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Cane toads (*Rhinella marina*) in south-western Queensland: invasion front, spread and how Cooper Creek geomorphology could enable invasion into north-eastern South Australia

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Abstract. The invasion of northern Australia by the poisonous cane toad is well recognised, as is its devastating impacts on numerous local native species. However, there is little recognition that the toads are spreading into south-western Queensland. Utilising local knowledge, a limited survey was undertaken within the Cooper Creek catchment to locate the invasion front. Dispersal during 2010–11 floods has established cane toads as far south as Jundah. Integrating this information with landform mapping indicates that cane toad invasion can continue south-west down the Cooper Creek. Though arid, Cooper Creek's geomorphology renders it partially independent of local climate, and permanent and semipermanent waterholes (including RAMSAR-listed wetlands) are found downstream from Windorah and into the Strzelecki Desert. Natural landforms provide potential daytime shelter and breeding sites, and additional suitable habitat created by human activity is also widespread. Even unsuccessful attempts at breeding may be detrimental to regional ecology, especially fish populations, at critical stages of their boom/bust cycle. We conclude that there is no reason why cane toads cannot penetrate further down the Cooper Creek, threatening wetlands in north-eastern South Australia. Published models of cane toad expansion, which conclude that north-eastern South Australia is too dry for cane toad populations to establish, are based on climatic parameters that significantly under-represent true habitat availability.

Additional keywords: *Bufo marinus*, *Chaunus marinus*, dispersal, semiarid, survey, wetlands.

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Introduction

After the misguided introduction of poisonous cane toads (*Rhinella marina* = *Bufo marinus*) into Queensland in 1935 and subsequent recognition of local impacts on predatory and scavenging animals, efforts have been made to elucidate the species' potential Australian distribution and identify at-risk fauna and ecosystems (e.g. Sutherst *et al*. 1996; Tingley *et al*. 2014). Although the spread of the cane toad across northern Australia is well recognised, this introduced pest is also continuing to spread into south-western Queensland along waterways that ultimately end in the RAMSAR (Convention on Wetlands of International Importance) listed Coongie Lakes in north-eastern South Australia. This is an area with vastly different environmental characteristics to those of the species' natural distribution in South and Central America. Thus this pest species continues to challenge established understanding of its predicted distribution and hence where, and how severe, any associated social and environmental impacts could occur.

The accepted understanding of cane toad habitat requirements is derived from places where cane toads are currently established. However, previous cane toad distributions in the Australian tropics and semitropics cannot be taken as identifying limits to their ability to expand into the arid inland. Cane toads are increasingly occupying zones where conditions are more extreme than those of their native range (Urban *et al*. 2007), with artificial water points a critical asset in this invasion (Letnic *et al*. 2014). Though they require warmth, they have demonstrated plasticity in cold tolerance, allowing them to invade colder regions of south-eastern Australia (Kolbe *et al*. 2010; McCann *et al*. 2014). They also require moisture but Krakauer (1970, cited in Lever 2001) states they can lose over half their 'total body water' before death, and their adaptive behaviours allow them to be increasingly well adapted to seasonal drought in northern Australia (Brown *et al*. 2011; Jessop *et al*. 2013; Webb *et al*. 2014). Cane toads at the invasion front display genetic adaptability, developing longer legs (fast forward progress providing better access to new breeding sites) (Phillips *et al*. 2007), enhanced dispersal abilities (Alford *et al*. 2009), and greater ability to deal with arid conditions (more rapid water uptake enabling long-distance travel while dehydrated: Tingley *et al*. 2012; rehydrating during the day rather than at night: Webb *et al*. 2014).

A survey of cane toads was conducted in April 2011 in the vicinity of the Thomson River and downstream along the Queensland reaches of the Cooper Creek in south-western Queensland to locate the current 'south-western front' and rate of spread of the toad, which is advancing towards north-eastern South Australia.

The results of the field survey are combined with published literature on preferred cane toad habitat and integrated with landform mapping in the Strzelecki Desert, South Australia, focussing on Cooper Creek and the Coongie Lakes, to give some prediction of their potential to spread further south and invade north-eastern South Australia.

Methods

Due to time and resource constraints searches were confined to strategic areas as determined from local knowledge. Because of the extensiveness of the river system, there were vast gaps between survey sites downstream from Jundah. We did not intend to determine the actual distribution of toads along the entire Thomson River and Cooper Creek; indeed, this would be a monumental task.

Local knowledge of when and where landholders had seen or heard cane toads, gained before and during the survey, guided the selection of search sites. The survey started from Stonehenge (see Fig. 1) because it was known as the approximate front in south-western Queensland (Angus Emmott, pers. comm. 2011) with local residents collecting 53 toads over two weeks in late February and early March 2011 (Rutherford 2011). Subsequent sites downstream from Stonehenge were primarily selected under local guidance and where the Thomson River and its associated channels were accessible.

The survey was initially planned to be carried out in November/December 2010 to correspond with the season when cane toad activity and calling was expected to be high. Males begin calling for mates after the first summer rains and/or when water temperatures reach 25°C (Hagman and Shine 2006). However, due to exceptional rains in the Lake Eyre Basin in late 2010, access to the survey area was not possible until April 2011.

At each site we recorded presence or absence of toads during a defined search to provide a relative index of abundance and some limited baseline data for possible future comparison.

Road surveys were conducted at night driving at 20 km h^{-1} along a 5–8-km length of road(s) at survey locations. Utilising the vehicle's high-beam driving lights, two observers scanned the road and its immediate verges for toads.

Timed, night-time surveys were conducted on foot along the banks of waterways with the two observers wearing head torches looking for toads or their eye shine, and listening for their distinctive call.

Opportunistically sighted toads and those recorded during defined searches (Fig. 1) were logged using a Trimble Juno Datalogger utilising ArcPad software to record locations, habitat information and toad parameters. The site survey details are provided in Table 1.

Geomorphology

Geomorphology is used here to assess habitats for possible cane toad invasion and establishment. The data are derived from a 2011–12 study (Costelloe 2012; Wakelin-King 2013) of the geomorphology and hydrology of Cooper Creek and its catchment in South Australia (including the RAMSAR-listed Coongie Lakes), which was part of independent studies of high-value aquatic ecosystems carried out by the South Australian Arid Lands Natural Resource Management Board in the Lake Eyre Basin (Schmarr *et al*. 2012). The geomorphology assessment combined regional studies (looking at tectonic setting, surface lithologies, large-scale hydrology within the context of modern and past climates, and literature) with site-specific field observations of sediment transport, fluvial and other landforms, and biota–landform spatial relationships (mapping). The outcome is an understanding of landscape processes and their roles in supporting local ecosystems and allows predictions of habitat and ecology to be extrapolated across a range of scales and climatic circumstances.

Survey results

Over six survey nights two observers surveyed seven locations by foot and conducted four road surveys within or near some foot survey sites. Searches at each site ranged from 20 min to over three hours. A total of 26 cane toads were observed between Stonehenge and Jundah and no toads were observed within or downstream of Jundah (see Table 2 and Fig. 1). All observed toads were adults and most were located in or near water. Relative abundance of toads declined in the search area the further south we searched, being nil at and south of Jundah.

Cooper Creek geomorphology

Cooper Creek (Fig. 1), a Channel Country river, experiences one of the driest climates in Australia as it traverses north-eastern South Australia. Rainfall is rare and sparse, while the potential annual evaporation is very high (Australian Bureau of Meteorology 2013). A shallow pond fed by local runoff would not be good cane toad habitat, as it would evaporate soon after rainfall. However, two factors make this scenario irrelevant: Cooper Creek is not reliant on local rainfall, and its landforms include many that retain water for months, years, even decades.

Cooper Creek extends from the semitropics into the arid lands: monsoonal flood pulses routinely travel as far as South Australia (Knighton and Nanson 2001), some traversing the Stzelecki and Tirari Deserts to reach Lake Eyre. It experiences frequent, long-lasting flow events with single, multiple, or compound flood peaks (Knighton and Nanson 1994, 2001; Nanson *et al*. 2008), and it contains the six wettest reaches in the Lake Eyre Basin (Silcock 2009). Large long-lasting flood events are especially associated with significant La Niña weather patterns (return recurrence interval 20–40 years). For example, at Cullyamurra Waterhole, Cooper Creek flowed for 598 days during the 2010–12 flood cluster (Costelloe 2012).

Cooper Creek's fluvial geomorphology is complex (Knighton and Nanson 1994, 2000; Gibling *et al*. 1998; Fagan and Nanson 2004), with multiple deep anabranching channels and a network of shallow braid-like channels coexisting within the often broad floodplain. Like other Channel Country rivers, Cooper Creek has many waterholes: especially deep and wide channel segments that hold water for long periods. In comparison to other Channel Country rivers, Cooper Creek has the most, and the most

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Survey data (April 2011) from Department of Primary Industries and Regions SA; Collaborative Australian Protected Areas Database (2012) from Australian Government Department of the Environment; topographic data from Geoscience Australia.
The relationship between these data is not guaranteed.

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Fig. 1. Cane toad detections and survey locations in south-west Queensland. The largely ephemeral waterbodies of the Channel Country below Windorah are shown. Much of this shaded area was flooded during the 2010–12 flood cluster.

densely clustered, permanent and semipermanent waterbodies, particularly south of Jundah (Silcock 2009). A waterhole's permanence depends on its depth: there must be enough water in storage to outlast daily evaporation until the next flow (Costelloe *et al.* 2007; Costelloe 2011). Waterholes whose inflow is usually more frequent than the time it takes for them to dry include Yalungah, Meringhina, and Nappa Merrie (Queensland) and Cullyamurra, Minkie and Embarka (South Australia) (J. Costelloe, pers. comm. 2012).

Near Innamincka township and the Queensland–South Australia border, the Innamincka Dome plays an important role in landscape evolution and thus habitat development. Uplifted hills confine Cooper Creek into a valley, within which megafloods have scoured deep refuge waterholes (Schmarr *et al.*

Table 1. Cane toad survey details

Locations are arranged north to south along the Thomson River and Cooper Creek

Location	Road survey	Timed search	Opportunistic
Stonehenge	Travelling west along the Warereccan Road from the main channel.	Two-hour daytime survey of the banks of the Thomson River north and south of the bridge (no toads heard or observed). A replicated two-hour night survey undertaken approximately three hours later.	Around town buildings and equipment after being given directions by local residents.
'*Barnsdale*'	Along Stonehenge Racetrack road and the access track to 'Barnsdale'.	Night survey undertaken along secondary channels on the eastern side of the main Thomson River channel.	On the roads between Stonehenge and 'Barnsdale' and then 'Barnsdale' and 'Goon Goon'.
'*Goon Goon*'		Night survey of the banks of the Thomson River main channel north and south of a windmill west of the station buildings.	
'*Carella*'		Night survey of the banks of the channel closest to 'Carella' homestead, accessed past the nearby cattle yards	Walked approximately 1 km south by south-east away from the channel closest to 'Carella' homestead towards the main road (towards calling toads).
Jundah	Along the road west from Jundah to Windorah, beginning on the outskirts of the town and crossing the Thomson River and associated channels.	Along the Thomson River and associated channels near to the main road west. Along the Wuringle Creek and Braidwood channel crossing of the Jundah to Windorah Road ~15 km west of Jundah. Upstream and downstream of the Thomson River crossing ~8 km south-west of Jundah.	Driving south along main road into Jundah.
Windorah	Along 8 km of the main road east of Windorah, from Jundah turnoff, crossing Cooper Creek and associated channels.	Night survey at five locations at the Cooper Creek and associated channels.	
Nappa Merrie	Along 2 km of the main road at the Nappa Merrie bridge, crossing Cooper Creek.	Night survey of the bed of the Cooper Creek upstream and downstream of the Nappa Merrie bridge.	

Table 2. Cane toad survey results

Locations are arranged north to south along the Thomson River and Cooper Creek

Location	Road survey		Timed search			Opportunistic		Total
	Distance (km)	Results	Search effort (h)	Results	Comments	Results	Comments	
Stonehenge	n/a	n/a	2	4	Adult toads all within 2 m of water	7	Most observed toads were near an outside light, water source or watered lawn	11
'*Barnsdale*'	5	0	1.5	2	Single dead adult toad in a cattle pug mark in a dry creek bed. Adult toad observed on the edge of a water hole off the main Thomson River channel, also in a cattle pug mark	3	Adult toads	5
'*Goon Goon*'	n/a	n/a	1.5	4	Located within 5 m of water	0		4
'*Carella*'	n/a	n/a	1	1	Adult within 5 m of water	4	Three adult toads observed calling on the far bank of a shallow, well vegetated ephemeral waterhole. Adult toad observed on the road ~5 km south of '*Carella*' homestead	5
Jundah	8	0	5	0		1	Large adult toad observed in an ephemeral pond located beside the main road ~2 km north of Jundah	1
Windorah	8	0	3	0		0		0
Nappa Merrie	2	0	1.5	0		0		0

2012; Wakelin-King 2013). At the downstream end of the Innamincka Dome, the Cooper Creek Fan is the river's gateway into the Strzelecki Plain (Callen and Bradford 1992; Wakelin-King 2013). The river adopts a distributary pattern in which the main channel is multiply breached by offtakes that divert flow to other channels. Amongst these offtakes are one that flows towards Lake Eyre, and another that waters the RAMSAR-listed Coongie Lakes wetlands.

Cooper Creek has extensive floodplains, lignum swamps and lakes, created and maintained by interacting geomorphic processes (Wakelin-King 2013). Inundation is an important and frequent part of the river cycle, and during wet years the landforms can be inundated for long periods, contributing to a biological 'boom'. In particular, the Coongie Lakes area hosts a huge ecological response (Reid and Puckeridge 1990), and Lake Hope, in the lower Cooper, can retain water for up to three years (J. Costelloe, pers. comm. 2012), during which large native fish populations develop.

In south-west Queensland and northern South Australia, Cooper Creek's water-retaining landforms have many elements that are suitable for cane toad habitat (Table 3). Their qualities include proximity to moisture, shade or cover; shallow water or gently-shelving banks; still or slow-flowing water, and open space near water's edge (see Wakelin-King 2013 for detailed descriptions).

Discussion

Cane toad movements

Local opinion holds that toads arrived in Aramac, ~130 km upstream of Longreach in 1997 and in Longreach in the summer of 2002–03 (Angus Emmott. pers. comm. 2008), suggesting a dispersal rate of ~25 km year^{-1} (Frank Keenan, pers. comm. 2008). A small number of toads were first observed at Lochern National Park on the Thomson River 120 km downstream from Longreach in the summer of 2009–10 (Shane Hume, pers. comm. 2011), suggesting a dispersal rate of 17 km year^{-1} from Longreach. In the following very wet summer of 2010–11, hundreds of cane toads were observed around waterholes of Lochern National Park, a marked increase compared with the previous year.

Local residents first observed toads in Stonehenge in January 2011, the same time landholders 42 km downstream at '*Carella*' first heard toads in a waterhole adjacent to the homestead.

During this survey the most southerly observation of a cane toad was a single adult toad detected in a roadside ephemeral pond 2 km north of Jundah and ~14 km downstream from the '*Carella*' station house. During the survey, despite searching the area, we were unable to substantiate the report from Jundah residents of a large toad found run over just west of Jundah 'on the road near the Braidwood channel' in January 2011. Similarly, our searches were unable to substantiate reports of 'isolated toads at Windorah', a township 70 km downstream from Jundah.

Our inability to observe or hear a toad at or south of Jundah and given that no Jundah residents reported having seen a toad in the town, suggests that at the time of this survey, the current cane toad front lay approximately at the northern outskirts of Jundah. Therefore, in the very wet 2010–11 season cane toads appear to have dispersed ~75 km from Lochern National Park south to Jundah at a rate equivalent to ~75 km year^{-1}. However, it is very plausible that the toads were already south of Lochern National Park in small numbers before the reported summer of 2009–10, and were at or south of Jundah during our survey, but were not detected.

All toads observed on this survey were adults, and only at '*Carella*' were a small number recorded calling. Although we sighted many native frogs, including the small *Crinia deserticola* (~12 mm), we observed no small toads. Similarly, we observed no cane toad eggs, either during night survey observations or during daytime site reconnaissance. However, toads had been heard calling for the previous three months by the '*Carella*' landholders, supporting the possibility that toads were breeding at locations we surveyed.

Suitable arid-zone habitat

Studies have predicted the eventual distribution of cane toads in Australia by matching their habitat preferences and biophysical limiting factors to climate zones. Empirically based models (Sutherst *et al*. 1996; Urban *et al*. 2007, 2008) find the best matches between climatic parameters (e.g. temperature maxima and minima, precipitation, humidity) and known cane toad distributions, then map those climatic parameters for Australia. In these, animal physical tolerances are compared against climatic extremes, and climatic parameters are used to make assumptions about habitat availability (e.g. Sutherst *et al*. (1996) combine rainfall and evaporation data into a soil moisture index, and Urban *et al*. (2007, 2008) combine precipitation with a mathematical

Table 3. Potential cane toad habitat elements (natural) in the Strzelecki Desert

Shelter	The tangles of exposed coolabah roots along the waterhole banks
	Beneath fallen branches and logs along waterhole banks, and in channel beds
	Beneath vegetation in gullies cutting through waterhole and channel banks
	Dense lignum thickets along the edges of swamps, or some channel and waterhole banks
	Within the deep cracks and crabholes of the black soil swamp country
	Under clusters of boulders where rocky outcrop is close to the water, e.g. Cullyamurra and Nappa Merrie Waterholes
Calling and breeding	Upstream and downstream edges of feeder channels and splay channels of the permanent waterholes
	Margins of secondary and minor channels; flood chutes, palaeochannels and anabranches
	Offtakes and distributary channels along the Cooper Creek Fan
	Lake edges
	Lake input and offtake channels
	Swamp edges
	Sandy benches where dunes meet channels, or where stock pads come down to the water's edge

model that proxies for topographic complexity to indicate desirable habitat). A process-based modelling program (Kearney *et al*. 2008, utilised in Tingley *et al*. 2014) stringently examines cane toad biophysical responses to climatic factors, and uses Australian climate data to model the spatial extent of breeding habitats.

A limitation of these predictive models is that they do not consider the geomorphic processes underpinning potential cane toad habitat. This is most clear in Kearney *et al*. (2008), where breeding ponds are modelled as being small, relatively shallow, and fed by local runoff. Using these parameters, Kearney *et al.* (2008, their p. 431 and figs 7a, S5a) and subsequently Tingley *et al*. (2014) map the Cooper Creek and Diamantina catchments in south-western Queensland and north-eastern South Australia as being beyond the interior limit of predicted cane toad range because of low water availability. In fact, the case is quite otherwise. The fluvial geomorphology is dominated by water-retaining landforms fed by large catchments extending from the semimonsoonal north. The Strzelecki Desert's waterholes and wetlands exist because Coopers Creek's fluvial processes outmatch local rainfall and evaporation conditions. In fact, the waterholes of the Coongie Lakes area support central Australia's richest frog community (Reid and Puckeridge 1990).

Similarly, range predictions based on empirical models would benefit by consideration of habitat geomorphology. The empirically determined climatic parameters reflect actual physical habitat conditions and geomorphic processes. The model's predictive value will be less if the conditions and processes are not consistent across the whole modelled area. Subsequent cane toad distribution and rate of spread has proven wrong the predictions made by Sabath *et al*. (1981) and Freeland and Martin (1985), and Sutherst *et al*. (1996) and Urban *et al.* (2007) did not predict the cane toad distribution shown by the present study. While biological factors (e.g. Tingley *et al.* 2012; Jessop *et al*. 2013; Webb *et al*. 2014) may underlie these unsuccessful predictions, it is also important to query the empirical studies' habitat assumptions. Was soil moisture truly the habitat parameter expressed by rainfall : evaporation values (Sutherst *et al*. 1996), and, if so, from what geomorphic process did that arise? Can coarse measures of elevation discern landscape complexity (Urban *et al*. 2007) in a low-relief fluvial system? Is local rainfall the dominant source of habitat water in all catchments? The answers will determine how applicable the models are to landscapes other than those of the models' origin.

While predictive models are not supposed to be taken beyond the limitations of their input data, readers unaware of those limitations will nonetheless likely take the conclusions at face value. Key studies (Sutherst *et al*. 1996; Urban *et al*. 2007; Kearney *et al*. 2008) have excluded north-eastern South Australia from maps depicting areas at risk from cane toad invasion, and later studies citing them also fail to consider the area (e.g. Peacock 2007; Phillips *et al*. 2008; Urban *et al*. 2008; Beckmann and Shine 2009; Shine 2010; Florance *et al*. 2011; Tingley *et al.* 2014). Across the literature, South Australia's arid north-east is portrayed as being in no danger of cane toad invasion, at least in part because the models treat landscape processes as an irrelevancy. This will not only influence future research, it may also affect funding priorities for cane toad control. The failure of modelling to capture the ability of invasive species to occupy climatic niches outside those recognised for their native range was recently highlighted in a study on the grey squirrel in Europe (Di Febbraro *et al*. 2013).

Cooper Creek has no shortage of damp or near-water natural landforms suitable for daytime shelter and for breeding (Table 3). While many will be only intermittently suitable, others will be effectively permanent, depending on their proximity to permanent or semipermanent water bodies. Cane toads can also utilise human-created habitats (Florance *et al*. 2011), making use not only of free water but also demountable buildings, sheds, and pallets; public media (e.g. ABC News 2011; Canetoadsinoz 2012) speaks of toads hiding in vehicles, the holes in Besser-blocks, building materials, and many other things. In Cooper Creek, human-created habitat resulting from the tourism, resources, and pastoral industries includes all these things, as well as artificial watering points and industrial evaporation ponds (Wakelin-King 2013). Even transient natural waters may allow invading toad populations to reach artificial permanent waters from where they can infect or reinfect the system in the next wet year.

In high-value aquatic ecosystems, breeding populations survive during long droughts to restock the entire ecosystem during wetter times (McNeil *et al*. 2011). In the Cooper Creek, high-value aquatic ecosystems include the Cullyamurra and Nappa Merrie waterholes and the Coongie Lakes with their associated channels and swamps. Established populations of cane toads in these important places will have a disproportionally great impact on the wider ecosystem. Land animals sheltering or foraging in the rich, often refuge, riparian zones will be at risk from predation on the terrestrial toads, especially species with high water reliance. Letnic *et al*. (2008) suggest that site aridity was a significant factor in the increased (up to 77%) mortality of *Crocodylus johnstoni* they recorded in their Victoria River (Northern Territory) site. Aquatic animals would be at risk from eating the highly toxic eggs, tadpoles and toadlets. Though in other locations larger fish and turtles are protected from the toxic eggs because of the eggs' emplacement in shallow water (Greenlees and Shine 2011), the variable flow pattern in Cooper Creek means that over successive flood peaks, eggs may be washed into deeper waters where larger animals can eat them. Established toad colonies along Cooper Creek are clearly undesirable.

Unsuccessful toad colonies are also likely to be highly detrimental to Cooper Creek ecology. Toad colonies may not be able to establish on floodplains whose inundation is short-term. The toads might lay eggs, but perhaps the shallow breeding ponds will not persist long enough to grow adult toads able to migrate. However, that brief time of floodplain inundation is an important time in desert fish ecology. Fish leave refuge waterholes and seek the floodplains to feed, grow and find new breeding grounds (Schmarr *et al.* 2012). The wet floodplains host a population explosion that is central to genetic diversity in arid-zone fish, and contributes to the food chain of fish-eating birds.

Our argument that the Cooper Creek provides suitable cane toad habitat presents the question of what can be done to protect it, and other suitable Australian habitats, from the impact of the poisonous toads. Although excluding toads from artificial water points (Florance *et al*. 2011; Letnic *et al*. 2014) may be theoretically feasible in some land systems, the reality of the low human population, low land management priority (e.g. Coongie Lakes and associated regional wetlands fall outside the Cane Toad Threat Abatement Plan) and cyclical vast regional floods (e.g. see shaded area in Fig. 1) makes any effective control of cane toads reliant on a biological control agent(s). Human effort, even with significant financial resources, was unable to prevent toads invading the Kimberley region of Western Australia (Peacock 2007). We recommend that the search for biological control agent(s) (Peacock 2006; Saunders *et al*. 2010), under the guidelines and recommendations of the former National Cane Toad Taskforce (Taylor and Edwards 2005), be recommenced as soon as possible if there is to be any hope of effectively minimising the cane toad's continued invasion of, and impact on, Australia.

Conclusions

Following the wet conditions in late 2010 and early 2011, a limited survey of the Cooper Creek system in Queensland (Australia) indicated established cane toad populations (at Lochern) 120 km downstream from Longreach, possible attempts at breeding (at '*Carella*') ~180 km downstream of Longreach and the invasion front near the northern outskirts of Jundah (~200 km downstream of Longreach). The dispersal rate during the very wet 2010–11 season appears to have been equivalent to ~75 km year^{-1}. That season was part of the larger 2010–12 flood cluster and it is reported that cane toads have spread further to the south-west down the Thomson River during 2011–14 to now be between Jundah and Windorah (A. Emmott, pers. comm. 2014).

Contrary to expectations based on previous modelling, desert environments in south-western Queensland and north-eastern South Australia potentially offer substantial natural cane toad habitat that is permanent or semipermanent. Human-created potential habitat is also widespread. Range expansion of the cane toad can threaten native fauna as permanent populations and as ephemeral (failed) attempts at establishment which, though transient, are a risk to native fish at a critical stage in their breeding cycle. High-value aquatic ecosystems and arid-zone wetlands are in the possible toad expansion pathway and they include the RAMSAR-listed Coongie Lakes and the refuge waterholes at Cullyamurra and Nappa Merrie.

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References

ABC News (2011). Cane toad hitches ride from Kununurra to Perth. Available at: http://www.abc.net.au/news/2011-09-20/cane-toad-captured-at-canning/2908188 (accessed 17 October 2014).

Alford, R. A., Brown, G. P., Schwarzkopf, L., Phillips, B. L., and Shine, R. (2009). Comparisons through time and space suggest rapid evolution of dispersal behaviour in an invasive species. *Wildlife Research* **36**, 23–28. doi:10.1071/WR08021

Australian Bureau of Meteorology (2013). Climate maps, average conditions: annual rainfall, 50th percentile; annual average number of days with rainfall greater than 2 mm; annual average pan evaporation. Available at: http://www.bom.gov.au/climate/averages/maps.shtml (accessed January 2013).

Beckmann, C., and Shine, R. (2009). Impact of invasive cane toads on Australian birds. *Conservation Biology* **23**, 1544–1549. doi:10.1111/j.1523-1739.2009.01261.x

Brown, G. P., Kelehear, C., and Shine, R. (2011). Effects of seasonal aridity on the ecology and behaviour of invasive cane toads in the Australian wet–dry tropics. *Functional Ecology* **25**, 1339–1347. doi:10.1111/j.1365-2435.2011.01888.x

Callen, R. A., and Bradford, J. (1992). Cooper Creek fan and Strzelecki Creek – hypsometric data, Holocene sedimentation, and implications for human activity. *Mines and Energy Review* **158**, 52–57.

Canetoadsinoz (2012). Cane toad stowaways. Available at: http://www.canetoadsinoz.com/cane_toad_stowaways.html (accessed 17 October 2014).

Costelloe, J. (2011). Hydrological assessment and analysis of the Neales Catchment. A report to the South Australian Arid Lands Natural Resources Management Board, Port Augusta.

Costelloe, J. F. (2012). Hydrological assessment and analysis of the Cooper Creek catchment, South Australia. A report to the South Australian Arid Lands Natural Resources Management Board, Port Augusta.

Costelloe, J. F., Shields, A, Grayson, R. B., and McMahon, T. A. (2007). Determining loss characteristics of arid zone river waterbodies. *River Research and Applications* **23**, 715–731.

Di Febbraro, M., Lurz, P. W., Genovesi, P., Maiorano, L., Girardello, M., and Bertolino, S. (2013). The use of climatic niches in screening procedures for introduced species to evaluate risk of spread: a case with the American eastern grey squirrel. *PLoS ONE* **8**, e66559. doi:10.1371/journal.pone.0066559

Fagan, S. D., and Nanson, G. C. (2004). The morphology and formation of floodplain surface channels, Cooper Creek, Australia. *Geomorphology* **60**, 107–126. doi:10.1016/j.geomorph.2003.07.009

Florance, D., Webb, J. K., Dempster, T., Kearney, M. R., Worthing, A., and Letnic, M. (2011). Excluding access to invasion hubs can contain the spread of an invasive vertebrate. *Proceedings of the Royal Society B: Biological Sciences* **278**, 2900–2908.

Freeland, W. J., and Martin, K. C. (1985). The rate of range expansion by *Bufo marinus* in northern Australia, 1980–84. *Wildlife Research* **12**, 555–559. doi:10.1071/WR9850555

Gibling, M. R., Nanson, G. C., and Maroulis, J. C. (1998). Anastomosing river sedimentation in the Channel Country of central Australia. *Sedimentology* **45**, 595–619. doi:10.1046/j.1365-3091.1998.00163.x

Greenlees, M., and Shine, R. (2011). Impacts of eggs and tadpoles of the invasive cane toad (*Bufo marinus*) on aquatic predators in tropical Australia. *Austral Ecology* **36**, 53–58.

Hagman, M., and Shine, R. (2006). Spawning site selection by feral cane toads (*Bufo marinus*) at an invasion front in tropical Australia. *Austral Ecology* **31**, 551–558. doi:10.1111/j.1442-9993.2006.01627.x

Jessop, T. S., Letnic, M., Webb, J. K., and Dempster, T. (2013). Adrenocortical stress responses influence an invasive vertebrate's fitness in an extreme environment. *Proceedings of the Royal Society B: Biological Sciences* **280**, 20131444.

Kearney, M., Phillips, B. L., Tracy, C. R., Christian, K. A., Betts, G., and Porter, W. P. (2008). Modelling species distributions without using species distributions: the cane toad in Australia under current and future climates. *Ecography* **31**, 423–434. doi:10.1111/j.0906-7590.2008.05457.x

Knighton, A. D., and Nanson, G. C. (1994). Waterholes and their significance in the anastomosing channel system of Cooper Creek, Australia. *Geomorphology* **9**, 311–324. doi:10.1016/0169-555X(94)90052-3

Knighton, A. D., and Nanson, G. C. (2000). Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. *Geomorphology* **35**, 101–117. doi:10.1016/S0169-555X(00)00026-X

Knighton, A. D., and Nanson, G. C. (2001). An event-based approach to the hydrology of arid zone rivers in the Channel Country of Australia. *Journal of Hydrology* **254**, 102–123. doi:10.1016/S0022-1694(01)00498-X

Kolbe, J. J., Kearney, M., and Shine, R. (2010). Modelling the consequences of thermal trait variation for the cane toad invasion of Australia. *Ecological Applications* **20**, 2273–2285. doi:10.1890/09-1973.1

Krakauer, T. (1970). Tolerance limits of the toad, *Bufo marinus*, in south Florida. *Comparative Biochemistry and Physiology* **33**, 15–26. doi:10.1016/0010-406X(70)90479-2

Letnic, M., Webb, J. K., and Shine, R. (2008). Invasive cane toads (*Bufo marinus*) cause mass mortality of freshwater crocodiles (*Crocodylus johnstoni*) in tropical Australia. *Biological Conservation* **141**, 1773–1782. doi:10.1016/j.biocon.2008.04.031

Letnic, M., Webb, J. K., Jessop, T. S., Florance, D., and Dempster, T. (2014). Artificial water points facilitate the spread of an invasive vertebrate in arid Australia. *Journal of Applied Ecology.* doi:10.1111/1365-2664.12232

Lever, C. (2001). ‘The Cane Toad. The History and Ecology of a Successful Colonist.’ (Westbury Publishing: West Yorkshire.)

McCann, S., Greenlees, M. J., Newell, D., and Shine, R. (2014). Rapid acclimation to cold allows the cane toad to invade montane areas within its Australian range. *Functional Ecology* doi:10.1111/1365-2435.12255

McNeil, D. G, Schmarr, D. W., and Rosenberger A. E. (2011). Climatic variability, fish and the role of refuge waterholes in the Neales River Catchment: Lake Eyre Basin, South Australia. Report by South Australian Research and Development Institute (Aquatic Sciences) to the South Australian Arid Lands NRM Board, Port Augusta.

Nanson, G. C., Price, D. M., Jones, B. J., Maroulis, J. C., Coleman, M., Bowman, H., Cohen, T. J., Pietsch, T. J., and Larsen, J. R. (2008). Alluvial evidence for major climate and flow regime changes during the middle and late Quaternary in eastern central Australia. *Geomorphology* **101**, 109–129. doi:10.1016/j.geomorph.2008.05.032

Peacock, D. (2006). Investigation of a pathogen for *Bufo marinus* in northern Argentina: could it be a trypanosome? In ‘Science of Cane Toad Invasion and Control. Proceedings of the Invasive Animals CRC/CSIRO/Qld NRM&W Cane Toad Workshop, June 2006, Brisbane’. (Ed. K. Molloy and W. Henderson.) pp. 98–105. (Invasive Animals Cooperative Research Centre: Canberra.)

Peacock, T. (2007). ‘Community on-ground cane toad control in the Kimberley: A review conducted for the Hon. David Templeman, MP, Minister for the Environment, Climate Change and Peel.’ (Invasive Animals Cooperative Research Centre: University of Canberra.)

Phillips, B. L., Brown, G. P., Greenlees, M., Webb, J. K., and Shine, R. (2007). Rapid expansion of the cane toad (*Bufo marinus*) invasion front in tropical Australia. *Austral Ecology* **32**, 169–176. doi:10.1111/j.1442-9993.2007.01664.x

Phillips, B. L., Chipperfield, J. D., and Kearney, M. R. (2008). The toad ahead: challenges of modelling the range and spread of an invasive species. *Wildlife Research* **35**, 222–234. doi:10.1071/WR07101

Reid, J. R. W., and Puckeridge, J. T. (1990). Coongie Lakes. In ‘Natural History of the North East Deserts’ (Eds M. J. Tyler, C. R. Twidale, M. Davies, and C. B. Wells.) pp. 119–131. (Royal Society of South Australia: Adelaide.)

Rutherford, N. (2011). ‘Stonehenge toad busters haul ‘em in’. *Longreach Leader*, 18 March, p. 5.

Sabath, M. D., Boughton, W. C., and Easteal, S. (1981). Expansion of the range of the introduced toad *Bufo marinus* in Australia from 1935 to 1974. *Copeia* **1981**, 676–680. doi:10.2307/1444573

Saunders, G., Cooke, B., McColl, K., Shine, R., and Peacock, T. (2010). Modern approaches for the biological control of vertebrate pests: an Australian perspective. *Biological Control* **52**, 288–295. doi:10.1016/j.biocontrol.2009.06.014

Schmarr, D. W., Mathwin, R., Cheshire, D. L., and McNeil, D. G. (2012). Aquatic ecology assessment and analysis of the Cooper Creek catchment: Lake Eyre Basin, South Australia. Report to the South Australian Arid Lands Natural Resource Management Board. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2012/000442–1. SARDI Research Report Series No. 679.

Shine, R. (2010). The ecological impact of invasive cane toads (*Bufo marinus*) in Australia. *The Quarterly Review of Biology* **85**, 253–291. doi:10.1086/655116

Silcock, J. (2009). Identification of permanent refuge waterbodies in the Cooper Creek and Georgina–Diamantina River catchments for Queensland and South Australia: A report to the South Australian Arid Lands Natural Resource Management Board. South Australian Arid Lands Natural Resource Management Board, Port Augusta; http://www.saalnrm.sa.gov.au/Portals/8/Publications_Resources/Project_Reports, accessed June 2012.

Sutherst, R. W., Floyd, R. B., and Maywald, G. F. (1996). The potential geographical distribution of the cane toad, *Bufo marinus* L. in Australia. *Conservation Biology* **10**, 294–299. doi:10.1046/j.1523-1739.1996.10010294.x

Taylor, R., and Edwards, G. (2005). A review of the impact and control of cane toads in Australia with recommendations for future research and management approaches. A report to the Vertebrate Pests Committee from the National Cane Toad Taskforce.

Tingley, R., Greenlees, M. J., and Shine, R. (2012). Hydric balance and locomotor performance of an anuran (*Rhinella marina*) invading the Australian arid zone. *Oikos* **121**, 1959–1965. doi:10.1111/j.1600-0706.2012.20422.x

Tingley, R., Vallinoto, M., Sequeira, F., and Kearney, M. R. (2014). Realized niche shift during a global biological invasion. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 10233–10238. doi:10.1073/pnas.1405766111

Urban, M. C., Phillips, B. L., Skelly, D. K., and Shine, R. (2007). The cane toad’s (*Chaunus* [*Bufo*] *marinus*) increasing ability to invade Australia is revealed by a dynamically updated range model. *Proceedings of the Royal Society B: Biological Sciences* **274**, 1413–1419. doi:10.1098/rspb.2007.0114

Urban, M. C., Phillips, B. L., Skelly, D. K., and Shine, R. (2008). A toad more travelled: the heterogeneous invasion dynamics of cane toads in Australia. *American Naturalist* **171**, E134–E148. doi:10.1086/527494

Wakelin-King, G. A. (2013). Geomorphological assessment and analysis of the Cooper Creek catchment (SA section). Report by Wakelin Associates to the South Australian Arid Lands Natural Resources Management Board, Port Augusta.

Webb, J. K., Letnic, M., Jessop, T. S., and Dempster, T. (2014). Behavioural flexibility allows an invasive vertebrate to survive in a semi-arid environment. *Biology Letters* **10**, doi:10.1098/rsbl.2013.1014

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