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RESEARCH ARTICLE

The longevity of para-aminopropiophenone (PAPP) wild dog baits and the implications for effective and safe baiting campaigns

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Abstract Considerable effort goes into mitigating the impacts caused by invasive animals and prohibiting their establishment or expansion. In Australia, management of wild dogs (*Canis lupus dingo* and their hybrids) and their devastating impacts is reliant upon poison baiting. The recent release of baits containing the humane toxin para-aminopropiophenone (PAPP) offers potential improvements for control of wild dogs, but little is known about the environmental persistence of PAPP in manufactured baits that could be used to inform best practice guidelines. We investigated the degradation rate of PAPP wild dog baits (DOGABAIT™) under typical field usage and storage conditions in north-eastern Australia and calculated optimal deployment and withholding periods. The PAPP content of buried baits declines faster than surface-laid baits, but both presentations retained lethal doses to wild and domestic dogs for considerable periods (6–16 weeks). Domestic or working dogs should be suitably restrained or excluded from baited areas for extended periods, particularly under dry conditions, to minimise poisoning risk. The period of persistence of PAPP baits may provide opportunities to improve the duration or longer term efficacy of baiting campaigns, but care is needed to protect domestic and working dogs to ensure responsible and safe use.

Keywords DOGABAIT™ · Dingo · Canid · Invasive species · Poisoning

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Introduction

Invasive animals can have major economic, environmental and social impacts. Whether native or exotic, pest animals are one of the primary drivers of global biodiversity loss; they can cause substantial damage to crops and other vegetation, and they can affect livestock enterprises by preying on stock or competing for pasture (e.g. Bellard et al. 2016; Gong et al. 2009). Considerable investment and effort goes into mitigating the damage caused by pest animals and prohibiting their establishment or expansion.

Wild dogs (*Canis lupus dingo* and their hybrids) are a pervasive vertebrate pest throughout much of Australia (Wicks et al. 2014), responsible for impacts that include spreading zoonotic diseases, maiming and killing domestic pets, livestock and native species and threatening people (Allen et al. 2013; Fleming et al. 2014; Gentle and Allen 2012). Methods used to manage the impacts of wild dogs include trapping, exclusion fencing, guardian animals and other lethal and non-lethal approaches, although, for efficient broadscale control, management remains heavily reliant on the use of bait-delivered toxins, specifically 1080 (sodium fluoroacetate) (viz Fleming et al. 2014). The advantages of 1080 use for wild dog control include relatively high target specificity, low cost and ready biodegradation. Disadvantages include a relatively long time to death (a few hours), the potential for secondary

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poisoning (arising from consumption of vomitus or carcasses from poisoned animals), distressing behaviour of poisoned dogs and the absence of an antidote for 1080 poisoning. Improving these and other animal welfare outcomes has been one key driver for the development of the toxin para-aminopropiophenone (PAPP) as an additional vertebrate pesticide (Eason et al. 2014; Fleming et al. 2006; Sherley 2007; Southwell et al. 2011).

Following oral ingestion, mammalian carnivores like dogs, foxes and cats rapidly convert PAPP into a toxic metabolite. This enters the bloodstream and is absorbed by red blood cells and induces methaemoglobin formation. This decreases the ability to transport oxygen throughout the body. Increased levels of methaemoglobinaemia (>70–80%) reduces oxygen to the brain, heart and muscles, ultimately resulting in death via respiratory failure (Coleman and Coleman 1996; Eason et al. 2014; NWR 2006). Thus, PAPP has many desirable attributes as a vertebrate pesticide including a humane, rapid and reliable mode of action; relative target specificity to mammalian carnivores; ease of formulation and manufacture as palatable bait; and oral bioavailability (Eason et al. 2014; Southwell et al. 2011). Methylene blue can reverse methaemoglobinaemia and is also considered an effective antidote to PAPP poisoning (Eason et al. 2014). PAPP is also readily biodegradable through microorganisms and has low toxicity to soil invertebrates, although little supporting data is currently in the public domain (McLeod and Saunders 2013; Southwell et al. 2011).

PAPP was originally synthesised in 1900, and initial research focussed on investigation as an antidote to cyanide poisoning in humans (Baskin and Fricke 1992). Toxicity studies established that mammalian carnivores were particularly susceptible to PAPP, leading to investigations as a toxin to control coyotes (*Canis latrans*) in the USA (Savarie et al. 1983; Eason et al. 2014). In Australia, development of PAPP over the last decade or so has focussed on applications to target feral cats (*Felis catus*), European red foxes (*Vulpes vulpes*) and wild dogs (Fleming et al. 2014; Marks et al. 2004). Manufactured baits containing PAPP were registered in January 2016 for wild canid control in Australia. Thus, PAPP became the first new predator toxin in bait to be registered since the advent of 1080 over 50 years ago (McDonald 2016). PAPP baits are commercially manufactured to contain either 1000 mg (DOGABAIT™) or 400 mg (FOXECUTE®) of PAPP in a shelf-stable bait medium. The availability of a methylene blue antidote provides a means of reversing the effects of accidental poisoning of non-target species, particularly companion or working dogs. The deployment of PAPP bait and availability of an antidote will be particularly advantageous for peri-urban areas or to reduce the risk of death from accidental poisoning of domestic dogs (Fleming et al. 2006). However, the antidote must presently be administered by a veterinarian, and due to the fast-acting nature of PAPP (unconsciousness typically occurs within an hour, and death within 2 h), administration of the antidote needs to be swift (30–90 min) (ACTA 2016; IACRC 2016). Additional precautions are therefore required to protect working and companion dogs during wild dog baiting programs.

Judicious governance of baiting programs should also consider the longevity of baits to determine appropriate guidelines for use. To be effective, bait needs to contain a lethal dose of toxin for long enough for the target species to find and consume bait, but ideally not for extended periods to avoid ongoing risk to non-target species (Gentle et al. 2007), including working dogs (e.g. on rural lands) or companion dogs (e.g. in peri-urban areas). Degradation rates for 1080 in different bait substrates have been well studied in a variety of environments (e.g. see Twigg et al. 2000; Twigg et al. 2001), but similar data for PAPP bait are not presently available. PAPP is reported to be readily biodegradable (McLeod and Saunders 2013), but few data exist on the degradation of PAPP, and none in the registered DOGABAIT™ bait substrate, that could be used to inform appropriate usage guidelines. It is therefore imperative that the environmental longevity of PAPP bait is investigated to provide safe and effective usage recommendations for practitioners.

This study investigates the degradation rate of DOGABAIT™ PAPP baits under typical field usage and storage conditions in north-eastern Australia. Firstly, the PAPP content was assessed in baits kept in typical storage conditions. Secondly, the degradation of PAPP was measured for common field deployment strategies—buried and surface-laid baits. Thirdly, we construct predictive models to estimate the period that baits contain a lethal dose for the target species (wild dogs, but also foxes) and likely non-target species (domestic dogs). Finally, we offer recommendations for the appropriate storage and use of commercially manufactured PAPP wild dog baits for the effective and safe control of wild dogs.

Materials and methods

The study was undertaken at the Maroochy Research Station (26.64° S, 152.94° E) in south-east Queensland, Australia. Maroochy Research Station is situated on the outskirts of Nambour on the Sunshine Coast and comprises horticultural crops and pastures, with some areas of remnant vegetation including rainforest fragments, and as such represents a typical peri-urban landscape where wild dogs occur and are subject to control (see Allen et al. 2013; McNeill et al. 2016). The climate of Nambour is coastal subtropical with warm to hot wet summers and mild dry winters; mean daily temperatures vary between 14.0 and 25.8 °C. Annual rainfall (mean) is 1693 mm (www.bom.gov.au).

The study was initiated in autumn 2015 to coincide with typical operational timing for wild dog control in peri-urban south-east Queensland (S. Harris and M. Gentle, unpublished data). Each DOGABAIT™ bait contains a nominal dose of 1000 mg PAPP and weighs approximately 60 g (mean weight = 60.5 g, SD = 1.4, $N = 28$). All baits used in the study were from the same manufactured batch and were kept in an air-conditioned (23 °C) storeroom until use. Baits were selected and allocated to one of three treatments (surface, buried or storage) at random. Each bait in the surface treatment was simply placed on the soil surface, whilst each bait in the buried treatment was placed in a small depression (~8–10 cm below the soil surface) then covered with soil. All baits were laid at least 30 cm apart. Baits were protected by cages (50-mm wire netting) within a fenced (50-mm netting, 1200 mm high) area to prevent access, interference and removal by birds or other animals. Remaining baits were stored in a chemical shed as per regulations.

Baits were deployed on day 0, and a sample of five baits removed per treatment every 1–5 weeks over a 25-week period. Individual buried baits were sampled until the bait substrate was indistinguishable from soil (25 weeks). At each sampling period, whole baits were removed from each treatment, weighed and individually bagged before being frozen (−18 °C) until analysis. All analysis was done within 2 weeks of the trial completion. Any insect or decomposition activity on baits was noted, and samples taken for identification of insect species.

Data loggers (Cool Tech® CT750) were used to record information on temperature (°C) and relative humidity (%) at 30-min intervals at both the trial site and storage shed throughout the trial period. Local daily rainfall data were collated from Maroochy Research Station records, acquired through the Bureau of Meteorology (Nambour DAFF Hillside 040988; www.bom.gov.au).

PAPP content assays

The PAPP content assays were undertaken in a National Association of Testing Authorities (NATA)-accredited laboratory (ISO 17025). For reasons of economy, three or four baits were assayed for each treatment and each sampling period. Baits were shredded and then twice extracted with 200 ml of methanol for 20 min in an ultrasonic bath. The extracts were combined and adjusted to 500 ml, and a fivefold dilution of the extract in methanol water (1:1) was then filtered through a PTFE syringe filter for high-performance liquid chromatography analysis.

Statistical analysis

Linear mixed models were used to assess the rate of PAPP decay in baits using the residual maximum likelihood (REML) method (Patterson and Thompson 1971). Initially, all treatments were analysed over time to enable comparisons with control sample (week 0) baits. Control sample baits were then excluded to examine the effect of treatment over time, with subsequent comparisons between field treatments (buried and surface). Effects where $\alpha \leq 0.05$ were followed with pairwise comparisons using Fisher's least significant difference (LSD) procedure. Statistical analyses were performed using Genstat® (Version 17).

Results

Climate data

Rainfall totals at Maroochy Research Station for the months immediately prior to, and during, the trial and relationship with long-term median rainfall (1952–2007) are shown in Table 1. Field baits were exposed to >500 mm of rainfall during the course of the experiment. Rainfall was distributed mostly in amounts of <5 mm, but several falls >25 mm occurred, including 93 mm during week 3 of the trial (Fig. 1). Rainfall during the month prior to bait deployment (March) was well below (−92.2 mm) the median. However, for the months encompassing bait deployment (April–October), rainfall was well above median monthly totals (pooled) for this period (+235 mm cumulative total).

In the storage shed, the mean (±SD) temperature over the 25-week period was 18.8 ± 5.8 °C and varied widely (range 4.6–35.7 °C). Mean relative humidity was 66.3 ± 18.2% (range 20.1–91.8%). Climatic conditions at the field site were more variable than in the storage shed but slightly cooler (average 17.0 ± 4.3 °C, range 5.1–31.9 °C; also see Fig. 1) and more humid (average relative humidity at 75.5 ± 16.5%, range 20.5–93.8%).

Table 1 The amount of rainfall (mm) that fell in the month before and during the trial period at Maroochy Research Station, Nambour in 2015

Month	Rainfall (mm)	±Median rainfall
March	66.8	−92.2
April	239.9	+129.4
May	177.4	+53.2
June	71.8	+29.0
July	18.7	−34.8
August	90.5	+37.3
September	63.7	+27.8
October	85.0	−6.8

The rainfall (mm) that fell in each month is shown relative to the long-term median, for example, +53 is 53 mm greater than the median

PAPP content and shelf stability of stored PAPP baits

The mean (±SD) PAPP content in day 0 (control) baits was 933.3 (SE = 25.7; N = 4), approximately 7% less than the nominal dose at manufacture (1000 mg PAPP) approximately 10 days prior. There was no significant difference in PAPP content between day 0 (control) baits and subsequent sampling of stored baits until after week 20 (LSD = 68.4 mg). After 25 weeks, baits still retained approximately 90% of their original dose (846.3 mg; SE = 25.7; N = 3).

The relationship between PAPP content in stored baits and time over 25 weeks (Fig. 2) conformed to a simple linear trend (adjusted R^2 = 67.3%), with the equation

$$\text{PAPP (mg)} = 945.9\ (\text{SE} = 8.35) - 4.94\ (\text{SE} = 0.66) \times \text{week} \quad (1)$$

Degradation and estimated longevity of PAPP in baits

PAPP content differed over all treatments and time, as expected ($F_{22,\ 47}$ = 147.91, p = <0.001). When removing the control and time 0, the factors treatment ($F_{2,\ 47}$ = 463.74, p = <0.001), time ($F_{7,\ 47}$ = 204.14, p = <0.001) and the treatment × time interaction ($F_{12,\ 47}$ = 64.25, p = <0.001) all showed significant differences in the rate of degradation in the buried, surface and storage treatments. Comparison of the two field treatments (buried, surface) showed a significant difference in treatment ($F_{1,\ 47}$ = 20.32, p = <0.001), time ($F_{7,\ 47}$ = 283.02, p = <0.001) and the interaction of treatment and time ($F_{5,\ 47}$ = 38.04, p = <0.001) suggesting different rates of decrease in PAPP for different treatments.

Comparisons between treatments within each time and pairwise tests (LSD = 73.1 mg PAPP) were undertaken to compare the mean PAPP content in treatments within each sampling period (Table 2). At week 1, there were no significant differences in the mean PAPP content detected between treatments, but at weeks 2 and 4, surface-laid and buried baits were significantly lower than stored baits, but not different from each other. The three treatments were significantly different for weeks 8, 12 and 16, and the remaining control and surface-laid treatments were significantly different for weeks 20 and 25.

From weeks 8 to 25, the mean PAPP content for each treatment became significantly different with buried baits having the least PAPP and stored baits the most.

The decline of PAPP content in surface-laid and buried baits was modelled using linear and logistic regression respectively (Figs. 3 and 4). Similar to stored baits, the decline of PAPP in surface-laid baits conforms well to a linear trend (adjusted R^2 = 94.9%), with the equation

$$\text{PAPP (mg)} = 948.6\ (\text{SE} = 22.3) - 33.75\ (\text{SE} = 1.63) \times \text{week} \quad (2)$$

The degradation of PAPP in buried baits follows a sigmoid trend and was well represented by logistic regression (adjusted R^2 = 98.8%), with the equation

$$\text{PAPP (mg)} = 7.6 + 1001.1/\left(1 + e^{0.427 \times (\text{week} - 6.706)}\right) \quad (3)$$

Equations 2 and 3 (above) were used as predictive models to estimate the time that field-deployed DOGABAIT™ baits will remain lethal to wild dogs and to other likely non-targets

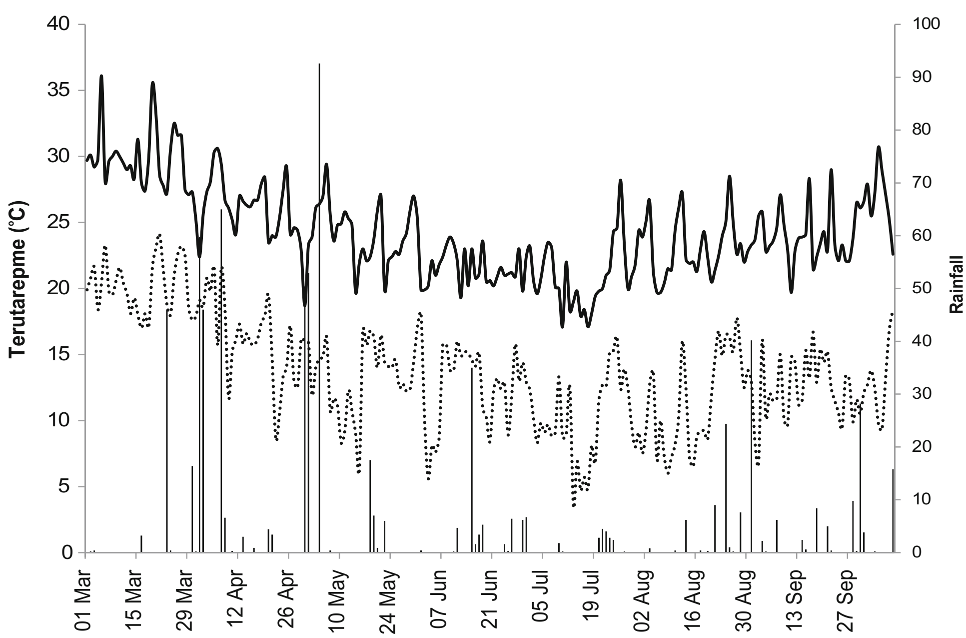

Fig. 1 Daily ambient minimum and maximum temperature and daily rainfall (mm) at Maroochy Research Station for the period immediately before and during the study period, specifically 17 April to 9 October 2015. Minimum temperature (*solid grey line*), maximum temperate (*solid black line*) and rainfall (mm) (*solid bar*)

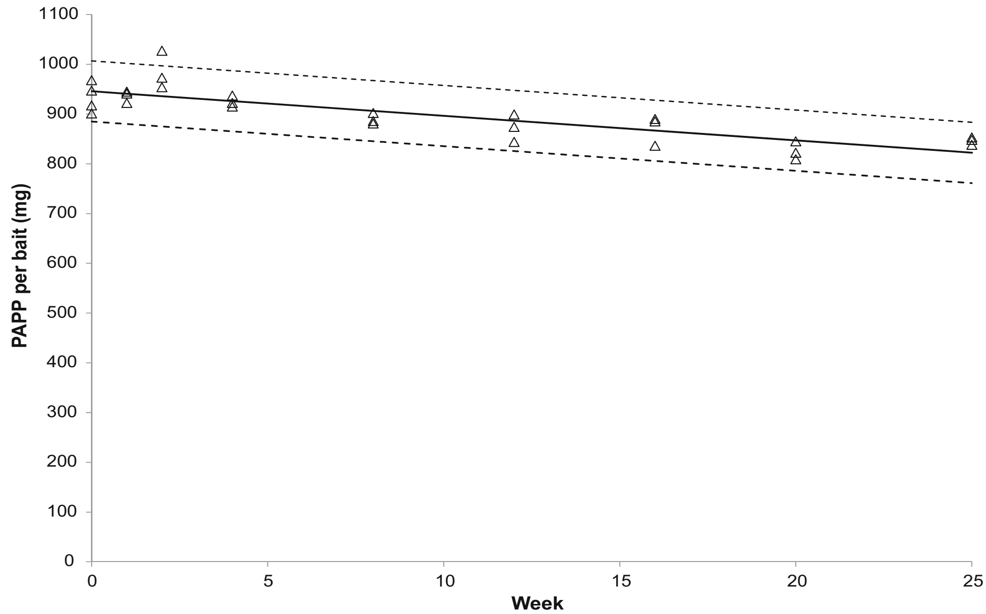

Fig. 2 Fitted model for the mean loss of PAPP (*solid line*) and 95% confidence limits (*dashed lines*) for individual baits stored up to 25 weeks in a chemical store

(domestic dogs, foxes) under similar conditions. The oral lethal dose (LD_{50}) for wild dogs is reported as 8.5 mg kg^{-1} (NWR 2006), although the bait-delivered LD_{50} is considered much higher (Humpreys and Staples, personal communication 2016). In the absence of lethal doses in bait for wild dogs, we used data from domestic dogs (conservatively estimated at 26 mg kg^{-1}; Murphy et al. 2007). This equates to a lethal dose of 416 mg of PAPP for an average-sized adult wild dog (~16 kg; Allen and Leung 2014) and 390 and 520 mg respectively for estimated adult sheep dogs (15 kg) and cattle dogs (20 kg; Fleming and Parker 1991). For an average adult red fox (~5 kg; Winstanley et al. 1999), the lethal dose was estimated as 126 mg of PAPP, given an LD_{50} of 25.2 mg kg^{-1} (Marks et al. 2004). The approximate lethal dose of PAPP (mg) for each species of interest was then applied to the decay curves to estimate longevity and risk (Table 3). This analysis indicated that 50% of surface-laid DOGABAIT™ should remain lethal to wild dogs for approximately 15.8 weeks, with 95% confidence limits predicting a lethal period between 11.7 and 19.8 weeks (Table 3). In contrast, the buried baits decayed to contain 416 mg PAPP in about half this time (mean = 7.6 weeks; 95% CI = 6.7–8.5 weeks). Buried baits still pose a theoretical poisoning risk (at LD_{50} levels) to large domestic dogs (e.g. sheep and cattle dogs) for at least 5.8 weeks.

Table 2 Mean PAPP content (mg) for each bait treatment (storage, buried, surface) at each sampling period (week)

Week	Storage	Buried	Surface	Significance probability
1	936.0a	923.7a	922.3a	0.918
2	984.7a	902.7b	864.0b	0.006
4	924.7a	756.7b	785.7b	<0.001
8	889.7a	383.0c	689.0b	<0.001
12	872.3a	88.7c	599.0b	<0.001
16	870.3a	34.1c	367.0b	<0.001
20	825.3a	–	329.7b	<0.001
25	846.3a	–	62.3b	<0.001

Significant differences between means within each sampling period using pairwise comparisons (Fisher's LSD = 73.1 mg PAPP) are indicated by different letters (a, b or c); means within sampling period sharing the same letter are not significantly different. Comparisons between conditions within a week (significance probability) were all significantly different except for week 1

Discussion

This is the first study to quantify the rate of environmental degradation of DOGABAIT™ PAPP baits for wild dog control, with degradation rates being influenced by bait presentation method. The PAPP content of buried baits declined faster than surface-laid baits. Our data suggest that surface-laid baits can retain lethal doses for wild dogs for up to 19.8 weeks (Fig. 3 and Table 3). Baits kept under storage conditions only show gradual loss of PAPP, as expected, and are considered relatively shelf-stable. These results and their application to the management of wild dog baiting programs are discussed below.

PAPP is considered biodegradable, but there is limited available information on degradation processes. PAPP may be susceptible to photolysis from sunlight and can degrade through atmospheric reactions with hydroxyl radicals (APVMA 2015; Meylan and Howard 1993). However, both of these processes appeared to be insignificant contributors to the degradation rates observed in our study given the relative

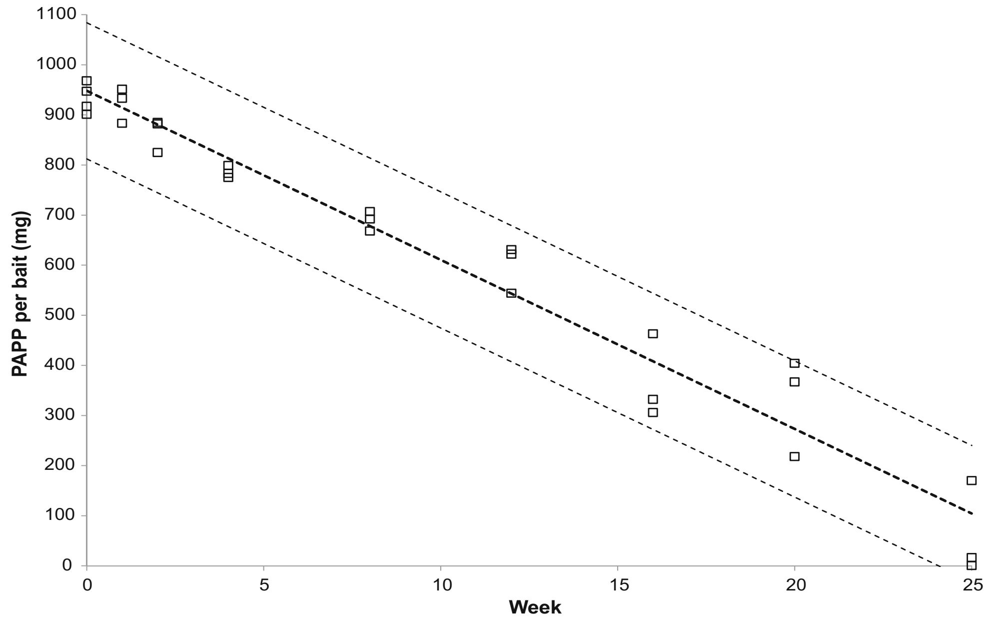

Fig. 3 Fitted model for the mean loss of PAPP (*solid line*) and 95% confidence limits (*dashed lines*) for individual surface-laid baits up to 25 weeks since initial deployment at Maroochy Research Station

slow speed of degradation of surface-laid baits (i.e. full sunlight, atmospheric exposure) compared to buried baits (i.e. no sunlight or atmospheric exposure). Laboratory tests indicate that PAPP is moderately water soluble and is highly mobile in soils (Brumley 2007), suggesting that leaching by rainfall is likely to be an important factor for loss of PAPP from bait material. However, PAPP in the DOGABAIT™ bait substrate appears relatively resistant to leaching given that baits were exposed to several large rainfall events during the trial period (Table 1). Leaching was probably not a major contributor to PAPP loss, given that surface-laid baits (directly exposed to rainfall) degraded at a slower rate than buried baits.

Physical decomposition of the bait structure is likely an important contributor to PAPP loss. Surface-laid baits showed gradual, rather than dramatic, decay in physical structure over 25 weeks. Buried baits were visibly soft at the first sampling period (1 week) and appeared to absorb and retain moisture from the soil, particularly following rainfall events. The PAPP content of buried baits declined rapidly following week 4 and was lower than in surface baits at the week 8 sampling period (Figs. 3 and 4). PAPP is reportedly readily broken down in soil and water by microbes (Southwell et al. 2011), and microbial abundance appears to increase following rain (Twigg et al. 2001). Burying bait is intended to reduce non-target risks,

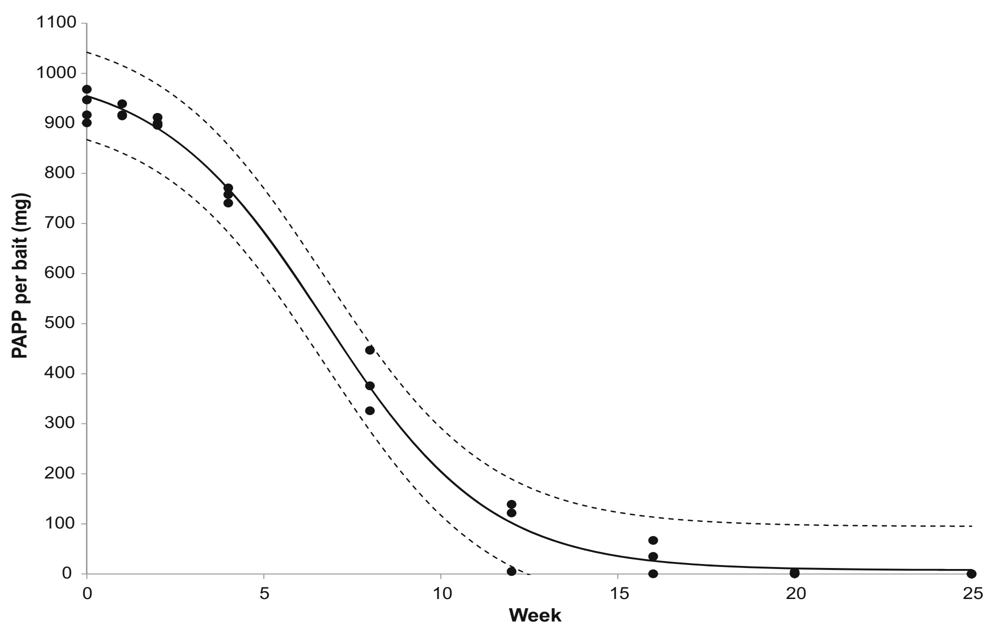

Fig. 4 Fitted model for the mean loss of PAPP (*solid line*) and 95% confidence limits (*dashed lines*) for individual buried baits up to 25 weeks since initial deployment at Maroochy Research Station

Table 3 The amount of PAPP (mg) required for a lethal dose and mean time (in weeks) that DOGABAIT™ remains lethal to wild dogs, sheep and cattle dogs and foxes after field deployed

	Wild dog	Sheep dog	Cattle dog	Fox
Approximate amount of PAPP (mg) for lethal dose	416	390	520	126
Surface—mean time (weeks) ≥ lethal dose	15.8 (11.7–19.8)	16.5 (12.5–20.6)	12.7 (8.7–16.7)	24.4 (20.3–28.4)
Buried—mean time (weeks) ≥ lethal dose	7.6 (6.7–8.5)	7.8 (7.0–8.7)	6.6 (5.8–7.4)	11.4 (9.9–14.8)

Figures in parentheses represent lower and upper confidence limits of predicted lethal period (weeks). Based on Gentle et al. (2007)

but also increases access to the bait substrate by soil microbes and provides favourable environmental conditions (temperature, moisture) to support microbial growth. Decomposer (bacteria, fungi and other microorganisms) activity and physical decay are probably the key drivers of PAPP loss. Insects can greatly assist in the decomposition process of meat-based baits (e.g. McIlroy and Gifford 1988), but observed insect activity on DOGABAIT™ baits was low. No fly larvae were recorded on any bait at any stage. Both buried and surface-laid baits showed signs of consumption by coastal brown ants (*Pheidole megacephala*) by 8 weeks which may have contributed to physical decay of the bait substrate, but appeared to contribute little to decay rates. Overall, the manufactured bait substrate used in DOGABAIT™ appears to be reasonably resistant to degradative processes, likely contributing to the longevity of PAPP. Similar observations of bait substrate persistence have been reported during earlier field trials of DOGABAIT™ under other environmental conditions (Allen 2011).

Our results have several practical implications for the storage and use of PAPP baits in control campaigns for wild dogs. DOGABAIT™ appears relatively shelf-stable, with only a gradual loss of PAPP (mean = ~10%) recorded after a 25-week period under typical storage conditions. If the degradation continued at the same rate, the fitted model indicates that after 1 year (52 weeks), shelf-stored baits would contain ~689 mg PAPP, which still exceeds the LD_{50} for wild dogs (416 mg; Table 3). While this apparent long shelf life is reassuring, bait ageing may reduce the attractiveness and palatability of manufactured baits after deployment. Given these considerations, our results suggest that operators should avoid storing bait for extended periods to minimise any potential changes that may affect efficacy (PAPP content).

Results from the field-deployed bait also indicate that PAPP baits can remain toxic to wild and domestic dogs for considerable periods. This not only has obvious advantages for extending the duration of baiting programs but also has ramifications for ensuring effective and safe baiting strategies. Immigration or reinvasion into baited areas from unmanaged areas is a known constraint to long-term effectiveness of baiting campaigns for wild dogs and foxes (e.g. Allen et al. 2014; Allen 2015; Newsome et al. 2014). Rapidly degrading bait (such as when 1080 is the toxin) will usually degrade to sublethal levels before immigrants' recolonising baiting areas have the chance to find and consume bait. Thus, additional, follow-up or 'pulse' baiting campaigns are often required to achieve a good level of control. The extended period that PAPP DOGABAIT™ remains lethal may therefore be advantageous to extend the duration of baiting campaigns and potentially target individuals immigrating or reinvading baited areas. However, extended bait longevity also warrant increased caution with respect to withholding periods or 'safe' time frames where at-risk non-targets (e.g. working dogs and domestic dogs) can be safely exposed to baited areas after baiting.

As for 1080, PAPP is a restricted Schedule 7 controlled substance, with limitations on access and usage (ACTA 2016). Given the long history of 1080 use in Australia, most pest practitioners are thoroughly familiar with strategies for the safe and effective deployment of 1080 baits for predator control. Much data are available on 1080 degradation in meat baits (e.g. Fleming and Parker 1991; McIlroy and Gifford 1988; Twigg et al. 2000), but little of relevance to the study area. Under the wet or humid conditions such as experienced at south-east Queensland, fresh meat 1080 baits would typically remain lethal for wild dogs for periods less than 4 weeks (Beck 1985; Gentle unpublished data), although bait type (fresh meat or manufactured) would also influence degradation rates (e.g. Gentle et al. 2007). Meat baits containing 1080 can also persist for up to 8 months under dry conditions (Twigg et al. 2000). Our data show that under 'wet' conditions, buried and surface-laid PAPP baits retain lethal doses for domestic dogs for approximately 2 and 5 months respectively. It is reasonable to expect that under dry conditions, PAPP baits could potentially persist for extended periods, but this needs further investigation. Available evidence suggests that PAPP baits would degrade at substantially slower rates than 1080 baits, and thus, extra care would be required by field users where risk to non-targets is a concern. We therefore recommend that working or domestic dogs should be excluded from or safely restrained in baited areas for extended periods, particularly under drier conditions than those experienced here, to provide a suitable margin for domestic dog safety. Where baiting is infrequent and continual exposure of toxic baits is undesirable, we also strongly recommend that any uneaten baits are retrieved at the end of the baiting campaign, to further minimise potential long-term risk. Following these recommendations will help ensure that the efficacy of PAPP baits for wild dog control is maximised and associated risks are managed.

The lethal doses and the calculated lethal periods (weeks) we report are estimates only and need to be interpreted and used with caution. PAPP baits are known to contain a high dose to ensure high efficacy for wild dogs (ACTA 2016). For all dogs, we used the conservative estimate of LD_{50} (26 mg kg^{-1}) based on published data from domestic dogs (Murphy et al. 2007), which is considerably higher than the (gavage-delivered) LD_{50} for wild dogs from the literature (NWR 2006). Additionally, field data are representative of the environmental and climatic conditions at the time of the study, and reported oral LD values can vary widely depending on protocols and determination method, as well as environmental and individual variations in animals studied (Eason et al. 2014; McIlroy 1981). This period should be viewed as a minimum, given individual variations in sensitivity to PAPP and the likelihood that a 50% risk of a lethal dose (i.e. LD_{50}) would probably be unacceptable to most dog owners. The calculated lethal periods to target wild dogs should also not be considered as unequivocal, but rather as informative for potential longevity periods, which appear considerably longer than for 1080.

It is also important to provide a caveat for the application of the outcomes from this study to other environments. The results of this study are not universal but are representative of environmental conditions encountered in south-east Queensland and north-east New South Wales where PAPP baits are likely to be used. PAPP baits cannot be deployed from the air (ACTA 2016), likely restricting their use to more settled areas where ground deployment is more feasible. Specifically, this includes peri-urban areas where wild dogs commonly reside and their impacts demand management intervention (McNeill et al. 2016).

Conclusions

The results are the first to quantify the degradation rate of wild dog baits containing the toxin PAPP, the first new predator toxin registered in Australia for more than 50 years. These findings have important implications for informing the development of effective and safe strategies for using PAPP in wild dog control operations. Predictive models indicate that buried and surface-laid DOGABAIT™ retain a dose of PAPP lethal to wild dogs for approximately 7 and 16 weeks (respectively), although the optimal period for bait deployment to maximise bait palatability and effective delivery of PAPP is likely to be considerably less. More research is recommended to determine the optimal length of baiting periods using DOGABAIT™ to target wild dogs. While the apparent long shelf life of DOGABAIT™ (in terms of PAPP content) is reassuring, field users must consider the potential for reduced attractiveness or palatability of bait resulting from long-term storage. Our data is also informative about withholding periods, suggesting that domestic dogs should be restrained or excluded from baiting areas for extended periods to minimise poisoning risk. This data is important for the effective and safe deployment of PAPP baits in peri-urban areas where the potential interactions with domestic or companion dogs, and the need for sensible withholding periods, are increased.

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References

ACTA (2016): Dogabait-PAPP wild dog bait—an additional tool for wild dog control. In: Australia ACT (Hrsg.), Somerton, Victoria., pp. 28

Allen BL (2011): Efficacy of para-aminopropiophenone (PAPP) to control dingoes (*Canis lupus* spp.) in the Strzelecki Desert of South Australia: Quinyambie field trial Animal Control Technologies Australia, Melbourne

Allen LR (2015): Demographic and functional responses of wild dogs to poison baiting. Ecological Management & Restoration 16, 58–66

Allen BL, Leung LKP (2014): The (non)effects of lethal population control on the diet of Australian dingoes. Plos One 9

Allen BL, Goullet M, Allen LR, Lisle A, Leung LK-P (2013) Dingoes at the doorstep: preliminary data on the ecology of dingoes in urban areas. Landsc Urban Plan 119:131–135

Allen BL, Allen LR, Engeman RM, Leung LKP (2014): Sympatric prey responses to lethal top-predator control: predator manipulation experiments. Frontiers in Zoology 11

APVMA (2015): Overview report and environmental risk assessment. Para-aminopriopiophenone in PAPP Wild Dog Bait (NCRIS 65094; ATS 50136), Australian Pesticides and Veterinary Medicines Authority Canberra, ACT, Australia

Baskin SI, Fricke RF (1992) The pharmacology of p-aminopropiophenone in the detoxificaton of cyanide. Cardiovascular Drug Reviews 10: 358–375

Beck JA (1985) The chemical control of animal pests using compound 1080. Queensland Agricultural Journal 111:23–24

Bellard C, Cassey P, Blackburn TM (2016) Alien species as a driver of recent extinctions. Biol Lett 12:20150623–20150623

Brumley C (2007) Report on para-aminopropiophenone. Environmental fate and environmental toxicological testing. Golder Associates, Hawthorn, Victoria

Coleman MD, Coleman NA (1996) Drug-induced methaemoglobinaemia. Treatment issues. Drug Saf 14:394–405

Eason CT, Miller A, MacMorran DB, Murphy EC (2014) Toxicology and ecotoxicology of para-aminopropiophenone (PAPP)—a new predator control tool for stoats and feral cats in New Zealand. N Z J Ecol 38:177–188

Fleming PJS, Parker RW (1991) Temporal decline of 1080 within meat baits used for control of wild dogs in New South Wales. Wildl Res 18:729–740

Fleming PJS, Allen LR, Lapidge SJ, Robley A, Saunders GR, Thomson PC (2006) Strategic approach to mitigating the impacts of wild canids: proposed activities of the Invasive Animals Cooperative Research Centre. Aust J Exp Agric 46:753–762

Fleming PJS, Allen BL, Allen LR, Ballard G-A, Bengsen A, Gentle MN, McLeod L, Meek PD, Saunders GR (2014) Management of wild canids in Australia: free-ranging dogs and red foxes. In: Glen AS, Dickman CR (eds) Carnivores of Australia: past, present and future. CSIRO Publishing, Collingwood, Victoria, pp 105–149

Gentle M, Allen L (2012) The nature and impact of peri-urban wild dogs. Queensland Pest Animal Symposium, Caloundra, Queensland

Gentle MN, Saunders GR, Dickman CR (2007) Persistence of sodium monofluoroacetate (1080) in fox baits and implications for fox management in south-eastern Australia. Wildlife Reseach 34:325–333

Gong W, Sinden J, Braysher M, Jones R (2009) The economic impacts of vertebrate pests in Australia. Invasive Animals Cooperative Research Centre, Canberra

IACRC (2016): PestSmart factsheet: frequently asked questions: PAPP for wild dog and fox control. In: Centre IACR (Hrsg.), Canberra, pp. 2

Marks CA, Gigliotti F, Busana F, Johnston M, Lindeman M (2004) Fox control using a para-aminopropiophenone formulation with the M-44 ejector. Anim Welf 13:401–407

McDonald I (2016) First new predator toxin in 50 years becomes available. Invasive Animals Cooperative Research Centre, Canberra

McIlroy JC (1981) The sensitivity of Australian animals to 1080 poison. I. Intraspecific variation and factors affecting acute toxicity. Australian Wildlife Research 8:369–384

McIlroy J, Gifford E (1988) The effect of rainfall and blowfly larvae on the toxicity of 1080 treated meat baits used in poisoning campaigns against wild dogs. Australian Wildlife Research 15:473–483

McLeod L, Saunders G (2013) Pesticides used in the management of vertebrate pests in Australia: a review. NSW Department of Primary Industries, Orange

McNeill AT, Leung LKP, Goullet MS, Gentle M, Allen BL (2016) Dingoes at the doorstep: home range sizes and activity patterns of dingoes and other wild dogs in peri-urban areas of north-eastern Australia. Animals 6:48

Meylan WM, Howard PH (1993) Computer estimation of the atmospheric gas-phase reaction rate of organic compounds with hydroxyl radicals and ozone. Chemosphere 26:2293–2299

Murphy EC, Eason CT, Hix S, MacMorran DB (2007): Developing a new toxin for potential control of feral cats, stoats and wild dogs in New Zealand. In: Witmer GW, Pitt WC, Fagerstone KA (Hrsg.), Managing vertebrate invasive species: Proceedings of an International Symposium. USDA/APHIS/WS, National Wildlife Research Center, Fort Collins, CO, pp. 469–473

Newsome TM, Crowther MS, Dickman CR (2014) Rapid recolonisation by the European red fox: how effective are uncoordinated and isolated control programs? Eur J Wildl Res 60:749–757

NWR (2006) New canid toxicant. PAPP non-target hazard assessment: data summary and interpretation (volume 1 of 3). Nocturnal Wildlife Research Pty Ltd., East Malvern, Victoria

Patterson HD, Thompson R (1971) Recovery of inter-block information when block sizes are unequal. Biometrika 58:545–554

Savarie PJ, Pan HP, Hayes DJ, Roberts JD, Dasch GJ, Felton R, Schafer Jr E. W. (1983) Comparative acute oral toxicity of para-aminopropiophenone (PAPP) in mammals and birds Bulletin of Environmental Contamination and Toxicology 30, 122–126

Sherley M (2007) Is sodium fluoroacetate (1080) a humane poison? Anim Welf 16:449–458

Southwell D, McGowen S, Mewett O, Hennecke B 2011: Understanding the drivers and barriers towards the adoption of innovative canid control technologies: a review, ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences) report prepared for the Invasive Animals Cooperative Research Centre, Canberra

Twigg LE, Eldridge SR, Edwards GP, Shakeshaft BJ, de Preu ND, Adams N (2000): The longevity and efficacy of 1080 meat baits used for dingo control in central Australia. Wildlife Research, 473–481

Twigg LE, Kok NE, Kirkpatrick WE, Burrow G (2001) The longevity of 1080 egg-baits in a regularly baited nature reserve in south-western Australia. Wildl Res 28:607–618

Wicks S, Mazur K, Please P, Ecker S, Buetre B (2014) An integrated assessment of the impact of wild dogs in Australia. Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Canberra

Winstanley RK, Buttemer WA, Saunders G (1999) Fat deposition and seasonal variation in body composition of red foxes (*Vulpes vulpes*) in Australia. Can J Zool 77:406–412