Approximately half of the Australian continent is arid and is characterised by low primary productivity, limited supply of food and pronounced daily fluctuations of ambient temperature ($T_a$). Despite these adverse conditions the diversity of small mammals in the Australian arid zone is high, although their abundance is generally low. The most successful groups of small arid zone mammals are the dasyurid marsupials, native rodents, and insectivorous bats. A probable reason for the success of the insectivorous dasyurids and bats, which must cope with strong fluctuations in food and water availability, is their extensive use of torpor. Mammalian torpor is characterised by substantial reductions of body temperature ($T_b$) metabolic rate (MR) and water loss. Small arid zone dasyurids use exclusively daily torpor, some even during the reproductive season, when most mammals maintain strict homeothermy. Dasyurids reduce $T_b$ from ~ 35ºC during normothermia to ~ 15ºC during torpor, the MR during torpor (TMR) is ~ 30% of basal metabolic rate (BMR). Mass loss, and thus water loss, is related to the duration of torpor bouts. Dasyurids usually enter torpor at night or in the early morning and arouse around midday or in the afternoon. Recent evidence shows that desert dasyurids may bask in the sun during rewarming from torpor. This can minimise energetic cost of arousal to a fraction of that required for endogenous warming. Arid zone bats are also likely to use torpor extensively, but few species, specific to the arid zone, have been studied. Nevertheless, widely distributed bats that occur in the arid zone, such as *Nyctophilus geoffroyi*, enter brief torpor for part of the day in summer and prolonged torpor (hibernation) for up to two weeks in winter and can reduce $T_b$ to a minimum of 2 - 3ºC and TMR to ~ 3% of BMR; mass loss and water loss are minimal during torpor. Patterns of torpor similar to those in bats also have been observed in the insectivorous echidnas and two species of insectivorous/nectarivorous pygmy-possums, which have distribution ranges that include semi-arid and arid areas. In contrast to these species, no detailed information is available on torpor in native Australian rodents, because little work with respect to torpor has been conducted in Australia. However, many arid zone rodents on other continents employ torpor and it is likely that Australian rodents do as well. In addition to reducing energy expenditure and water loss, use of torpor also appears to prolong life span. This is important for bridging adverse conditions and for subsequent re-colonization of areas after droughts and fires in inland Australia. Thus it appears that the success of small insectivorous/nectarivorous mammals and perhaps rodents in the Australian arid zone is partially due to their use of torpor.

Key words: torpor, rodents, bats, marsupials, echidnas, diet, arid-zone, hibernation, metabolism.
Living in arid areas creates a number of problems for small endothermic mammals, because of limited food and water supply and pronounced daily fluctuations of $T_a$ (Schmidt-Nielsen 1979; Brashaw 2003). Endotherms have high metabolic rates (MR) and water loss when their $T_b$ is high, so their food and water requirements may quickly exceed available resources. This is especially true for insectivorous and nectarivorous endotherms because food availability declines with $T_a$ while energy requirements increase (Speakman and Thomas 2003). Presumably because of these limitations not all endotherms are permanently homeothermic. Many are capable of entering a state of torpor (Hudson 1973; Lyman et al. 1982; Geiser and Ruf 1995), where is characterised by substantial reductions of $T_b$, MR, water loss and other physiological processes, thereby reducing water and food requirements.

Species capable of entering a state of torpor are often referred to as ‘heterothermic endotherms’. Heterotherms during the normothermic season when torpor is not used or during other periods of activity are able to maintain a high $T_b$ via physiological thermoregulation just like homeotherms. However, unlike homeotherms, they are also able to employ torpor during acute or potential energy or water limitations. Heterotherms save energy because; i) thermoregulation at high $T_b$ is abandoned and no energy is required for normothermic thermoregulation, ii) temperature effects due to the fall of $T_b$ reduce the MR below BMR and, iii) some species are able to use metabolic inhibition in addition to temperature effects on MR to further minimise energy expenditure (Malan 1986; Geiser 1988; Guppy and Withers 1999). Consequently, MR can be reduced to a fraction of BMR, which in normothermic individuals represents the minimum maintenance MR (Dawson and Hulbert 1974; Geiser and Ruf 1995). Nevertheless, thermoregulation during torpor is not entirely abandoned. The $T_b$ during torpor is regulated at a species or population-specific minimum via an increase of MR, and this minimum $T_b$ or $T_a$ setpoint is regulated by the hypothalamus (Heller and Hammel 1972).

Two general patterns of torpor are widely recognised. The first of these, prolonged torpor or hibernation in the hibernators, may last for several day or weeks, but is interrupted by periodic arousals and brief normothermic periods throughout the hibernation season, which usually lasts for ~6 months (Wang 1989). However, at high $T_a$ hibernators may exhibit short bouts of torpor lasting less than one day and may even forage between torpor bouts. When exposed to low $T_a$, the $T_b$ in torpid hibernators usually falls below 10°C and MR during torpor (TMR) is on average only 5% of the basal MR (BMR). The second common pattern, daily torpor in the daily heterotherms, always lasts less than a day, $T_b$ is usually maintained between 10 and 25°C and TMR is on average ~30% of BMR (Geiser and Ruf 1995). ‘Aestivation’ is often used to describe daily or prolonged torpor in summer, but, because there is no evidence that it differs functionally from the other torpor patterns, apart from occurring at somewhat higher $T_a$, this term is not used in this review.

Traditionally torpor in endotherms was seen predominantly as an adaptation of cold climate species. It now is established that torpor occurs in many diverse mammals from a wide range of habitats ranging from the arctic to the tropics and includes species from arid zones (Barnes 1989; Geiser and Ruf 1995; Bartels et al. 1998; Lovegrove 2000; Fietz et al. 2003). The shift in the perception about torpor in recent years is evident from the literature. A book on desert animals by Schmidt-Nielsen (1979) covers Australian mammals, but torpor in marsupials is not mentioned, and bats are not discussed at all. As is summarised below we now know that in Australia torpor occurs in echidnas, insectivorous/carnivorous dasyurids, pygmy-possums, bats, and perhaps rodents from the arid zone (Table 1). The only groups of small arid zone mammals for which no information on torpor is available are the bandicoots and small macropods (Hulbert and Dawson 1974; Dawson 1989). Thus torpor is very common in Australian arid zone mammals and is likely a crucial key to their success. The purpose of this review is to summarise what is currently known about torpor patterns in Australian arid zone mammals and how it is likely to affect their life.

**Echidnas**

The short-beaked echidna (*Tachyglossus aculeatus*) is distributed over the entire continent. *T. aculeatus* has been observed to enter prolonged torpor in many areas of Australia including the arid zone (Coleman 1935; Augee et al. 1970; Grigg et al. 1992; Nicol and Andersen 1996; Grigg and Beard 2000). Whereas torpor bouts with $T_b < 10°C$ may last for more than two weeks during a ~6-month hibernation season in the Australian Alps, the Northern Tablelands and Tasmania (Grigg and Beard 2000; Nicol and Andersen 2000; Frank et al. 2001), in the arid zone torpor bouts tend to be shorter and the hibernation season may last only for a few months or less (Nicol and Andersen 1996). In semi arid southwestern Queensland, *T. aculeatus* remained torpid for up to 9 days during winter with $T_b$ of ~14°C and occasionally for one day in summer (Brice et al. 2002). Metabolic rates in captive *T. aculeatus* fall to values characteristic of those in other hibernators (Nicol et al. 1992), but because of their low BMR,
which appears to be partially due to the low normothermic $T_\text{b}$ of ~32°C, the TMR/BMR ratio of ~13% is larger than in other hibernating species (Table 1, Fig. 1). The low $T_\text{b}$ during activity and the low TMR and $T_\text{b}$ during torpor will reduce both energy and water requirements and likely contribute to the survival of the species in a large variety of habitats including the arid zone.

Thus prolonged and deep torpor in echidnas is similar to that observed in hibernators from other continents (Geiser and Ruf 1995). As many other

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**Table 1.** Summary of body mass and physiological variables in heterothermic arid zone mammals. The longest torpor bouts and the lowest metabolic rate during torpor are reported. BM = body mass, $T_\text{b}$ = normothermic body temperature; Min $T_\text{b}$ = minimum body temperature; BMR = basal metabolic rate; TMR = metabolic rate during torpor; °C; likely not a regulated minimum body temperature.
hibernating species, *T. aculeatus* relies heavily on stored fat during the hibernation season, and, unlike daily heterotherms, can survive without eating for weeks or months. However, torpor in *T. aculeatus* appears to be more opportunistic than in strongly seasonal hibernators (Körtner and Geiser 2000a) and may occur at any time of the year.

Physiological variables associated with torpor of dasyurids are similar to those in other daily heterotherms found elsewhere in the world, in which torpor lasts on average for several hours and the average minimum *T*<sub>b</sub> is ~17°C (Geiser and Ruf 1995). Dasyurids, like other small daily heterotherms, generally do not fatten substantially before the torpor season, and often lose mass before they will use torpor frequently (Morton 1978a,b; Holloway and Geiser 1996; Körtner and Geiser 2000b). Dasyurids appear to rely predominantly on foraging for energy in winter (Geiser 2003) and, when food is withheld, perish after a few days (Kennedy and McFarlane 1971).

Whereas daily energy expenditure decreases with the use of torpor, two major activities raise daily energy expenditure in daily heterotherms and these are foraging and endothermic arousal from torpor. Obviously, in species relying heavily on ingested rather than stored energy resources, foraging must be adequate for replenishing fuel resources and is therefore essential, although torpor use may lower the time required for foraging. On the other hand, energy expenditure for arousal, which is perceived as an unavoidable energetic drawback of torpor (Ellison and Skinner 1992), can be reduced, especially in a desert environment. Recent evidence from arid zone dasyurids shows that, similar to lizards, torpid fat-tailed pseudantechinus (*Pseudantechinus macdonnellensis*: ~30 g), bask in the morning and use the sun as an energy source during rewarming (Geiser et al. 2002). In winter, *P. macdonnellensis* emerge from their deep rock crevices ~2.5 h after sunrise with *T*<sub>b</sub> around 26°C (basking *T*<sub>b</sub> minimum 19.3°C), bask until they reach normothermic *T*<sub>b</sub>, and continue to bask for much of the rest of the day. Usually *P. macdonnellensis* sit with their side or back to the sun close to a crevice for escape and alternate sun-exposed sides like sunbathers on a beach (Fig. 2). In the laboratory it has been estimated that passive rewarming via an increase in *T*<sub>a</sub> reduces rewarming costs in stripe-faced dunnarts (*Sminthopsis macroura*) to ~35% of active rewarming (Lovegrove et al. 1999). During radiant heat assisted passive rewarming by *S. macroura* basking under a heat lamp, rewarming costs were as low as 15% of that required for active endothermic rewarming at the same *T*<sub>a</sub>, even though the lamp provided much less radiant heat than the sun (Geiser and Drury 2003). Basking during normothermia, which also appears common in arid zone dasyurids (Geiser 2003), allows a reduction of energy expenditure to BMR without thermoregulatory costs over a wide range of *T*<sub>a</sub>.

![Fig. 1. TMR/BMR ratio in arid zone mammals.](image)

**Insectivorous/carnivorous marsupials**

The group of Australian arid zone mammals that has been studied most extensively for their use and patterns of torpor are the insectivorous/carnivorous marsupials of the family Dasyuridae (Godfrey 1968; Tyndale-Biscoe 1973; Wallis 1982; Dawson 1989; Dickman 1996; Geiser 2003; Table 1). Heterothermic arid zone dasyurids range in body mass from ~6 g in *Planigale* spp. to ~1000 g in the western quoll (*Dasyurus geoffroii*). All dasyurids that have been studied use daily torpor exclusively, with torpor bouts lasting for several hours from the late night or morning to the following late morning or early afternoon. Minimum *T*<sub>b</sub> measured during torpor range from 11 to 15°C in the small species (<100 g) and ~15 to 23°C in the larger species (>100 g)(Table 1). Minimum TMR range between 13 and 54% of BMR (Table 1). The reduction in daily energy expenditure by the use of torpor usually is in the range of 10 to 40% of individuals that remained normothermic at the same *T*<sub>a</sub> (Frey 1991; Holloway and Geiser 1995; Song et al. 1995; Geiser and Drury 2003). Daily torpor in captive dasyurids does not only occur at low *T*<sub>a</sub>. Animals may enter torpor at *T*<sub>a</sub> between 25 and 30°C, especially when food is withheld. However, because of the high *T*<sub>b</sub>, torpor is shallow and brief (Geiser 1986, 2003; Song et al. 1995). Moreover, arid zone dasyurids frequently enter spontaneous torpor when food and water are freely available, which is likely an adaptation to the general resource availability in their desert environment.
Fig. 2. A basking *Pseudantechinus macdonnellensis*.

(Geiser and Drury 2003). So a combination of low TMR, access to solar energy during passive rewarming from daily torpor, and access to solar energy during the normothermic rest phase allows a mammal like *S. macroura* to reduce daily energy expenditure by up to 50%. Thus, while the desert environment may be limiting with respect to food availability, the high T_s fluctuations and access to solar radiation provides another potential source of energy that is not commonly available to heterothermic species in cold climates with long and dark winters.

The importance of torpor in arid zone dasyurids is further emphasised by its use during reproduction when many other species are strictly homeothermic and raise MR. Moreover, torpor is employed even during development and growth. Female fat-tailed dunnarts (*Sminthopsis crassicaudata*) entered daily torpor during lactation in the field without adversely affecting the development of the young (Morton 1978a). Captive female mulgaras (*Dasyurus cristicauda*) regularly used spontaneous daily torpor (food and water available) during pregnancy and over the same time period increased their body mass by 35%. Perhaps this strategy helps to build up fat stores for the more energetically demanding period of lactation (Geiser and Masters 1994). In young kowaris (*Dasyurodon hyrnet*) at about half adult body mass (~ 50 g), but fully capable of endothermic thermoregulation, torpor is deeper and longer than in adults (Geiser et al. 1996). This demonstrates that even during the growth phase, which is usually associated with an increase in energy expenditure, torpor may be employed to conserve energy in desert dasyurids.

As pointed out above, torpor also affects water loss. Unfortunately direct data on water loss in torpid dasyurids are not available, but daily mass loss, which to a large extent is caused by water loss, is related to torpor bout duration in both kultarr (*Antechinomys laniger*) and Giles’ planigale (*Planigale gilesi*) (Geiser 1986, 2003); mass loss during long torpor bouts (> 10 h) was ~ 50 - 60% (~ 4 - 6 mg g^{-1} h^{-1}) of that during shorter bouts (< 10 h; ~ 7 - 12 mg g^{-1} h^{-1}). In the American mouse *Peromyscus eremicus*, which shows a similar pattern of daily torpor as dasyurids, pulmocutaneous water loss in torpid individuals declined in parallel with TMR to < 50% of that during normothermia (MacMillen 1965) and it is likely that similar relationships occur in dasyurids.

Daily torpor also occurs in numbats (*Myrmecobius fasciatus*) and the pattern of torpor and torpor depth appear similar to that in dasyurids (Cooper 2003). Moreover, marsupial moles (*Notoryctes* spp.) may be heterothermic, but little published information is currently available (Tyndale-Biscoe 1973; Withers et al. 2000; Table 1). It is likely that heterothermy in these species has similar effects on energy and water conservation as in the dasyurids.

**Pygmy-possums**

Two of the pygmy-possums, the western pygmy-possum (*Cercartetus concinnus*) and the little pygmy possum (*Cercartetus lepidus*) extend their ranges from coastal regions into semi-arid and arid regions (Menkhorst and Knight 2001). Unlike the carnivorous marsupials, these insectivorous/
nectarivorous pygmy-possums can remain torpid for one or two weeks when exposed to low Ta, lower their Tb to a minimum of ~ 5°C and their minimum TMR is ~ 4% of BMR (Table 1, Fig. 1). Even at the relatively high Ta of 19°C, torpor bouts lasting for two days were observed in captive C. lepidus. Both species enter torpor at Ta 26 - 27°C, although at these high Ta torpor lasted only for part of the day and TMR was ~ 50% of BMR because Tb during torpor remains above the Tb. Mass loss during bouts of > 12 h were ~ 2 mg g⁻¹ h⁻¹ in C. concinnus and < 1 mg g⁻¹ h⁻¹ during a 6-day torpor bout in C. lepidus (Geiser 1987), emphasising the effectiveness of long bouts in reducing water and energy requirements.

As for echidnas, the physiological variables of torpor in these pygmy-possums are similar to hibernators in general (Bartholomew and Hudson 1962), but at least in the laboratory torpor appears not strongly seasonal. Prolonged torpor can be induced at any time of the year by exposing individuals to low Ta. The ability of possums to reduce TMR to less than half BMR at high Ta above Tb makes this a useful adaptation in a desert environment. Because torpor in these pygmy-possums is not highly seasonal, it appears to be an adaptation to unpredictable adverse changes in weather and food availability at any time of the year rather than a predictable winter.

**Bats**

Torpor in Australian bats with wide distribution ranges that include the arid zone suggests that torpor in arid zone bats is widely used. However, species that are restricted to the arid zone have not been studied in detail with regard to torpor. Five of the six families of Australian microbats (insectivorous Microchiroptera; Churchill 1998) contain species that are known to enter torpor, but most of the data are available on the family Vespertilionidae, including those species that extend their distribution into the arid zone (Kulzer et al. 1970; Hall 1982; Geiser 2004; Table 1). Most data are available on long-eared bats (Nyctophilus geoffroyi and Nyctophilus timoriensis), Gould’s wattled bat (Chalinolobus gouldii) and the inland broad-nosed bat (Scotoropsens balstoni). These species show much lower minimum Ta (1.4 - 6°C) and TMR (~ 3 - 4% of BMR) than the dasyurids, but similar values to those found for echidnas, pygmy-possums and many other hibernating species (Hock 1951; Geiser and Ruf 1995). It is likely that these, and many related Australian bats, are capable of prolonged hibernation especially in the southern half of the continent (Lumsden and Bennett 1995; Brigham and Geiser 1998). Data from free-ranging N. geoffroyi show that although some foraging does occur in winter this species can remain torpid for up to two weeks (Turbill et al. 2003a), which at a low TMR will result in enormous reduction in energy requirements. Prolonged bouts of torpor (2 days) were even observed in summer during cool weather. However, when Ta was high in summer, bats were active for part or most of the night, although torpor during the morning was observed on 100% of roost days (Turbill et al. 2003b). In captivity, torpor in N. geoffroyi may occur at Ta as high as 27°C, well above the hibernaculum Tb of many bats (Webb et al. 1996). There was a substantial drop of TMR to 25% of BMR at Ta (~ 27°C) commonly experienced in a desert environment. Similar observations with torpor at high Ta have also been made in the Angolan bat Mops condylurus that at times are exposed to hot Ta in their roost (Maloney et al. 1999).

In comparison to normothermic individuals (Baudinette et al. 2000), torpid bats also exhibit low water loss (Thomas and Cloutier 1992; Hosken 1997; Hosken and Withers 1997). In N. timoriensis (major) and Chal. gouldii, evaporative water loss at low Ta was ~ 10% of that in normothermic individuals, demonstrating that torpor is very effective not only in reducing energy expenditure, but also water requirements. This is also reflected in daily mass loss of N. geoffroyi which, when exposed to Ta between 5 and 10°C and torpid for most of the day, loses only ~ 0.6 mg g⁻¹ h⁻¹ (Geiser and Brigham 2000).

**Rodents**

In contrast to some other Australian arid zone mammals, little is known about torpor in Australian rodents. Predavec (1997) described a torpor-like state in a laboratory study on the sandy inland mouse (Pseudomys hermannsburgensis). He reported a minimum Tb of 21°C in animals captured in November, whereas individuals captured in September were homeothermic. Although torpor use is likely in this species, the study did not report whether the mice were able to actively rewarm from torpor, and the ~ 2.6-fold difference in BMR between November and September raises questions as to the reliability of the results. Our own observations (Drury, Seckerdiek, McAllan, Geiser, unpubl. data) suggest that captive-bred P. hermannsburgensis are reluctant to enter torpor, but reduce heat loss at low Ta by a change in thermal conductance without an apparent drop of core Tb. Those individuals that lowered Tb below 30°C were clearly pathologically hypothermic and could not rewarm. It is possible that the same was the case in Predavec’s (1997) study. However, unequivocal observations on daily torpor are available for the introduced house mouse (Mus musculus) (Table 1), which during the cold season were sharing nests with S. crassicaudata (Morton 1978a).
Clearly Australian rodents require further attention with respect to torpor. Desert rodents on other continents use torpor extensively (MacMillen 1965; Schmidt-Nielsen 1979; Lovegrove 2000) and there is no reason to predict that Australian rodents avoid torpor use. However, if heterothermy is employed in Australian rodents, daily torpor rather than prolonged hibernation is the likely pattern.

Implications of torpor on life in arid zone mammals

While torpor use has direct and obvious advantages for energy and water conservation in arid zone mammals as well as in birds (Geiser et al. 2004), it has other potential benefits that are rarely considered in an ecological or wildlife management context. Torpor in Australian mammals appears to be an important survival strategy, because they not only have to cope with seasonal changes in weather and food availability, but also have to survive unpredictable droughts, fire or floods. Frugal use of energy and water may be essential in coping with these challenges. However, use of torpor has other potential advantages. For example, use of torpor during reproduction in desert dasyurids allows them to reproduce on limited food and water availability, which is a truly remarkable achievement for endotherms. Torpor use during the period of development and growth, which is usually associated with an increase, rather than decrease in energy expenditure, also is a potentially crucial adaptation for life in deserts. Finally, because life span in many heterothermic mammals is longer than in related homeothermic species (Lyman et al. 1981; Wilkinson and South 2002), they possess the potential of survival of prolonged periods of adverse conditions. While the number of individuals surviving the bad times is likely to be low these individuals can multiply when things improve and maintain a high diversity of Australian arid zone mammals.

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