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Still a good dog! Long-term use and effectiveness of livestock guardian dogs to protect livestock from predators in Australia's extensive grazing systems

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ABSTRACT

Context. Livestock predation is a significant problem for livestock producers all over the world. Livestock guardian dogs (LGDs) can protect livestock from predators, but little is known about the factors that affect their use over long periods of time. **Aims.** Our aims were to investigate the long-term use of LGDs in Australia and determine whether their effectiveness remained high over time, and to establish the reasons for discontinued use. We also wanted to collect data on the fate of LGDs, and how using LGDs affected the use of other methods for predation control. Last, we wanted to estimate the rate at which the use of LGDs is spreading through word-of-mouth. **Methods.** We re-contacted participants from a previous survey of LGD users in Australia and interviewed them about their long-term experience. We were able to include 82% (112) of the original participants, a mean of 8.9 (±0.08) years after the first survey. **Key results.** Half of all original participants were still using LGDs, and in most cases the effectiveness of LGDs had not changed since the first survey. The main reason for ceasing use of LGDs was a change in business that made the dogs unnecessary, followed by unwanted behaviour of dogs, and problems with neighbours. Most LGDs that died prior to old age were euthanised, fell victim to lethal predator control, or were killed by wildlife. Farmers with LGDs reduced other forms of predation control. Informal information transfer among farmers is leading to a net increase in the use of LGDs in Australia. **Conclusions.** LGDs can remain an effective predator control method in Australia with long-term use, and their use is spreading. However, a substantial number of livestock producers experience difficulties in properly training and managing LGDs, leading to failure of the method in some cases and presumably limiting uptake. **Implications.** Given the effectiveness of LGDs for predation management and the many advantages gained by their use, Australia could greatly benefit from programs by government or management agencies both to promote uptake of LGDs and to reduce the incidence of problems by providing farmers with advice and information on best-practice management.

Keywords: dingo, human–wildlife conflict, LGD, livestock predators, predation, predator control, red fox, wild dog, wildlife management.

Introduction

Livestock guardian dogs (LGDs; *Canis familiaris*) are working dogs that live with livestock and protect them from predators and other threats. Most LGD breeds originate in southern and eastern Europe and central Asia, where they have been used for millennia (Gehring *et al.* 2010; Ivaşcu and Biro 2020; Welker *et al.* 2022). In the 20th century, use of LGDs declined following the eradication of large predators from large parts of Europe, but more recently has been revived and has spread to most continents of the world, including Australia (Rigg 2001; Gehring *et al.* 2010; van Bommel and Johnson 2012). LGDs are often highly effective in reducing livestock losses to predators (van Bommel and Johnson 2014; Van Eeden *et al.* 2018). Provided an adequate number of dogs is used and those dogs are properly selected and managed, they can be effective in protecting a wide range of livestock species on large as well as small farms (Breitenmoser *et al.* 2005; van Bommel and Johnson 2012). This makes LGDs a good option for predator control in Australia.

In Australia, predators cause considerable financial losses to livestock producers, especially in the sheep and cattle industries (McLeod 2016). Dingoes (*C. familiaris*) are the largest terrestrial predators in Australia and cause the most losses because they affect all livestock species. Of the smaller predators, the red fox (*Vulpus vulpus*) causes most losses. Dingoes are estimated to cost the livestock industry AUD89 million/year in lost productivity; foxes come in second at AUD28 million/year (McLeod 2016). The main methods used in Australia to prevent predation of livestock are lethal control of predators (by trapping, shooting, and poisoning) and exclusion fencing (Fleming *et al.* 2001; Allen and Fleming 2004; Smith *et al.* 2021). Various non-lethal methods for predator control are available; among these, LGDs are relatively popular (van Bommel and Johnson 2014) but still not widespread.

The first LGDs in Australia were a pair of Pyrenean mountain dogs imported in 1843 and used to protect sheep from dingoes (Fetherstonhaugh 1917). However, a reduction in dingo numbers and confinement of sheep to paddocks led to the breed dying out in Australia. The next Pyrenean mountain dog was imported in 1936, and LGD breeds and numbers have slowly increased since then (Crago 1991). The Australian National Kennel Council currently registers 14 breeds of LGDs, but most occur in low numbers (ANKC 2021). The breed most commonly used for livestock protection is the Maremma Sheepdog (van Bommel and Johnson 2012).

Previously, we found that LGDs can be an effective predation control method in Australia (van Bommel and Johnson 2012). Of 150 survey participants representing a range of property and livestock types throughout the country, 68% reported that predation ceased after obtaining LGDs, and a further 30% reported that it decreased. In addition, LGDs were found to be cost-effective, with a financial break-even point reached within 1–3 years of implementation, depending on the livestock type being protected (van Bommel and Johnson 2012).

However, Australia does not have a long history of use of LGDs and therefore little is known about their long-term effectiveness in this country. There could be several reasons why the effectiveness of LGDs for predation control might decrease over time, leading to a return of predation rates to pre-LGD levels and abandonment of their use. First, predators have flexible behaviour and can adjust to their environment and the challenges it poses. Their initial response to a novel threat in their environment in the form of LGDs might be avoidance of the area where the LGDs work, and therefore a reduction or cessation of stock losses occurs. However, predators might adjust to the behaviour of LGDs and learn how to launch successful raids on livestock despite LGD presence.

Second, farmers need to invest time and effort if they are to use LGDs successfully (van Bommel 2010). Behavioural problems can arise with LGDs, and these problems need management and correction. The first 1–2 years in the life of a LGD is the most difficult period to navigate, because adolescent dogs may develop unwanted behaviours that limit their effectiveness in protecting livestock (Green 1993; Lorenz and Coppinger 1996; Marker *et al.* 2005*a*; van Bommel 2010). Problems can also arise with adult LGDs, such as excessive roaming (Gehring *et al.* 2011). Farmers might struggle to maintain the level of attention and interventions needed to properly manage their dogs and correct behavioural problems, or might lack the knowledge required to successfully manage these issues. With insufficient management, unwanted behaviours in LGDs can accumulate and be passed on to other LGDs, leading to a further decline in their effectiveness and ultimately to abandonment of their use.

Third, LGDs are often allowed to roam freely so they can offer protection to large numbers of livestock spread over large areas (van Bommel and Johnson 2012). This is especially the case on larger properties in Australia, and it can result in LGDs straying outside property boundaries and trespassing on neighbours' properties, generating conflict with these neighbours if they mistrust the dogs. This conflict can lead neighbours to use lethal means to deter LGDs from their property and could eventually cause farmers to abandon the use of LGDs.

Last, long-term use of LGDs may become impractical if mortality rates of the dogs are excessively high. It takes up to 2 years for a pup to become a fully functional guardian, and a considerable investment of time and effort is required from the farmer to successfully raise a pup (van Bommel and Johnson 2012). If experienced dogs are exposed to high risk of death, the high rate of replacement needed to maintain numbers of working dogs creates extra work for the farmer and reduces protection for livestock, potentially discouraging farmers.

In this study, we investigated the factors affecting long-term use and effectiveness of LGDs on Australian farms. We did this by re-contacting participants of an earlier survey of LGD users for a follow-up interview approximately 10 years after they were initially interviewed. We had several specific aims. First, we wanted to investigate if farmers continued using LGDs over longer periods of time, and if use was discontinued, to identify the reasons. In addition, we wanted to find out if there was any difference in perception of LGDs between farmers that persist in their use and farmers that did not. Second, we wanted to determine if LGDs maintained their effectiveness if they work in an area for an extended period, or if their effectiveness reduces over time. Third, we wanted to collect data on the fate of working LGDs in Australia and determine the main causes of death of guardian dogs that died before reaching old age. LGDs are one of many predation-control methods available for farmers, and our fourth aim was to investigate how the use of LGDs affects the use of other predation-control methods by farmers, and if this changes over time.

Lastly, we wanted to estimate if, and how quickly, the use of LGDs has been spreading by word-of-mouth. LGDs evidently provide effective control of predation on livestock in Australia, but there are no government programs that promote or support their use. The tasks of obtaining LGDs, finding information on how to raise, train, and manage them, and solving problems that may arise in maintaining working LGDs, remain at the initiative of individual farmers. Our experience from the earlier survey suggested that in the absence of institutional support, information exchange among farmers is important for new users to become aware of the potential of LGDs in the first place, to gain information on how to implement and manage them, and often to obtain the dogs themselves. We also suspected that word-of-mouth transfer is the main process responsible for increasing use of LGDs, to the extent that such increase is occurring (although rural media and the availability of publications such as van Bommel (2010) might also be significant). Therefore, we wanted to establish whether farmer-to-farmer contact is resulting in net increase in the number of LGD users, and to quantify the approximate rate of such increase.

Materials and methods

Survey methods

We re-surveyed LGD users who participated in a LGD survey that was conducted in 2008/2009 (van Bommel and Johnson 2012). We selected 137 of the original 150 participants for re-contacting; 13 subjects in the first survey were excluded because they had already ceased using LGDs at the time of the first survey and these participants considered it unlikely that they would resume use of LGDs in the future. If an original participant could not be re-contacted at their original telephone number (i.e. phone disconnected, or phone answered by a different person unfamiliar with the original participant), we tried in two ways to re-locate them. First, we asked the person who originally referred us to the participant if they knew an alternative way to get in touch with them. Second, we did a Google search on the person's name to attempt to find publicly accessible contact information. We were able to re-contact 112 of the original participants (71 through their original contact details, 41 after obtaining updated contact details), and failed to re-contact 25. Uncontactable participants were not over-represented in any Australian State, livestock category (sheep, goats, cattle, poultry or other) or property size-category (<99 ha, 100–999 ha, 1000< ha). The mean time (±s.e.) between the first and second interviews for individual participants was 8.9 (±0.08) years.

Following the methods from the first survey (van Bommel and Johnson 2012), we took a multi-method approach to the research, incorporating both qualitative and quantitative research methods. The interviews were semi-structured, with open questions. This format was chosen to allow participants to elaborate when answering questions, which allowed us to gain a greater understanding of their individual situation. Topics included: whether participants were still using LGDs or not; if not, the reasons for ceasing use; how many LGDs they had lost since the first survey and what happened to them; current management of livestock and LGDs; current losses to predators; use of other forms of predation control; and the number of other farmers that the participant was aware of who had taken up LGDs as a result of contact with the participant in the period since the participant started using LGDs. The full list of survey questions can be found in the supplementary file. All interviews were conducted by one researcher (LvB) between October 2016 and February 2019. Surveys were conducted by phone at a time that suited the participant, except three surveys that were sent by email as requested by those participants. Notes were taken by the researcher during the interviews to record responses to the questions of the survey. If a participant was unable to answer a question, a 'no response' answer was recorded.

Statistical analyses

The open-ended nature of the interviews allowed participants to answer questions in their own words. Therefore, when analysing the responses to the questions dealing with the reason of loss of a LGD, the reason for ceasing use of LGDs, and the advantages and disadvantages of the use of LGDs, responses were assigned to categories. An approach similar to hermeneutic research design was followed (Yanow and Schwartz-Shea 2015); by reading and re-reading the answers, patterns started to emerge based on commonality of responses to the question being analysed. Categories were chosen based on this grouping of responses.

The number of participants citing the different categories of advantages and disadvantages associated with use of LGDs were analysed to test for differences between participants still using LGDs and participants no longer using LGDs, using paired *t*-tests in Microsoft Excel (Microsoft Office 365, ver. 2211; Microsoft Corporation 2011). For participants still using LGDs, we obtained a measure of change in effectiveness for livestock protection in two ways. First, we compared user-reported yearly stock loss in the second survey with that in the first survey. If the losses in the second survey fell within 5% of the losses reported in the first survey, the LGDs were classed as 'equally effective'. If in the second survey, losses had increased by more than 5%, they were classed as 'less effective'; in these cases, we investigated if there had been any change in livestock or dog management that could account for this change. There were no cases where losses had decreased by more than 5%. Second, we asked participants themselves whether they thought the effectiveness of their guardian dogs had increased or decreased (or stayed the same) compared with the time of the initial interview. To obtain details on the fate of lost LGDs, answers from the relevant question in the first and second surveys were combined. We obtained information about the fate of 703 LGDs from 110 survey participants.

We investigated the use of predation control approaches other than LGDs in two ways. In the first survey, participants were asked about their use of other forms of predation control, and how their use of such approaches had changed when they started using LGDs. In the repeat survey, we again asked participants about the use of predation control other than LGDs and determined how this use had changed compared with the first survey. To investigate the factors affecting the use of predation control other than LGDs, we used multinomial logistic regression analysis implemented in the package 'nnet' (ver. 7.2–18) in R statistical software (R Core Team 2013). We analysed what type of predation control was being used during the first survey (lethal/non-lethal/both lethal and non-lethal/no other control), and the change in levels of other predation control being used (increase/decrease/no change) in the first survey compared with pre-LGD use. We also analysed the change in levels of other predation control being used between the first and second survey, and what type of control was increased (lethal/non-lethal/both lethal and non-lethal/no increase). Five covariates were considered *a priori* to potentially influence use of predation control other than LGDs: (1) livestock type (sheep/goats/cattle/poultry/other); (2) property size (log-transformed for analysis); (3) livestock losses (as a binary variable, losses/no losses); (4) main predator type (dingoes/stray dogs/foxes/raptors/other); (5) LGDs free ranging or confined to paddocks. For each dependent variable, a 'base model' was created without any explanatory variables and we compared the 'base model' with models containing one of the other explanatory variables at a time according to AIC value (Burnham and Anderson 2002). Only the models containing the variables 'property size' and 'livestock losses' ranked higher than the base model. For the dependent variables 'type of control used in first survey' and 'change in control between the first survey compared with pre-LGDs', one additional model was created containing both these variables, and this was ranked with the the other models. However, for the other two dependent variables, 'property size' and 'livestock losses' were significantly correlated ($r_{pb}(105) = 3.24$, $P < 0.01$), so no additional models were created. We considered all models that fell within 2 ΔAIC of the top model to be reasonable descriptors of the data.

We estimated the rate of uptake of LGDs by farmers other than participants in the following way. Each participant was asked if they knew anybody who had taken up the use of LGDs as a direct result of their own use of LGDs. The sale of pups by farmers who breed from their LGDs was excluded from analysis because it seems likely that most people obtaining pups from breeders would only seek out a breeder after independently deciding to get a guardian dog. However, because it also seems likely that breeders could inspire others to try LGDs, each LGD-using farmer who also actively bred and sold pups was assumed to have had two other properties take up the use of LGDs at the time of the second survey as a result of using LGDs themselves. From these figures, a yearly LGD uptake rate was calculated as follows. First, for each participant, the number of other properties taking up the use of LGDs as a direct result of them using dogs was divided by the number of years that participant had used LGDs themselves. Then, the mean of that value was calculated for all participants. To calculate the yearly rate at which members of the cohort of original participants ceased using LGDs, we assumed that in addition to the interview participants who indicated they were no longer using LGDs, the uncontactable participants were also no longer using LGDs. The rate of decline in the cohort was then calculated as: no. participants no longer using LGDs (81)/mean time between first and second survey (8.9)/total no. participants (137). We then estimated the net rate of change in the use of LGDs by subtracting the rate of decrease in use of LGDs in the original cohort from the yearly LGD rate of uptake by other farmers with connections to members of the original cohort.

Results

Continued use of LGDs

Of the 112 participants in the follow-up survey, 56 (50%) had continued using LGDs through the almost 10 years since the initial survey and 56 (50%) had not (Fig. 1). The main reason for ceasing use of LGDs was a change in business that meant LGDs were no longer needed (53%; decisions unrelated to predation on livestock), followed by behavioural issues with the dogs (24%), and problems with neighbours (19%). See Table 1 for a full list of reasons.

The main advantages of using LGDs as reported by survey participants were: the protection they offered to livestock, property, or people (65%); peace of mind resulting from effectiveness of protection (12%); the loyalty and good temperament of the dogs (12%); improvements in livestock management other than protection from predators (6%); and reduced need for other forms of predation control (4%). There was a significant difference in the number of survey participants stating an advantage in each of these categories between participants still using LGDs and participants who had ceased using LGDs ($t(7) = 3.17$, $P = 0.03$). Participants who had discontinued their use of LGDs were more likely to mention an advantage related to the protective nature of LGDs (see Table 2).

The main disadvantages of using LGDs as reported by survey participants were: the commitment required to look after the dogs (40%); the commitment required for training, and difficulties that can arise with training (24%); occurrence of unwanted behaviour in dogs (19%); the presence and

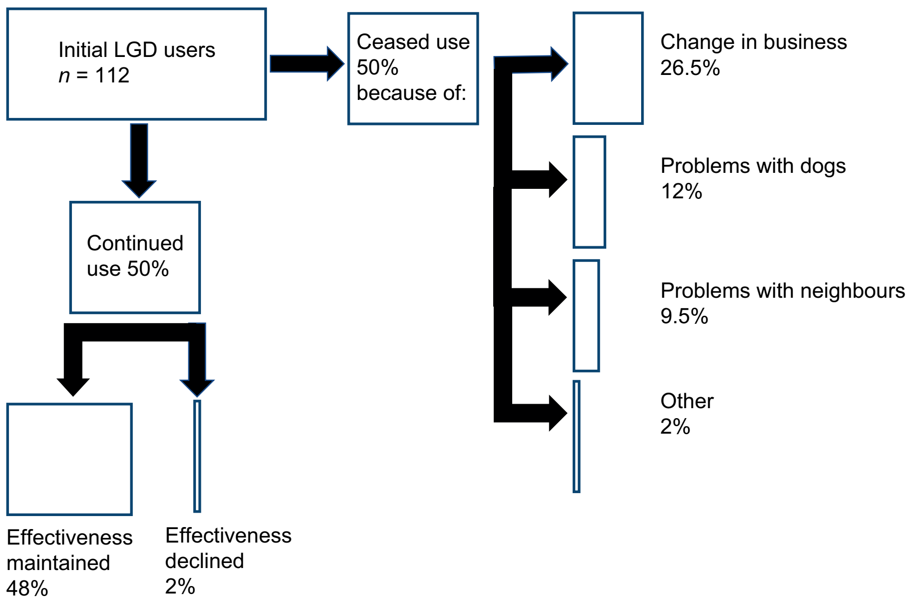

Fig. 1. Overview of survey outcomes, showing continued use of LGDs, reasons for discontinuation of their use, and effectiveness of long-term use. The width of each box represents the percentage of its category.

Table 1. Reasons why survey participants are no longer using LGDs.

Reason	Number		(%)
Change in business	38		53
Retired/about to retire/owner passed/different stock (not vulnerable)		29	
Sold business, other work altogether		9	
Problems with dogs	17		24
Behavioural (roaming/aggressive/harassing stock)		9	
Perceived non-effective		4	
Dog died, no suitable replacement		3	
Too much maintenance		1	
Problems with neighbours	14		19
Complaints about barking		9	
Neighbours killing LGDs (intentionally or accidentally with 1080)		5	
Other	3		4
No more predation, no need		1	
Not recovered from flood yet, lost dogs and stock		1	
Focusing on other control (alpacas)		1	

N = 56. There can be multiple reasons per respondent.

behaviour of LGDs adding complications to management of livestock (4%); cost (3%); and incompatibility with lethal control (3%). Participants differed in the disadvantages they stated according to whether they were still using LGDs or had ceased use ($t(7) = -2.33$, $P = 0.05$): those who had discontinued use were more likely to mention a disadvantage related to behavioural issues and the commitment required for training (Table 2).

When asked if they would recommend LGDs to other farmers, 100% of participants still using LGDs (N = 56) said they would, and 98% of participants no longer using LGDs (N = 42) also said they would. In most cases (46% of participants still using LGDs and 64% of participants no longer using LGDs), the participants clarified they would only make that recommendation if the farmer met certain criteria. Two main categories of criteria were mentioned: having the right situation (in terms of farm size, livestock type, area, and good neighbours) and being willing to commit time and effort to make the dogs work properly (that is, following good practice in bonding, training, caring for, and containing the dogs). Only one participant (without LGDs in the second survey) said they would not recommend them to anybody – in this case due to a perception of the dogs' aggressiveness.

LGD effectiveness after long-term use

Based on user-reported yearly stock losses, effectiveness of LGDs remained high for 96% (53 of 55) of participants who had continued their use (Fig. 1). In two cases, user-reported yearly stock losses were >5% higher in the second survey than in the first. In one of those cases, the ratio of number of livestock to dogs had increased 9-fold and the sole remaining LGD was over 10 years old; in addition, the participant indicated they had a problem of drench-resistant worms causing poor health in their livestock, which was contributing to the stock

Table 2. Advantages and disadvantages of the use of LGDs as reported by survey participants.

	Participants still using LGDs (*N* = 42)		Participants no longer using LGDs (*N* = 35)		Total (*N* = 77)	
	Number	(%)	Number	(%)	Number	(%)
Advantages						
Protection (livestock/property/personal)	42	59	32	76	74	65
Peace of mind knowing livestock is safe	12	17	2	5	14	12
Nice nature of the dogs (loyal, good temperament)	8	11	5	12	13	12
Improved livestock management	6	8	1	2	7	6
Reduced need for other control	3	4	2	5	5	4
Disadvantages						
Nothing	4	6	2	4	6	5
Looking after the dogs	35	53	16	28	51	43
Unwanted behaviour	10	15	13	25	23	19
Investment needed for training, and the difficulty of training	8	12	20	38	28	24
Complications with stock management	3	5	2	4	5	4
Cost	3	5	0	–	3	3
Incompatible with lethal control	3	5	0	–	3	3

Multiple reasons could be given by each participant. *N* indicates the number of participants whose answer could be included in the analysis.

Table 3. Reasons for the death of LGDs prior to old age.

Reason for loss	Number		Percentage of dogs that died (296)	Percentage of total (703)
Euthanised	78		26	11
Behavioural		61		
Medical		15		
Unspecified		2		
Lost to lethal predator control	77		26	11
Poisoning		67		
Shot		9		
Trapped		1		
Killed by other animals	56		19	8
Snake bite		44		
Wildlife (wild dog/kangaroo/pig/eagle)		7		
Domestic dog fight		4		
Cattle		1		
Disease (prior to old age)	29		10	4
Motor vehicle accident	10		3	1
Paddock accident	9		3	1
Unknown	37		13	5

Information was obtained on the fate of 703 LGDs from 110 survey participants. Of these 703 LGDs, 255 died of old age and 152 were re-homed; 296 (42%) died.

loss that year. In the second case, the participant indicated their number of livestock had increased 1.5-fold. They also increased the number of LGDs, but overall, the dog:stock ratio had decreased.

The results from the user-reported change in effectiveness of LGDs closely matched the results from the difference in yearly stock losses. Of 56 participants, 32 (57%) indicated they thought their dogs had become more effective in protecting livestock from predators over time (either because the LGDs' effectiveness improved with age, or because predators learned to avoid the farm) and 18 (32%) reported no change in effectiveness. Another two (4%) participants were unsure whether effectiveness had changed. Four (7%) said they thought their LGDs were less effective than in the first survey, which they attributed to the older age of their dogs (1), an increase in predators in the environment (1), and predators learning to work around LGDs, necessitating an increase in number of LGDs (2). Three of the participants who indicated that they thought their dogs were less effective were experiencing similar predation rates compared with the first survey, and one was experiencing increased predation.

Reasons for LGD loss

Of the 703 individual LGDs in our sample that were no longer in the possession of the survey participants, 296 (42%) died prior to old age. The three main reasons for death were: euthanasia (26%, mostly because of unwanted behaviour); being subjected to lethal predator control (either inadvertently or purposely), mostly poisoning (26%); and being killed by other animals (19%, mostly snake bite). Among the remaining 407 dogs, 255 died of old age and 152 were rehomed. Reasons for rehoming were: dogs surplus to requirements (140), dogs exhibiting unwanted behaviour (11), or unspecified (1). See Table 3 for a full list of fates of LGDs.

Predation control other than LGDs

Responses from the first survey showed that 60% ($N = 135$) of the participants had ceased or decreased the use of other forms of predation control when they began using LGDs (Table 4). Only 1% indicated they had increased other forms of predation control. Comparison of use of other forms of predation control between the first and second surveys indicated a partial recovery of alternative methods used together with LGDs. Compared with the use of predation control pre-LGDs, in the second survey 46% ($N = 46$) of participants had ceased or decreased the use of other forms of control; 17% had increased the use of other predation control (Table 4).

'Property size' was included as a covariate in the top-ranking models for all four dependent variables ('type of control used in first survey'; 'change in control between the first survey compared with pre-LGDs'; 'change in control between the first and second survey' and 'type of control being increased between the first and second survey'), and 'livestock losses' was included for the dependent variables 'type of control used in first survey' and 'change in control between the first survey compared with pre-LGDs' (Table 5). In all cases, the top model was more than 2 ΔAIC removed from the next best model and was therefore considered the best descriptor of the data. Participants on smaller properties were less likely to use other forms of predation control in addition to LGDs, and if they did use alternatives, these were more likely to be non-lethal methods. Participants on larger properties were more likely to use lethal control, or a

Table 4. The change in use of predation control other than LGDs, indicated in percentages of participants falling in each of the categories of change.

	First survey compared with pre-LGDs (%)	Second survey compared with pre-LGDs (%)	Second survey compared with first survey (%)
Cessation of other predation control	36	22	15
Reduction in other predation control	24	24	2
No change	25	24	23
Never used any other predation control	13	13	19
Increase in other predation control	1	17	42

Table 5. Ranking of models analysing the use of predator control other than LGDs, and the covariates included in those models.

Model covariates	AIC	Delta AIC	AIC weight
Type of predator control used in addition to LGDs in the first survey			
Property size, livestock losses	272.81	0.00	0.92
Property size	277.70	4.90	0.08
Livestock losses	323.78	48.48	0.00
BM	336.09	50.00	0.00
Change in control between the first survey compared with pre-LGDs			
Property size, livestock losses	143.16	0.00	0.87
Property size	145.70	2.53	0.22
Livestock losses	168.47	25.31	0.00
BM	173.25	30.08	0.00
Change in control between the first and second survey			
Property size	97.30	0.00	1.00
Livestock losses	108.60	11.30	0.00
BM	111.50	14.20	0.00
Type of control increase in second survey			
Property size	121.03	0.00	0.89
Livestock losses	125.35	4.32	0.10
BM	130.65	9.26	0.01

Only models ranking higher than a base model 'BM' (without covariates, only including the intercept) are included.

combination of lethal and non-lethal control, in addition to LGDs. Participants still experiencing livestock losses were more likely to use lethal control or a combination of lethal and non-lethal control methods, whereas participants not experiencing any livestock losses were more likely to use non-lethal control or no control in addition to LGDs. Participants on larger properties were more likely to decrease their use of predation control other than LGDs compared with pre-LGD use, whereas participants on smaller properties were more likely to continue using the same level of other predation control with LGDs as they did pre-LGD use. Participants who were still experiencing livestock losses were more likely to increase their use of other predation control in addition to LGDs compared with pre-LGD use.

Compared with the first survey, participants on larger properties were more likely to increase the use of predation control other than LGDs in the second survey, and they were more likely to use lethal control compared with other control options; participants on mid-sized properties were more likely to increase both lethal and non-lethal control efforts. Participants on smaller properties were more likely to have maintained the same level of control. See Fig. 2 for an overview of the relationship between property size and the use of predation control methods other than LGDs.

LGD uptake

The uptake rate of additional users of LGDs as a result of the influence of existing users was 0.12 farmers/existing user/year (data from 96 participants); the rate of decrease of the use of LGDs in the original cohort of participants was 0.07 LGD users/existing user/year. The difference in these values was 0.05, indicating a net increase of 5% per year in the number of farmers using LGDs.

Discussion

Our results show that LGDs can maintain effective control of predation on livestock over long periods of time, and that there is no strong or consistent tendency for their effectiveness to decrease with long-term use. This confirms our conclusion from previous research (van Bommel and Johnson 2012) and agrees with other studies of programs in which LGDs were placed on cooperating farms and followed over time to monitor their effectiveness (Coppinger *et al.* 1988; Marker *et al.* 2021). Due to its consistent effectiveness, the use of LGDs in Australia appears to be increasing as a result of uptake by farmers who are influenced by the positive experiences of other farmers known to them. Half of the farmers in our original sample ceased using LGDs mainly due to retirement or other changes in their business rather than dissatisfaction. However, each farmer in the sample influenced more than one other to begin using LGDs, suggesting a positive rate of growth in the total number of users due to personal contacts alone.

In almost all cases where effectiveness of LGDs in protection livestock could be compared over the decade between the first and the repeat survey, it remained high. In the two cases where impact of predation increased, the number of livestock had increased without a corresponding addition of LGDs. For LGDs to be effective in controlling predation, a sufficient number of dogs needs to be used

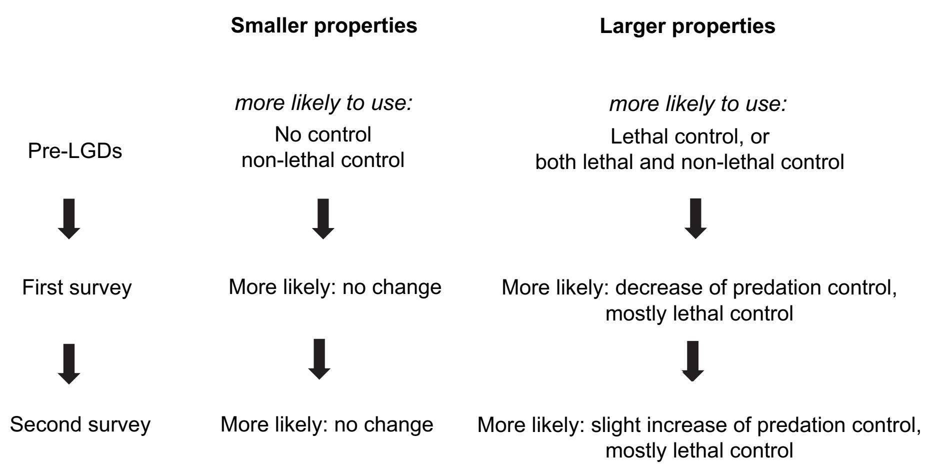

Fig. 2. The relationship between property size and the use of predation control methods other than LGDs between the first and second survey, obtained from multinomial logistic regression models (Table 5). In addition to property size, continuing livestock losses were also found to be an important explanatory variable. Participants still experiencing livestock losses were more likely to use lethal control (or a combination of lethal and non-lethal control) in the first survey, and were more likely to have increased their use of predation control in the first survey compared with pre-LGDs.

(Breitenmoser *et al.* 2005; van Bommel and Johnson 2012). The number of livestock needing protection is an important factor determining how many dogs are needed (van Bommel and Johnson 2012; Potet *et al.* 2021). Therefore, running more livestock without increasing LGDs to maintain a suitable ratio of stock to dogs is likely to see a decrease in effectiveness of protection. Even though reported predation rates in the second survey increased for only two participants, four participants indicated that they thought their dogs had decreased in effectiveness. However, only one of these participants experienced an actual increase in predation. Perception does not always match reality, and the perception of effectiveness of LGDs can lack objectivity (Gehring *et al.* 2010). User-reported predation rates can also be unreliable (Green and Woodruff 1983). However, given the overall low number of users either reporting increased predation or perceiving lower effectiveness of their LGDs, we are confident that the true number of cases of declining effectiveness of LGDs was low.

Discontinuation of use of LGDs was mostly for reasons unrelated to the dogs themselves, such as retirement of the farmer or a change in business. However, the second most important reason was due to problems related to dog behaviour. This is also reflected in statements by farmers who no longer used LGDs that training demands and behavioural problems are the main disadvantages of LGDs, and is probably linked to the result that one of the leading causes of death for working livestock guardian dogs is euthanasia due to unwanted behaviour (both on farms continuing the use of LGDs and farms where their use was discontinued). It appears that despite the general success of LGDs, some farmers in Australia experience problems of unwanted behaviour in their LGDs, which they have difficulty solving. Possibly, this is related to the relatively small gene pool of the available LGDs. Lorenz *et al.* (1986) found a genetic component to behavioural problems with LGDs in their study. Given the small number of imported LGDs in Australia, any genetic component of unwanted behaviour could be widespread throughout the LGD population. Unwanted behaviour could also be due to crossbreeding with non-livestock guarding breeds of dogs. Cross-breeding could lead to the loss of specialised LGD traits, such that progeny are less suitable for the task of protecting livestock (Coppinger and Coppinger 2001).

It is also possible that the widespread reporting of unwanted behaviours reflects a lack of information and support for Australian farmers regarding proper training, raising, and management of LGDs. It is our view that many of the behavioural problems mentioned by interviewees could be prevented or solved by good practice in training and management of the dogs. Studies have shown that problem behaviour in LGDs can be solved with corrective training (Marker *et al.* 2005*a*; Rust *et al.* 2013; Whitehouse-Tedd *et al.* 2020). Coppinger *et al.* (1987) had success in solving behaviour problems by transferring dogs that displayed unwanted behaviour to new situations to which they were individually better suited and where they became effective guardians. Implementation of such a strategy would require an agency able to provide information to farmers and intervene as needed to resolve problems, but no such organisation exists in Australia.

The reported rate of euthanasia in our survey (26%) was similar to that found in other studies (Lorenz *et al.* 1986; Green and Woodruff 1990; Marker *et al.* 2005*b*). However, the leading cause of death of LGDs in other studies is often reported to be accidents. For example, Green *et al.* (1984) reported 35% of deaths in the USA to be due to accidents (vehicle and field accident), and Marker *et al.* (2021) found that in Namibia, 54.2% of deaths were due to accidents, but did not elaborate on exact causes. Lorenz *et al.* (1986) report that in the USA, 57.4% of deaths were accident-related; however, they included disappearance of the dog, poisoning and shooting as accidents – poisoning and shooting accounted for 12.9% of deaths, and the authors assumed that most missing dogs also died from lethal predator control, bringing the contribution from lethal control to 31.4%. Lethal predator control was also a second leading cause of LGD death in our study (26%). The high number of LGDs killed by wildlife (mainly by snake bite) in our research is similar to the rate of death by snake bite of LGDs in South Africa (Rust *et al.* 2013). Although the high percentage of dogs euthanised for behavioural reasons seems to be common to most studies, the other main causes of death of LGDs seem to differ among regions, most likely related to environmental and social factors.

We found that the use of LGDs reduces the need for other predation control methods. Following initial deployment of dogs, farmers generally reduced or ceased other forms of predation control. Over the longer term, farmers resumed other forms of control to some extent, but use of these methods remained below pre-LGD levels. Reduction in other forms of predation control can represent a significant saving in time, effort and cost (van Bommel 2010). Non-lethal control is often labour intensive (van Bommel and Johnson 2014), but lethal control must also be intensive, well-coordinated and applied over large areas on a continuing basis to achieve an effective long-term reduction in predator numbers (Ballard *et al.* 2020); otherwise, local reductions in predator abundance are quickly reversed by immigration (Saunders *et al.* 1995; Allen and Gonzalez 1998; Corbett 2001). In addition, there is concern about the impact of lethal control on non-target animals (Fleming *et al.* 2001; Glen and Dickman 2003; Glen *et al.* 2007) and on dingo populations. Dingoes perform an important ecological function as Australia's top predator, and reducing their numbers could negatively affect biodiversity (Johnson *et al.* 2007; Letnic *et al.* 2011, 2012). Use of LGDs does not have these disadvantages, so an associated reduction in other predation control efforts could entail many benefits, for both farmers and Australian biodiversity.

The use of LGDs as a predation control method can be effective for extended periods of time, and as a result it tends to spread from users of LGDs to non-users in the surrounding region. We estimated that the rate of uptake by new users was higher than the rate of discontinuation by existing users, leading to a net increase, albeit at a slow rate. LGDs offer many benefits to farmers, extending beyond protection from predators and reduced need for other forms of predation control. LGDs can alleviate stress in livestock associated with predator attacks (van Bommel 2010), and this can increase the stock's productivity and make them easier to manage. This alleviation of stress also extends to the livestock owners, who gain peace of mind knowing the guardian dogs' continual presence will keep their livestock safe from predation. LGDs can also play a role in disease management, by separating livestock from wildlife that could potentially transmit pathogens (Gehring *et al.* 2010). However, the successful implementation of LGDs requires time and knowledge from producers, especially if unwanted behaviour is encountered.

Given the advantages of LGDs, it would be very beneficial for governments and management agencies to further promote their use and offer support to farmers in the form of training, and advice in management and problem-solving. This form of support is currently available for many other methods of predation control in Australia but is non-existent for LGDs. Support of that nature would greatly benefit producers who are interested in using LGDs, or who are already using them but are experiencing problems. It would likely further increase the success of this method for control of predation of livestock in Australia, and contribute to the economic and environmental sustainability of livestock production.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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