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Terrestrial mammals of the Gnangara Groundwater System, Western Australia: history, status, and the possible impacts of a drying climate.

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Abstract

Over the last 30 years declining rainfall and increased aquifer abstraction have heavily impacted water availability and ecosystems on the Gnangara Groundwater System (GGS). The mammal fauna of the area is considered to have been rich, with up to 28 terrestrial and 5 volant native species recorded since European settlement. This study investigated previous and current distribution of mammals on the GGS, and assessed potential impacts of predicted rainfall and groundwater declines on mammals. A general survey was conducted at 40 sites, and targeted trapping was undertaken for *Hydromys chrysogaster* and *Isoodon obesulus fusciventer* at wetlands. Nine native and seven introduced terrestrial mammal species were recorded during the general survey and capture rates were very low (1.05%). The most commonly captured native species was *Tarsipes rostratus*. There is evidence that only 11 (9 recorded and 2 considered to be extant) of the 28 historically recorded terrestrial native mammals are still persisting in the area. The species predicted to be most susceptible to rainfall and groundwater level declines include *H. chrysogaster*, *I. obesulus fusciventer*, and *T. rostratus*. Management and recovery actions required to protect mammals under predicted climatic changes include identification and maintenance of refugia and ecological linkages, supplementation of lakes, development of ecologically appropriate fire regimes, and control of predators.

Additional keywords:

Western Australia, Northern Swan Coastal Plain, aquifer, ecological linkages, fire regimes, groundwater dependency.

Introduction

In the past decade numerous studies have demonstrated the impacts of climatic changes in a variety of ecosystems and communities around the world (Hughes, 2000; Walther *et al.*, 2002; Parmesan and Yohe, 2003). In Mediterranean systems, such as south-western Australia, climate change predictions include lower rainfall and extended drought periods (IPCC, 2007). If correct, these changes to the climate are likely to pose significant threats to vulnerable mammal species, especially in fragmented ecosystems.

Low rainfall has been shown to have a significant influence on the abundance of small mammals, including brush-tailed phascogales (*Phascogale tapoatafa*) (Rhind and Bradley, 2002) and honey possums (*T. rostratus*) (Wooller *et al.*, 1998; Bryant, 2004; Bradshaw *et al.*, 2007) in south-western Australia. There is also recent evidence that low rainfall and drought have severe impacts on the abundance of species such as agile antechinus (*Antechinus agilis*) and swamp antechinus (*A. minimus*) in south-eastern Australia (Wilson *et al.*, 2007; Parrott *et al.*, 2007; Sale *et al.*, 2008; Magnusdottir *et al.*, 2008). Although there has been little work on the relationship of mammals and groundwater levels, Braithwaite and Muller (1997) found strong correlations between mammal population declines and decreased groundwater levels in an area of the Australian wet-dry tropics. In contrast, Woinarski *et al*. (2001; 2010) did not find a direct link between rainfall and mammal abundance at the same site, and suggest that declines in mammal abundance may be due to other threatening processes such as a high frequency of fire.

The record of extinction of mammals in Australia since European settlement is recognised as being higher than elsewhere in the world (Burbidge and McKenzie, 1989; Morton, 1990; Short and Smith, 1994; Maxwell *et al.*, 1996). A number of disturbance factors have been identified as contributors to the extinctions and declines including land clearance and habitat fragmentation, introduced predators, changed fire regimes, disease and rainfall decline (Burbidge and McKenzie, 1989; Morton, 1990; Maxwell *et al.*, 1996; Johnson, 2006). McKenzie *et al.* (2007) found that the loss of mammal species was greater in arid regions compared to high rainfall regions. Most of the region-to-region variation in attrition was attributed to variables such as mean annual rainfall, environmental change, phylogenetic similarity, and body-weight distribution. Mammals that occur in areas predicted to have reduced rainfall and ground water levels are thus highly susceptible to population declines.

The IPCC (2007) has identified a number of regions (coastal) and ecosystems (wetland and Mediterranean) where faunal biodiversity is likely to be at particularly high risk from the impacts of climate change. South-western Australia is predicted to undergo the most intense drying of any region in Australia by 2100 (Pitman and Perkins, 2008), with modelling suggesting that rainfall will decline by as much as 20% by 2030 and 60% by 2070 (Jones and Preston, 2006). The declines in rainfall will predominantly occur during winter months, although declines in spring and summer rainfall are also expected. In addition to direct impacts of declining rainfall on mammals, there are threats from indirect impacts of declining aquifers. The ecological impacts of groundwater declines on groundwater dependent ecosystems (GDEs), including surface terrestrial and aquatic systems, have been recognised as significant (Eamus *et al*. 2006; Nevill *et al*. 2010).

The Gnangara Groundwater System (GGS), which is located in south-western Australia on the Swan Coastal Plain (SCP), is an area at particularly high risk to rainfall declines (Malcolm *et al.*, 2006). The system covers approximately 220 000 ha and provides the city of Perth with approximately 60% of its drinking water (Figure 1). The groundwater system consists of an unconfined, superficial aquifer known as the Gnangara Mound (Government of Western Australia, 2009). In the past 30 years, a drying climate has been a significant feature of the GGS. Rainfall has declined largely compared to the long-term average (Figure 2) and, together with increased aquifer abstraction, have strongly influenced the groundwater storage (Figure 3), resulting in groundwater levels that have decreased by up to 4 m in some areas (Yesertener, 2007; Vogwill *et al.*, 2008). It is predicted that in the future there could be an even greater decline in rainfall (IOCI, 2005; Jones and Preston, 2006; Preston and Jones, 2006) and under all but the most optimistic assumptions for climate, groundwater levels will decline (Vogwill *et al.*, 2008).

Declining groundwater levels have emerged as a significant threat to wetland-associated vertebrate fauna across the SCP and in the GGS area. The wetlands are some of the most biologically productive areas of the SCP and directly or indirectly support most of the wildlife (Horwitz *et al*. 2009). Declines in wetlands are likely to have significant impacts on mammal fauna and their habitats; however, there is little knowledge of both the habitat components that are most affected, and the communities or taxa that are most susceptible to declining groundwater levels. Further, there is strong evidence of a progressive reduction in canopy foliage cover and change in floristic composition of the *Banksia* woodlands on the GGS as the regional water table has declined (Sommer and Froend 2011).

The mammal fauna of the northern SCP that covers the GGS area is considered to have been historically rich, with up to 33 native species recorded since European settlement (Kitchener *et al.*, 1978). However, in the 1970s only 12 species were recorded across large contiguous and relatively undisturbed vegetation in the north of the GGS area (Kitchener *et al.*, 1978). Subsequent studies in inner urban fragments (1 - 338 ha in size) found few mammals surviving with only seven native and six introduced species recorded (How and Dell, 1993; 1994; 2000). However, a comprehensive fauna survey has not been conducted in the large remnants since the late 1970s and the current status and persistence of mammals is unclear (Mitchell *et al.* 2003).

In this paper we assess the historic and current occurrence and distribution of terrestrial mammal fauna across the GGS, and assess the susceptibility of taxa to declining rainfall and groundwater levels. We consider the implications for conservation, recovery and management under a drying climate.

Materials and methods

Study area

The area covered by the GGS is located on the SCP and represents a distinct water catchment that extends from Perth (Swan River) in the south, to the Moore River and Gingin Brook in the north, and from the Darling Scarp in the east to the Indian Ocean in the west (Figure 1) (DOW, 2008; Government of Western Australia, 2009). Although there have been large amounts of clearing for urbanisation and agriculture, the total remnant native woodland in the GGS covers more than 100 000 ha and includes the largest continuous area of remnant vegetation on the SCP, south of the Moore River. The distribution of vegetation is predominantly determined by the underlying landforms, soils, depth to water table and climatic conditions (Heddle *et al.*, 1980). The Swan Coastal Plain can be divided into a sequence of broad geomorphic units lying parallel to the coast that are characterised by a progression of aeolian sands in the west to alluvial and/or colluvial deposits in the east (Playford *et al*. 1976). Within the GSS study area, the major landforms include three main dune systems Quindalup, Spearwood and Bassendean dunes (Government of Western Australia 2000; Playford *et al*. 1976). These landform units are composed of a variety of soils and varying surface geology. The younger Quindalup Dunes are close to the coast, followed by the Spearwood Dunes associated with Tamala Limestone ridges within about ten kilometres of the coast, and the inland Bassendean Dunes which are older and flatter, and contain leached and slightly acidic sands. The vegetation is typically a *Banksia* overstorey, with sporadic stands of *Eucalyptus* and *Allocasuarina*, and an understorey consisting mainly of low shrubs from the Myrtaceae, Fabaceae and Proteaceae families. Interspersed among these woodlands are many seasonal damplands, swamps and permanent wetlands, fringed by *Banksia littoralis* and *Melaleuca* trees (Semeniuk *et al.*, 1990).

The GGS experiences a dry Mediterranean-type climate (Beard, 1984), with hot dry summers (December – March) and cool wet winters (June – August), and an annual average of 807 mm. Rainfall and runoff declines in the last 30 years have been substantial, with approximately 21% less rainfall and 64% less runoff between 1997 - 2003 compared to 1911 – 1974 (Yesertener, 2007).

Assessment of the historic occurrences of mammals

Information on previous records and studies was collated from publications, survey team reports and fauna surveys conducted on the GGS, including peer-reviewed journals, state and local government surveys, and university theses (see references listed in Table 1). Records of the historic occurrence and abundance of mammal species were collated and compared to the records for the current study.

Fauna surveys

Fauna surveys were conducted between 2007 and 2008. A general trapping program was conducted on terrestrial mammal species across the study area, as well as two targeted trapping programs for southern brown bandicoot (*I. obesulus fusciventer*) and water rat (*H. chrysogaster*).

General survey trapping

The sampling regime consisted of 40 sites in the major areas of continuous remnant bush land in the northern and eastern areas of the GGS. A stratified sampling procedure was employed to select sites to represent the major landform units (Quindalup, Spearwood and Bassendean), vegetation communities (Banksia woodland, coastal scrub, jarrah forest, tuart forest and Melaleuca wet or dampland). Some categories, such as the Quindalup landform were not well represented due to their limited occurrence and/or poor accessibility in the study area.

The trapping design included an array of pitfall traps (20 L buckets), and a transect line of small aluminium box traps (Elliotts: 9 x 10 x 33 cm) and cage traps (Sheffields: 20 x 20 x 56 cm). Each site contained one pitfall trap array, consisting of 10 pitfall traps arranged in a Y shape with three pitfall traps along each radiating arm and a central pit. Pitfall traps were placed at approximately 7 metre intervals and were connected with 30 cm high aluminium fly wire drift fence. Twenty Elliott and ten cage traps were positioned along a 300 m-long transect between two adjacent sites of pitfall trap arrays. Elliott traps were located at 15 m intervals, and cage traps at 30 m intervals. Both trap types were baited with universal bait comprising a mixture of peanut paste, rolled oats and sardines. Traps were opened for 12 – 20 nights in total for the three trapping periods (spring 2007, autumn 2008 and spring 2008). While open, all traps were checked once per day in the early morning. Captured animals were identified, processed and released onsite. Mammals were ear notched for recapture purposes (*I. obesulus* received an individually numbered ear tag). Taxonomic nomenclature, including common names, followed the Western Australian Museum protocols. Incidental observations of species were also recorded.

Targeted trapping surveys

A targeted trapping survey for *I. obesulus* was undertaken at nine sites in May 2008 (Figure 1). Sites were located in areas of suitable habitat or based on historical records in areas that contained a permanent wetland or were swampy or damp for part of the year (T. Friend, M. Bamford, *pers. comm*., 2007). The targeted trapping survey for *H. chrysogaster* was conducted in May 2008 at permanent lakes considered to provide suitable habitat for the species (Lake Joondalup, Lake Goolellal and Lake Loch McNess).

Transects of cage traps set at 50 m intervals were established in vegetation along the wet or dampland for the target species. Between 10 and 30 traps were set depending on available habitat. Results were standardised to captures per 100 trap nights. Universal bait (a mixture of peanut paste, rolled oats) was used in traps set to capture *I. obesulus* and sardines were used as bait for *H. chrysogaster*. All sites were trapped over 4 nights, except for Lake Goolellal, which was trapped for 3 nights. Captured animals were identified, measured and released onsite. Captured *I. obesulus* individuals were ear-tagged in each ear with unique identification tags. *Hydromys chrysogaster* individuals were ear-notched in one ear.

Assessment of susceptibility of mammals to groundwater and rainfall declines

Information on those mammal species likely to be impacted by decreased aquifer levels and declining rainfall was assessed based on the life history of species and information collated from the literature.

The extent of reliance on groundwater, either in wetland or phreatophytic habitats, was used to classify species into one of three categories (modified from Bamford and Bamford (2003) as:

High: Species that rely on aquatic habitats in wetlands and likely to become locally extinct if surface water disappears.

Strong: Species reliant on wetland vegetation and likely to be impacted depending on changes to riparian vegetation.

Low: Species likely to be indirectly affected.

Further we assessed the potential effect of declining rainfall on the abundance of *T. rostratus* on the GGS using capture rate as a surrogate for population density (see Wooller *et al.*, 1981). First, a linear equation for the relationship between capture rate and the annual rainfall from the previous year was calculated using Wooller *et al.*

(1998) data on capture rates of *T. rostratus* and rainfall from the Fitzgerald River National Park area. These data represent a long-term data set (conducted over 13 years) and establishes a relationship between rainfall and capture rates of *T. rostratus* that is useful for predicting potential change in capture rates in the GGS. We used this linear equation to predict density of *T. rostratus* using rainfall data from the GGS area. We modelled the effect of declining annual rainfall on the predicted density of *T. rostratus* using a number of scenarios, ranging from no decline in annual rainfall to a maximum of 60% decline. Initial values (i.e. assuming no decline) were calculated based on the long-term estimated annual rainfall for the GGS area of 807 mm average from 1905–2007 (Bureau of Meteorology). We then overlaid annual rainfall from recent years (2006 to 2010).

Results

Historic occurrences of mammals in study area

Early collections of mammals from the northern SCP were by John Gilbert in two expeditions (1839-1840 and 1842 -1843), and Shortridge from 1904 to 1907 (Kitchener *et al.*, 1978). These and some other early records resulted in a total of 33 native mammal species, including 5 bat species, as occurring on the northern SCP (Table 1). The Western Australian Museum undertook a comprehensive survey of the extant mammals on the northern SCP in 1977-78 (Kitchener *et al.*, 1978). This survey comprised 24 443 trap nights and confirmed the persistence of only 12 native species (9 ground-dwelling and 3 bat species) of the original 33 species recorded. The areas surveyed included representative communities of the major landforms on the plain including Quindalup, Spearwood, Bassendean and Pinjarra plain soils and were considered to be most likely to still contain extant species as they consisted of large tracts of relatively undisturbed vegetation (e.g. Yeal Nature Reserve, Yanchep National Park) (Kitchener *et al.*, 1978).

Of the original mammal species listed as occurring on the GGS during the last century, 11 species are now gazetted under the WA *Wildlife Conservation Act 1950* as Schedule 1 and one species, the crescent nailtail wallaby (*Onychogalea lunata*), is listed as Schedule 2 (see Table 1 for category definitions). Under the DEC Priority Fauna List (i.e. taxa that have not yet been adequately surveyed to be listed under Schedule 1 or 2), two species are listed as Priority 4 and one as Priority 5 (Table 1).

Eight species are also listed as vulnerable and one species as endangered under the *EPBC Act 1999* (Table 1).

There is little information on the historical abundance and distribution of the mammalian taxa on the northern SCP, although some anecdotal evidence has been compiled by Abbott (2008). Since the late 1970s, a number of species have not been recorded (Table 1).

Western grey kangaroos (*Macropus fuliginosus*) were historically recorded as abundant on the northern SCP and continue to be recorded commonly. They utilise woodland, shrubland and heath formations (Kitchener *et al.*, 1978). Historically western brush wallabies (*Macropus irma*) were frequently sighted from coastal sites in the west to Gingin in the east but appears to have declined since the 1970s (Kitchener *et al.*, 1978). The only population of this species that now occurs on the GGS is in Whiteman Park where fox baiting is undertaken.

Woylies (*Bettongia penicillata ogilbyi*) occurred in the northern SCP (and further north) before disappearing from the area (Maxwell *et al.*, 1996). Historically *I. obesulus* was considered plentiful near Perth; however, by the 1970s it was sparsely distributed on the northern SCP and only two specimens were captured in 1977-88 (Kitchener *et al.*, 1978).

Historically chuditch (*Dasyurus geoffroii*) were common close to the Swan River and specimens in the Western Australian Museum from the northern SCP were collected mainly during the 1900s. This species was not trapped during the 1977-78 Western Australia Museum survey (Kitchener *et al.*, 1978), nor have any been trapped in subsequent fauna surveys. However, there have been intermittent sightings and road kills of *D. geoffroii*, which indicate that the species may persist at a low level in the area (B. Johnson *pers. comm.*, M. Bamford, *pers. comm.*). These individuals may be itinerant individuals moving into the area from populations in the Darling Scarp.

Common brushtail possums (*Trichosurus vulpecula*) were recorded as plentiful on the northern SCP however only one specimen was recorded (Yanchep National Park) in the 1970s survey (Kitchener *et al.*, 1978). The species is likely to still survive in very low numbers in isolated pockets of vegetation (e.g. Bold Park, Yanchep National Park, Ellenbrook Nature Reserve, Lake Goolellal) and in some north-western suburbs of Perth (How *et al.* 1996, J. Wheeler *pers. comm*., M. Bamford *pers. comm*). Kitchener *et al.* (1978) considered that western pygmy possums (*Cercartetus concinnus*) were uncommon across the northern SCP during the 1900s as only 20 specimens were lodged at the museum. The species was not caught in the 1970s survey and since then the only record of their persistence on the GGS is from the Lexia Wetlands area in 2006 (R. Davis, *pers. comm*). Historically *T. rostratus* was considered uncommon on the northern SCP and only one specimen was recorded in the 1970s survey (Kitchener *et al.*, 1978). However, *T. rostratus* has been recorded infrequently in subsequent fauna surveys in the GGS area since this time (Ecologia Environmental Consultants, 1997). Echidnas (*Tachyglossus aculeatus*) were not collected in the 1977-78 survey and are considered to be uncommon in the south west and on the northern SCP (Kitchener *et al.*, 1978; Abbott, 2008).

The Western Australian sub-species *R. fuscipes fuscipes* is considered to be sparsely distributed on the northern SCP with specimen records limited to the coastal Yanchep area in 1975, and 1977-78 (Kitchener *et al.*, 1978). There are few records of *H. chrysogaster* between Moore River and Swan River on the northern SCP; however this species has been recorded at locations in the GGS area at Lake Jandabup and Lake Joondalup in 1977-78 (Kitchener *et al.*, 1978).

A total of nine introduced species have been recorded in the GGS study area since settlement (dingo (*Canis lupus dingo*), red fox (*Vulpes vulpes*), ferret (*Mustela putorius*), feral cat (*Felis catus*), black rat (*Rattus rattus*), house mouse (*Mus musculus*), European rabbit (*Oryctolagus cuniculus*), feral pig (*Sus scrofa*), and goat (*Capra hircus*).

Current occurrence and distribution of fauna

General survey trapping

The trapping effort (2007-08) included 5 600 pitfall trap nights, 5 600 Elliott trapping nights and 2 800 cage trapping nights. Six mammal species were trapped, four native species (*T. aculeatus, Sminthopsis sp., T. rostratus, R. fuscipes*) and two introduced species (*M. musculus* and *R. rattus*) (Table 2). Mammal capture rates were very low

(1.05%). Captures were higher in pitfalls (1.88%) than cage or Elliott traps (0.50%), although different species were captured in the different trap types. The introduced *M. musculus* was captured at 45% of sites and the native *T. rostratus* at 30% of sites. One *R. fuscipes*, three *T. aculeatus* and one *Sminthopsis sp.* were also captured. The most consistently captured native mammal species was *T. rostratus*. A total of 26 individuals were captured at 14 sites that were widely distributed across the study area (Figure 1). They were captured on Bassendean and Spearwood soils in *Banksia*, Jarrah and *Melaleuca* vegetation types. A further three native species (*T. vulpecula, M. fuliginosus, M. irma*) and five introduced species were observed (*V. vulpes, F. catus, O. cuniculus, S. scrofa, C. hicrus*).

Targeted trapping surveys

The trapping effort for the targeted surveys involved 930 cage trap nights. *Isoodon obesulus* was captured at five of the nine sites where trapping was conducted (Table 3). At two sites, Little Badgerup Swamp and Nowergup Nature Reserve, only one individual was captured while the highest number was recorded at Twin Swamps Nature Reserve (Table 3). Non-target native captures included *R. fuscipes* and *T. aculeatus*. *R. fuscipes* was only captured at two sites, but were recorded in greater numbers at Loch McNess. The introduced *R. rattus* and *M. musculus* were captured at most sites and seem to be ubiquitous throughout the area.

Hydromys chrysogaster was captured at all three of the selected sites (Table 3). The highest number of individuals was captured at Lake Goolellal (3 males, 3 females) and Loch McNess (3 males, 3 females), while only one individual was captured at Lake Joondalup (1 female). Non target captures included *R. fuscipes*, *R. rattus* and *M. musculus* (Table 3).

Susceptibility of mammals to declining groundwater levels

Of the terrestrial mammals considered to be extant on the GGS (Table 1), four are highly or strongly susceptible to altered groundwater levels (Table 4).

Hydromys chrysogaster is the only strictly groundwater-dependent mammal and thus is significantly threatened by declining rainfall and associated declines in groundwater level (Morris, 2000; Bamford and Bamford, 2003; Atkinson *et al.*, 2008). *Hydromys* *chrysogaster* lives in permanent bodies of fresh or brackish water including lakes, rivers and streams, and the presence of the species in these systems is related to the size of the wetland (Olsen, 1985; Morris, 2000; Smart, 2009). Habitat requirements identified for the species include areas suitable for location of burrows and nests such as steep banks, the presence of logs, rocks or reeds as feeding areas, and adequate riparian and stream vegetation cover (Woollard *et al*., 1978).

Across the GGS, the occurrence of *I. obesulus* appears to be strongly linked to wetland-associated vegetation (Bamford and Bamford, 1994). In our study, the species were captured at five of the nine targeted survey sites that were located in areas that contained a permanent wetland or were swampy or damp for part of the year. The highest numbers of *I. obesulus* were recorded at Twin Swamps Nature Reserve, which is both baited and fenced to deter foxes.

Historically *R. fuscipes* has only been recorded sporadically across the GGS and were captured at only three sites in our study, which were located either on coastal dune swales or associated with lakes and wetlands. The highest density (n = 4) was recorded in wetland vegetation at Loch McNess.

On the GGS *M. irma* prefers *Eucalyptus* and *Banksia* woodland with a dense understorey about one metre in height but has been observed to forage in burnt areas (Arnold *et al*., 1991; Bamford and Bamford 1999). The preference for dense long-unburnt understorey vegetation appears to be related to shelter and refuge requirements. On the GGS this vegetation attributes are associated with wetlands and damplands of both the Spearwood and Bassendean soils. The species is thus susceptible to declining groundwater levels that lead to changes in vegetation structure surrounding wetlands and damplands.

Susceptibility of mammals to declining rainfall

There is evidence from the current scientific literature that seven mammal species considered to be extant on the GGS are likely to be impacted by declining rainfall (see studies listed in Table 5). For example, *H. chrysogaster* may be indirectly affected by low water levels in wetlands and lakes due to low rainfall levels. High and low population numbers of *R. fuscipes* are related to high and low levels of rainfall.

Declines in population numbers of *M. fuliginosus* are commonly recorded when droughts result in food shortages, for example in Western Australia, New South Wales, South Australia and southern Queensland. A study of a population in Western Australia (Arnold and Steven, 1988) found that the number of *M. fuliginosus* declined by 40% (from 800 to 500) during a drought year and remained at the reduced level for at least the next 3 years.

Reduced rainfall is also likely to have an indirect negative impact on *Macropus irma*, due to the potential reduction in dense vegetation understorey of wetlands and damplands that the species is dependent upon.

Relationship of *T. rostratus* to declining rainfall

We modelled possible changes in abundance of *T. rostratus* with incremental declines in rainfall (Figure 4). The relationship between *T. rostratus* capture rate and rainfall in the GGS was obtained using data from Wooller *et al.* (1998) (linear equation: *T. rostratus* capture rate (per 1000 trap night) = 0.119*annual rainfall (mm) + 2.84; r^2 = 0.65) and then applied to our study area using rainfall data from the GGS. The extreme scenario modelled a 60% decline in rainfall, and resulted in a 58% decline in predicted capture rates. The annual rainfall of recent years (2006 – 2010) indicates that extremely dry years are currently occurring on the GGS, and that *T. rostratus* abundance would be predicted to be comparatively quite low (e.g. prediction of ~ 37% reduction in capture rates in 2006).

Discussion

Historic occurrences and declines of mammals

The decline of mammals on the GGS following European settlement has been dramatic with a loss of species and declines in distribution. In addition, a number of remaining species are now most likely restricted to isolated remnants. Surprisingly, few studies on mammal persistence have been conducted in the GGS area. Once species-rich, with up to 28 terrestrial native mammal species, the northern SCP has suffered a drastic decline in mammal species, with only 9 species recorded (captured or observed) in the current study, and two species (*C. concinnus* and *D. geoffroii*) considered to exist in the study area based on recent sightings outside this study. Mammal capture rates were very low, with the exception of *M. musculus* and *T.*

rostratus, which were the most frequently captured mammal species. The remaining 17 terrestrial mammal species recorded prior to the 1970s are considered unlikely to still occur in the GGS area.

For some species, records have been sporadic throughout the last few decades. For example, Ash-grey mice (*Pseudomys albocinereus*) were recorded historically on the northern SCP and were trapped at a range of sites in woodland and heath habitats by Kitchener *et al.* (1978). It has not been recorded since 1987, but has been recorded nearby to the north-east of the study area on the Dandaragan plateau (Bamford, 1986; Burbidge *et al.*, 1996) and may possibly persist in isolated pockets of habitat in the GGS area (R. Davis, *pers. comm*.). Species, such as *C. concinnus*, were not recorded by Kitchener *et al*. (1978) or in the current study, although recent observations of *C. concinnus* (R. Davis, *pers. comm.*) indicate that remnant populations may exist. During the current study a juvenile of an unidentified *Sminthopsis* species was captured, indicating that at least one *Sminthopsis* taxon is still extant on the GGS, albeit in small numbers.

A number of threatening processes have been implicated in the decline of mammal fauna in the study area following European settlement. These include habitat clearance and fragmentation as a result of agriculture and urbanisation (Kitchener *et al.*, 1980; How and Dell, 2000), changed fire regimes (How *et al.*, 1987; Wilson *et al.*, 2010), predation by introduced foxes and cats (Kinnear *et al.*, 2002;) and possibly wildlife disease (Abbott, 2008). Recently, the impacts of the plant pathogen *Phytophthora cinnamomi* dieback on flora and ecosystems have been identified as threatening mammal fauna on the GGS (Wilson *et al.*, 2009). Mammal declines are unlikely to be attributed to a single factor, and it is more likely that each species has been affected differently by various combinations of factors. Importantly, individual threatening processes may have synergistic effects, resulting in compounded impacts (McKenzie *et al.*, 2007; Wilson and Valentine, 2009).

Susceptibility of mammals to declining rainfall and groundwater levels

In addition to the threatening processes discussed above, declining rainfall and groundwater levels due to climate change have recently been identified as major threats to terrestrial mammal species on the GGS (Wilson and Valentine, 2009; Isaac *et al.*, 2009). There is a strong geographical pattern of the highest species loss in arid regions (McKenzie *et al.*, 2007), and recent modelling suggests that mammals in the critical weight range (i.e. non-flying mammals with an average body weight in the range 35-4200 g) in the GGS area may be very susceptible to the impacts of declining rainfall including *H. chrysogaster*, *I. obesulus* and *R. fuscipes*. Similar results have been found by Isaac *et al.* (2009), although this was in Australia's wet tropics. There is recent evidence that factors such as drought have had significant impacts on some native small mammals in southern Australian communities resulting in reduced body weight, survival and population size (e.g. Sale *et al.*, 2008; Magnusdottir *et al.*, 2008; Recher *et al.*, 2009).

In particular, the survival of *H. chrysogaster* on the GGS is critically linked to declining rainfall and groundwater levels and the persistence of wetland ecosystems. While large populations of *H. chrysogaster* have been recorded in eastern Australia (e.g. Murray Goulburn valley, Victoria, Griffith New South Wales (McNally, 1960; Woollard *et al.*, 1978) the populations on the northern SCP appear to be smaller than populations in Victoria and New South Wales. *Hydromys chrysogaster* has already suffered a significant decline in south-west Australia and is highly susceptible to loss of habitat through the contraction and drying out of lakes, the filling in and draining of wetland ecosystems for alternative land use (Burbidge and McKenzie, 1989; Lee, 1995; Morris, 2000) and loss of wetland-associated prey (Atkinson *et al.*, 2008). It is likely that food resources and low availability of suitable water bodies limits these populations.

In this study the captures at Lake Goolellal and Loch McNess indicated that there are likely to be small populations at these lakes whereas only one individual was captured at Lake Joondalup, which is a substantially larger lake. The vegetation surrounding Lake Joondalup had recently been burnt (< 3 years since last fire) and it is possible that the reduced vegetation structure and cover had impacted on the *H. chrysogaster*. In addition, unlike Lake Goolellal and Loch McNess, Lake Joondalup lacks islands located close to the lake edge, which are likely to provide feeding areas and refugia from predation or disturbance from humans.

A more recent study than the current study assessed the occurrence of *H. chrysogaster* at 39 sites in the greater Perth area (Smart, 2009). Animals were captured at only two sites, while indirect evidence of their presence (footprints, scats, midden feeding) was recorded at a further four sites. Re-sampling of the current study's sites by Smart (2009) resulted in few captures of *H. chrysogaster* (Loch McNess: n = 0; Lake Goolellal: n = 2; Lake Joondalup: n = 1), while camera trapping at Loch McNess has recently recorded two individuals (K. Bettink *pers comm*, 2011). These findings support our results that *H. chrysogaster* population numbers on the GGS are very low, and provide evidence that there may be differences in trappability or annual or seasonal differences in population numbers.

Isoodon obesulus prefers scrub habitats or areas that provide dense ground cover throughout Australia (Hocking, 1990; Paull, 1995), and in Western Australia *I. obesulus* occurs in two distinct habitats across its range, open forest and dense vegetation around swamps and watercourses (Cooper, 2000a; Cooper, 2000b). The distribution of *I. obesulus* on the GGS appears to be strongly linked to dense wetland-associated vegetation around swamps and watercourses (Bamford and Bamford, 1994; Cooper, 2000a; Cooper, 2000b). Any decline in wetland vegetation associated with rainfall and groundwater decline is predicted to severely impact this species.

In eastern Australia, *R. fuscipes* is an omnivore and is considered to be a habitat generalist occurring in a wide range of habitats including coastal heath, rainforest, wet and dry forests, and woodlands (Newsome and Catling, 1979; Moro, 1991; Lunney 2008). Although, *R. fuscipes* exhibits a preference for increased vegetation cover at all structural levels, it is associated with some floristic factors (Laidlaw and Wilson, 2006). On the GGS it appears that the level of vegetation complexity and cover is only provided in vegetation surrounding wetlands, and that *R. fuscipes* will therefore be susceptible to changes in vegetation structure induced by declining rainfall and groundwater levels.

Species such as *T. rostratus* are not considered to have a high reliance upon groundwater levels as they mostly occur in upland *Banksia* woodlands. However, declining groundwater levels and reduced rainfall rates are predicted to alter these vegetation communities (Groom *et al.*, 2000) and changes in vegetation cover, floristics composition and productivity have already been recorded (Sommer and Froend 2011). For nectar-feeding species such as *T. rostratus*, declining rainfall and a lowering groundwater table may affect the flowering period of the species upon which these marsupials feed, such as banksias. Groom *et al.* (2000) found that three species of banksia, in particular *Banksia ilicifolia* were severely impacted by drought stress within the GGS area. This was attributed to a significant lowering of the groundwater table caused by the cumulative effects of groundwater abstraction and below average rainfall (Groom *et al.*, 2000). Deaths of banksia trees on the Scott River plains (south coast of Western Australia) may also be due to a lowered ground water table, and are thought to be the cause of a corresponding decrease in honey possum populations (Phillips *et al.*, 2004). The GGS area is already experiencing declines in annual rainfall, with a 9% decline in rainfall from 1976 to 2007, and a 13% decline in rainfall from 1997 to 2007 (Government of Western Australia, 2009). As *T. rostratus* typically only lives for 1 to 3 years, there is the potential for successive dry years to affect the persistence of *T. rostratus* populations.

The loss of surface water and aquatic habitat for mammals such as *H. chrysogaster*, is likely to be catastrophic and the impacts could be quick. There is recent evidence that some lakes (e.g. Loch McNess) have undergone a sudden transition since 2006 and are now disconnected from the aquifer (DOW, 2011). This has resulted in the lowest peak water levels ever recorded and the drying out of 80% of lakes, such as Loch McNess, in summer. The disappearance of surface water would most certainly have a negative effect on the health of wetland vegetation, and thus mammal species that rely on wetland vegetation.

Management implications for mammals in a drying climate

Effective management will be needed to protect key mammal species on the GGS that are predicted to be impacted by declining rainfall and groundwater levels. Although it is impossible to control rainfall, it is possible that the management of some of the other threatening processes on the GGS (habitat loss and fragmentation, altered fire regimes and introduced predators) may increase the resilience of species such as *I. obesulus*, *H. chrysogaster* and *T. rostratus* to the threats of declining rainfall and groundwater levels. Management procedures to increase resilience could include actions such as provision of suitable refugia, establishment of ecological linkages and baiting of predators. In addition, on the GGS a number of management interventions that aim to prevent loss of, or permanent change in, groundwater-dependent wetland systems have been employed, including turning off nearby extraction bores to reduce drawdown effects, and using artificial water supplementation pumped from the superficial aquifer (Groom *et al*. 2000; DOW 2008).

Identification and management of wetland refugia

Providing key refuge sites can buffer species from a number of threats, such as impacts of climate change. While approximately 75% of the wetlands of the SCP have been filled in or drained (Commonwealth of Australia, 1997), groundwater modelling predicts that those wetlands closest to the top of the Gnangara aquifer located in the northeast (e.g. Yeal Nature Reserve) will be significantly affected by lower water levels and terrestrialisation in the future, up to an 11 metre decline by 2030 (Government of Western Australia, 2009). Smaller water level declines are likely by 2030 for Lakes Joondalup and Goollelal, the most southern of the long chain coastal wetlands. A preliminary set of wetlands including both permanently and seasonally inundated wetlands (i.e. lakes and sumplands) have been identified on the GGS as significant in terms of biodiversity values including wetland associated mammals and ecological function (Government of Western Australia, 2009; Horwitz *et al.*, 2009). It is recommended that key refugia be selected from the identified wetlands and managed so as to protect them from further loss and modification, particularly along lake banks where buffers need to be implemented. Habitat requirements that need to be maintained to encourage successful breeding and feeding of *H. chrysogaster* include areas suitable for location of burrows and nests such as steep banks, the presence of logs, rocks or reeds as feeding areas, and adequate riparian and stream vegetation cover (Woollard *et al.*, 1978; Smart, 2009).

Of major importance for the management of wetland refugia will be the implementation of specific ecological fire regimes to protect them from inappropriate fires, such as frequent lethal and intense fires (Horwitz *et al.*, 2009; Wilson *et al.*, 2010). In particular the ecological fire regimes must ensure the retention and protection of the long-unburnt wetland-associated vegetation (Wilson *et al.*, 2010).

Predator control is likely to be an essential component of management for the wetland refugia. In the GGS area *I. obesulus* is restricted to dense wetland-associated vegetation, although it occupies upland habitat in areas where predators have been suppressed (Bamford and Bamford, 1994; Valentine *et al.*, 2009). This was interpreted as a response to the diminution of the threat of predation (Bamford and Bamford, 1994). Although foxes have been recorded regularly in fauna surveys on the northern SCP (Kitchener *et al.*, 1978; Valentine *et al.*, 2009), and there is evidence that both *I. obesulus* and *M. irma* have increased in numbers since baiting commenced (C. Rafferty *pers. comm.* 2009), there is no coordinated baiting program throughout the study area.

Identification and management of ecological linkages

A major recommendation of the Gnangara Sustainability Strategy (Government of Western Australia, 2009) is to establish ecological linkages covering 9 000 ha across the GGS. The ecological linkages proposed include viable remnants (e.g. conservation reserves, Bush Forever sites), vegetated waterways and drainage lines, large remnant vegetation patches within pine plantations, and areas of pine plantations that will be rehabilitated (9 000 ha post-harvest). It is vital that these linkages be managed to support fauna species, such as *H. chrysogaster* and *T. rostratus.*

During the current study *T. rostratus* was recorded both in native vegetation and within small vegetation remnants in the pine plantations across the GGS. The ecological linkages need to be designed and managed to provide food resources and vegetation of suitable post-fire age and structure for the species. Although *T. rostratus* in south-west Western Australia is known to return to burnt areas within 2 – 4 years since fire (Bamford, 1986; Richardson and Wooller, 1991; Everaardt, 2003), higher densities are recorded in older vegetation, with peaks in abundance in vegetation 20 – 30 years since last burnt (Everaardt, 2003; Bradshaw *et al.*, 2007). It is recommended that native remnant vegetation within the ecological linkages consist predominantly of preferred post fire age for this species (20-30 years since last fire).

There is little information on the distribution, population dynamics and habitat requirements of key mammal species on the GGS that are predicted to be severely impacted by declining rainfall and groundwater levels. The population dynamics and breeding of *H. chrysogaster* in the wetlands within the GGS, in particular what the population sizes are, how the populations fluctuate seasonally or annually, and the stability of the populations needs to be determined. This is a species that will require substantial consideration and careful management as any reduction in the viability of wetlands and food resources on the GGS as a result of declining rainfall and groundwater are likely to significantly impact on breeding and feeding of water rats. Species that exhibit a positive relationship between population abundance and rainfall, such as *T. rostratus*, are likely to decline under future rainfall scenarios. As a relatively short-lived species, *T. rostratus* may also be susceptible to extreme weather events, such as sequential very low rainfall years. Without detailed biological and ecological information on the species of the GGS area, it is difficult to make accurate predictions on the extent of the impacts of declining rainfall. The fauna survey sites that were established in the GGS area for this project should provide a basis for monitoring programs for these species.

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Table 1: Historic occurrence of non-volant native mammal species in the GGS and the time periods in which they have been recorded (Arnold *et al.*, 1991; Bamford, 1986; 1990; 1994; 1999; Burbidge *et al.*, 1996; Drew, 1998; Ecologia Environmental Consultants, 1990; 1997; Friend, 1996; How and Dell, 2000; How *et al.*, 1996; Kinhill Pty Ltd, 1997; Kitchener *et al.*, 1978). Endemicity: RE (regional SWWA), WA (restricted to WA). Grey highlight refers to mammals considered to be extant in the GGS.

Species	**Common name**	**Endemicity**	**1800-1850**	**1850-1900**	**1900-1950**	**1950-1977**	**1977-2000**	**2000-2008**
Macropus fuliginosus	Western grey kangaroo	AUS	✓	✓	✓	✓	✓	✓
Macropus irma	Western brush wallaby * (P4)	RE	✓	✓	✓	✓	✓	✓
Macropus eugenii	Tammar wallaby	AUS		✓	✓		✓	
Petrogale lateralis lateralis	Black-footed rock-wallaby* (V,S1)	WA		✓				
Onychogalea lunata	Crescent nailtail wallaby* (E,S2)	AUS		✓		✓ **		
Bettongia penicillata ogilbyi	Woylie or brushtail bettong* (S1)	AUS	✓	✓	✓			
Bettongia lesueur lesueur	Burrowing bettong or boodie* (V,S1)	AUS	✓	✓		✓ **		
Setonix brachyurus	Quokka* (V,S1)	RE	✓		✓	✓		
Lagostrophus fasciatus fasciatus	Banded hare-wallaby* (V,S1)	WA		✓				
Trichosurus vulpecula	Brushtail possum	AUS			✓	✓	✓	✓
Pseudocheirus occidentalis	Western ringtail possum* (V,S1)	RE	✓		✓	✓		
Cercartetus concinnus	Western pygmy possum	AUS		✓	✓	✓		✓
Tarsipes rostratus	Honey possum	RE		✓	✓	✓	✓	✓
Isoodon obesulus fusciventor	Southern brown bandicoot or quenda* (P5)	WA			✓	✓	✓	✓
Macrotis lagotis	Greater bilby* (S1)	AUS		✓	✓			
Dasyurus geoffroii	Chuditch* (V,S1)	AUS		✓	✓	✓	✓	✓
Antechinus flavipes leucogaster	Mardo	WA	✓	✓	✓			
Parantechinus apicalis	Dibbler* (V,S1)	RE				✓ **		
Phascogale tapoatafa	Brush-tailed phascogale* (S1)	AUS	✓					
Sminthopsis crassicaudata	Fat-tailed dunnart	AUS			✓	✓		
Sminthopsis griseoventer/ Sminthopsis dolichura †	Grey-bellied dunnart/Little long-tailed dunnart	AUS	✓		✓			✓***
Sminthopsis granulipes	White-tailed dunnart	WA			✓			
Myrmecobius fasciatus	Numbat* (V,S1)	AUS	✓		✓			
Rattus fuscipes	Southern bush rat	AUS				✓	✓	✓
Rattus tunneyi	Tunney's rat	AUS				✓ ?		
Pseudomys albocinereus	Ash grey mouse or noodji	WA	✓			✓	✓	
Hydromys chrysogaster	Water rat or rakali* (P4)	AUS			✓	✓	✓	✓
Tachyglossus aculeatus	Echidna	AUS			✓	✓	✓	✓

* Threatened species, threat status is in brackets: IUCN Red List and EPBC Act: 'E' – Endangered (species considered to be facing a very high risk of extinction in the wild) and 'V' – Vulnerable (species considered to be facing a high risk of extinction in the wild); WA Wildlife Conservation Act

1950: ‘S1’ – Schedule 1 (fauna that is rare or likely to become extinct and ‘S2’ – Schedule 2 (presumed extinct fauna); and Department of Environment and Conservation Priority Fauna List (i.e. taxa that have not yet been adequately surveyed to be listed under Schedule 1 or 2: ‘P4’ – Priority 4 (taxa which are considered to have been adequately surveyed, or for which sufficient knowledge is available, and which are considered not currently threatened or in need of special protection, but could be if present circumstances change. These taxa are usually represented on conservation lands); and ‘P5’ – Priority 5 (taxa which are not considered threatened but are subject to a specific conservation program, the cessation of which would result in the species becoming threatened within five years). ** superficial cave deposit. † *Sminthopsis griseoventer* and *S. dolichura* were previously part of the of *S. murina* complex and during the WAM 1977-78 survey were recorded as such. They are now separate species whose distribution includes the NSCP. The distribution of *S.murina* is now restricted to Eastern Australia. *** One *Sminthopsis sp*. individual was trapped during the GSS fauna survey. It is likely to have been *Sminthopsis griseoventer*, which has been recorded recently not far from this location. ? indicates uncertainty regarding species record.

Table 2: Species captured during pit-fall trapping or age and Elliott trapping during general fauna surveys throughout the GGS study area, excluding targeted fauna surveys.

			No. sites	**Landform unit[a]**			**Vegetation type[b]**				
	Pit-fall traps	Cage or Elliott traps	Total (40)	Q (2)	Sp (20)	Bn (18)	Cs (2)	Tt (4)	Jh (4)	Me (14)	Bk (16)
Species captured	**Abundance**			**Presence / Absence**			**Presence / Absence**				
Tachyglossus aculeatus	0	3	3	0	0	1	0	0	0	1	1
Sminthopsis sp	1	0	1	0	0	1	0	0	0	0	1
Tarsipes rostratus	26	0	14	0	1	1	0	0	1	1	1
Mus musculus	77	36	27	1	1	1	1	1	1	1	1
Rattus fuscipes	1	1	2	0	1	0	0	0	0	1	0
*Rattus rattus**	0	2	2	0	1	0	0	1	0	1	0
Species Richness	4	4	NA	1	4	4	1	2	2	5	4
Total individuals	105	42	NA	21	88	38	21	11	11	49	55

[a] Landform Unit: Q = Quindalup, SP = Spearwood Dunes, Bn = Bassendean Dunes
[b] Vegetation Type: Cs = Coastal Scrub, Tt = tuart forest, Jh = jarrah forest, Me = *Melaleuca* wetlands, Bk = *Banksia* woodlands

Table 3: Captures per 100 trap nights of mammal species captured at sites targeted for trapping *Isoodon obesulus fusciventer* and *Hydromys chrysogaster*.

	Muckenburra NR	Yeal NR	Lake Gnangara	Little Badgerup Swamp	Neaves Road NR	Twin Swamps NR	Maralla Road NR	Nowergup NR	Loch McNess*	Lake Joondalup**	Lake Goolellal**
***Isoodon obesulus fusciventer* Survey**											
I. obesulus fusciventer	0.0	0.0	7.5	2.5	6.5	16.3	0.0	1.3	0.0		
Rattus fuscipes	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0		
Rattus rattus	1.7	3.0	7.5	0.0	18.8	3.8	2.5	0.0	10.5		
Mus musculus	0.0	1.0	0.0	2.5	6.3	2.5	1.3	2.5	1.3		
***Hydromys chrysogaster* Survey**											
H. chrysogaster									13.6	1.3	20.0
Rattus fuscipes									9.0	0.0	0.0
Rattus rattus									4.6	0.0	0.0
Mus musculus									0.0	2.5	0.0

* Located in Yanchep National Park; ** Located in Yellagonga RP

Table 4: Mammal species predicted to decline in abundance or range due to a low, moderate or high dependence on groundwater levels. Adapted from Bamford and Bamford (2003). (‘Low’ = ‘Low’ category in Bamford and Bamford (2003), ‘Strong’ = ‘Moderate’ and ‘High’ categories in Bamford and Bamford (2003), and ‘High’ = ‘Very High’ category in Bamford and Bamford (2003).

Family	**Species name**	**Common name**
High dependence upon groundwater		
Muridae	*Hydromys chrysogaster*	water rat or rakali
Strong dependence upon groundwater		
Peramelidae	*Isoodon obesulus fuxciventer*	southern brown bandicoot or quenda
Macropodidae	*Macropus irma*	western brush wallaby
Muridae	*Rattus fuscipes*	southern bush rat
Low dependence upon groundwater		
Phalangeridae	*Trichosurus vulpecula*	brushtail possum
Burramyidae	*Cercartetus concinnus*	western pygmy possum
Tachyglossidae	*Tachyglossus aculeatus*	echidna
Dasyuridae	*Dasyurus geoffroii*	chuditch
Dasyuridae	*Sminthopsis dolichura*	little long-tailed dunnart
Dasyuridae	*Sminthopsis griseoventer*	grey-bellied dunnart
Tarsipedidae	*Tarsipes rostratus*	honey possum
Macropodidae	*Macropus fuliginosus*	western grey kangaroo

Table 5: Susceptibility of extant terrestrial mammals to declining rainfall on the GGS.

Species	Relationship with Rainfall	Study
Macropus fuliginosus	Rainfall is the dominant influence on population dynamics in arid, semi-arid systems. Significant population declines with drought when females may cease breeding and mortality may exceed 40%. A short response lag (6 months) implies that survival, not breeding is impacted most.	Arnold and Steven 1988; Cairns *et al*. 2000; Caughley 1987; Caughley *et al.* 1984; Caughley *et al.* 1985; Coulson 2008
Cercartetus concinnus	Population sizes can fluctuate widely in dry regions. May be response to variability in rainfall and consequent food availability.	Carthew *et al.* 2008
Tarsipes rostratus	Low rainfall significantly influences abundance, and correlated with rainfall from 1-2 years previous. Reduction in numbers following low rainfall attributable to a decrease in nectar production.	Bradshaw *et al.* 2007; Bryant 2004; Wooller *et al.* 1998
Isoodon obesulus fusciventer	Substantial geographical variation in body size associated with habitat structure and associated with the amount of annual rainfall.	Cooper 1998; 2000a
Rattus fuscipes	Population fluctuations related to rainfall and the density of groundcover. High populations related to increased rainfall, drought associated with low numbers.	Lunney 2008; Lunney *et al*. 1987; Seebeck and Menkhorst 2000; Recher *et al*. 2009
Hydromys chrysogaster	*Hydromys chrysogaster* is found in fresh, brackish and saltwater wetlands. Indirect effect of rainfall based on water levels in wetlands and lakes.	Seebeck and Menkhorst 2000
Tachyglossus aculeatus	Indirect effect of rainfall on termites in arid areas. Rainfall, soil moisture affect termite availability-they move deeper if soil moisture is low.	Abensperg-Traun 1994

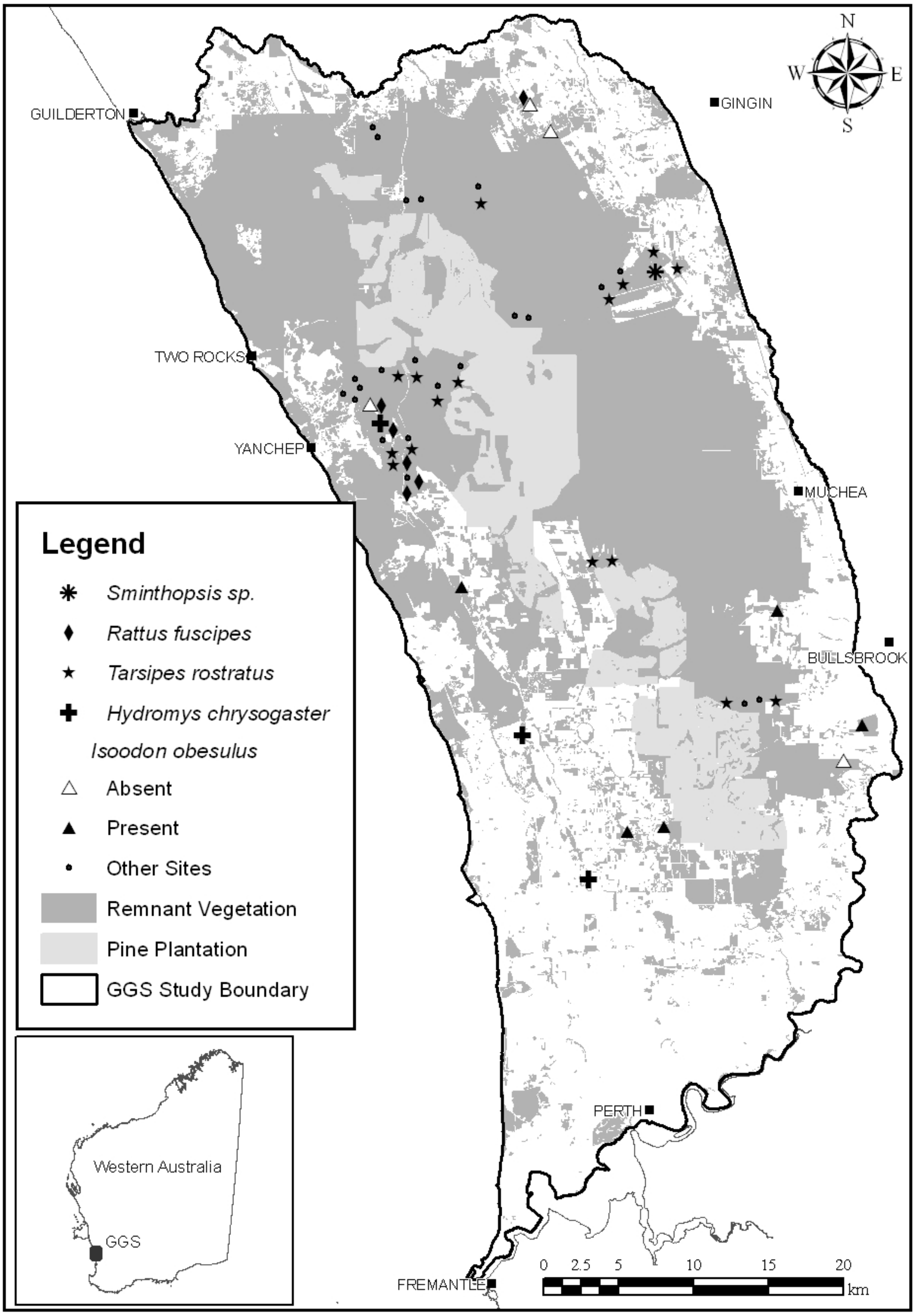

Figure 1. The remnant vegetation extent and DEC managed lands located within the GSS study area. Fauna survey sites, including targeted mammal trapping areas are also indicated.

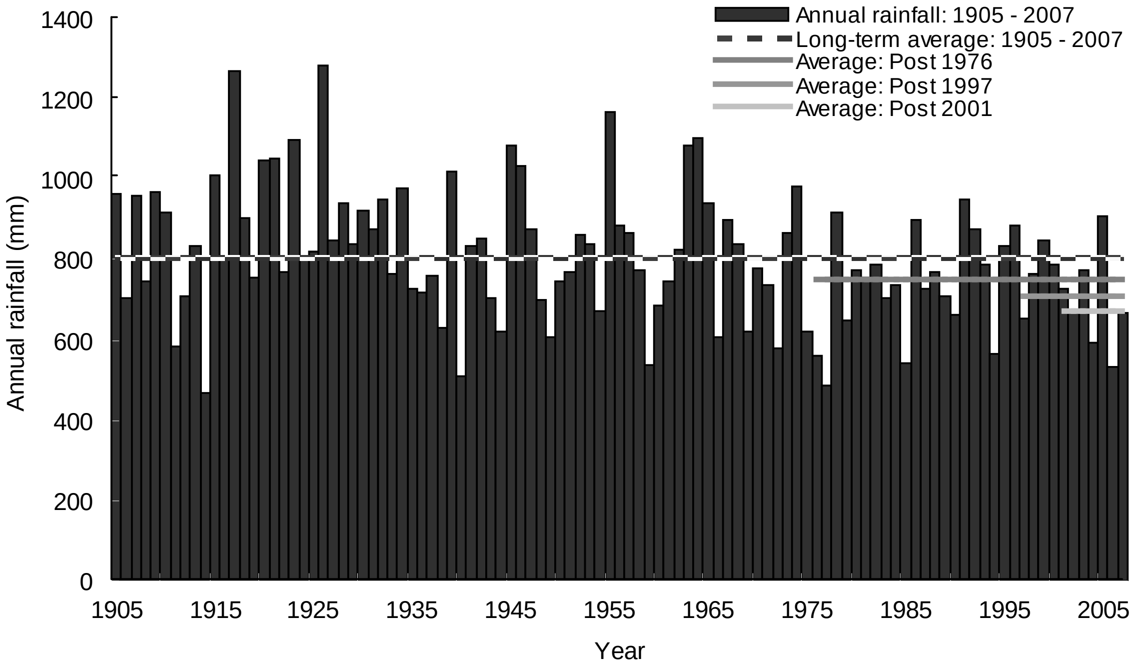

Figure 2. Long-term (1905-2007) annual rainfall for Wanneroo site 9105. (Source: Bureau of Meteorology.)

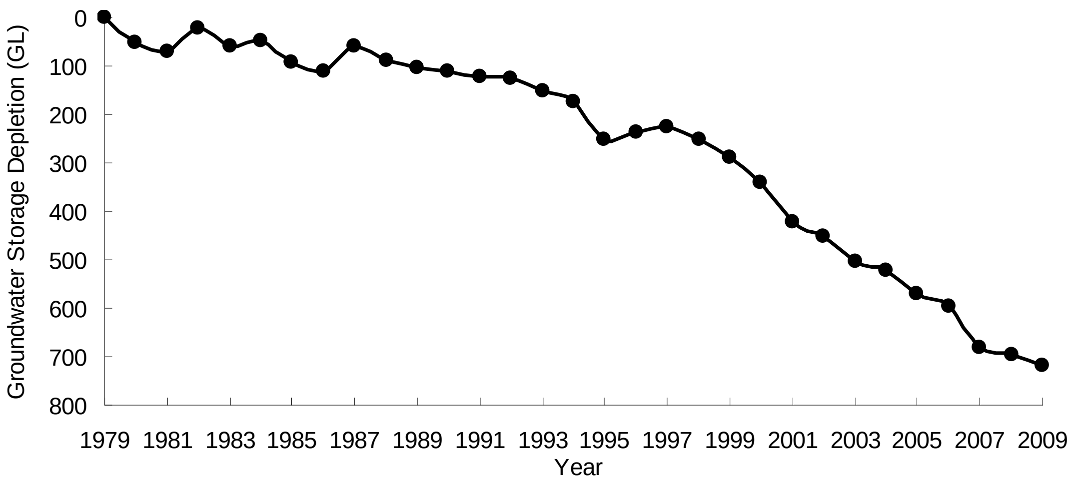

Figure 3. Groundwater storage decline in the superficial aquifer since 1979. (Source: Department of Water.)

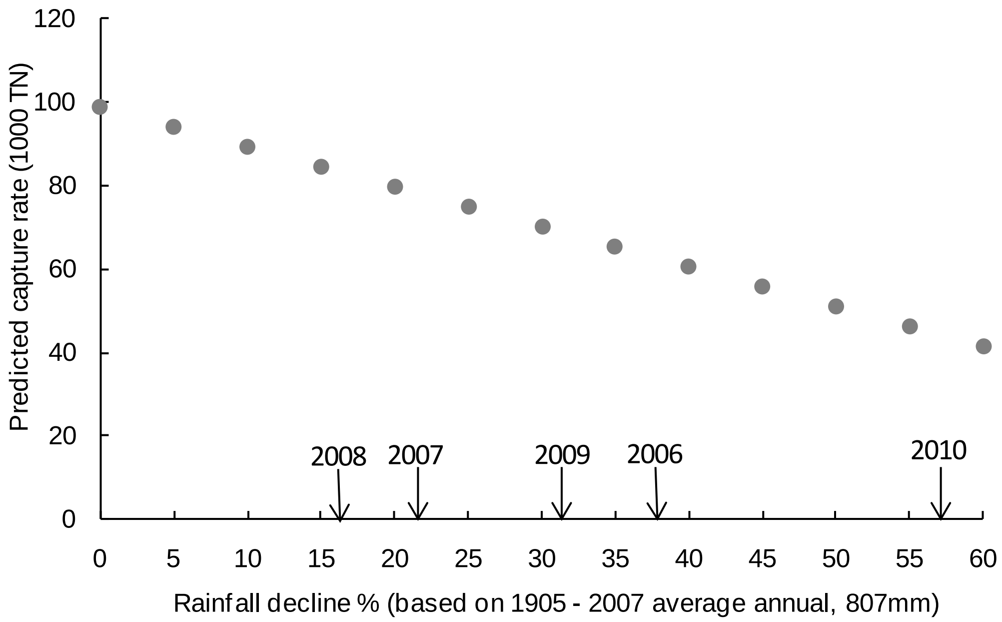

Figure 4. The predicted impact of incremental declines in annual rainfall (based on the long-term average annual rainfall of 807 mm / year) on the density of *Tarsipes rostratus* capture rates (using the relationship between honey possum capture rates and rainfall described in Wooller *et al.* (1998); capture rate = 0.199* annual rainfall + 2.8378). Annual rainfall records within the GGS (data from Bureau of Meteorology, Pearce RAAF station number 009053) from 2006 – 2010 are indicated.