrochroma (Jones)	Hemiptera: Tingidae	Leaf tying moth.	Larvae leaf feeding	Argentina, Brazil and Paraguay
Clydonopteron pomponius Druce	Lepidoptera: Pyralidae	Seed-feeding caterpillar	Larvae feeding on mature seeds	Brazil
Neocrassana undata Linnavuori	Hemiptera: Cicadellidae	Cats claw creeper leafhopper	Adults and nymphs feed on leaves	Argentina, Brazil and Paraguay
Cecidomyiid (unidentified)	Diptera: Cecidomyiidae	Gall midge	Larvae induce shoot galls	Brazil and Paraguay
Plant pathogens				
Prospodium macfadyenae Meir. Silva, O.L. Pereira & R.W. Barreto	Pucciniales: Uropyxidaceae	Leaf rust	Leaf	Brazil
Uropyxis rickiana Magnus	Pucciniales: Uropyxidaceae	Gall-forming rust	Leaf and stem	Argentina, Brazil and Paraguay
Neoramulariopsis unguis-cati (Speg.) Ragav. Singh & Kushwaha	Capnodiales: Mycosphaerellaceae	Leaf-spot disease	Leaf	Argentina, Brazil and Paraguay
Passalora macfadyenae Meir. Silva, O.L. Pereira & R.W. Barreto	Capnodiales: Mycosphaerellaceae	Leaf-spot disease	Leaf	Brazil

specificity of *C. auroguttata* (Sparks, 1999; Williams, 2002). The agent was approved in South Africa in 1999 and field releases continued until 2010 (King et al., 2011). Under glasshouse conditions, feeding by *C. auroguttata* larvae significantly reduced shoot length and total plant biomass (Ziganira & Olckers, 2012). Despite repeated releases across multiple sites over multiple years, the establishment of the agent was evident at only a few sites and at these sites, the population levels of the beetle remained low resulting in negligible impact (King et al., 2011, 2021; King & Dhileepan, 2009).

Charidotis auroguttata was imported from South Africa to Australia in 2001 for host-specificity testing (Dhileepan et al., 2005). In no-choice tests, adults and larvae fed on multiple non-target species, although larval development was completed in only one Australian native non-target species *Myoporum boninense* subsp. *australe* Chinnock (Dhileepan et al., 2005; Raghu et al., 2007). However, larval survival was 83% lower and development took twice as long to complete on *M. boninense* subsp. *australe*, relative to the target weed (Dhileepan et al., 2005). In choice demographic studies, initiation of oviposition was delayed by 10 weeks and there was a very low adult incidence (10% adults) and oviposition (<12% eggs) on the non-target species in comparison to the target weed. The results highlighted that although the agent has the potential to spill-over from the target weed onto the co-occurring non-target species, the non-target species is unlikely to sustain a viable population of the agent on its own. However, because of the perceived non-target risk, the agent was not approved for release in Australia.

3.2.2 | *Carvalhotingis visenda* (Drake & Hambleton)

Carvalhotingis visenda (Tingidae: Hemiptera), a leaf-sucking tingid, is native to Argentina, Brazil, Paraguay and Peru, where it has been recorded only on cat's claw creeper (Drake & Ruhoff, 1965; Montemayor & Coscarón, 2005). In the native range, *C. visenda* occurs on both the LP and SP forms. Both adults and nymphs feed on the cell contents of the leaves from the underside, resulting in leaf chlorosis (Williams, 2003c). Adults live about 120 days and females lay about 265 eggs along the veins on the underside of the leaves. *Carvalhotingis visenda* has a shorter (4–5 weeks) generation time, completing multiple generations in a year (Dhileepan, Treviño, & Snow, 2007; Williams et al., 2008).

Carvalhotingis visenda from northern Argentina and southern Brazil were imported to South Africa in 2002. Host-specificity tests involving nymphal no-choice and adult choice tests have also been conducted (Williams et al., 2008). Under no-choice conditions, the nymphs survived and completed development only on the cat's claw creeper. Similarly, under choice conditions, adults fed and laid eggs on cat's claw creeper only. The agent was approved in South Africa in 2007 (King et al., 2011) and field releases have continued to date. There is widespread establishment and dispersal of *C. visenda* in South Africa, particularly in areas at higher elevations, high rainfall sites and along riparian corridors, resulting in leaf chlorosis and defoliation (King et al., 2021). However, the establishment of *C. visenda* is restricted to the cat's claw creeper plants along the ground, resulting in 5–38% leaf loss (King et al., 2021).

Carvalhotingis visenda was imported from South Africa to Australia in 2004. Studies on nymphal survival and development, adult feeding and survival and egg laying using choice and no-choice tests have confirmed that *C. visenda* is highly host specific with no non-target risk (Dhileepan, Treviño, & Snow, 2007). *Carvalhotingis visenda* feeding reduced the chlorophyl content by 60–90% in 6 weeks (Trevino et al., 2006), resulting in significant reductions in plant height, leaf biomass, underground tuber size and tuber biomass (Bayliss, 2006; Conrad & Dhileepan, 2007). Adults showed tolerance to a wide range of temperatures (0–45°C) for survival. In contrast, egg laying, egg hatching and nymphal development are adversely affected by high (>30°C) and low (<20°C) temperatures (Dhileepan, Treviño, et al., 2010). Thermal models have predicted that *C. visenda* has the potential to complete a higher number of generations in coastal areas than inland areas in Australia (Dhileepan, Bayliss, & Treviño, 2010).

Carvalhotingis visenda was approved for release in Australia in 2007. Field releases were made during 2007–2009 across 72 sites covering both riparian and non-riparian sites in Queensland and NSW (Dhileepan, Treviño, et al., 2010). Although establishment was evident at over 80% of the release sites within 3 years, dispersal remained slow and patchy. As predicted by the thermal model, *C. visenda* abundance peaked during cooler months, with the population declining during hot summers. High populations of *C. visenda* caused severe leaf chlorosis in more than 50% of the leaves at ground level (Figure 2; Dhileepan, Treviño, et al., 2010). Currently, *C. visenda* is widespread in most riparian areas with cat's claw creeper infestations. Community organizations such as Gympie Landcare and NSW Biocontrol Task Force are actively involved in the rearing and field release of the agent in Queensland and NSW, respectively. More recently, *C. visenda* has been introduced into Vanuatu, but its establishment status is currently unknown.

3.2.3 | *Carvalhotingis hollandi* (Drake)

The leaf-sucking tingid bug, *C. hollandi* (Tingidae: Hemiptera), has been recorded on both the LP and SP forms of cat's claw creeper in Argentina, Brazil and Paraguay, where it often co-occurs with *C. visenda*. *Carvalhotingis hollandi* adults are flatter than *C. visenda* adults, with a dark mark on the corium of the hemelytron. In contrast, *C. visenda* adults have a black protruding knob in the corium of each hemelytron. The lifecycle and feeding habits of *C. hollandi* are very similar to those of *C. visenda*, except that *C. hollandi* has a longer pre-oviposition period than *C. visenda* (Williams et al., 2008). Both *C. hollandi* and *C. visenda* caused similar feeding damages. Feeding by *C. hollandi* nymphs significantly reduced the leaf chlorophyll content, with increasing nymphal densities, but the impact of nymphal feeding on above and below ground biomass was not significant (Williams et al., 2008).

FIGURE 2 Leaf chlorosis due to feeding by *Carvalhotingis visenda* adults and nymphs.

Carvalhotingis hollandi was imported to South Africa from Brazil and Argentina in 2002. In the no-choice tests, nymphal feeding and development occurred only on the cat's claw creeper. In the choice tests, adults fed and laid eggs only on the cat's claw creeper. *Carvalhotingis hollandi* was approved in South Africa in 2007 and field releases were conducted throughout the country until 2014 (King et al., 2021). The initial establishment of *C. hollandi* was low, with feeding damage observed in only 23% of release sites. Little population buildup was evident at these sites and recent surveys have failed to recover the insect around any of the original release locations (King et al., 2021).

Carvalhotingis hollandi was imported to Australia from South Africa in 2004. Due to the difficulties in establishing a colony in quarantine conditions, no further research has been conducted.

3.2.4 | *Hypocosmia pyrochroma* (Jones)

The leaf-tying moth *H. pyrochroma* (Lepidoptera: Pyralidae) is native to Argentina, Brazil and Paraguay, where it occurs in both the LP and SP forms of cat's claw creeper. Adults live for approximately 2 weeks and lay about 150 eggs singly on the underside of the leaves. The generation time (egg to adult) without pupal diapause is approximately 10 weeks (Dhileepan et al., 2007; Dhileepan et al., 2021; Dhileepan, Taylor, McCarthy, et al., 2013; Williams, 2003a). From the middle of autumn to late spring, pupae undergo diapause in the soil, in response to declining photoperiod. Adults emerge from pupal diapause from mid-spring onwards, with emergence peaking in early summer. Larval feeding causes severe defoliation (Figure 3) and reduces plant growth and below-ground tuber production (Snow et al., 2006).

Hypocosmia pyrochroma larvae sourced from Brazil and Argentina were imported to South Africa in 2002 (Williams, 2003a). In no-choice tests, larvae completed development only on cat's claw creeper, although there was some feeding on a South African native non-target species, *Markhamia obtusifolia* (Baker) Sprague, and the larvae did not develop beyond the second instar (Williams, 2003a). In choice oviposition tests adults laid eggs only on cat's claw creeper and no eggs were laid on any of the non-target test plant species, including *M. obtusifolia* (Williams, 2003a). The agent was approved for release in South Africa and it was released in the field from 2010 to 2022, both as adults and larvae (King et al., 2021). There has been no evidence of the establishment of *H. pyrochroma* in South Africa.

Hypocosmia pyrochroma was imported from South Africa to Australia in 2005. Feeding and development of larvae in the no-choice and choice tests occurred only on the cat's claw creeper (Dhileepan, Treviño, & Snow, 2007). Eggs were laid only on the cat's claw creeper during the choice tests. The agent was approved for release in Australia in 2007. Adults survived and eggs developed across a wide temperature range (12–40°C), whereas the egg laying as well as larval and pupal development were inhibited by low (<20°C) and high (>30°C) temperatures (Dhileepan, Taylor, McCarthy, et al., 2013).

Hypocosmia pyrochroma larvae and adults were released at 40 sites in Queensland and northern NSW from 2007 to 2010. Evidence of its establishment has increased from three release sites in 2012 to 80 in 2020 (Dhileepan et al., 2021). *Hypocosmia pyrochroma* was established on both LP and SP forms of cat's claw creeper and higher establishment success was achieved at sites where releases were made in insect-proof cages (50%) than at sites with open field releases (9%). As predicted by the thermal and climex models (Dhileepan, Taylor, McCarthy, et al., 2013), the establishment of *H. pyrochroma* has been limited to riparian corridors in coastal areas, highlighting the role of microclimate as a limiting factor for its establishment and spread. Larval feeding damage by *H. pyrochroma* is evident from late spring to mid-autumn. Incidence and damage levels have been steadily increasing since 2015. Currently, community

FIGURE 3 Defoliation due to larval feeding by *Hypocosmia pyrochroma*.

Annals of Applied Biology aab An international journal of the aab

organizations such as the Gympie Landcare and NSW Biocontrol Task Force, are involved in the field collection and redistribution of *H. pyrochroma* larvae in Queensland and NSW, respectively.

3.2.5 | *Hedwigiella jureceki* (Obenberger)

The leaf-mining jewel beetle *Hedwigiella jureceki* (Buprestidae: Coleoptera) (syn: *Hylaeogena jureceki*) is native to Argentina, Brazil, Paraguay and Trinidad and occurs on both forms of cat's claw creeper. Adults feed on young leaves and live for up to 32 weeks. Females lay an average of 58 eggs on the lower surface of mature leaves (Dhileepan, Taylor, Lockett, & Treviño, 2013; Williams, 2003b). The eggs hatch within 15 days and the newly emerged larvae mine the leaves between the upper and lower epidermal layers. When mature, larvae go through a non-feeding pre-pupal and pupal stages within a circular pupal disc near the larval mine. The generation time (egg to adult) is approximately 55 days.

Hedwigiella jureceki adults from northern Argentina and southern Brazil were imported to South Africa in 2002 (Williams, 2003b). In the adult no-choice and choice trials, adults fed and laid eggs only on the cat's claw creeper. The agent was approved for field release in South Africa and releases were made between 2007 and 2023. Under semi-field conditions, *H. jureceki* feeding over two summer seasons caused 67% defoliation, resulting in 40% and 51% reductions in the above- and below-ground biomass, respectively (King et al., 2011). The agent is well established in warmer subtropical regions but has largely failed to persist in cooler regions in South Africa (King et al., 2021). Defoliation levels in the field vary widely and the impact of the beetle remains very low.

Hedwigiella jureceki was imported from South Africa to Australia in 2009 (Dhileepan, Taylor, Lockett, & Treviño, 2013). In the no-choice tests, adults lived significantly longer (>32 weeks) on cat's claw creeper than on any other test plants (<3 weeks). Egg laying under no-choice conditions was evident on the cat's claw creeper and on an exotic non-target species, *Citharexylum spinosum* L. (Verbenaceae); however, larval development occurred only on the cat's claw creeper (Dhileepan, Taylor, Lockett, & Treviño, 2013). Under choice conditions, adult feeding and oviposition were observed only in the cat's claw creeper. *Hedwigiella jureceki* was approved for release in Australia in 2012 (Snow & Dhileepan, 2014) and field releases continued until 2016. Under glasshouse conditions, *H. jureceki* negatively affected both the LP and SP forms of the cat's claw creeper, but its impact was more severe on the SP form (Rahman et al., 2023). At higher adult densities, *H. jureceki* significantly increased leaf loss (up to 40%) and reduced leaf area (up to 60%) and underground tuber biomass (50–62%) (Rahman et al., 2023).

Over 72,000 adults were field released across 124 sites in Queensland (K. Dhileepan, unpublished data). Since 2016, community organizations have been involved in the rearing and field release of these biological control agents in Queensland and NSW. As predicted, establishment was observed at all release sites, on both forms of cat's claw creeper, but the incidence and intensity of adult feeding and larval mining damage (Figure 4) remained very low. Both adults and larvae are uncommon in the winter months, suggesting that they are likely to overwinter as adults. Pupal parasitism by *Pleurotroppopsis* sp. (Eulophidae; Hymenoptera) was evident in the field (Rahman et al., unpublished data), which may may have limited the impact of the biological control agent.

FIGURE 4 Leaf mining due to larval feeding by *Hedwigiella jureceki*.

3.3 | Agents under evaluation

3.3.1 | *Neoramulariopsis unguis-cati* (Speg.) Raghv. Singh & Kushwaha

The leaf-spot pathogen *Neoramulariopsis unguis-cati* (Capnodiales: Mycosphaerellaceae) is native to Argentina, Brazil and Paraguay, where it causes necrotic lesions and premature leaf abscission on both forms of cat's claw creeper (Colmán, 2014; Da Silva et al., 2012; Spegazzini, 1911). The causal agent of the leaf-spot from collections made in Brazil was identified as *Pseudocercospora unguis-cati* (Speg.) U. Braun by Da Silva et al. (2012), based on the descriptions of a specimen ex. Argentina by Braun (1994). In South Africa, leaf-spot symptoms on cat's claw creeper (Figure 5), very similar in appearance to those caused by *P. unguis-cati* in the native range, were first reported in 2012 (King et al., 2021). The pathogen in South Africa was subsequently described by Crous et al. (2014) as a new species, *Cercosporella dolichandrae* Crous & den Breeÿen. Subsequent morphological and molecular studies confirmed that both species are the same (Colmán et al., 2020). This confirms that the leaf-spot pathogen is native to South America and not to South Africa. Following a recent taxonomic revision, the leaf-spot pathogen has now been placed in the newly erected genus *Neoramulariopsis* under the species name *Neoramulariopsis unguis-cati* Raghav. Singh & Kushwaha (Yadav et al., 2023).

The leaf-spot pathogen was never originally considered as a prospective biological control agent, nor was it ever imported into a quarantine facility in South Africa for host specificity testing. The presence of *N. unguis-cati* in South Africa, therefore, appears to be due to an accidental introduction, likely with its plant host (King, 2017). The pathogen is demonstrating high levels of host specificity in the field, infecting only cat's claw creeper in South Africa (King, 2017). The leaf-spot pathogen has become widely established in South Africa, where it causes necrotic lesions (Figure 5), resulting in the widespread defoliation of cat's claw creeper infestations (Figure 6; King et al., 2021).

Based on field observations in the native range and its documented impact in South Africa, the leaf-spot pathogen was prioritised as a prospective biological control agent for cat's claw creeper in Australia. The pathogen was exported from South Africa to CABI, UK where host-specificity testing was completed (Kate Pollard & Marion Seier, CABI, UK, unpublished data). The leaf-spot pathogen exhibits a high level of host specificity, sporulating only on cat's claw creeper. An application seeking approval to release leaf-spot pathogen has been submitted to the Australian regulatory authorities. If approved, the agent will be field released in Australia to complement the previously released agents.

3.3.2 | *Uropyxis rickiana* Magnus

The gall-inducing rust, *U. rickiana* (Pucciniales: Uropyxidaceae), is known only to occur on cat's claw creeper from Argentina, Brazil and Paraguay (Hernández & Hennen, 2003; Hennen et al., 2005; Sotão et al., 2006). This rust is macrocyclic and autoecious; thus, its lifecycle comprises all five known spore stages and is completed exclusively on the cat's claw creeper without the need for an alternate host (Hernández & Hennen, 2003). Surveys in Paraguay showed that gall rust was more prevalent on the LP form than the SP form of cat's claw creeper.

Infection with the pathogen induces conspicuous galls on cat's claw creeper stems and shoots (Figure 7) which are the source of prolific continuous rust sporulation (Kate Pollard & Marion Seier, CABI, UK, unpublished data). These galls act as ‘sinks’ for plant reserves, thereby reducing plant fitness and competitiveness over time.

FIGURE 5 Disease symptom caused by the leaf-spot pathogen *Neoramulariopsis unguis-cati* on cat's claw creeper in South Africa.

FIGURE 6 Before (a) and after (b) the incidence of the leafspot pathogen *Neoramulariopsis unguis-cati* in South Africa. (*Source*: Anthony King).

Symptoms of *U. rickiana* infection were also observed on the leaves and petioles of cat's claw creeper plants (Kate Pollard & Marion Seier, CABI, UK, unpublished data). Based on field observations in the native range *U. rickiana* is thought to have good potential as a biological control agent because the pathogen causes significant damage (Figure 7) and targets a different plant part than other released agents. Future research will focus on conducting host specificity tests for *U. rickiana* under quarantine conditions at CABI in the UK. Low levels of spore germination and difficulties in producing and maintaining the pathogen either as an uredinial or telial culture in vivo under greenhouse conditions are potential limiting factors for conducting host-specificity tests for *U. rickiana* in quarantine.

3.4 | Other agents under consideration

3.4.1 | *Apteromechus notatus* (Hustache)

The seed-feeding weevil *A. notatus* (Curculionidae: Coleoptera) is native to Argentina, Brazil and Paraguay, and occurs on both the LP

FIGURE 7 A gall induced by the rust *Uropyxis rickiana* on cat's claw creeper stem in the native range.

and SP form of cat's claw creeper. The adults are long-lived (up to 2 years) and lay eggs on the outer surface of developing (green) pods (King et al., 2011). Emerging larvae chew through the walls of immature fruit pods and feed on the developing seeds. The larvae pupated within the seeds inside the fruit pods. It is suspected that seed-feeding weevils overwinter as pupae and adults emerge from late spring to early summer, coinciding with flowering and fruit set (King et al., 2011). Seed-feeding weevils are widespread in their native range and can cause up to 80% seed loss (King & Dhileepan, 2009).

Apteromechus notatus was imported to South Africa in 2009 and again in 2016, for colony establishment and host-specificity testing. Due to the difficulty in inducing flowering and fruiting in potted cat's claw creeper plants under glasshouse and quarantine conditions, a colony of the weevil could not be established. No further importation of the weevil has occurred in South Africa or Australia.

3.4.2 | *Neocrassana undata* Linnavuori

The leafhopper *N. undata* (Hemiptera: Cicadellidae) occurs on both forms of cat's claw creeper in Argentina, Brazil and Paraguay. Both adults and nymphs feed on leaves, petioles and young stems. Feeding on leaves results in chlorosis, followed by the development of red lesions, leaf curling around feeding sites and eventually leaf abscission (King et al., 2021).

Neocrassana undata sourced from Brazil were exported to South Africa in 2016. A colony of *N. undata* was maintained on cat's claw creeper plants sourced from Brazil but could not be established on cat's claw creeper plants from South Africa.

Neocrassana undata adults and nymphs were imported twice into Australia in 2018. An attempt to establish a colony of the leafhopper was made on both forms of cat's claw creeper in quarantine but failed with no evidence of oviposition on either the SP or LP form of Australian cat's claw creeper plants. It may be possible that the cat's claw creeper varieties in Australia and South Africa are unsuitable for *N. undata*.

3.4.3 | *Prospodium macfadyenae* Meir. Silva, O.L. Pereira & R.W. Barreto

The leaf rust *P. macfadyenae* (Puccinales: Uropyxidaceae) has only been reported on cat's claw creeper in Brazil (da Silva et al., 2012).

Infection causes severe disease symptoms on cat's claw creeper foliage leading to premature leaf abscission. The symptoms initially appear as chlorotic spots on leaf veins, but occasionally also across the lamina developing later into larger necrotic lesions that can spread across the entire leaf surface. The full life cycle of the rust is currently unknown; only four of the five spore stages of the rust have been recorded, with the aecial stage unknown (Da Silva et al., 2012). The rust was prioritized as a prospective biological control agent for cat's claw creeper in Australia, based on its field host-specificity and damage potential. However, due to difficulties in locating the rust during field surveys in 2019 and 2020 in Brazil and Paraguay, to date no further work on the pathogen could be pursued.

4 | DISCUSSION

Biological control offers a long-term, self-sustaining method for controlling the cat's claw creeper. To date, in an effort to reduce shoot growth and limit the vine's ability to climb and smother native vegetation, priority has been given to the testing and assessment of leaf-feeding insects. As a result, five and three insect agents have been released as biological control agents in South Africa and Australia respectively, but the establishment and impact of each agent varies, often depending on environmental conditions at the release sites.

The leaf-feeding beetle *C. auroguttata* has become widely established in South Africa, but its incidence is low and its impact is insignificant. This is possibly due to the agent not being able to complete multiple generations in a year and its inability to overwinter in cooler months. Reintroduction of the agent into South Africa, from climatically more compatible areas (e.g., southern Paraguay, southwest Brazil and northern Argentina; Rafter et al., 2008) could be worth trialling.

The tingid, *C. visenda* is more widely established in Australia (Dhileepan, Treviño, et al., 2010) than in South Africa (King et al., 2021), possibly because of its better climatic suitability (Rafter et al., 2008) and the greater prevalence of cat's claw creeper infestations along riparian corridors in Australia than in South Africa. In Australia, *C. visenda* is more abundant during cooler months (Dhileepan, Bayliss, & Treviño, 2010), whereas in South Africa, *C. visenda* remains more active during the summer months, when higher humidity levels prevail (King et al., 2021).

The leaf-tying moth *H. pyrochroma* has only been established in Australia (Dhileepan et al., 2021) where it is restricted to certain riparian corridors in southeast Queensland, with limited dispersal between different river/creek systems. The prolonged pupal diapause limits the number of generations the agent can complete in a year. It is expected that the agent will continue to spread to new riparian corridors in the coming years. However, to facilitate its dispersal sooner, the collection and redistribution of the agent (as larvae) from established sites to new riparian sites is recommended. Based on experience from Australia, it is recommended to redirect future *H. pyrochroma* release efforts to riparian areas in South Africa.

The leaf-mining beetle *H. jureceki* was established in South Africa and Australia soon after the commencement of the field releases. Unlike in South Africa where it has limited establishment and impact (King et al., 2021), in Australia, the agent occurs more widely (Snow & Dhileepan, 2014); however, its abundance and the damage levels remain low and patchy. This is possibly due to the buildup of natural enemies (larval parasitism) and the limited number of generations the agent completed in the field. The potential role of parasitism in limiting the abundance of *H. jureceki* in the field requires further investigation.

The leaf-spot pathogen *N. unguis-cati*, though not intentionally introduced as a biological control agent, demonstrates high levels of control of ground-dwelling populations of cat's claw creeper in South Africa. Field observations indicate that the leaf-spot pathogen is specific to cat's claw creeper with no evidence of any non-target attack in South Africa. Based on its damage levels, there is a perception that no additional biological control agents are required in South Africa. In view of its impact and apparent field host-specificity, the pathogen has been prioritized for its introduction into Australia. Following host specificity assessments of the leaf-spot pathogen at CABI, UK, an application seeking approval for its release in Australia was submitted. . Field releases of the leaf-spot pathogen, which are anticipated to complement the existing insect agents, will commence once approval has been received.

However, because the cat's claw creeper is a perennial vine with abundant subterranean tuber reserves, release of multiple agents targeting various parts of the plant may be required for adequate control. Other potential biological control agents for consideration and evaluation for release in Australia include the gall-forming rust *U. rickiana* and the seed-feeding weevil *A. notatus*, both of which target different parts than those released to date.

With more than two decades of research into the biological control of cat's claw creeper in Australia and South Africa, these programs offer a wealth of information and an opportunity for countries yet to implement a biological control program. This would significantly reduce the time and costs associated with starting a project. All agents released in Australia and South Africa have demonstrated a high degree of host-specificity, with no non-target effects. As such, these agents should be considered for new biological control programs against cat's claw creeper. Prioritization of these agents for other countries should be based on establishment success, rate of dispersal, environmental requirements, and damage levels in Australia and South Africa. Careful consideration of the plant, its form, and growth habit in addition to an evaluation of the local environmental conditions should also be undertaken to ensure the best opportunity for the establishment of each agent. For example, both the leaf-sucking *C. visenda* and the leaf-tying moth *H. pyrochroma* are suitable for riparian areas and should be considered for release in countries where cat's claw creeper infestations are predominantly in riparian areas. To further enhance the likelihood of success, CLIMEX and MaxEnt models for each of the agents successfully established in Australia and South Africa can be built and used to help model the potential of its establishment in other countries.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

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