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Invasive *Passiflora foetida* in the Kimberley and Pilbara: understanding the threat and exploring solutions

Phase 1 Final Report

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Copyright and disclaimer

Important disclaimer

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Previous reports

This report builds on the content previously outlined in the following interim reports:

Webber BL, Yeoh, PB and Scott JK (2013) Invasive *Passiflora foetida* in the Kimberley and Pilbara: understanding the threat and exploring solutions. Interim 12 month report. CSIRO, Australia.

Webber BL, Yeoh, PB and Scott JK (2013) Invasive *Passiflora foetida* in the Kimberley and Pilbara: understanding the threat and exploring solutions. Mount Gibson Iron summary update. CSIRO, Australia.

1 Introduction

Stinking passionflower (*Passiflora foetida* L., Passifloraceae) is a herbaceous vine from south and central America that is now widely introduced into many tropical regions of the world. The vine is an invasive weed that is commonly found in forest edges, coastal vegetation and disturbed areas, including riparian habitat and roadsides (Fig. 1). In many of these regions the plant is a weed of concern. The first confirmed record in Australia dates from 1892 (Queensland), while the first record from Western Australia was from near Derby in 1921. However, the threat of *P. foetida* pre-dates these official records, with Holtze (1892) noting that in the Northern Territory "*Passiflora foetida*, although introduced hardly ten years ago, is suffocating already, to a great extent, the undergrowth of the forest near Fannie Bay, and as the fruit is relished by birds and natives, this plant promises to become a great nuisance".

Over 120 years later, pre-project consultation and prioritisation confirmed this prophecy, ranking *P. foetida* as one of the most significant problem weeds in the north west of Australia. The weed is thought to be one of the biggest threats to the highly fragmented and environmentally important rainforest patches scattered across the Kimberley. Currently, *P. foetida* is listed under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) as being amongst the main weed threats to the monsoon vine thickets of the Dampier Peninsula.

There is *prima facie* evidence to suggest that *P. foetida* may be able to tolerate a broader range of climatic extremes than was once thought, and may be partially adapted to surviving the fire regimes common to the drier parts of these landscapes. This broad climatic tolerance implies that the weed is likely to be a threat to a variety of areas with high conservation value across the north west.

A significant impediment for implementing effective weed management strategies for *P. foetida* is that very little is known about its biology and life history, particularly in areas where it has been introduced. It is clear that the species has a very high dispersal ability (e.g. by birds, bats) due to its attractive pulp-covered seeds. Although the original point of introduction is not known, current observations suggest the species has spread to Western Australia from the Northern Territory, is widespread throughout the Kimberley, and has been found as far south as Shark Bay.

Fig. 1: *Passiflora foetida.* Invasion near Kununurra overtopping trees and shrubs (a), open flower (b), leaves & young fruit (c), mature fruit (d).

Current control methods advise hand-pulling or herbicide application, and both of these labour-intensive methods have been used on *P. foetida* by management groups in the recent past. Current control methods are labour intensive and accessibility problems makes long term control unlikely and impractical. In the long term the only practical solution will be biological control, although all control options require an improved understanding of the biology of the plant. Other *Passiflora* species are being examined for biological control potential in Hawaii and New Zealand and an initial assessment indicates that *P. foetida* would also be a suitable target species. With a better knowledge of the threat posed by *P. foetida* to the north west of WA, significant improvements in the cost, effectiveness and efficiency of weed control may be possible. Thus, our project set out to address these gaps in current knowledge.

This two year project aimed to characterise the life history of *P. foetida* to establish its requirements and limits for growth, reproduction and colonisation. More specifically, the project set out to (i) measure the plant's response to climatic limits in the field and under controlled climate conditions, so as to understand plant growth and potential climatic limits to invasion, (ii) assess seed and seedling ecology, (iii) describe plant-herbivore and plant-pathogen interactions as part of an assessment of biological control potential, and (iv) model the potential distribution in Australia.

2 Project outcomes

2.1 Outcome 1: An assessment of the threat of spread by the weed and an improved understanding of its ecology

Methods

Documenting local insight

Consultation with local weed management personnel and managers of protected areas was undertaken throughout the project. Information was sought on all aspects of the biology of the species with particular reference to temporal and spatial variation. Insight relating to potential limits to growth and reproduction was specifically requested, as well as any observed change in co-occurring vegetation or perceived impact on local ecosystems.

Field site selection & installation

Permanent field sites were installed to monitor *P. foetida* invasion dynamics in natural populations and to provide baseline data against which to ultimately compare biological control agent impacts. Field site scoping was undertaken in the two primary study regions (i.e. Kununurra, Koolan Island) in the Kimberley in 2012. It quickly became apparent that (i) it would be impossible to identify individual *P. foetida* plants, and that a cover-based approach would be required for assessing change in vegetative dynamics, (ii) access to vine thicket sites would not be possible with available time and logistics, and (iii) the vine was far more prevalent in drier, fire-prone landscapes. The final sampling design for monitoring vegetation dynamics saw the installation of paired transects (30-60 m long) installed across putative moisture gradients at six sites on Koolan Island, two sites near Kununurra (Darram Conservation Reserve and on DAFWA land on the riverbank of the Lower Ord), and three sites at the northern end of Lake Argyle (Table 1, Fig. 2). Nearby mining activity meant we had to abandon one of the Koolan Island sites ('ACA01') in 2013 for safety reasons. Sites were chosen for their large size and high density of *P. foetida* invasions, on the presumption that we needed to know the current upper limits of what might be possible for growth, reproduction and any associated threats. Sites in the Kimberley were installed and the first sample (i.e. pre-wet season) collected in November 2012. Further collections were made in Apr 2013 (post-wet season), Nov 2013 (pre-wet season) and Apr 2014 (post-wet season), spanning two wet seasons and 18 months of growth. For the Pilbara component of the research, four sites were installed in the Millstream-Chichester National Park close to the Fortescue River, following the same siting priorities and sampled on a single occasion in Oct 2013 (Table 1, Fig. 2).

Table 1: Study site details for permanent monitoring populations of *Passiflora foetida* in the Kimberley and Pilbara regions.

Region	Site	Abbrev	Georeference
Koolan Island	Acacia Ridge	ACA01	16.125S, 123.748E
	Airport	AIR01	16.126S, 123.782E
	Barra Limb	BAR01	16.143S, 123.769E
	Camp Water Track	WAT01	16.131S, 123.770E
	Murungung Bay	MUR01	16.144S, 123.793E
	Sprinkler Field	SPF01	16.129S, 123.775E
Kununurra	Darram Conservation Reserve	DAR01	15.811S, 128.692E
	DAFWA land (Lower Ord)	DAF01	15.646S, 128.693E
	Gundarim Ridge (Lake Argyle)	GUN01	16.149S, 128.763E
	Lathe Bay (Lake Argyle)	LAT01	16.157S, 128.740E
	Nanalung Ridge (Lake Argyle)	NAN01	16.138S, 128.715E
Millstream	Deep Reach Tributary	DRT01	21.615S, 117.103E
	Fortescue Crossing	FXG01	21.628S, 117.124E
	Fortescue Pipeline	FPL01	21.572S, 117.055E
	Millstream Delta	MDE01	21.585S, 117.069E

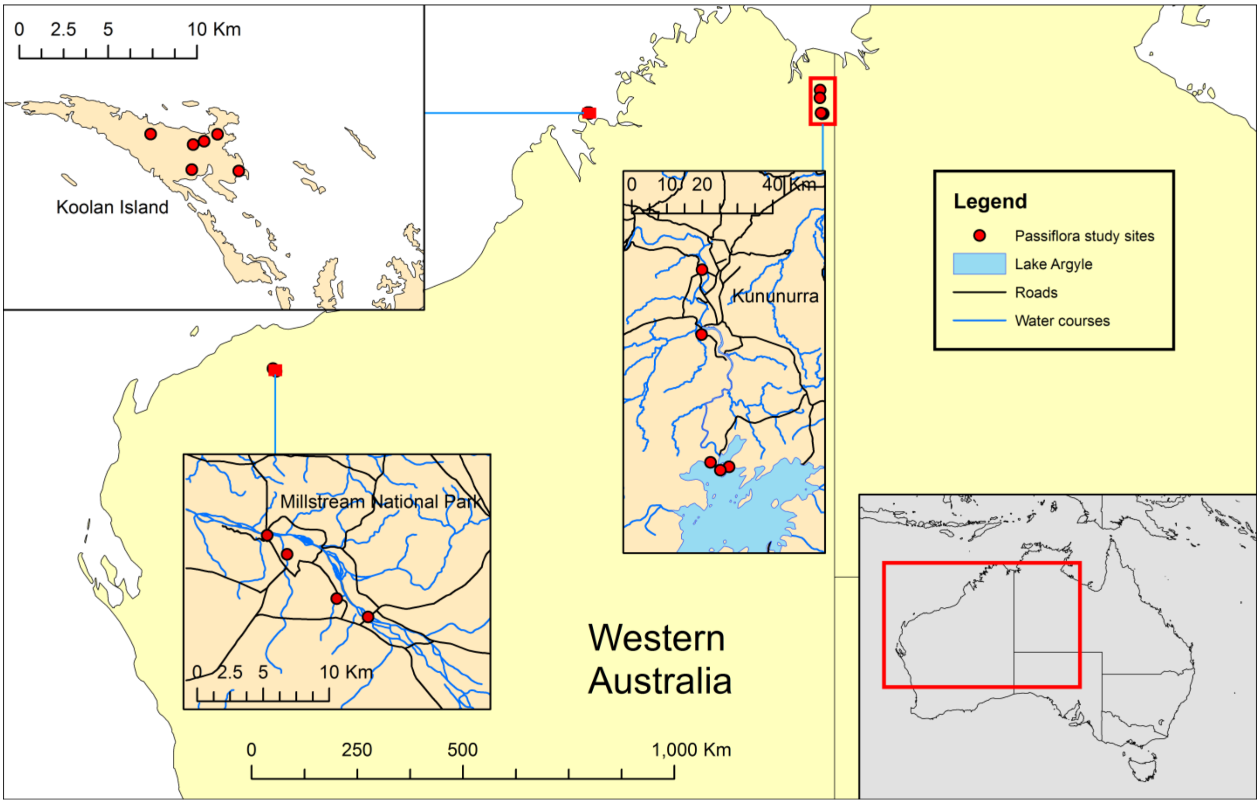

Fig. 2: Study site locations for permanent monitoring populations of *Passiflora foetida* in the Kimberley and Pilbara regions.

To provide better characterisation of local site characteristics, two recording systems were deployed. At two sites in each primary region (i.e. Kununurra, Koolan Island), data logging stations were set up in each stratification across one of the transects, recording soil moisture and temperature (at 30 cm below the soil surface), air temperature, relative humidity and photosynthetically active radiation (PAR) at 1.5 m above the ground. Remote camera traps were also installed at six of the Kimberley sites to record daily photos capturing temporal change in *P. foetida* cover and phenology.

Field-based plant growth & reproduction measures

Measures of *P. foetida* abundance at each site were characterised in three ways. Firstly, three randomly assigned quadrats (1 × 1 m) of vegetation were quantified for each of three stratifications along the transect (either defined by vegetation change where present or equal distances when within a single vegetation type). Quadrat pairs were used for each sampled wet season (i.e. left side pre-wet season, right side post-wet season). Within each quadrat, cover scores and vegetation profiles for *P. foetida* and other plants (trees, shrubs and grasses) was recorded, before the entire *P. foetida* biomass was removed (Fig. 3). This biomass was separated into plant organ components stratified by age for leaves, stems, fruits and flowers to be weighed, measured and counted. Biomass up to 2 m from the ground was sampled in its entirety, while biomass > 2 m from the ground (i.e. in trees) was sub-sampled using pole pruners. Secondly, measures of *P. foetida* abundance (i.e. biomass and reproductive effort) on all trees > 3 m in height was characterised in a belt of 6 m wide, following the same transect used for quadrat sampling. Details of the subject trees were also characterised, including species, size and bark texture traits, as well as any other co-occurring vines. Lastly, to get a better idea of total *P. foetida* biomass in trees, a select number of trees (Kununurra: n = 4; Koolan Island: n = 4; Millstream: n = 9) were entirely stripped of *P. foetida* biomass and bagged for subsequent separation into the same

Fig. 3: Quadrat sampling after *Passiflora foetida* cover has been removed.

characteristics as for the quadrat data. Biomass above and below 2 m in height was kept separate to allow for comparison to the quadrat data.

Results & Discussion

Local insight

Observations from across the invasion area and discussions with relevant people were able to draw out broad, reasonably consistent trends. Firstly, it appears as if there is a recent trend toward invasions in more intact native vegetation, with initial presence of *P. foetida* not necessarily associated with any known large scale disturbance. This may imply that we are seeing the end of an initial 'lag phase' as the *P. foetida* invasion transitions into a period of rapid expansion. Observations that the vine is worse at certain times of the year were not consistent within or between regions, suggesting that local context may be playing a big role in habitat suitability.

Secondly, conversations with rangers from regions outside our focal study areas have highlighted the contrasting dynamics of *P. foetida* invasions across the Kimberley. For example, in Purnululu National Park, *P. foetida* appears to be spreading rapidly in recent years. In 2012, reports suggested the infestations were concentrated in the more remote areas, away from human disturbance. However, in 2014 it was reported that *P. foetida* had started to invade around the walking trails and significantly increasing its footprint. At Geikie Gorge National Park, preliminary observations suggested that *P. foetida* is now dominating local landscapes at a level not observed anywhere else in the Kimberley (Fig. 4). Considerable annual control efforts, including the rolling of vine mats and clearing with machinery, is now required. Similar large-scale clearing efforts on an annual basis were also required on the Mitchell Plateau (e.g. Mitchell Falls walk) and at Mirima National Park near Kununurra. These contrasting invasion dynamics may well provide critical and complementary insight into the invasion dynamics of *P. foetida* and, therefore, greater insight into strategies for biological control. Greater thought should be given to including these locations as study sites in upcoming phases of this research.

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Fig. 4: Manual removal of *Passiflora foetida* cover at Geikie Gorge National Park, includes rolling of vine mats and the use of heavy machinery.

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Fig. 5: Canopy overtopping by *Passiflora foetida* in a remote vine thicket on the Bougainville Peninsula in the western Kimberley.

Thirdly, as part of fieldwork for another biodiversity-focused project, we visited 32 of the remote vine thickets in the western Kimberley. The widespread coverage, density and invasiveness of *P. foetida* in this region, and its ability to overtop and infiltrate these vine thickets was very noticeable (e.g. Fig. 5). Given observations from permanent study plots on vegetative growth dynamics and the possible interaction with fire (see below), there appears to be considerable scope and relevance to consider broadening the current study to consider the contrasting dynamics in these threatened communities.

Vegetative growth dynamics

Based on quadrat samples of *P. foetida* vine mats, considerable biomass was enough to smother and supress any other vegetation in the area. Vine mats consisting of stem layering up to 80 cm thick contained in excess of 1 km of stem length in 1 m^2 (Fig. 3). For quadrats with dense vine mats, very few native plants remained alive underneath. The bulk of the growing appears to take place in the latter half of the wet season and on into the dry season provided there is enough soil moisture for growth. Total biomass density was generally higher at the end of the dry season, relative to the end of the wet season, particularly for dead biomass (Fig. 6). Relative to the two Kimberley sites, *P. foetida* biomass on the ground and shrub layers was much lower at the Millstream site in the Pilbara at the end of the 2013 dry season (Fig. 6).

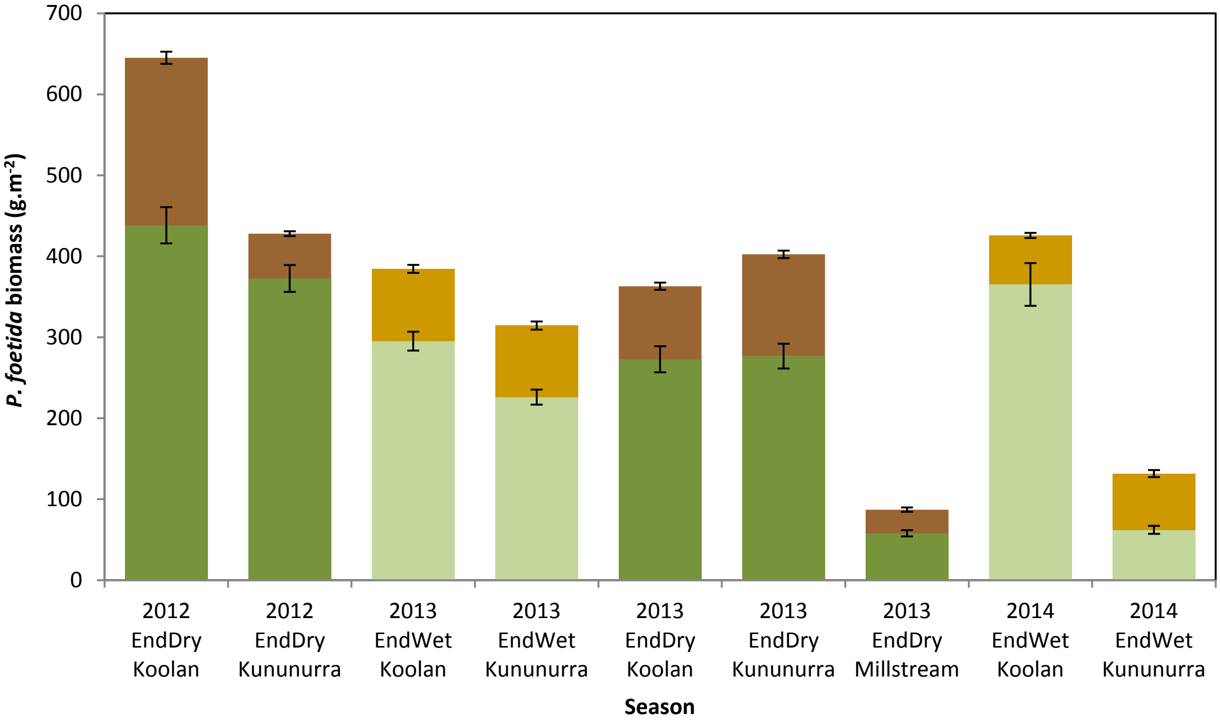


Fig. 6: Biomass of *Passiflora foetida* from quadrat based samples of infestations < 2 m from the ground (i.e. ground & shrub layers) for sites across three regions (Koolan Island, Kununurra, Millstream National Park) and two wet seasons (2012/13 and 2013/14). Dead biomass is shown in browns, live biomass is shown in greens.

Very dense mats of cane quickly build up over the post-wet season months, with the vast majority of canes losing their leaves and dying back as the vine mat increases in thickness. Over the subsequent wet season, the canes that have died back appear to break down quickly, leaving only a thin layer of live canes toward the end of the wet season. Those canes that do survive can thicken and become woody very quickly, and these appear to have the ability to re-sprout over multiple seasons. Very thick canes in areas known not to have burnt on Koolan Island were greater than 40 mm in diameter.

Based on *P. foetida* biomass stripped from entire trees, the variation between regions was more even. Live trees maintained up to 33 kg DW of *P. foetida* biomass, comprising up to 85% as dead, highly flammable material (Figs. 7, 8). Tree transect surveys showed that more than 50% of trees (> 3 m tall) across the three regions had *P. foetida* infestations on their trunks or in their canopies (Table 2), and trees up to 14 m tall were totally overtopped by vines in some cases. A much greater proportion of trees had infestations in the Kununurra region (75%), relative to Koolan Island (45%) and Millstream (46%). Certain tree species, such as *Melaleuca argentea*, *Nauclea orientalis* and *Corymbia hamersleyana* were over represented in infested trees, while *Corymbia cadophora*, *Eucalyptus tectifica* and *Eucalyptus camaldulensis* were relatively under represented (Table 2). There was considerable variation between tree species as to how far into the tree the infestation progressed, with some species being entirely over-topped, and others having the infestation restricted to the lower portion of the main trunk (Table 2). It was noticeable that a number of factors influenced tree infestation and over-topping, including the presence of other vines, the proximity of other trees, the texture of the host's bark and the presence of low branches. Further studies on this area may be able to draw out risk profiles based on a match to the climbing and binding characteristics of *P. foetida*.

Table 2: Tree colonisation by *Passiflora foetida* at fieldsites around Kununurra, on Koolan Island and in Millstream National Park. Trees > 3 m tall were scored for the presence of *P. foetida*, with quantification of the infestation height and volume.

Region	**Genus**	**Species**	**# trees observed (% of total infested)**	***P. foetida* infestation volume (m^3; mean ± SE**	***P. foetida* max height (relative to infested tree) (%; mean ± SE)**
Koolan Island	*Acacia*	*colei*	1 (0)		
		tumida	3 (0)		
	Brachychiton	*diversifolia*	5 (40)	1.68 ± 0.44	41.9 ± 29.6
		viscidulus	2 (100)	0.43 ± 0.38	71.2 ± 50.3
	Callitris	*columellaris*	3 (67)	2.99 ± 0.22	98.4 ± 69.6
	Canarium	*australianum*	4 (0)		
	Corymbia	*cadophora*	12 (8)	0.95 ± n/a	30.4 ± n/a
		confertiflora	8 (25)	7.89 ± 7.65	69.3 ± 49.0
		greeniana	5 (80)	1.76 ± 0.89	49.8 ± 24.9
	Erythrophleum	*chlorostachys*	12 (50)	1.47 ± 0.75	74.9 ± 30.6
	Eucalyptus	*miniata*	76 (55)	5.50 ± 1.21	30.8 ± 4.8
		tectifica	16 (25)	0.42 ± 0.28	86.9 ± 43.4
	Ficus	*opposita*	9 (78)	2.33 ± 1.85	76.9 ± 29.1
	Grevillea	*pyramidalis*	4 (25)	1.44 ± n/a	105.6 ± n/a
	Premna	*acuminata*	1 (0)		
	Unknown species (all dead stags)		12 (33)	2.01 ± 1.38	76.3 ± 38.1
Koolan Island Total			173 (45)		
Kununurra	*Acacia*	*sp.*	7 (100)	43.71 ± 22.88	99.1 ± 37.4
	Azadirachta	*indica*	6 (33)	21.68 ± 0.00	102.3 ± 72.4
	Corymbia	*confertiflora*	4 (25)	3.31 ± n/a	94.4 ± n/a
	Eucalyptus	*sp.*	14 (57)	1.51 ± 0.40	44.8 ± 15.8
	Ficus	*racemosa*	5 (20)	1.91 ± n/a	100.0 ± n/a
	Grevillea	*pyramidalis*	1 (0)		100.0 ± 70.7
	Indigofera	*sp.*	2 (100)	19.48 ± 3.56	94.3 ± 21.6
	Melaleuca	*argentea*	19 (100)	20.15 ± 5.42	94.1 ± 21.0
	Nauclea	*orientalis*	20 (100)	11.78 ± 3.31	80.6 ± 30.5
	Parkinsonia	*aculeata*	9 (78)	4.69 ± 2.44	87.9 ± 10.7
	Sesbania	*formosa*	4 (0)		
Kununurra Total			91 (74)		
Millstream	*Acacia*	*sp.*	18 (61)	1.89 ± 1.03	98.4 ± 29.7
	Corymbia	*hamersleyana*	14 (86)	22.05 ± 7.97	101.0 ± 29.2
	Eucalyptus	*camaldulensis*	71 (34)	4.65 ± 0.88	77.9 ± 15.6
	Melaleuca	*argentea*	37 (41)	5.27 ± 3.19	82.9 ± 21.4
		bracteata	10 (70)	2.68 ± 1.09	102.0 ± 38.5
	Sesbania	*formosa*	1 (0)		
Millstream Total			151 (46)		
All sites Total			415 (51)		

Fig. 7: *Passiflora foetida* overtopping trees in the Kununurra region (DAFWA site; a) and at Millstream NP (b). Millstream populations had a greater proportion of dry biomass in tree canopies and fewer vine mats growing over the ground layer.

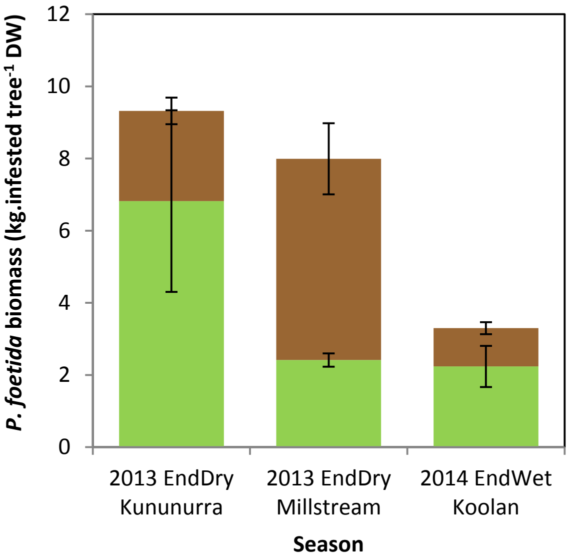


Fig. 8: Biomass of *Passiflora foetida* entirely removed from individual trees for sites across three regions (Koolan Island, Kununurra, Millstream National Park). Dead biomass is shown in brown, live biomass is shown in green.

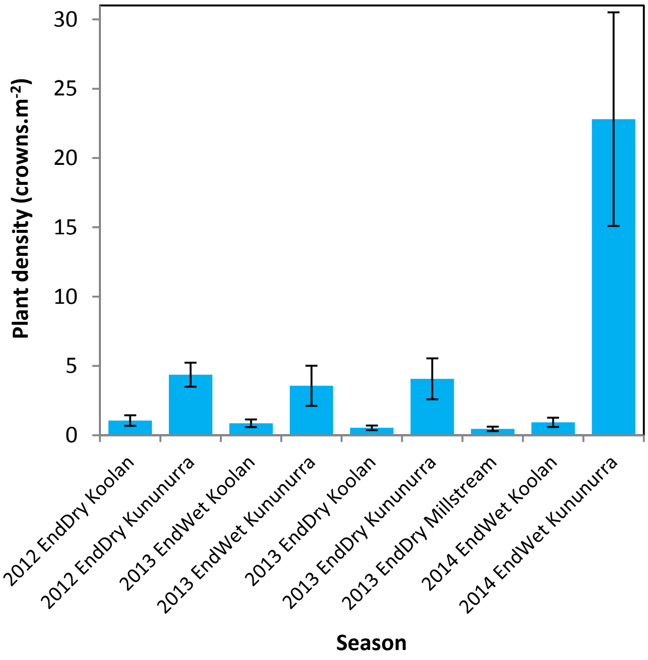


Fig. 9: Density of *Passiflora foetida* plant crowns across quadrat samples from the three study regions.

Lastly, while we were not able to undertake widespread surveys of individual plant biomass, it was possible to quantify crown (i.e. plant) density across the sampled quadrats. Crown densities were generally below 5 crowns.m^{-2}, but were as high as 194 crowns.m^{-2} in areas of high seedling density in the end of wet season sampling at Kununurra sites (Figs. 9, 10). There was no detected relationship between crown density and biomass density in sampled quadrats, suggesting the most important unit to measure is area-based biomass. In summary, this detailed quantification of biomass not only provides clear evidence of the scale of current invasions, but also provides solid baseline data for establishing future impacts of introduced biological control agents. Given the contrasting and unusual wet seasons in 2012/13 and 2013/14, it would be prudent to extend this baseline out for at least one more wet season so as to get a better handle on the range of normal variation in between year biomass fluctuations.

Fig. 10: *Passiflora foetida* seedling carpets, representing thousands of individual plants establishing on the retreating waterline of Lake Argyle (Sep 2012; a) and in a previously inundated flood zone of the Darram Conservation Reserve (Apr 2014; b).

2.2 Outcome 2: an assessment of reproductive potential, including seed and seedling ecology, so as to better inform control strategies

Methods

Reproductive phenology

Standard field sampling procedures (as outlined in Outcome 1) provided a measure of seasonal variation in reproductive output which could be related to cane biomass and length (quadrat sampling) as well as per overtopped tree (whole tree samples). Daily observations of flower phenology during field sampling visits documented flower development cycles and flower visitation by putative pollinators. Representative fruit samples were collected in Mar 2013 (n = 63) and Apr 2014 (n = 60) to quantify relationships between fruit and seed parameters.

Field dispersal, reproduction & establishment

Fig. 11: Post-fire regrowth at Murungung Bay (Koolan Island) site three months after a lightning fire in Feb 2013.

Although the emergent properties of *P. foetida* vine mats ruled out detailed studies on the establishment and growth of individual plants, observations on seed and seedling ecology in the field were recorded when and where possible. Extreme weather events and fire also aided the process. Two Kununurra region sites (Darram and DAFWA in Apr 2013) were underwater due to flooding for extended periods of time, during which the majority of live *P. foetida* biomass died and rotted away. A further site at Koolan Island (Murungung Bay) was burnt after a lightning strike in Feb 2013 (Fig. 11), while the Darram site burnt in May 2014. These 'reset' points allowed for the monitoring of seedling germination, establishment and early stage plant growth. Germination activity was noted and described at all sites during field visits. Following the fire at Murungung Bay, seedling germination and size was recorded in a 2 m wide belt along the two vegetation sampling transects in May 2013 (3 months post-fire) and then again in Nov 2013 and Mar 2014 (13 months post fire). Seedling germination density, size and survivorship were noted. An additional set of 15 newly germinated seedlings were permanently tagged in May 2013 to monitor growth over time.

Randomly selected subsets (n = 5) of these seedlings were destructively harvested for above-ground biomass in May 2013, Nov 2013 and Mar 2014 and fully partitioned into plant organ categories comparable to the quadrat-based harvests.

Controlled condition germination

To understand the effect of temperature on germination, seeds were collected from ripe yellow fruit on vines growing within the Lake Argyle area in Mar 2013 and Apr 2014. Fruit contents (i.e. seeds and pulp) were spread out and dried on tissue paper in the field for transportation back to Perth, stored (air dried pulp on seeds in tissue paper) in the laboratory until just prior to being used for this experiment, then subsequently treated to remove the pulp. Briefly, the seeds were soaked in a 2% pectinol solution (Brewcraft; www.wabrewcraft.com.au) in tap water for 24 hours, rinsed and soaked in tap water for 5 days (water solution changed periodically), and then lightly scrubbed to remove remnants of fruit pulp and paper towel before being randomly assigned to two groups. The first group had no further treatment while the second group had a small corner (c. 2mm) of the distal end of the seed coat chipped with a scalpel. All seeds were then treated with plant preservative mixture (Plant Cell Technology, Inc; PPM™), a broad-spectrum biocide and fungicide for plant tissue culture, using a 0.2% solution in tap water, placed on tissue paper in sealed petri dishes (100 mm diameter; 10 seeds per plate) and then germinated in controlled condition growth cabinets at a range of temperatures (10, 15, 20, 25, 30, 35, 40, 45°C; 5 plates of each seed treatment per cabinet). Seeds were monitored for germination daily for 12 days and then every second day for 7 more days until the termination of the experiment at 19 days. The experiment was terminated after no new germinations were noted for 7 days. Seeds were checked for imbibition, the beginning of germination (i.e. when a radicle was first visible), and germination (when the emergent radicle was > 2 mm in length). The paper in each plate was kept moist as appropriate using a water solution with the 0.2% PPM™ solution.

Results & Discussion

Reproductive phenology

Field based reproductive phenology observations revealed a number of interesting trends. Firstly, flower anthesis takes place very early in the morning, and flowers are usually fertilised and closed by mid-morning. These observations agree with observations from *P. foetida* invasions in India (Raju, 1954), in a study that also documented both autogamy and outcrossing pollination syndromes. Secondly, while flowering and fruiting was more concentrated in the late wet season (see quantified results below), areas in the landscape where soil moisture is maintained at a higher level appear to produce flowers and fruit continuously. For example, this occurs at the Lake Argyle boat ramp, where the below-ramp *P. foetida* population benefits from the water runoff from draining boats parking on the ramp nearby.

A representative selection of ripe yellow fruits harvested in the late-wet seasons of 2013 and 2014 revealed a significant relationship between fruit diameter and seed number (Fig. 12), with a mean (± 1SE) of 14.8 ± 0.69 seeds per fruit (min = 1, max = 41). No significant variations for fruit seed number or fruit size was noted between Kununurra and Koolan Island regions or between sampling years. All fruits examined had fully formed, apparently viable seed.

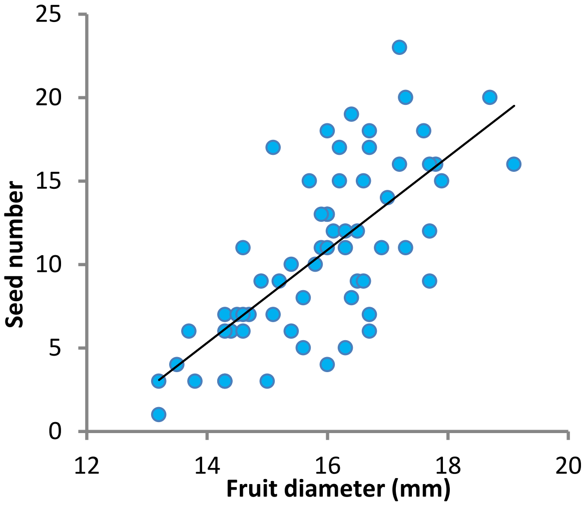


Fig. 12: *Passiflora foetida* fruit diameter versus number of contained seeds for samples collected in the Kununurra region in 2013 and 2014.

Based on quadrat harvesting, flower and fruit production was variable between regions, sites and years, with no clear emergent seasonality for reproduction (Fig. 13). There were generally more flowers at the Kununurra sites at the end of the dry season, while there was no clear pattern for Koolan Island. The reproductive output at Millstream at the end of the dry season was particularly low, but this was largely driven by a low overall biomass density in the quadrats, relative to the two Kimberley regions studied (Fig. 13). The main conclusion to draw from this insight is that at any given time of the year, *P. foetida* can produce flowers and fruits given the right growing conditions.

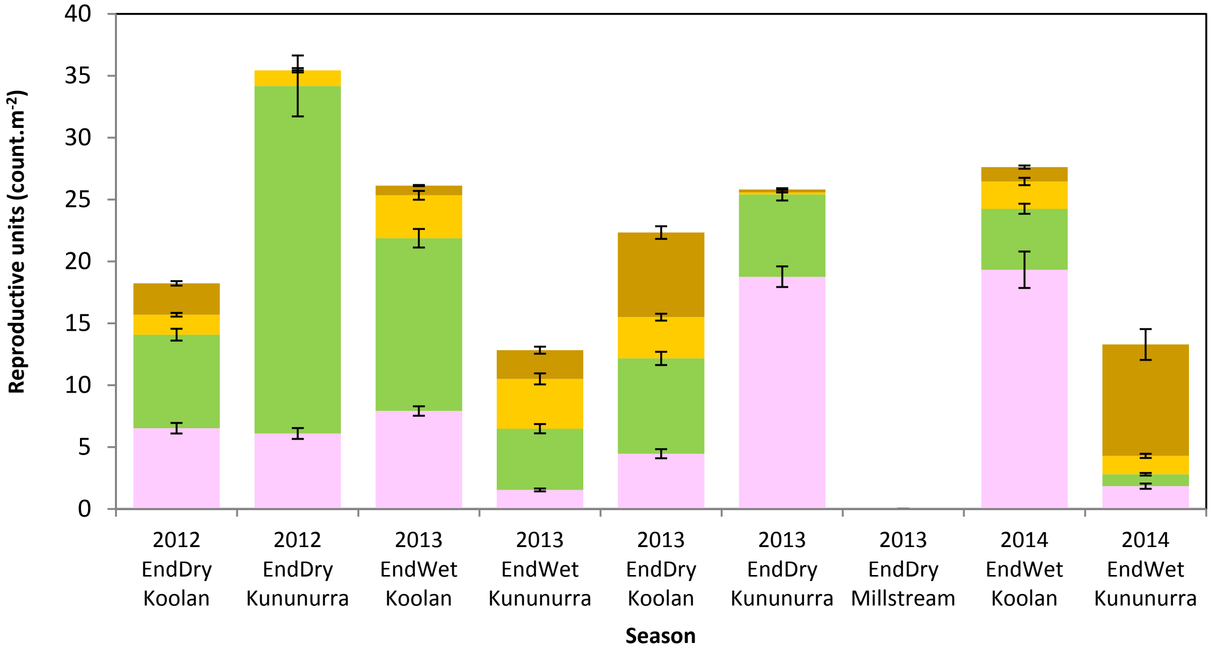


Fig. 13: *Passiflora foetida* reproductive output across seasons for quadrat samples detailing flowers (mauve), immature fruit (green), ripe fruit (yellow) and dried fruit (brown).

For overtopped trees, up to 2600 flowers and 540 fruits were recovered from individual overtopped trees. Again fruit and flower production was variable across years and regions, with very little reproductive output at Millstream and particularly high reproductive output at the end of the 2013 dry season for Kununurra samples (Fig. 14).

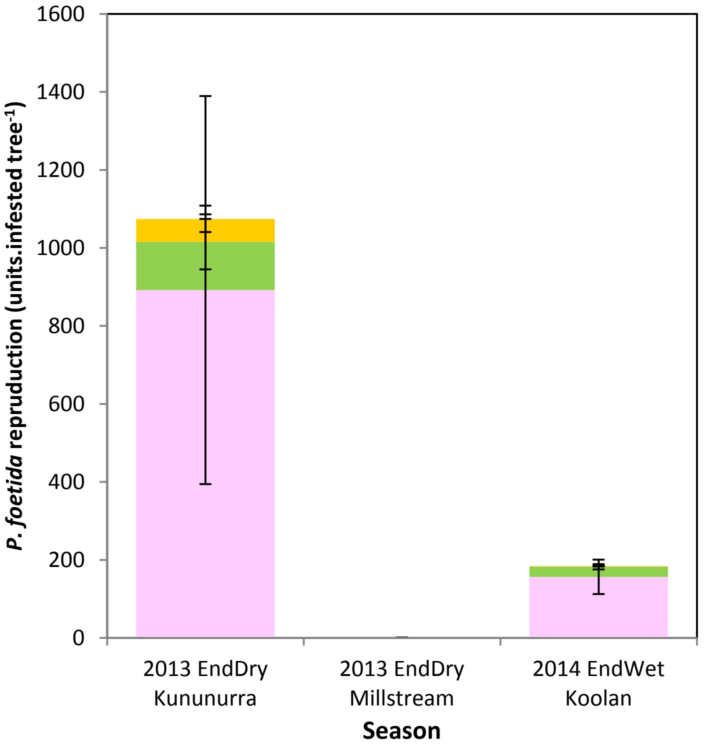


Fig. 14: *Passiflora foetida* reproductive output across seasons for overtopped tree samples, detailing flowers (mauve), immature fruit (green), ripe fruit (yellow) and dried fruit (brown).

Field dispersal, reproduction & establishment

Fig. 15: Little corellas (*Cacatua sanguine*) flocks feeding on *Passiflora foetida* fruit on the shores of Lake Argyle.

Field observations have documented three primary ways in which *P. foetida* reproduces and/or re-establishes following fire or flooding disturbance: prolific seed production, stem layering and crown re-sprouting (Fig. 16). Based on documented fruit production, seed load in the environment within the dispersal kernels of known agents is likely to be high. Further work is required to understand the temporal viability of seeds in the field. There appears to be no limitation to *P. foetida* dispersal over short or long distances. Putative long-distance dispersal agents either viewed or captured on field cameras actively targeting fruit for eating and removal include corellas (*Cacatua sanguine*; Fig. 15), magpie geese (*Anseranas semipalmata*) and dingoes (*Canis lupus dingo*). Flocks of corellas in excess of 40 birds were observed feeding on *P. foetida* fruits at Koolan Island during both post-wet season sampling trips. Significant numbers of seeds washed up in shore detritus on the shores of Lake Argyle or contained as part of vegetation fragments washed downstream in flooding rivers, suggesting that water based dispersal is also a significant contributor to seed dispersal. Furthermore, seeds appear to be able to survive fires both in the ground, often protected by rocks and boulders, as well as in fruits on vines overtopping tree canopies. Stem layering has been observed for thicker (> 5mm) brown canes, starting with roots forming on stems in contact with the ground or located in thick decomposing leaf litter. Ultimately these canes can detach from the primary crown via stem breakdown or severance, and function as independent plants. Greater leaf deposition and thicker layers of decomposing leaves by *P. foetida* under dense vine mats appears to increase the chance of layering towards the end of the wet season (Fig. 16b). Crown re-sprouting after fires can occur within a few days of the burn (Fig. 16c) and older, thicker crowns appear to be more likely to survive a fire. Resprouting has been observed to occur from crowns up to 2 cm under the ground, where protection from fire is likely to be slightly greater. Re-establishing after fire from resprouting crowns and seed can be extremely rapid (Fig. 17).

Fig. 16: *Passiflora foetida* reproduction and spread can take place via seeds (a), stem layering (b) or crown re-sprouting (c).

Quantification of post-fire regeneration at the Murungung Bay site (Koolan Island) documented 94% of post-fire germinant seedlings still alive after 14 months. Moreover, within 3 months of the fire, some seedlings already had matured and were bearing ripe fruit, suggesting a full life cycle of less than 3 months is possible for *P. foetida*.

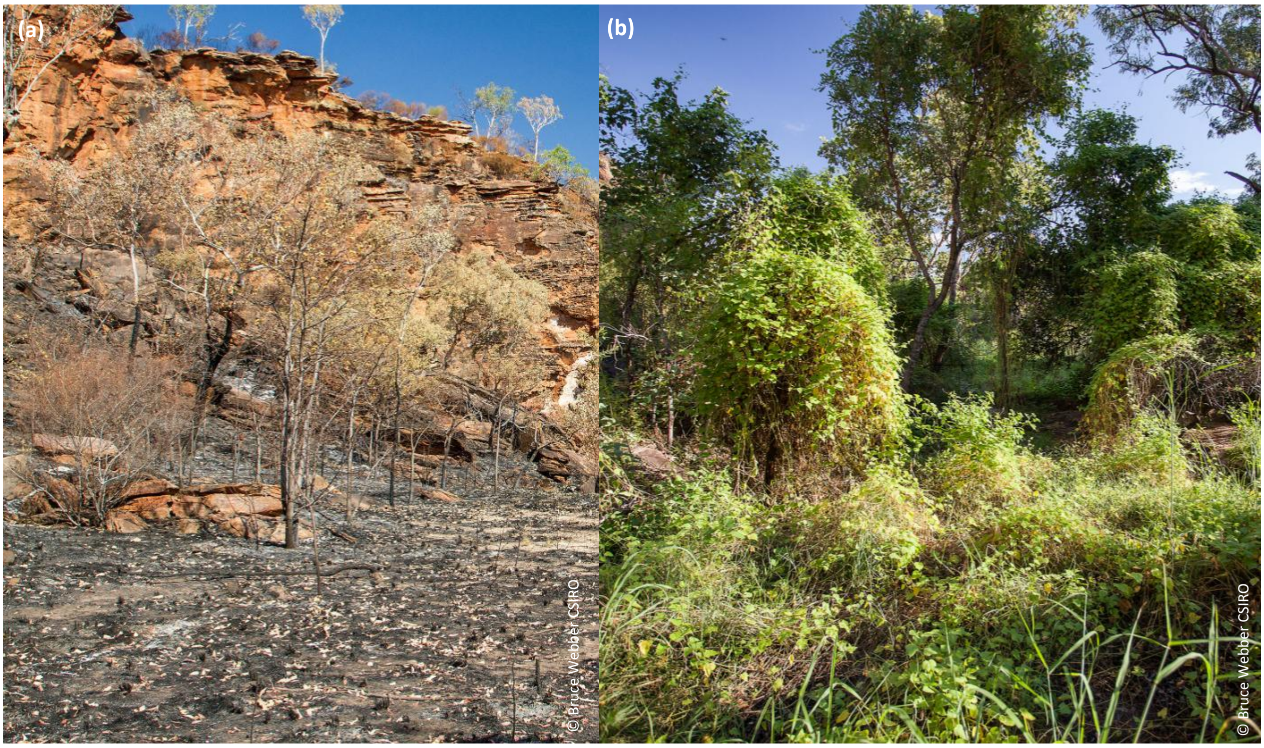


Fig. 17: *Passiflora foetida* recovery following a fire at Merima National Park in September 2012. One week (a) and six months (b) after the fire.

Growth rates during the initial establishment of young seedlings appears driven by moisture availability. Growth rates were highest in the three months following the fire that coincided with the late wet season (Fig. 18). However, growth rates subsequently slowed during the dry season, and showed an overall slight decline in biomass over the wet season of 2013/14 (Fig. 18).

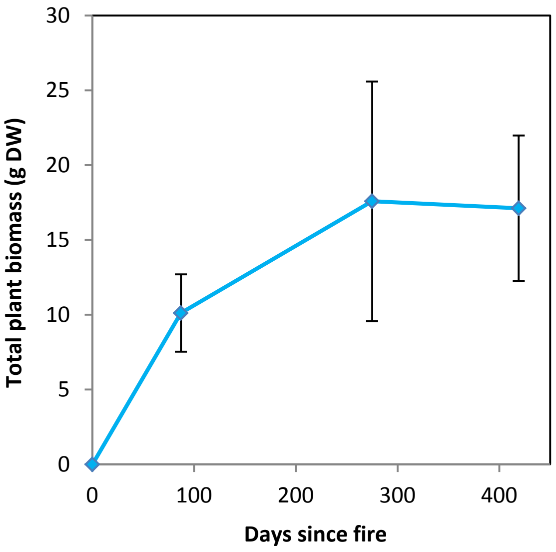


Fig. 18: Growth rates for *Passiflora foetida* seedlings germinating after a fire on 4th Feb 2013 at Murungung Bay, Koolan Island.

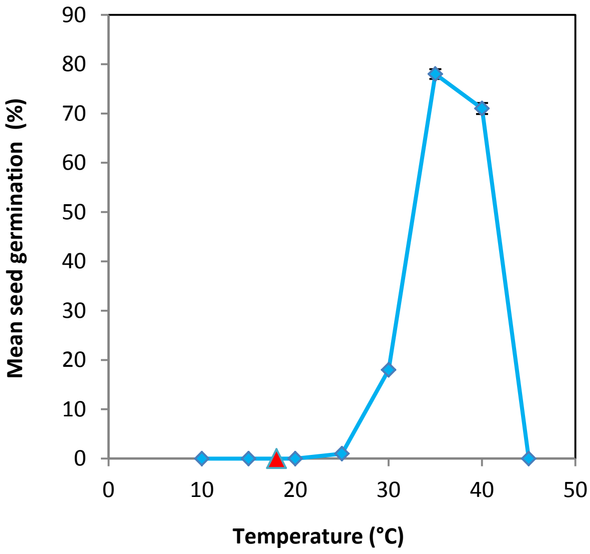


Fig. 19: Germination response to temperature for *Passiflora foetida* seeds in constant temperature controlled conditions.

Controlled condition germination

Seed germination was significantly influenced by temperature in controlled condition germination experiments. Across a temperature gradient from 10 to 45 degrees, optimal germination was between 35 and 40 °C, while the range of temperatures where germination took place was 25 to 40 °C (Fig. 19). Higher temperatures generally germinated fastest, with 60 % of seeds at 35 °C germinating within 3 days (Fig. 20).

The lack of germination at colder temperatures appears not to be due to insufficient degree-day accumulation. After the quantified observation period (19 days), seeds from the cooler cabinets (10, 15, 20 and 25°C) were relocated into the 35°C cabinet and again observed daily. Subsequent germination ensued, improving zero germination rates to 40% within 4 days of transfer. This behaviour suggests that seeds may have a physiologically-induced dormancy at low temperatures and that short term exposure to low temperatures did not appear to have any deleterious effects.

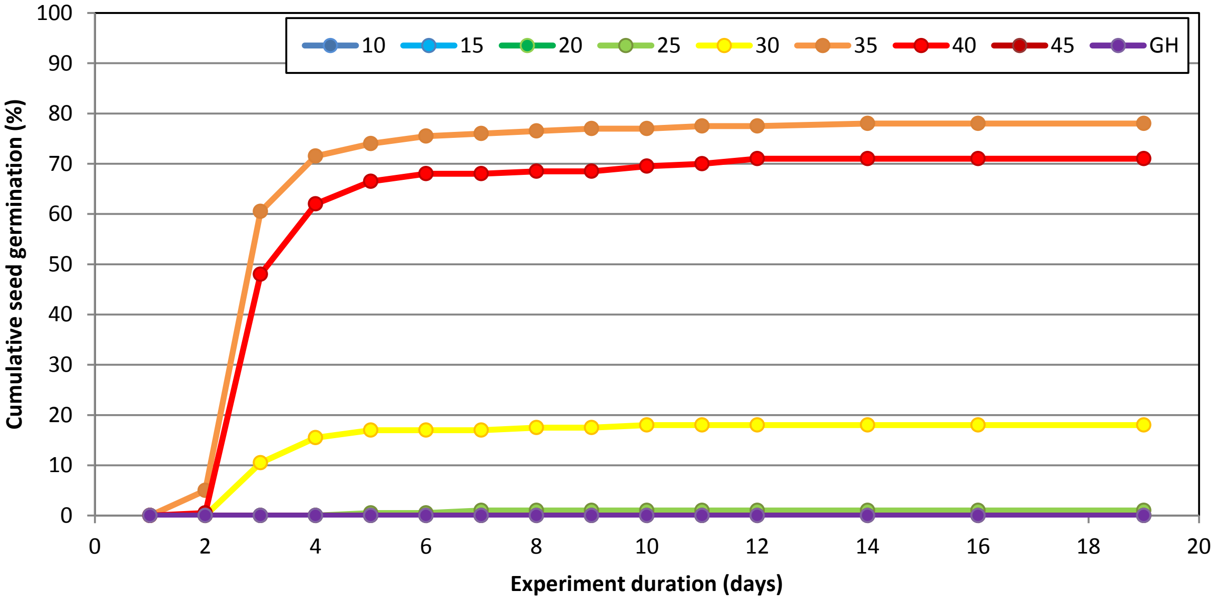


Fig. 20: Germination response to temperature for *Passiflora foetida* seeds in constant temperature controlled cabinets (10 to 45 °C) and in an unheated glasshouse in Perth (GH).

2.3 Outcome 3: a preliminary contribution towards developing biological control for *P. foetida*.

Methods

Establishing negative impacts

Establishing negative impacts on native ecosystems, such as a threat to native biodiversity, is an essential component of satisfying the requirements for getting approval to work on a new biological control agent. After the site scoping phase, it was clear that establishing negative impacts of *P. foetida* on native vegetation would be extremely challenging. Avoiding confounding factors and bias due to site selection is already difficult for impact studies, and impacts may not be evident for many years. Given the short duration of the current funding and the challenges associated with quantifying changes in native vegetation, we decided to prioritise quantification of the possible impact of *P. foetida* on the availability and quality of freshwater crocodile (*Crocodylus johnsoni*) nesting sites at Lake Argyle. Quantifying these impacts was viewed as a more efficient way to show negative impacts. It does not, however, diminish the consistent observations from the quadrat-based data of likely threats to native flora, inferred from the complete mortality of native vegetation that had been smothered by vine mats (Fig. 21).

Fig. 21: After *Passiflora foetida* removal, little native vegetation remains alive underneath.

A range of known freshwater crocodile nesting sites on Lake Argyle (identified during the PhD research of Ruchira Somaweera) were scoped for suitability as study sites for ongoing impact research. Further investigation of the dynamics of the nesting site encroachment situation revealed it to be far more complex than initially imagined. It became clear that a better understanding would require, at a minimum, tracking the interaction between vine cover, suitable nesting space, substrate quality, actual nest locations and the relative position of the water level throughout the year. Moreover, this would need to be done at a very high resolution. Aerial photography is now being pursued as the method of choice for characterising these interactions. Data has been collected for the 2013 nesting season and will be used to compare these metrics across multiple seasons, subject to ongoing funding availability. These quantifiable observations were supplemented by boat-based observations of nesting sites to document *P. foetida* abundance.

Plant-pest interactions

An ongoing monitoring approach during fieldwork and through targeted visits to unmonitored *P. foetida* populations has generated baseline information on the pest and disease load carried by the vine.

Biological control barriers

Consultation with relevant organisations and individuals, including DAFWA and commercial Passionfruit growers, was undertaken to identify potential barriers to a biological control program against *P. foetida*.

Taxonomic considerations

A desktop search for relevant literature and distribution records was conducted on known taxonomic relationships within the Passifloraceae. This data was interrogated for issues of relevance for implementing a biological control program against *P. foetida*.

Understanding potential range

Bioclimatic modelling using the semi-mechanistic model, CLIMEX, was used to get a first pass understanding of the potential range of *P. foetida* in Australia. Given the uncertain status of taxon delimitation in *P. foetida sensu lato*, the decision was made to begin with a conservative approach. We thus classified the taxon in the broadest sense and informed the model with all distribution points determined as *P. foetida*. At this point in time we do not have enough evidence to support the hypothesis presented in Vanderplank (2013), that the taxon of interest is distinct to the Kimberley coastline. Modelling methodology, including data cleaning procedures and model parameterisation techniques following Webber *et al*. (2011). In addition to information gleaned from herbarium records, we also informed the temperature components of the model (TI) using physiological parameters derived from the germination trials (Fig. 22). We acknowledge that the resulting model must be considered an initial insight only. With further resolution on taxonomic uncertainty and more physiological data with which to parameterise the model, confidence in the modelling projections is likely to increase.

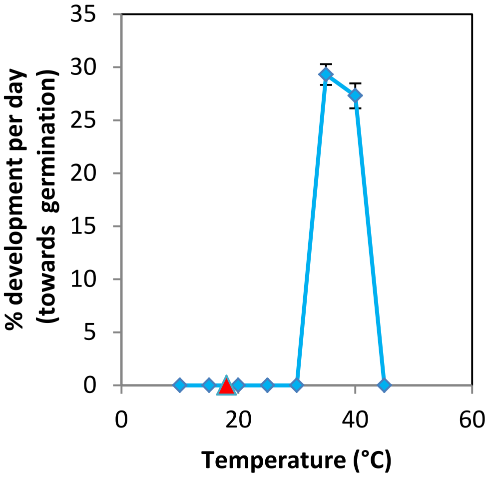


Fig. 22: Progress towards germination as influenced by temperature for *Passiflora foetida*.

Results & Discussion

Establishing negative impacts

It is clear from basic survey photography that *P. foetida* is a significant presence in the nesting site areas of crocodiles on Lake Argyle (Fig. 23a). While *P. foetida* is not restricted to these regions, suitable nesting substrate is limited at Lake Argyle. Therefore, it could be that *P. foetida* is impacting on crocodile nesting in one or more of three ways. Firstly, the vine may be reducing the total area available to nests, either leading to reduced nesting, more crowded nesting or nests located in sub-optimal substrate. Secondly, the vine may be overtopping nests during the incubation period, possibly impacting on temperature-determined sex ratios. Thirdly, the vine may be impacting on the ability of mother crocodiles to return to their nest to assist with the hatching process. Further investigations into these nesting dynamics are already being explored for feasibility and funding.

It is apparent that inter-year differences will be considerable, requiring an ongoing study to track this variation. The record high wet season watermark in 2011 seems to have changed the *P. foetida* invasion baseline on the shores of Lake Argyle, but it remains unclear if this is due to substrate changes, seed deposition, vegetation change, or a combination of one or more of these drivers or other factors. Furthermore, the extremely low wet season maximum for the level of Lake Argyle in 2012/13, followed by unusually high wet season maximum levels in 2013/14, may represent an additional significant change in the dynamics of nesting site encroachment. Nesting site over-topping is also happening at Geikie Gorge (Fig. 23b), suggesting these impacts may not only be a function of the unique geology of Lake Argyle.

Fig. 23: *Passiflora foetida* vine mats overtopping suitable nesting substrate for freshwater crocodiles (*Crocodylus johnsoni*) at Lake Argyle (a) and Geikie Gorge (b).

Plant-pest interactions

Qualitative observations suggest very low invertebrate herbivory across all seasons. Small outbreaks of Pterophorid moth larvae (Fig. 24a; reared adult Fig. 24b) concentrated in the post-wet season sampling periods were noted in the Kununurra and Koolan Island regions. Some patchy but intense fungal dieback noted on Koolan Island in September 2012, including affected leaves, stems and fruits (with aborted seeds; Fig. 24c) was the only observation of pathogen impacts. Vertebrate herbivory in the Millstream region appeared significant on many ground-level plants at the Millstream Delta site. Both cattle and kangaroo scats were found in close proximity to grazed crowns. Crowns were often heavily callused from browsing, but were actively re-sprouting. It could be that the focused grazing pressure associated with this localised supply of fresh water keeps *P. foetida* density on the ground in check. We caution that further testing of this hypothesis would be required, potentially based on exclusion fencing, before drawing firm conclusions.

Fig. 24: Pterophorid larvae (a) and adult moth (b). Fungal dieback affecting *Passiflora foetida* leaves, stems and fruits (with aborted seeds; c).

Biological control barriers

We have been unable to identify any barriers to nominating *P. foetida* as a candidate for biological control. In the Ord River Irrigation Area, trial plantations of commercial passionfruit using *P. foetida* as a root stock have been largely unsuccessful and the weed has been abandoned as an option in favour of an alternative *Passiflora* species.

Taxonomic considerations

In the *Dysosmia* section of *Passiflora*, to which *P. foetida* belongs, species-level delimitation remains somewhat controversial, with no molecular phylogeny to date. This contrasts with a robust taxonomic understanding at the sub-genus level (Muschner *et al.*, 2012). From a biological control perspective, *P. foetida* is somewhat distantly related to the predominant commercial variety, *Passiflora edulis*, as well as the three *Passiflora* species native to Australia (subgenus *Decaloba*; Fig. 25). This genetic distance makes specificity requirements for agent choice less of a challenge. A recent taxonomic revision for *Dysosmia*, however, has cast uncertainty on the identity of the taxon invading in the north west of Australia. Vanderplank (2013) has proposed that this taxon be considered as *Passiflora foetida* var. *ellisonii*, a newly described variety. Unfortunately Vanderplank (2013) does not provide a region of origin for *P. f. ellisonii*, and his description of the variety does not fit with our knowledge of the taxon invading across the Kimberley and Pilbara. Rather, his description of *Passiflora foetida* var *hispida*, which he proposes to synonymise with *Passiflora vesicaria*, is the best morphometric fit to the Kimberley and Pilbara taxon.

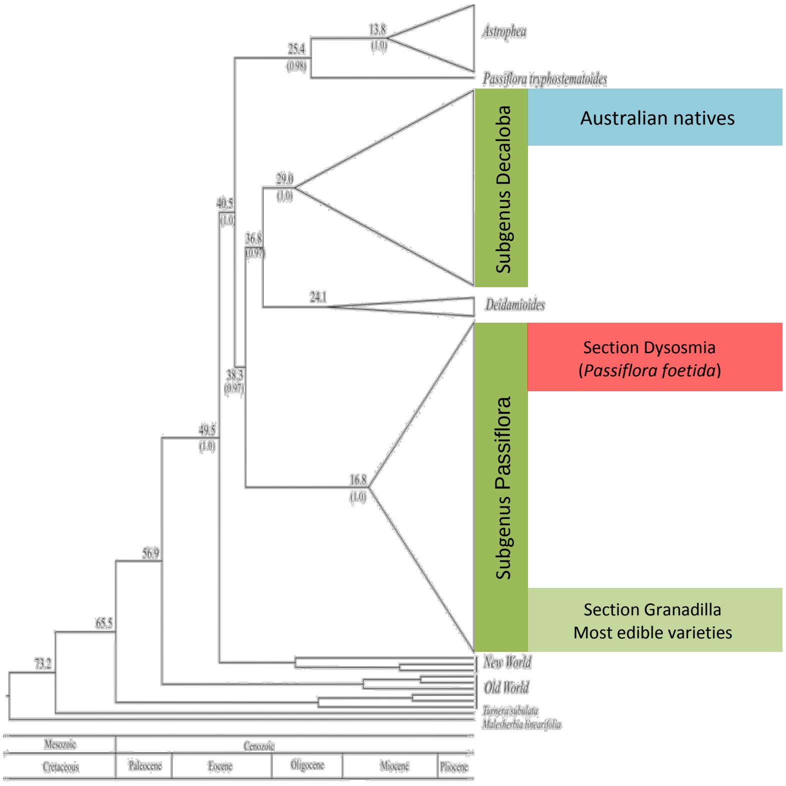


Fig. 25: Molecular phylogeny for *Passiflora* following Muschner *et al.* (2012)

Fig. 26: The native range of *Passiflora foetida sensu lato.*

Vanderplank (2013), like many taxonomists before him working on the Passifloraceae, recognised that considerable morphometric plasticity within species makes it hard to delineate between taxa on physical characters alone. To proceed with the search for a specific biological control agent, it is imperative to have the taxonomy of the target plant resolved with molecular insight. This will need to be a core component of any further work. Until then, we consider it prudent to view the invasive taxon as *P. foetida sensu lato* until more information is available, and suggest that the Vanderplank (2013) revision of *Dysosmia* is treated cautiously. This interpretation leads to a very broad circumscription of herbarium records, and consequently a very large native range (Fig. 26) and breadth of climatic niche. Focusing further work on narrowing this species concept would be prudent, not only for improving the match between the targeted taxon in Australia and its region of origin, but also for obtaining a better climatic match between invaded regions in Australia and potential search areas for targeting putative biological control agents. A closer match in this regard would improve the chances of agent establishment and subsequent spread post-introduction. Such a revision may well result in a split of the taxon into a South American and Central American pair, a pattern shown by many other weed species.

Understanding potential range

The presence of distribution records for Africa, Asia Australia and the Pacific Islands represents the known introduced range for *P. foetida* (Fig. 27). Introductions into different climatic regions of the wet tropics of west Africa and the seasonally dry savannah of Australia supports the idea that the current species delimitation is not monospecific. There are also coastal records in the native range, as well as introductions to islands, perhaps pointing to a coastal taxon, as indicated by Vanderplank (2013). Lastly, the South American distribution could be further divided in Argentina where the plant is found from sea level to 2800 m altitude in moist and dry environments (Deginani, 2001). However, these ideas need to be balanced against the possibility of wide dispersal in the Americas, some of which was probably by humans (Vanderplank 2013), thus masking any point of origin.

Despite the taxonomic uncertainty, it was possible to model the broader concept of a species potential distribution in CLIMEX. The model was parameterised in an iterative manner using a combination of information derived from distribution points in the Americas and information from the seed temperature germination trial (Fig. 22; Table 3). The moisture and temperature parameters are a requirement of all models. Only one stress factor was used, that of cold stress. Thus, it must be recognised that this is a simple model and should be regarded as a first approximation.

Table 3: CLIMEX parameters values used for modelling the distribution of *Passiflora foetida sensu lato* based on the temperature requirements for development and native distribution. Note that parameters without units are a dimensionless index of plant available soil moisture scaled from 0 (oven dry) to 1.0 (field capacity). See Sutherst *et al*. (2007) for a detailed description of parameters.

Index	Parameter	Values	Units
Temperature	DV0 = lower threshold	20	°C
	DV1 = lower optimum temperature	30	°C
	DV2 = upper optimum temperature	40	°C
	DV3 = upper threshold	45	°C
Moisture	SM0 = lower soil moisture threshold	0.2	
	SM1 = lower optimum soil moisture	0.5	
	SM2 = upper optimum soil moisture	1	
	SM3 = upper soil moisture threshold	1.5	
Cold stress	DTCS = cold stress degree day threshold	15	DD
	DHCS = cold stress accumulation rate	-0.001	Week^{-1}

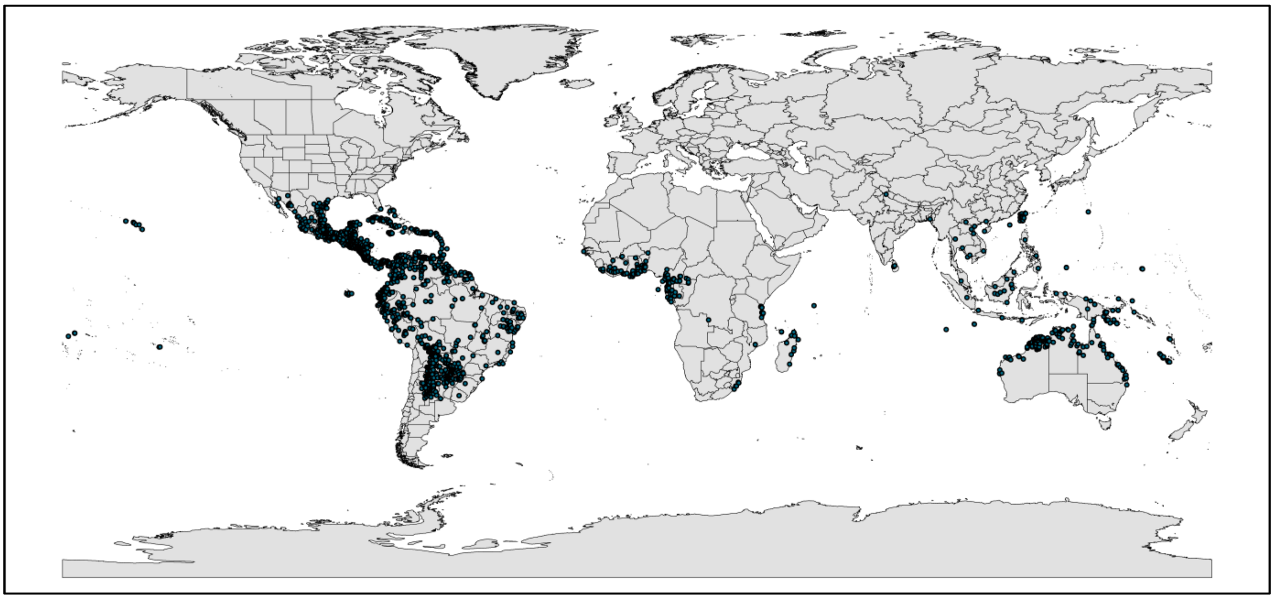


Fig. 27: Global distribution records of *Passiflora foetida sensu lato*. Points were downloaded from GBIF and quality controlled where necessary.

The modelled suitability projection (Ecoclimatic Index, EI; (Sutherst *et al.*, 2007) showed high modelled suitability for the native range. The model is based, in part on the American records, so a close match is expected. The model also encompasses the introduced range with a few exceptions, as discussed for the Australian distribution (Fig. 28).

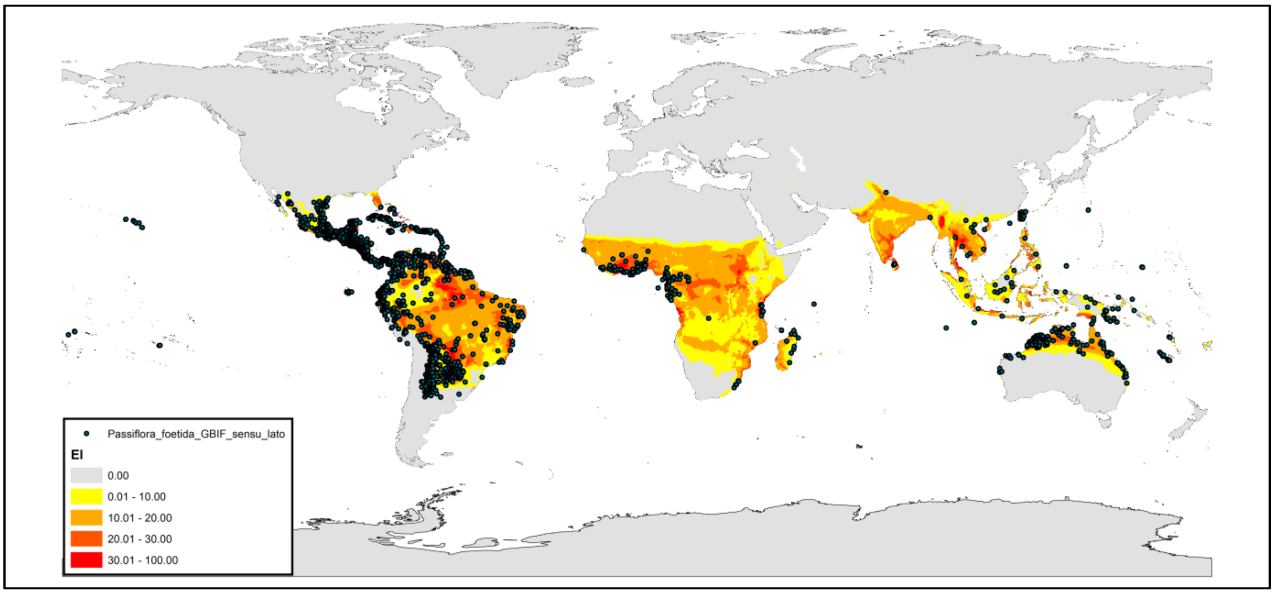
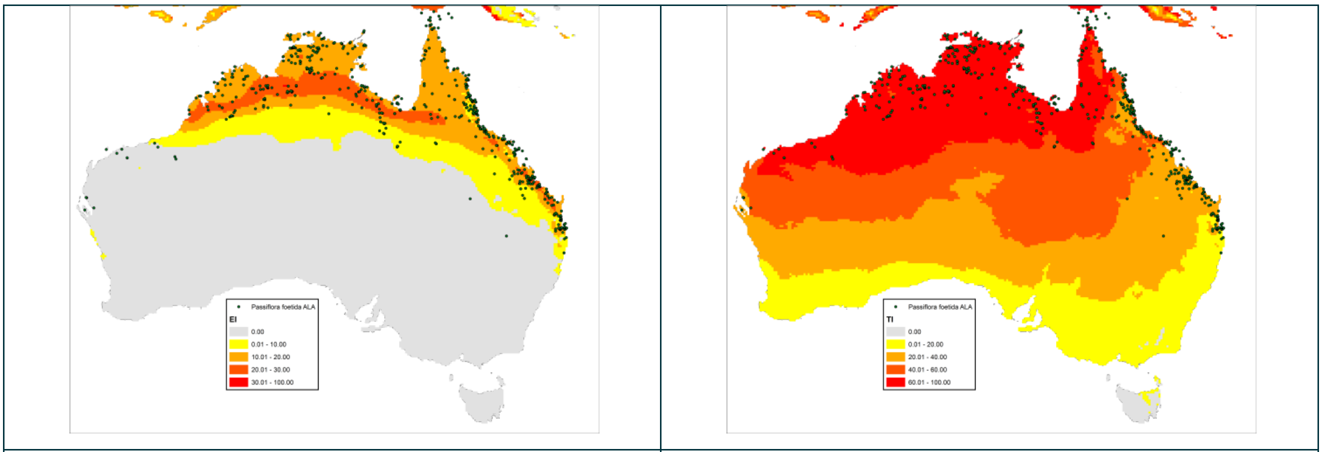


Fig. 28: Modelled climatic suitability (Ecoclimatic Index, EI) for a CLIMEX model of *Passiflora foetida sensu lato*. The colour gradient (yellow to red) shows the increasing EI values projected with current climate averages (CliMond 10' gridded climate data centred on 1975). The higher the EI value, the more suitable is the climate for the plant's survival. Values of EI = 0 (grey areas) indicates regions where populations are projected not to persist on an annual basis. Black dots indicate the global distribution of quality controlled herbarium records as sourced from GBIF.

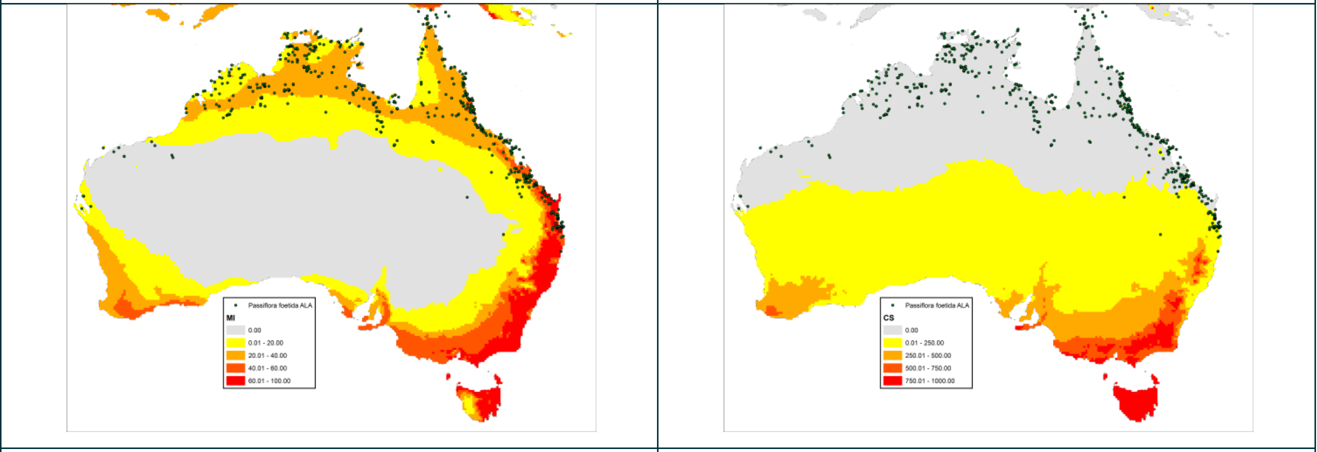
The components contributing to the overall Ecoclimatic Index (EI), the temperature index (TI), moisture index (MI) and cold stress (CS), all influence the measure of overall annual climatic suitability for species survival. There is a high correspondence between the modelled suitability (EI) and known distribution records (Fig. 29a). In particular, all records in the Kimberley region fall within the projected region of moderate to high suitability. The map (Fig. 29a) also indicates that *P. foetida* has probably reached its full distribution in northern Australia and further spread would be due to infilling between infestations. Based on this modelling, it appears that *P. foetida* does not represent a threat to central and southern Australia – it is either too dry or too cold.

The maps of the other parameters (Fig. 29b, c, d) explain the observed presence in the Pilbara (eight records). The temperature index (TI, Fig. 29c) shows that the temperature is favourable for growth, however, at the scale used in this modelling, it is clear that it is too dry for the plant. The distribution records in the Pilbara are found in microhabitats with water present (e.g. Millstream), and given that cold stress is not an issue (Fig. 29d), these microhabitats are highly suitable for the growth of *P. foetida*. In contrast, the surrounding vegetation (typically spinifex) is not threatened by the weed. The single record for Barrow Island may have been ephemeral, as there are no recent reports of the plant being present despite extensive surveys. The three distribution points in the Gascoyne represent plants found in urban settings (Denham) or moist microhabitats (a possibly irrigated area east of Carnarvon, Wooramel River). It is likely that similar explanations will account for the distribution points inland of the main distribution in Queensland. We caution again that further information is needed to properly develop the model, using more physiological information to inform the parameterisation process (particularly response to soil moisture) and revisiting the assumption that only a single species is involved.



(a) Ecoclimatic Index (EI)

(b) Temperature Index (TI)



(c) Moisture Index (MI)

(d) Cold stress (CS)

Fig. 29: Modelled components for a CLIMEX model of *Passiflora foetida sensu lato* projected to Australia. The colour gradient (yellow to red) shows increasing modelled values projected with current climate averages (CliMond 10’ gridded climate data centred on 1975). The Ecoclimatic Index (EI) shows overall climatic suitability for the plant’s survival (a). Values of EI = 0 (grey areas) indicates regions where populations are projected not to persist on an annual basis. The Temperature Index (TI) shows temperature suitability (b). The Moisture Index (MI) shows moisture suitability (c). The Cold Stress index (CS) shows cold stress (d). Black dots indicate the Australian distribution of quality controlled herbarium records as sourced from ALA.

3 Management insight

3.1 Current control efforts

Current control methods for *P. foetida* advise hand-pulling or herbicide application, often in combination. These control methods, however, are costly (particularly in remote areas), labour intensive, and amount to little more than window dressing with minimal impact on long-term control. With an ever-increasing expansion into areas of high tourist visitation, this essentially cosmetic control to minimise the visual impact on tourism is only going to increase in area and, therefore, cost and logistics.

It would be a priority to understand the effort being expended annually on *P. foetida* control in Australia. Despite efforts to source this data from the Department of Parks and Wildlife, the information was not forthcoming in time for the completion of this Phase 1 research. Estimates from the sandalwood industry in the Ord River Irrigation Area suggest that up to $500,000 has been spent on an annual basis in recent years. Further control efforts may be being undertaken across the Kimberley and Pilbara by the WA Department of Agriculture and Food as well as ranger groups. All of these control efforts could easily be viewed as being an indefinite annual commitment, having no impact on the long term management of the weed and producing benefits that are purely cosmetic and short term (i.e. a few months at best).

3.2 Emerging invasion properties

Based on the results captured in this first phase of research, it appears at least six factors may have a significant influence on *P. foetida* establishment, growth and reproduction dynamics: (1) initial localised disturbance, (2) timing of germination, (3) nutrient availability, (4) seasonal precipitation and local soil moisture, (5) wet season standing water, and (6) local fire history. Further resolution on the influence of these drivers, both individually and in an interactive way, will be an important component of further research phases. However, significant variation in observations between study sites suggests that without careful consideration of local context and identification of relevant factors driving or limiting invasion, management and control plans are likely to remain ineffective.

3.3 Invasion threats

The threat that *P. foetida* represents to the north west of Australia is diverse in its nature and targets:

Tourism values:

Passiflora foetida is becoming increasingly common in areas of high tourism value in the W.A. parks and reserves system (e.g. Purnululu, Geikie Gorge, Mirima, Mitchell Plateau, Lake Argyle, Millstream; Fig. 30). The visual impact is high due to tree overtopping and the formation of thick and vast vine mats over the ground and understorey. While inefficient and costly manual control is used for short-term control at times of high visitation at some sites, the spread of *P. foetida* into new areas is proving impossible to keep up with. For example, in the two years of this project alone, the weed has expanded out of only remote areas in Purnululu and into areas of high visitation such as Piccaninny Creek and Cathedral Gorge.

Recommendations for locally specific protected areas management are already emerging from this first research phase:

- The apparent absence of *P. foetida* at Karijini National Park in the Pilbara is pleasing, but this is a situation that warrants careful consideration. Although the park was not part of the current project, it appears to be ideally suited to supporting *P. foetida* in areas of higher soil moisture (e.g. riverine environments). With both the Fortescue and George rivers being in close proximity to the west carrying significant *P. foetida* infestations, an active population of fruit bats and vehicle transport between Millstream NP and Karijiji NP ensuring a reasonable chance of seed dispersal, and the very short establishment phase documented in this study, prompt action would be advised for any detected introductions.

- The influence of periodic inundation on *P. foetida* survival on the shoreline of Lake Argyle suggests that active water level manipulation in the wet season may be able to reduce biomass in areas close to the shoreline.

Fig. 30: Invasion of *Passiflora foetida* over the cliffs at the popular Crossing Pool lookout in Millstream National Park between Oct 2013 and Jun 2014.

Mine site restoration

The weed favours disturbed areas and is a strong competitor for the increased available resources (e.g. light, disturbed soil) that characterise mine site restoration areas. With dispersal a non-limiting factor, *P. foetida* is likely to quickly colonise restoration areas and threaten the long term presence of any restored native vegetation via overtopping and smothering from vine mats (Fig. 31).

Fig. 31: Early stages of *Passiflora foetida* colonisation of restoration test areas on Koolan Island. Subsequent expansion of the invasion area has *P. foetida* overtopping establishing and senescing acacias.

Agroforestry

The Ord River Irrigation Area is the location of the world's primary source of sandalwood oil from *Santalum album*. The manual control of *P. foetida*, to prevent it from overtopping trees in sandalwood plantations, represents an ongoing and considerable annual cost to these operations over the many growing seasons required to reach harvest size (Fig. 32).

Fig. 32: *Passiflora foetida* colonisation of *Santalum album* (Sandalwood) trees and host trees in the Ord River Irrigation Area plantations. Vine overtopping of trees as well as leaf bleaching after vine removal impacts on tree growth rates.

Native flora

Overtopping tree canopies can lead to tree death as well as increased fuel load to raise the likelihood and intensity of tree canopy fires. In the vine thickets, this fire regime modification can lead to a gradual reduction in the area of vine thickets via damage to the thicket edge. Mats of *P. foetida* growing on the ground and on shrubs results in a complete absence of other vegetation, with likely impacts on native seed banks should the vine mat be able to persist.

Native fauna

The vine is reducing available nesting space for freshwater crocodiles on Lake Argyle, where suitable nesting space is already limited due to substrate suitability. Recent high flood levels may have exacerbated the problem. Emerging between-year patterns suggest that this impact may be minimised, but not eliminated, by manipulating lake water levels in the wet season. Overtopped tree canopies may also likely to lead to reduced vertebrate habitat, such as nesting hollows. In all mature tree sampling, no evidence was found for vertebrate presence, habitation or nesting activity.

4 Future directions

4.1 New opportunities

Additional priorities for field sites

Contrasting dynamics from other regions with *P. foetida* invasions not included in this study, may well provide critical and complementary insight into the invasion dynamics of *P. foetida* and, therefore, greater insight into strategies for biological control. Such observations would be particularly important to source from regions of recent rapid expansion (e.g. Purnululu) or regions with very significant infestation (e.g. Geikie Gorge). The addition of a coastal site in the Western Kimberley may give better insight into fire encroachment dynamics for vine thickets and would provide a moderated climate that may be advantageous for biological control establishment.

Establishment of a long-term crocodile nesting impact program

Greater clarity on the likely influential factors regulating the interplay at Lake Argyle between freshwater crocodile nesting site space and *P. foetida* encroachment suggests an ongoing monitoring program could generate significant insight for the creation and maintenance of a successful management plan. In that regard, we have already formed a collaborative association with Ruchira Somaweera (Biologic Environmental) and Nikki Mitchell (University of Western Australia) to establish an appropriate sampling and monitoring design.

Collaborations

We see a number of likely new collaborations that would be beneficial for one or both parties in the future phases of this research, in addition to maintaining and building on the existing collaborations with partners from Phase 1 (i.e. Department of Parks and Wildlife, Mount Gibson Iron):

- *Department of Parks and Wildlife*: existing research expertise and capacity for molecular studies (Margaret Byrne) would be worth exploring for collaborating on the molecular aspects of the research planned for Phase 2.

- *Ord sandalwood growers*: given the active management of their plantations and the ongoing problem with managing *P. foetida* invasions, focusing some aspects of the research on sandalwood plantation impacts and management solutions would be a logical addition to the work.

- *Indigenous Ranger groups*: there exists great potential for involving ranger groups in the later stages of agent development, including field trials, breeding programs, release programs and post-release impact monitoring. Given that many of the worst invasion sites are in remote areas on-country in the Western Kimberley, closer engagement with ranger groups in this phase is likely to have considerable reciprocal benefits for both parties.

- *University of Western Australia*: local expertise in the modelling and ecophysiology of temperature determined sex ratios is available at the University of Western Australia (Nikki Mitchell). As a complementary research avenue to the work on *P. foetida* biological control, investigating ways to understand and minimise the impact of this weed on crocodile nesting sites would have considerable conservation benefits. Discussions are already underway in this regard.

- *Overseas biosecurity agencies*: when taxonomic resolution of the weed has been achieved, it will be an opportune moment to push for greater engagement on biocontrol agent selection with other countries that may have a desire to manage the same taxon.

4.2 Overall research framework

Phase 1 research has delivered against the planned outputs while adapting to research challenges and uncovering new potential research directions and synergies.

Phase 2 research is planned to take the overall project to a point where it will be ready to commence the short listing and testing of potential biological control agents (Table 4). Important prerequisites for this goal, including sorting out taxonomic uncertainty and further quantification of the limiting factors for invasion, will also be addressed.

Later phases will focus more on identifying and testing the suitability of agents, driving the management and logistics of release programs, and monitoring the post-release impacts.

Table 4: Planned phases of research contributing to the *Passiflora* invasions overall framework

Phase 1 (2012-2014)	**Phase 2 (2014-2017)**	**Phase 3 (2017-2019)**	**Phase 4 (2019-2022)**
- Characterise core life history traits (e.g. growth, reproduction, ecology). - Identify invasion drivers and limitations. - Develop an understanding of threats and impacts. - Model the potential range of the weed.	- Quantify limiting factors for invasion. - Molecular studies of introduced genotypes and biogeographical variation. - Quantification of threats posed. - Application for biocontrol program. - Native range scoping for biological agent short listing.	- Agent short listing. - Agent testing for suitability, including fitness and specificity. - Quantify limiting factors for invasion. - Quantification of threats posed. - Application for agent approval.	- Field trials of approved agents. - Agent breeding programs. - Agent release programs. - Agent impact monitoring. - Post-agent introduction characterisation of weed life history traits.

- NB: While this broad outline represents a most likely framework for working towards the project endpoint, unanticipated future developments may bring forward or delay aspects of later phases or require revised content.

4.3 Project funding

- Phase 1 research (24 months, Jul 2012 to Jun 2014) will be completed via a c. $310K budget, representing investment of $155K from the Department of Parks and Wildlife (including funds from Mount Gibson Mining) and $155K from CSIRO.
- Preliminary costing for Phase 2 research (36 months, Jul 2014 to Jun 2017) suggests an additional c. $175K per annum is required, over and above CSIRO financial support and in-kind logistics support from the Department of Parks and Wildlife and Mount Gibson Iron.

4.4 Imminent research activities & deadlines

- *30th Jun 2014*: Phase 1 final report submitted / Phase 1 funding finishes

Depending on Phase 2 funding:

- *25th Aug 2014*: Pre-nesting survey for 2014 crocodile nesting season
- *17th Nov 2014*: Post-nesting survey for 2014 crocodile nesting season / pre-wet season survey for invasion dynamics transects

5 Conclusions

This two year block of research provides a much needed first insight into the dynamics and magnitude of *Passiflora foetida* invasions in the north west of Australia. Across two contrasting atypical seasons, vine biomass, reproductive output, seedling survival and seedling growth rates were characterised. This was combined with germination data from controlled condition experiments to understand potentially relevant factors driving or limiting invasion and to model the potential distribution of the species. The research has identified that taxonomic uncertainty remains an important issue that must be addressed to progress the overall research, and that local context appears to be very important for invasion success. It has also shown that the impacts of this weed are varied, affecting diverse interest groups, and that there is no known barrier to using biological control as a management tool for *P. foetida*. Such insight is critical for underpinning the approval of establishing a biological control program against the weed, and to ensure that the resulting control program can be as efficient and effective as possible. With long term study sites in place, a network of collaborators familiar with and trained in necessary project logistics, and future phases of research designed to build on this foundational work, securing ongoing funding is now the highest priority for this work.

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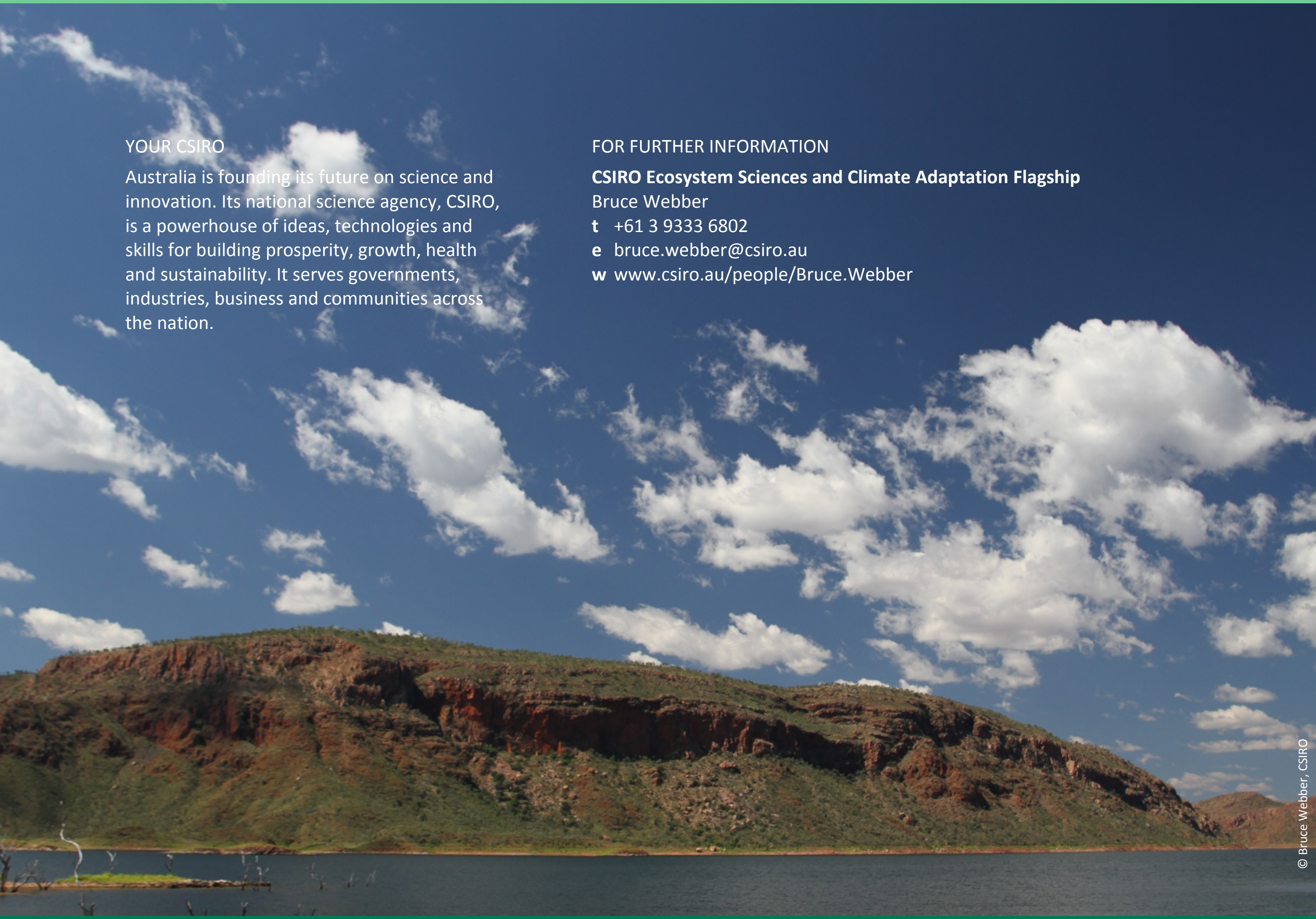

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