Animal Conservation

REVIEW

Why Australian farmers should not kill venomous snakes

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Abstract

Many Australians who work outdoors (notably, farmers and graziers) routinely kill venomous snakes. We argue that this attitude is misguided and dangerous. Despite their fearsome reputation, venomous Australian snakes pose little risk to human health (snakes kill an average of less than three people per year in Australia). Also, snakes confer a substantial benefit by consuming agricultural pests such as rodents. We estimate the magnitude of that benefit with data on snake diets, feeding rates and abundances. The most valuable rodent-controllers are Brownsnakes (genus *Pseudonaja*), which are rodent-specialists as adults and are abundant in agroecosystems across much of Australia. We calculate that a free-living adult Eastern Brownsnake consumes at least 50 mice per year (probably twice that number), and that population densities of Brownsnakes in agricultural areas can exceed 100 per km^2. Thus, Brownsnakes remove thousands of mice per square kilometre of farmland per year. That offtake plausibly reduces rodent densities because Brownsnakes take all age classes and both sexes of rodents by hunting in burrows. Tolerating Brownsnakes also would benefit the environment (e.g. less reliance on toxic chemicals) and the health of humans and domestic pets (fewer rodent-mediated diseases) and counter-intuitively, might reduce rates of snakebite (because many bites occur when a snake is attacked). In summary, a societal policy of coexisting with highly venomous snakes would confer multiple benefits to Australian farmers.

'The part which these and kindred reptiles play in maintaining the balance of nature in a group of such remarkable fecundity as the rodents must therefore be of considerable importance to man…, the more so that the greater number of rodents are among the most serious depredators on cultivation in general'.

> J.J. Quelch. 'The Boa-Constrictors of British Guiana', Annals and Magazine of Natural History 1888, p. 298.

'At Lake Narran, in northern New South Wales, Brown Snakes are sometimes so common that a person standing on the black soil near the lake's edge might see four or five snakes in a sweeping glance'.

> H. G. Cogger, 'Australian Reptiles in Colour', A. H. and A. W. Reed, p. 94.

Introduction

For centuries, farmers have realized that encouraging rather than extirpating native animals can benefit agricultural production.

For example, predatory insects and birds remove crop-eating pests (González *et al*., 2020; Retallack, 2021), and European farmers in the Middle Ages released toads in urban gardens for insect control (Turvey, 2013). However, wild animals dangerous to man or to livestock have been hunted rather than conserved, leading to worldwide declines in apex predators such as wolves, big cats and grizzly bears and consequent increases in crop damage by herbivores (Prowse *et al*., 2015; Wallach, Ripple, & Carroll, 2015). A similar decline of large predators has occurred in marine environments also (e.g. Pepin-Neff & Wynter, 2018). One group of animals that has been widely persecuted are snakes (e.g. Whitaker & Shine, 2000; Marshall *et al*., 2018; Keener-Eck, Morzillo, & Christoffel, 2020; Tucker *et al*., 2021; Derez & Fuller, 2023). Many rural people attempt to kill every snake that they encounter, especially species that are perceived to be venomous (Valkonen & Mappes, 2014); in one questionnaire-based study in rural Australia, 38% of respondents said that they tried to kill snakes wherever possible (Whitaker & Shine, 2000).

Southern Australia offers an escalated example of this wildlife-human conflict because the snake fauna is dominated by members of the Elapidae (a family that comprises cobras,

mambas, taipans and their kin). As a result, some of the most commonly encountered snakes in southern Australia possess highly toxic venom (Shine, 1995; Mirtschin, Rasmussen, & Weinstein, 2017; Zdenek *et al*., 2019; for an international perspective see Luiselli *et al*., 2020). Attitudes towards snakes tend to be negative as a result, and many people kill these reptiles because the perceived danger of fatal snakebite is thought to outweigh any beneficial effects of snakes as pest-controllers. Below, we challenge that assertion and instead, we argue that the benefits of snake populations in agricultural land far outweigh the potential costs, and hence that farmers should tolerate rather than kill venomous snakes.

Snakes and agriculture in southern Australia

Although the ophidian fauna of southern Australia is dominated by venomous snakes, most species are too small or rare to offer any significant risk to humans. The deadly species most often found in disturbed agricultural habitats are Brownsnakes (*Pseudonaja* spp.), elongate diurnally active fast-moving species that thrive in disturbed habitats ranging from semi-arid rangelands to montane meadows (Shine, 1989; Mirtschin, Rasmussen, & Weinstein, 2017). The most important taxa (based on body sizes and abundance in disturbed habitats, as well as the incidence of snakebite) are Eastern Brownsnakes (*Pseudonaja textilis*; see Figs 1–3b).

Brownsnakes are not the only large venomous snakes in southern Australia, but the other large venomous taxa typically are restricted to riparian habitats and swamps (Tigersnakes *Notechis scutatus*; Copperheads *Austrelaps* spp.; Blacksnakes *Pseudechis porphyriacus*) or are rarely encountered (Death Adders *Acanthophis* spp.) (Mirtschin, Rasmussen, & Weinstein, 2017). Red-bellied Blacksnakes

Figure 1 The most abundant venomous snake in agricultural landscapes across large areas of semi-arid eastern Australia is the Eastern Brownsnake, *Pseudonaja textilis*. Photograph by Peter Mirtschin.

Figure 2 Eastern Brownsnakes, *Pseudonaja textilis*, thrive in highly disturbed agroecosystems. Photograph by Chris Hay.

(*Pseudechis porphyriacus*) are abundant in eastern Australia, including on farmland in well-watered habitats, but have never been recorded to deliver fatal snakebites to humans (Mirtschin, Rasmussen, & Weinstein, 2017). Due to a belief that Blacksnakes consume Brownsnakes, many farmers tolerate Blacksnakes on their properties in order to reduce numbers of the more toxic species (e.g. Shine, 2022).

Costs of tolerating venomous snakes

All of the large elapid species listed above (with the apparent exception of Blacksnakes) can deliver a fatal bite to a human being, but they rarely do so. Bites from Australian snakes are rare (around 3000 cases annually; that is, 3 to 18 bites per 100 000 people) and a high proportion of those bites result from retaliation by a snake that was attacked by a person (Johnston *et al*., 2017). Only a few of those 3000 bites per annum result in human fatalities, which total about two to three fatal snake bites per year to humans in Australia (Welton, Liew, & Braitberg, 2017). Brownsnakes are the most common cause of fatal snakebite (Mirtschin, Rasmussen, & Weinstein, 2017). Livestock and domestic pets are bitten more often than are people; each
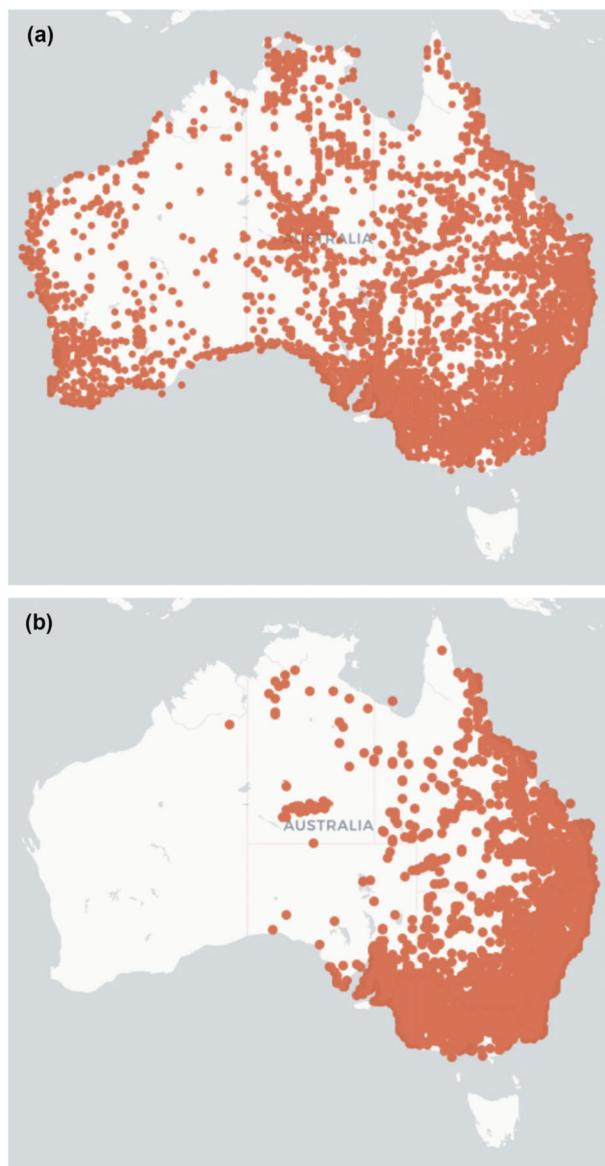
Figure 3 Geographic distribution of (a) Brownsnakes (genus *Pseudonaja*) and (b) the most abundant species, the Eastern Brownsnake (*Pseudonaja textilis*), from records in the Atlas of Living Australia (https://www.ala.org.au/). Accessed 8 January 2023.

year, around 6000 to 7000 such bites are reported to veterinary practices (Mirtschin *et al.*, 1998; Zdenek *et al.*, 2020). Most bites to domestic pets occur in rural areas, and overwhelmingly are due to Brownsnakes (76%) rather than other species; most snake-bitten dogs and cats survived if given antivenom and some survived without antivenom (Mirtschin *et al.*, 1998).

The low incidence of fatal snakebite to humans reflects several factors (Zdenek, 2022). One is that Australian snakes (including Brownsnakes) generally retreat rather than attack, even when provoked (Whitaker & Shine, 1999a, 1999b, 2000). Another factor is that most rural people in southern

Australia wear shoes and pants thick enough to reduce the risk of envenomation by the relatively short-fanged elapids (Chippaux, 1998; Zdenek, 2022). Thirdly, first-aid treatments (pressure-immobilization bandages) are easy to apply and can delay the onset of snakebite symptoms for hours (Mirtschin, Rasmussen, & Weinstein, 2017). Lastly, medical care, transport infrastructure and effective antivenoms are readily available over most of the Australian continent (Chippaux, 1998; Zdenek, 2022).

In the case of Eastern Brownsnakes (the only species whose behaviour has been examined in detail), risks of snakebite are further reduced by the tendency of snakes to spend most of their time in places where they are unlikely to be encountered by people. The snakes spend cooler months inactive, hidden below-ground and even in summer, radio-tracked snakes are above-ground for only a few hours per day (overall annual mean = 93% of time underground, 7% above-ground: Whitaker & Shine, 2002). Even in months of peak snake activity, trained observers aware of the presence of a radio-tracked snake active above-ground actually sighted the snake on <25% of occasions (Whitaker & Shine, 1999a). This secretive behaviour reduces rates of encounter between farmworkers and Brownsnakes even in sites where the snakes are abundant.

Venomous elapids such as Brownsnakes undeniably pose a risk to people and domestic pets and livestock, but fatal snakebite is far less common than perceived by the general population. For example, in countries such as the USA more people are killed by horses and cows than by snakes (Langley & Morrow, 1997; Welton, Williams, & Liew, 2017).

Benefits of tolerating venomous snakes

The most obvious benefit of maintaining Brownsnake populations is to reduce the abundance of rodents (e.g. Hisaw & Gloyd, 1926). Introduced species of rats and mice are a major cost to Australian agriculture: Brown & Singleton (2000) estimated that damage from a single species (*Mus domesticus*) sometimes exceeds US$60 million per year. In extreme cases, mice can cause destruction of most or even all of an entire crop (Mutze, 1998; Brown & Henry, 2022).

In summary, Brownsnakes dominate the 'deadly snake' fauna of agroecosystems in southern Australia from Perth to Brisbane (see Figs 1–3b); in our experience, other large elapid species usually outnumber Brownsnakes only in well-watered locations. Unlike the only other large elapid species with similar abundance (the Red-Bellied Blacksnake), Brownsnakes are attacked and killed by a high proportion of all agricultural workers (e.g. Shine, 2022); and adult Brownsnakes feed primarily on rodents (Shine, 1989, 1995) and thus may improve farm productivity. We thus focus on Brownsnakes in the current analysis.

The magnitude of rodent offtake by Brownsnakes depends upon two factors: the number of rodents consumed per snake per year, and the abundance of snakes on farmland. Below, we estimate those two variables based on published and unpublished information.

Materials and methods

Proportion of Brownsnake diet consisting of rodents

We obtained data on the proportion of Brownsnake diets that consisted of rodents from dissection of museum specimens from all available Australian museum collections (see Shine, 1989 for details). Gut contents were revealed via a mid-ventral incision and identified to species level if possible. In the case of amphibian gut contents, identification was possible only to generic level, based on the state of decomposition of the food item.

Number of prey items consumed per year

Feeding rates of snakes vary considerably. We estimated the number of prey items consumed per year by Brownsnakes using three methods.

1 Feeding rates of captive snakes. – We obtained feeding records from a venom-collection facility (Venom Supplies, South Australia) and a wildlife park (Australian Reptile Park, NSW) that house captive brownsnakes. Our calculations are based upon the number of items consumed rather than all prey items offered to the animals.
2 Conversion of prey to snake biomass. – We obtained data from commercially farmed pythons (*Malayopython reticulatus* and *Python bivittatus*) in farms in Thailand and Vietnam to estimate annual consumption of prey required for a snake of a given size.
3 Energy budgets. – We used data from studies on North American colubrid snakes (*Masticophis flagellum*) that are morphologically and ecologically similar to Brownsnakes, but smaller (to 200 g rather than 1 kg). Secor & Nagy (1994) used rates of influx of doubly labelled water to estimate energy intake rates of 24.1 g kg^{-1} day^{-1} for free-ranging animals.

Abundance of Brownsnakes on farms

Despite their abundance and wide distribution, there have been no published demographic (mark-recapture) studies on Brownsnakes. To estimate the abundance of Brownsnakes on farms we employed three methods.

1 Previous research on Brownsnake abundance. – We used data from a detailed radio-tracking study of Brownsnakes by Whitaker & Shine (1999a, 1999b, 2000, 2002, 2003), which included intensive surveys of an agricultural site near Leeton, New South Wales (NSW).
2 Rates of capture from fieldwork. – We obtained data on rates of capture of free-ranging Brownsnakes from previous research that focused on a sympatric species (Red-bellied Blacksnakes) to obtain estimates of Brownsnake abundance.
3 The Atlas of Living Australia (ALA). – We obtained data from the ALA, an online compendium that incorporates several sources of information, including listings of specimens in all Australian museums.

Results

Proportion of Brownsnake diet consisting of rodents

Dissection of museum specimens shows that most Australian elapids feed mainly on amphibians and reptiles, but adult Brownsnakes primarily consume mammals (Shine, 1989, 1995). Most of those mammals are rodents, especially house-mice (Shine, 1989). The exact proportions of rodents in the diet differ among different Brownsnake species, among populations within species, and with body size within the life of a single individual (Shine, 1989), but house-mice are the staple diet for large Brownsnakes in many agricultural landscapes in southern Australia.

Number of prey items consumed per year

Feeding rates of captive snakes

Institutions that maintain captive Brownsnakes offer food weekly or fortnightly throughout the warmer months of the year; a typical weekly meal for an adult Brownsnake would be one or two domestic mice, each weighing around 30 g. This equates to an annual prey consumption of around 20 to 50 domestic mice per year (600 g to 1.5 kg). Actual data for captive adult Eastern Brownsnakes (maintained for venom production) provide records of total annual prey consumption rates of 780 g to 1.6 kg per snake per year ($N = 13$ snakes, Australian Reptile Park) and 435 g to 1 kg per snake per year ($N = 35$ snakes, Venom Supplies).

Conversion of prey to snake biomass

Based on data and personal communications of feeding schedules from commercial python farms, we estimate that about 3.5 g of food (mostly rodents) is required to add an extra gram of python body mass (D. Natusch, pers. comm. 2022). Thus, for example, a growth increment of 1 kg required about 3.5 kg of prey. Adult Eastern Brownsnakes can attain a body mass >1 kg, at around 3–5 years of age (Shine, 1978, 1989). That calculation suggests consumption of around 1 kg of prey per Brownsnake per year (approx. 33 mice), with juveniles eating <1 kg and adult snakes eating more.

Energy budgets

An energy intake rate of 24.1 g kg^{-1} day^{-1} (as estimated by Secor & Nagy, 1994 for North American snakes that are ecologically and morphologically similar to Brownsnakes; see above) would equate to several kilogrammes of food per year for a 1 kg Brownsnake. This may overestimate feeding rates of Brownsnakes because it is several times higher than

the food intake rates suggested by our other two methods of calculation. The discrepancy may partly reflect the facts that (1) the North American species is smaller than the Brownsnake, and food consumption rates per gram body mass may not increase linearly with body size; and (2) the other two estimates are based on captive snakes, whose metabolic rates are lower than for free-ranging conspecifics. Animals in the wild must move around to find food and evade predation rather than remaining sedentary within a cage, and also expend energy on activities such as mate-searching and male–male combat (in males) and vitellogenesis and egg-laying (females). Thus, feeding rates in captivity (around 1 kg of rodents per adult Brownsnake per year) may underestimate feeding rates in the wild. Adult wild mice generally average about 15 g, half the mass of domestic (laboratory) mice (Garland Jr. *et al.*, 1995).

Summary

We conservatively estimate that a free-ranging adult Brownsnake that feeds only on rodents consumes the equivalent of around 50 domestic mice, or around 100 wild mice, per year.

Abundance of Brownsnakes on farms

Previous research on Brownsnake abundance

In their Leeton study area, Whitaker & Shine (1999a) reported that Eastern Brownsnakes were most abundant in and around extensive mouse-burrow systems in the sides of irrigation canals; in some places, the canal sides were honeycombed by rodent burrows. The authors of that study captured and recaptured a resident population of 45 adult Brownsnakes within the linear 'core study site', a 25-m-wide area running along 3 km of canal (i.e. total area 3000 m by 25 m). That abundance translates into 600 Brownsnakes per km^2. In prime habitat, there was about one snake for every 25 m of canal shoreline. Snake numbers were lower in adjoining farmland, with encounter rates 0.24 vs. 0.35 snakes h^{-1} in the core area. These data are significant for two reasons. First, they document remarkably high population densities of Eastern Brownsnakes. Second, they show that even in an area containing abundant snakes, experienced snake-catchers encountered only 1 Brownsnake per 3 h searching.

Rates of capture from fieldwork

During fieldwork in the Macquarie Marshes of central NSW, one of us (RS) captured an average of 9.3 Eastern Brownsnakes per day (range: 2–19). Given the low rates of encounter per snake in Whitaker & Shine's (1999a) study (<0.35 snakes h^{-1}: see above), the absolute densities of Brownsnakes likely were far higher in the Macquarie Marshes than in the Leeton study site. Many areas of farmland doubtless contain fewer Brownsnakes than do either of those study areas because those sites were selected for study

partly because of perceived high densities of snakes. Nonetheless, Brownsnakes are the most-commonly encountered large elapids over a massive area of southern Australia (see below) and we doubt that the two study sites with data on Brownsnake abundances are outliers in this respect.

The atlas of living Australia (ALA)

Our search of the ALA found 26 225 records of the genus *Pseudonaja*, primarily the Eastern Brownsnakes *P. textilis* (*N* = 15 161 records). The only other elapid snake species with comparable abundances (based on these numbers) is the Red-Bellied Blacksnake (21 709 records; for the genus *Pseudechis*, 26 673 records). We cannot translate that relative measure into actual abundances, but note that mark-recapture programmes on other Australian snake species – all of which are far less often collected than Brownsnakes, based on museum collections – have reported high population densities in suitable habitats (e.g. Madsen & Shine, 2000; Bonnet *et al.*, 2002; Reading *et al.*, 2010; Shelton, Goldingay, & Phillips, 2018). If Brownsnakes are among the most abundant snake species over much of Australia (see Fig. 3), the absolute number of individual Brownsnakes must be enormous.

Total offtake of rodents by Brownsnakes

Based on the combined data obtained from various sources, our calculations suggest that a square kilometre of farmland can contain hundreds of adult Eastern Brownsnakes, even in areas where rates of encounter between people and those snakes are low. If each adult Brownsnake consumes around 100 wild mice per annum (likely an underestimate), the combined annual offtake of rodents by Brownsnakes must equate to several thousand mice per square kilometre (100 mice × 100 snakes = 10 000 mice per square kilometre per annum). At typical rates of food consumption by mice (3–5 g day^{-1}; https://agriculture.vic.gov.au/biosecurity/pest-animals/priority-pest-animals/house-mouse), this would equate to around 1.5 kg of food per annum per mouse. Wild mice can live for at least 3 years (Miller *et al.*, 2002), so each mouse removed by a Brownsnake may reduce total grain consumption by several kilogrammes.

Discussion

By combining data from a range of sources, we estimated that a policy of tolerating rather than killing Brownsnakes on farmland could generate substantial benefits in productivity (due to snake predation on mice) and reduce rather than increase the risk of snakebite.

Impact of predation by snakes on rodent populations

Because of their diurnal habits, slender body form and willingness to penetrate deep into narrow burrows, Brownsnakes capture most mice underground rather than when the small mammals are active above-ground (Whitaker & Shine, 2003).

Predation may be especially high on rodents with poor locomotor ability, such as very young animals and heavily pregnant females. Differential rates of predation on prey individuals with respect to age, sex and reproductive condition can massively affect the demographic impact of a given rate of offtake (e.g. Saunders, Cuthbert, & Zipkin, 2018). For example, in many species of rodents, the individuals most often found active above-ground are reproductive adult males and dispersing adolescents (Ward-Fear et al., 2017); culling those cohorts may have little impact on underlying population growth rates. In contrast, predation that focuses on reproductive females (as is probable for burrow-foraging snakes) may have greater demographic impact.

The spatial concentration of predation also may affect a snake's impact on prey populations. Thus, for example, if an individual snake remained within the same mouse-burrow system for long periods, it might maintain low rodent abundances in one such system but have no effect on neighbouring warrens. In practice, however, radio-tracked Eastern Brownsnakes typically remained within a single burrow system for around 6 days before moving to another warren system where mice were more abundant (Whitaker & Shine, 2002, 2003). Serial targeting of rodent hotspots means that even a single Brownsnake could reduce rodent abundances over a substantial area.

The best evidence that predation by snakes can reduce prey populations comes from the inadvertent introduction of snakes to areas outside the species' native range. For example, the invasion of Burmese Pythons (*Python bivittatus*) in southern Florida rapidly extirpated small to medium-sized mammals across the Everglades (Dorcas et al., 2012). Avoidance of python scent cues may exacerbate some of these effects (Beckmann, Avila, & Farrell, 2022). Likewise, the invasion of Brown Tree Snakes (*Boiga irregularis*) decimated the native avian fauna of the island of Guam (Rodda & Savidge, 2007). On another small tropical island (Christmas Island), invasive Asian Wolfsnakes (*Lycodon capucinus*) are driving native lizards to extinction (Emery et al., 2021). On the Balearctic island of Ibiza, the invasive Horseshoe Whipsnake *Hemorrhois hippocrepis* is extirpating populations of endemic lizards (Montes et al., 2022). In addition to those well-documented cases, an extensive anecdotal literature describes irruptions of rodents (with consequent damage to agricultural productivity) following campaigns to exterminate snakes (e.g. Jacobsen, 2014).

Nonetheless, the extraordinary fecundity of many 'pest' rodents buffers any impact of offtake by predators (Blackwell, Potter, & Minot, 2001). For example, predators may not prevent rodent plagues, but predation may limit the magnitude and duration of such irruptions (Blackwell, Potter, & Minot, 2001).

Would predation by snakes reduce grain consumption by rodents?

The relationship between rodent abundance and economic damage to crops is unlikely to be linear (Brown & Singleton, 2000), but several studies have noted higher damage levels when rodents were more abundant (e.g. Poché et al., 1982; Lefebvre et al., 1989). Intuition suggests that a reduction in rodent abundance will reduce the damage inflicted to crops and complement the impact of native avian and mammalian predators on rodents.

The total amount of grain 'saved' by Brownsnake predation is difficult to estimate because of uncertainty about diet composition and survival rates of wild mice.

In some cases, however, that saving might be substantial. With 100 adult Brownsnakes per square kilometre, each consuming 100 mice per year, simple calculations suggest that the reduction in grain consumption could reach 8000 kg (8 tonnes) per square km of farmland per year (100 snakes × 100 mice per snake per year × 4 g of grains per mouse per day × 200 days mean longevity of mice). Total crop yields in Australia average around 2.6 tonnes per hectare (260 tonnes per square km; https://grdc.com.au/about/our-industry) and mice often consume around 10% of the crop (Brown et al., 2007). Based on those numbers, the estimated offtake of mice by Brownsnakes (8 tonnes per square km) would reduce grain consumption by 30% (i.e. from 26 to 18 tonnes per square km). That reduction is similar to that achieved in experimental trials of rodenticide efficacy, especially given that rodenticide effects on mouse densities often are short-term only (e.g. Saunders, 1983; Twigg, Singleton, & Kay, 1991; Mutze, 1993). The effect of Brownsnakes on grain production will be reduced by factors such as winter inactivity of snakes, inaccessibility of some mice to snake predation and low abundance of adult Brownsnakes in some agricultural systems. Also, the seasonal timing of snake predation is important because removal of mice early in the growing season affects total offtake of grain more than equivalent predation late in the season (Brown et al., 2007; Brown & Henry, 2022). Although the exact impact of Brownsnakes on grain production doubtless vary enormously through time and space, our calculations suggest that Brownsnakes consume enough rodents to significantly affect the magnitude of crop damage by these pests.

The financial benefit of Brownsnake predation on crop-damaging rodents is hence substantial as well. Using average values from the paragraph above, farmers obtain around 260 tonnes of seed per square kilometre, and Brownsnakes may increase that offtake by around 8 tonnes per square kilometre (=3% of total crop). Given a gross production value of around $19 billion across southern Australia, an increase of 3% in grain production would be worth over $500 million. Although this estimate is imprecise and based on studies from only one region, it suggests that exploiting the rodent-killing ability of Brownsnakes confers significant economic benefits to Australian agriculture.

Other potential benefits of using snakes for rodent control

Existing methods for rodent control are expensive, often ineffective, and may have negative effects on the environment and on the long-term abundance of the targeted rodents. Chemical rodenticides, especially second-generation

anticoagulant types, cause residual build-up in the livers of snakes and lizards that consume those prey (Lettoof *et al.*, 2020) and may affect many other native predators (Kaukeinen, 1982; Lohr & Davis, 2018; Cooke *et al.*, 2022). Rodents that consume such poisons may become active above-ground by day before dying, increasing the risk of secondary poisoning (Brown & Singleton, 1998). By killing non-target predators, these rodenticides may facilitate increases in abundances and thus impacts of rodents (e.g. Lotts & Stapp, 2020), and thus encourage even more widespread reliance on rodenticides.

Using rodenticides can also directly threaten the health of humans, livestock and pets (Chua & Friedenberg, 1998; Eisemann & Swift, 2006). People taking blood-clotting medication such as warfarin can be sensitive to even small doses of brodifacoum (a variant of warfarin commonly used in rodenticides), and patients with pre-existing liver diseases are at risk from rodenticides (Jindal & Sarin, 2022). Accidental consumption of rodenticides causes inadvertent poisoning in domestic animals (Mackintosh *et al.*, 1988; Ayala *et al.*, 2007). Rodents (and their ticks and fleas) also play a significant role in transmitting pathogens to humans (Meerburg & Kijlstra, 2007; Palis *et al.*, 2007; Meerburg, Singleton, & Kijlstra, 2009; Jacobsen, 2014).

Importantly, a policy of tolerating rather than killing Brownsnakes might reduce the incidence of snakebite (Seigel & Mullin, 2009; Pandey, 2015). Surveys suggest that around 30% (Chippaux, 2017) to 57% (Curry *et al.*, 1989) of bites are inflicted when the snake defends itself from perceived attack. Fewer attempts to kill snakes will translate into fewer fatal snakebites. Another potential benefit of tolerating snakes is to modify the behaviour of snakes when they encounter people, as well as the reverse. Mirtschin, Rasmussen, & Weinstein (2017) suggest that snakes that are long-term residents of an area pose relatively little threat because they are less agitated by close encounters with people, and know the location of nearby safe havens. In contrast, culling snakes results in an influx of new animals unfamiliar with the specific location and not habituated to human presence.

The obvious rebuttal to the above suggestion is that killing snakes can also reduce the future incidence of snakebite, by reducing overall snake abundances. However, that argument assumes that direct killing reduces snake abundances in the long-term. Available data suggest that even high rates of culling by humans can have little impact on underlying snake abundance, as exemplified by high densities of rattlesnakes despite decades of intense harvesting during annual 'Rattlesnake Roundups' in North America (e.g. Campbell, Formanowicz Jr., & Brodie Jr., 1989; Fitzgerald & Painter, 2000). That paradoxical result fits well with field studies showing that snake abundances are driven by 'bottom-up' processes (i.e. prey availability) rather than by 'top-down' processes (i.e. mortality through predation; e.g. Brown *et al.*, 2013).

Lastly, maintaining viable populations of snakes has an ecological benefit. Removing high-level predators destabilizes food webs and thus disrupts ecosystem function (Schmitz & Suttle, 2001). For example, declines in the abundance of large varanid lizards in tropical Australia, due to lethal ingestion of invasive cane toads, had substantial flow-on effects to lower trophic levels (Brown *et al.*, 2013). The conservation of snakes also has merit in its own right; many species of snakes are in decline, and it is predicted that some species will be seriously threatened by 2040 (Geyle *et al.*, 2021). A widespread inability of people to reliably identify snakes means that many of the 'Brownsnakes' killed by farmworkers are actually other species, some of them already rare (Morrison *et al.*, 1983; Wolfe, Fleming, & Bateman, 2020).

Future work could compare neighbouring farms with differing policies about tolerating snakes with respect to variables such as farmland productivity, rodent-caused damage and the incidence of snakebite. Our strong impression from fieldwork is that some farmers tolerate snakes whereas other people (often on adjacent properties) do not. That diversity provides a robust opportunity to quantify the costs and benefits of peaceful coexistence between venomous snakes and farmers.

Other species of snakes

Most large-bodied elapid snake species in mesic habitats of southern Australia feed on frogs and/or lizards rather than rodents, and hence contribute less to rodent control (Shine, 1995; Welton, Liew, & Braitberg, 2017), but Brownsnakes are not the only elapids that consume large numbers of rodents and occur in agricultural areas. For example, coastal Taipans (*Oxyuranus scutellatus*) can be abundant in sugarcane plantations and eat many rodents (Shine & Covacevich, 1983). Cane farmers suffer major economic losses due to rat predation and use poisons for rodent control (Smith *et al.*, 2003; Lohr & Davis, 2018). Taipans are highly toxic but fatal bites to humans are rare (Mirtschin, Rasmussen, & Weinstein, 2017). Thus, the potential benefits of tolerating snakes on farms may apply to Taipans as well as Brownsnakes. More generally, abundant snakes may curtail rodent abundance even in the case of snake species for which mammals comprise a minor part of the diet.

Summary

Brownsnakes (*Pseudonaja*) are persecuted in agroecosystems across southern Australia because of the widespread view that these highly venomous snakes pose a major danger to human life. In actuality, bites from Brownsnakes are rarely fatal, and often result from attempts to kill the snake. Our review suggests that Brownsnakes attain high abundances in farmland, even in areas where people rarely see these snakes, and that Brownsnakes remove vast numbers of rodents that otherwise would curtail agricultural productivity. We thus call for a more balanced view of the costs and benefits of these much-maligned serpents. Tolerating these snakes may confer benefits (economically, environmentally, and in terms of snakebite risk) that outweigh the already low incidence of life-threatening snakebite. Some people may see the (low) risk of fatal snakebite as unacceptable, especially for snakes that live close to places where people spend much of their

time (e.g. around houses). But, especially in broad-scale agriculture, where a snake in some far-flung paddock will be encountered by farmworkers very infrequently, the benefits of tolerating such a prolific pest-controller surely outweigh the miniscule risk of dangerous snakebite.

Changing the attitudes of rural citizens towards venomous snakes will require targeted campaigns to educate stakeholders about the issues we have reviewed in this paper. Notably, all age groups, from schoolchildren onwards, should be given access to information about the real (as opposed to exaggerated) risks of fatal snakebite, the methods that can be used to identify snake species, the best first-aid procedures in case of bites and the advantages as well as costs associated with coexistence between people and venomous snakes. Field-based environmental education programs can rapidly change the opinions of people (especially children) towards snakes (e.g. Ballouard *et al.*, 2012, 2013). Attitudes of the Australian public towards snakes are now vastly more positive than they were a few decades ago (Shine, 2022), an encouraging sign for the ability of education campaigns to further reduce casualties in this perennial human-wildlife conflict.

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Author contributions

PM and RS conceived the ideas and designed methodology; PM and ND and JA collected the data; PM and RS analysed the data; PM and RS led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Conflict of interest

The authors declare no conflicts of interest.

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