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Re-Use or Refuse? The Stability of Para-Aminopropiophenone (PAPP) and Sodium Fluoroacetate (1080) in Canid Pest Ejector Capsules

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ABSTRACT

Toxins for vertebrate pest control in bait material degrade under field conditions but there are limited data available on the degradation of toxins used in canid pest ejectors (hereafter ejectors). Re-use of non-activated capsules would be practical for end-users and support the optimal and cost-efficient use of vertebrate toxins. This study assessed the degradation of capsules intended for wild dog applications containing sodium fluoroacetate (1080) or para-aminopropiophenone (PAPP) under storage and field conditions in north-eastern Australia (Queensland) and Western Australia. Only 2.6% of 1080 capsules showed any signs of potential leakage, and only a minimal loss of 1080 content occurred over the 2-year study period in Queensland. The rate of degradation was not significantly different between 1080 capsules deployed in the field and those kept in storage, while field-deployed capsules in Western Australia decayed at a faster rate than those kept in storage. Regardless, degradation rates were minimal across both sites, with modelling suggesting that the 1080 content in capsules would still exceed that required for a lethal dose for wild dogs ($LD_{50} = 1.76$ mg) for extended periods (~4–9 years). Intact, undamaged PAPP capsules were highly resistant to degradation, with neither stored nor field-deployed PAPP capsule treatments at either site showing any significant loss in PAPP content after 2 years. However, ~4% of PAPP capsules in the Western Australian study suffered physical failure, and subsequently contained only trace amounts of toxin, but could be easily identified for disposal. Collectively and conservatively, our findings support the use of undamaged (and non-activated) PAPP or 1080 capsules for at least 2 years, following careful inspection and subsequent rejection of damaged capsules. These results are reassuring and provide valuable recommendations to inform users on the effective, safe and efficient use (and re-use) of toxic capsules in ejectors for wild canid control.

1 | Introduction

In Australia, wild canids, including wild dogs (*Canis familiaris*) and foxes (*Vulpes vulpes*), impact animal production, the environment and human health which commonly result in interventions by land managers (Fleming et al. 2014; Harriott et al. 2019). Despite the increase in popularity of non-lethal tools to mitigate their impacts, broadscale population management of wild canids remains heavily reliant upon the use of poison baits (Fleming et al. 2014). Traditionally, toxins presented to wild canids were impregnated into fresh meat or meat-based substrates considered attractive and palatable to the target species (e.g., Allen et al. 1989). Since 2015, canid pest ejectors or CPEs (hereafter ejectors) have been commercially available in Australia and provide an additional tool to the use of traditional meat-based baits for wild canid control (Marks et al. 1999, 2003; Allen 2019; Harriott et al. 2021; Kreplins et al. 2022).

Implications for Managers

- The degradation of sodium fluoroacetate (1080) and para-aminopropiophenone (PAPP) capsules for wild dog control was assessed under storage and field conditions in north-eastern and Western Australia.
- Leakage from capsules was rare; the toxin content of undamaged PAPP capsules was relatively stable, but minor loss of 1080 occurred over time.
- Our findings support the use of undamaged (and non-activated) PAPP or 1080 capsules for at least 2 years, following careful inspection and subsequent rejection of damaged capsules.
- These results are reassuring and provide guidelines for the effective and efficient use of toxic capsules for wild dog control.

Ejectors have several inherent advantages over conventional poisoned meat baits. Being fabricated from robust materials, ejectors are considered relatively target-specific to canines given that they require a significant upwards pull-force to activate, limiting the suite of species that can activate it and therefore mitigating the exposure hazard. Unlike conventional baits, the toxin used in these devices cannot be cached or moved to unbaited areas by animals or birds, providing greater safety against accidental poisoning by domestic dogs and other potentially bait-consuming species in (Harriott et al. 2021). Importantly, unlike baits which can degrade rapidly under field conditions (see Saunders et al. 2000), the lures used on ejectors can remain viable and lethal to wild canids for extended periods, providing a long-acting control tool (Kreplins et al. 2022).

There are two toxins registered and commercially available for wild dogs and foxes in Australia, sodium fluoroacetate (1080) and para-aminopropiophenone (PAPP) (Harriott et al. 2021). Canids are highly sensitive to 1080 (McIlroy 1981), and it has a long history of use for target-specific control of wild dogs and foxes in Australia (Fleming et al. 2014). Highly soluble in water, 1080 in bait also readily degrades under moist field conditions where exposure to soil and rainfall supports losses primarily through leaching, microorganism activity and consumption by insects (Gentle et al. 2007; McIlroy et al. 1988; Twigg and Socha 2001). The toxin PAPP was registered for wild dog control in 2016, the first new predator toxin in Australia since 1080 was introduced over 50 years ago (Marks et al. 2004; McDonald 2016). While both 1080 and PAPP are considered readily biodegradable toxins (McLeod and Saunders 2013), 1080 meat baits persist for typically only weeks under moist conditions (e.g., Fleming and Parker 1991), but can remain toxic for months under drier conditions (e.g., Crawford et al. 2025; Twigg et al. 2000), while equivalent PAPP-dosed baits will persist for months, even under high humidity and rainfall conditions (Gentle et al. 2017). When either toxin is presented in sealed plastic capsules as used in ejectors, preventing exposure to prevailing weather conditions, toxin degradation is likely to be considerably reduced, but data are lacking.

Plastic capsules used in ejectors are approximately 1 cc in volume and contain toxin in viscous liquid (1080) or compressed powder (PAPP) form. The plastic end-cap of each capsule is sealed with wax to prevent any leakage of the enclosed toxin and to reduce environmental contamination from moisture and microorganisms that support key toxin degradative processes (Gentle et al. 2017). Sealed packaging suggests that degradation of the encased toxin should be minimal, and any intact capsules at the completion of a scheduled ejector deployment campaign could be re-used. However, there are reports of occasional leakage or rupturing (liquid) and discolouration or clumping (powder) in un-activated capsules during field baiting campaigns (B. Knuckley, Sunshine Coast Regional Council, pers. comm. 2020; L. Harriott and M. Gentle pers. obs.), but the effects on toxin content are unquantified. Re-use of intact capsules is practical for end-users and supports the optimal and cost-efficient use of vertebrate toxins. Re-deployment of unused capsules reduces the unnecessary disposal of capsules that must be completed according to product label directions for use, helping to minimise the expenses associated with ejector programmes. However, there are limited data on the rate of capsule leakage or toxin content over time to help guide optimal deployment periods.

This study assesses the longevity of PAPP and 1080 capsules used in ejector programmes for wild dogs in typical field usage and storage conditions in north-eastern Australia (Queensland) and Western Australia. Firstly, the toxin content of capsules containing either PAPP or 1080 was assessed under storage conditions over a 12–24-month period. Secondly, the degradation of capsules under field conditions was assessed to determine the rate of degradation over a 12–24-month period in a semi-arid, rangeland environment (Western Australia), and a sub-tropical, peri-urban environment (Queensland), respectively. These data are compared and used to provide recommended periods for the shelf-storage and field use of capsules for wild dog control.

2 | Methods

2.1 | Study Sites and Sampling Methods

This study was undertaken at two study areas, one in sub-tropical Queensland, north-eastern Australia and the second in semi-arid Western Australia (Figure 1). Both sites are representative of areas that regularly undertake wild dog control using toxins, including with ejectors. Commercially manufactured capsules used in the trial nominally contained either 1080 (1 mL of 6 mg/mL 1080 solution) or PAPP (1000 mg PAPP powder).

2.1.1 | Queensland

Maroochy Research Station (64 ha) is situated on the outskirts of Nambour (26.64° S, 152.94° E), in coastal, sub-tropical south-east Queensland. This site represents a typical fragmented agricultural peri-urban landscape, with a mixture of pastures and horticultural crops, and remnant vegetation including rainforest and riparian pockets (Gentle et al. 2017). The rainfall is summer-dominated, averaging (median) 1793 mm annually. Mean daily temperatures range from 15.9°C–26.1°C (www.bom.gov.au).

The trial was initiated in Autumn 2021. All capsules were from the same (respective toxin) manufacturing batch, stored in an air-conditioned storeroom for the short period (< 14 days) prior to field deployment. Each capsule was numbered with a marker

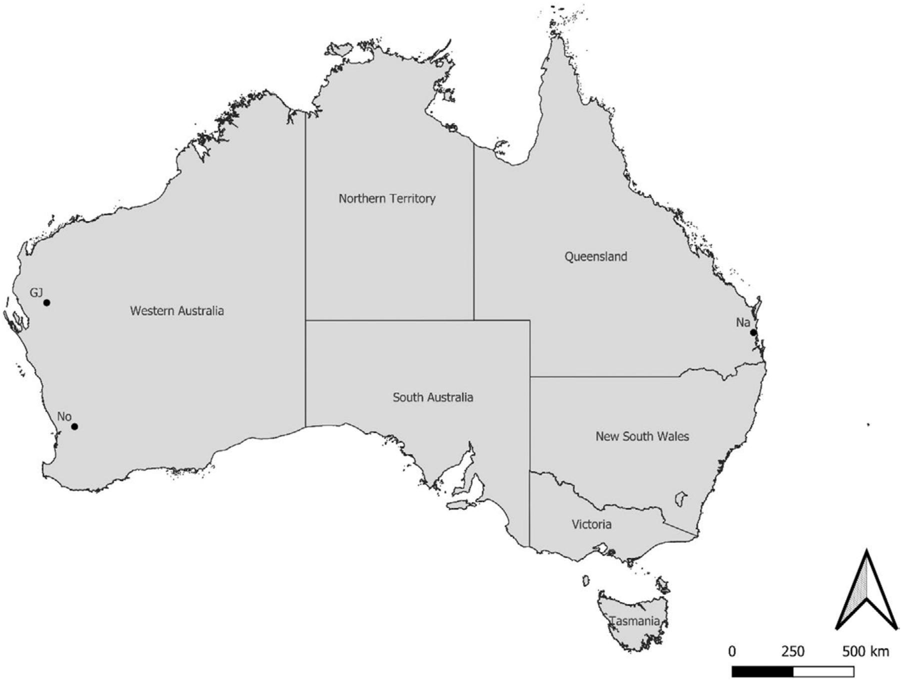


FIGURE 1 | Study sites and treatments used in this trial at Nambour (Na), Queensland, north-eastern Australia (store and field) and Northam (No; store) and Gascoyne Junction (GJ; field), Western Australia.

pen, weighed (to the nearest 0.1 mg) and allocated to each trial treatment (field or storage).

The field treatment consisted of capsules deployed in ejectors placed within a locked enclosure (8 m long × 10 m wide × 3 m high). The enclosure was fenced with 50 mm heavy wire netting to prevent access and interference by animals but to provide exposure to the prevailing conditions (i.e., rain and sunlight).

On 9 April 2021, ejectors containing capsules of each toxin (PAPP or 1080, respectively) were deployed alternatively in a grid pattern just above ground level and were placed at least 40 cm apart. The trigger and plunger mechanism of all ejectors was removed prior to deployment to protect against accidental activation. The metal capsule holder was covered in double-sided adhesive tape (3 M) and rolled in ground dried liver treat as a 'lure' prior to deployment. Remaining capsules were kept in their original packaging and placed into a chemical storage facility, as per chemical regulations.

Capsules were deployed on Day 0, and a random sample of five capsules of each treatment group (Field, Store) for each toxin (PAPP, 1080) was sampled over 17 occasions over 104 weeks (Table 1). At each sampling period, each capsule was inspected for signs of damage, leakage or discoloration, photographed, then individually bagged before being frozen at −18°C.

Data loggers (TinyTag Ultra 2 TGU-4500) recorded ambient temperature (°C) and relative humidity (%) at 30-min intervals at the field and storage site (ventilated chemical store) throughout the trial period. Other climate data (including rainfall [mm]) were recorded at the official meteorological station on site (Nambour DAFF Hillside 040988; www.bom.gov.au/climate/data, accessed 17 April 2023).

2.1.2 | Western Australia

Northam Grains Research Facility and the Department of Primary Industries and Regional Development offices (31.65° S, 116.70° E) are located in the central wheatbelt region of Western Australia. The region is comprised of large farms for cropping and livestock production around Eucalypt and Acacia woodland forests. The annual rainfall for 2020 was 286.6 mm. The mean temperature for the town is 27.2°C, but the range is between 13.9°C–45.2 (Northam010111; www.bom.gov.au/climate/data, accessed 26 June 2025).

The PAPP and 1080 capsules placed in storage at the Northam facility were locked in the chemical facility from August 2021 to July 2022. All capsules were from the same manufacturing batch. Each month, up to 10 capsules of each toxin type were removed from the storage facility and placed into labelled zip lock bags in a locked chest freezer.

On 1 August 2021, approximately 72 PAPP and 1080 capsules were deployed in defunct ejector capsule holders on the ground within an unused shearing shed yard on a private property in the Gascoyne region of Western Australia. This station was 50 km south of Gascoyne Junction townsite (25.05° S, 115.21° E). In 2020, the annual rainfall was 153 mm. The annual mean temperature for the region is 32.2°C, but the range is 18.5°C–43.5°C (Gascoyne Junction 006022; www.bom.gov.au/climate/data, accessed 26 June 2025).

Each month from August 2021 to July 2022, up to 10 capsules of each poison type were removed from the field deployment and placed in a locked chest freezer. These were placed in a zip lock bag and labelled after visual inspection. Any changes to the poison capsule were photographically recorded.

TABLE 1 | Mean (±SE) PAPP (mg) or 1080 (mg) content for capsules sampled (number = *n*) under each treatment (Field, Store or Control) for each sampling period (Week) at Nambour, Queensland.

	PAPP						1080					
Week	**Control**[a]	***n***	**Field**	***n***	**Store**	***n***	**Control**[a]	***n***	**Field**	***n***	**Store**	***n***
0	963.67 (40.0)	3					6.23 (0.10)	3				
4			961.0 (20.07)	3	972.33 (11.86)	3			6.18 (0.08)	3	6.24 (0.08)	3
8			948.33 (16.58)	3	925.67 (8.45)	3			6.16 (0.12)	3	6.19 (0.03)	3
13			944.33 (16.50)	3	942.67 (29.54)	3			6.09 (0.10)	3	6.07 (0.17)	3
16			970.67 (37.71)	3	952.67 (26.85)	3			6.25 (0.04)	3	6.35 (0.09)	3
20			999.00 (15.28)	3	954 (13.23)	3			6.39 (0.04)	3	6.70 (0.45)	3
24			952.67 (11.26)	3	945.67 (12.13)	3			6.01 (0.75)	3	6.03 (0.19)	3
28			963.00 (7.09)	3	965.0 (27.23)	3			6.24 (0.07)	3	5.90 (0.08)	3
36			974.67 (3.71)	3	937.33 (11.85)	3			6.26 (0.18)	3	5.98 (0.08)	3
44			963.00 (35.79)	3	936.0 (22.94)	3			5.27 (0.41)	3	5.87 (0.25)	3
52			947.33 (18.89)	3	938.33 (35.55)	3			5.65 (0.31)	3	5.63 (0.23)	3
68			961.67 (9.82)	3	957.33 (6.06)	3			5.70 (0.23)	3	5.73 (0.00)	3
84			963.33 (15.62)	3	949.33 (27.09)	3			4.24 (1.12)	3	5.73 (0.19)	3
104			977.67 (12.35)	3	953.33 (17.07)	3			5.72 (0.13)	3	5.77 (0.23)	3
Total *n*		3		39		39		3		39		39

[a]Data from control capsules used for both Week 0 Store and Field 1080 treatments.

A Hobo (HOBO MX1101 Temp/RH Bluetooth data logger) was also placed in the shearing yard to record humidity and temperature. Unfortunately, it was not found at the end of the trial. No temperature recorder was placed in the Northam facility for storage for this trial.

2.2 | Chemistry Assays—1080 and PAPP

PAPP and 1080 content assays were completed in a National Association of Testing Authorities (NATA)-accredited laboratory. Results were provided for each toxin (1080 or PAPP) as mg capsule^{-1}.

Initially, the mass of 1080 solution or PAPP powder in each capsule was measured by difference after transferring the formulation or powder, respectively, to a 4 mL vial, and then washing and re-weighing the empty capsule. The 1080 solution was then diluted in de-ionised water, and PAPP powder was dissolved in methanol water (1:1) to give a concentration of approximately 500 mg/L for each toxin. Finally, the concentration of 1080 or PAPP in each capsule was measured by high-performance liquid chromatography against external calibration standards, prepared using reference material of known purity.

2.3 | Statistical Analysis

Analysis of covariance was used to determine whether the mean amount (mg) of toxin (PAPP or 1080) at sampling was influenced by time (week), treatment (store, field), and for the Queensland data, the initial weight of the capsule (mg). For each toxin (1080 and PAPP), control sample capsules (Week 0) were initially excluded to examine differences between treatments over time. Both storage and field treatments for 1080 or PAPP were then examined for the effect of time by comparison with control capsules (Week 0). The significance level was $\alpha \leq 0.05$. The declines in 1080 or PAPP content over time were subsequently modelled using linear regression. The Wilcoxon rank sum test was used to examine for differences in capsule weights between treatments (Crawley 2009). Statistical analysis was completed in R 4.0.5 (R Core Team 2021).

3 | Results

3.1 | Climate Data

Rainfall at the Queensland site (Maroochy Research Station) totalled 3891.5 mm during the trial (9 April 2021 to 7 April 2023), which well exceeded the long-term (2007–2025) median (2751.6 mm) for this period (Table S1).

Average daily ambient minimum–maximum temperatures (±SD) at the site from BOM records during this period were 15.7 (±4.4) – 25.7 (±3.7)°C, with a minimum and maximum of 3.0°C–37.4°C (respectively, Figure 2A). The climate data loggers at the field site and in the chemical store only recorded the initial 308 days following deployment (9 April 2021–10 February 2022), so comparative averages are only available for this period. The average temperature in the chemical store was 19.9 (±6.7)°C (range 1.8°C–39.4°C), similar but more variable than that recorded in the field (19.6°C ± 4.9°C (range

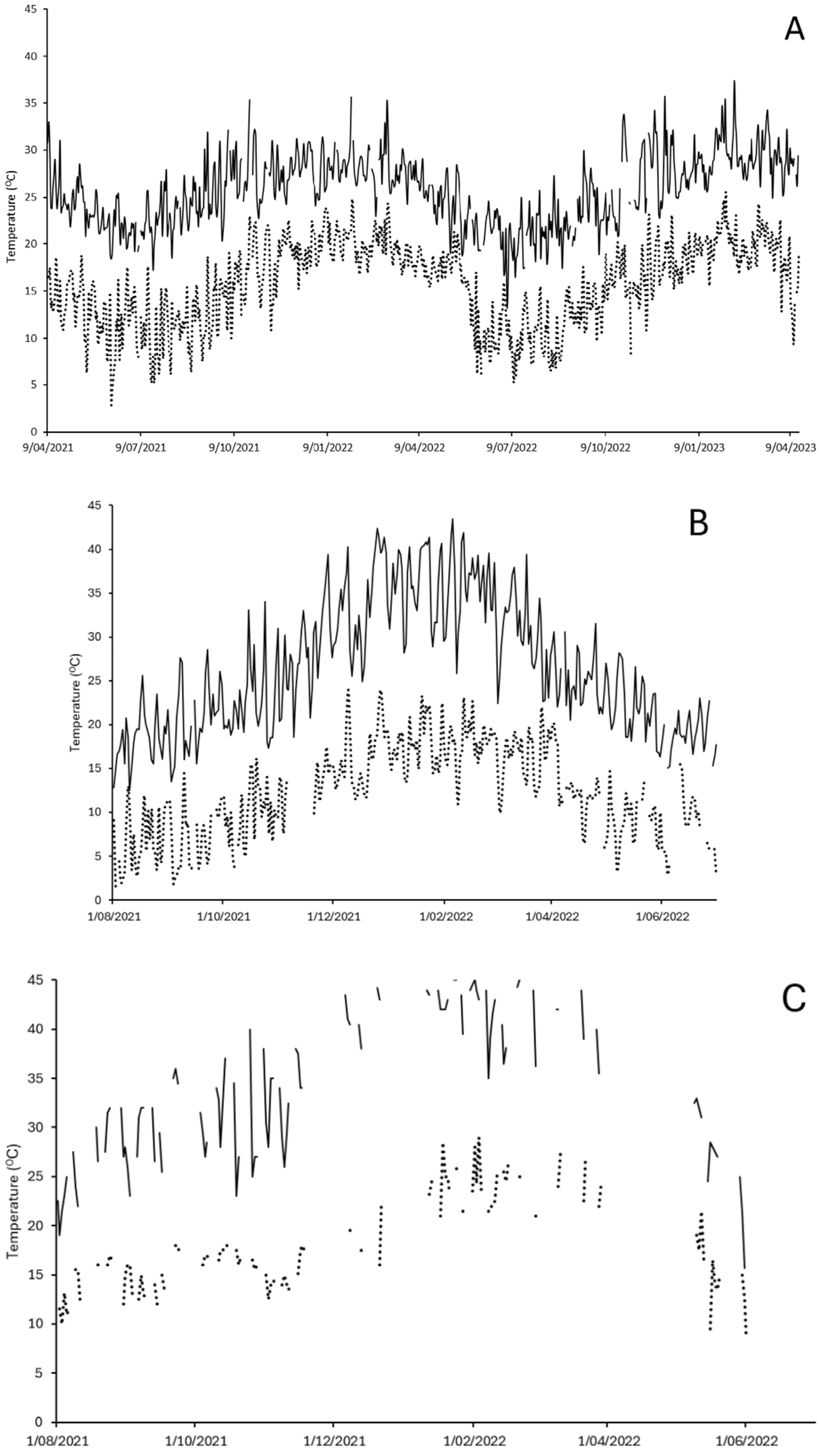


FIGURE 2 | (A–C) Daily minimum (dotted line) and maximum (solid line) ambient temperatures from meteorological records (www.bom.gov.au/climate/data) over 24 months at (A) Maroochy Research Station, Queensland (9 April 2021–7 April 2023); and 12 months at (B) Northam (store) and (C) Gascoyne Junction (field), Western Australia (1 August 2021–1 July 2022).

4.8°C–37.7°C)). The average relative humidity (±SD) in the store was 76.0 (±7.9)%, greater but more consistent than in the field (72.1% ± 15.9%).

Rainfall for the private station in Western Australia was well below average in 2021/22 at 112.8 mm for the year. On average, the rainfall is 200 mm per annum in the region. At the Northam

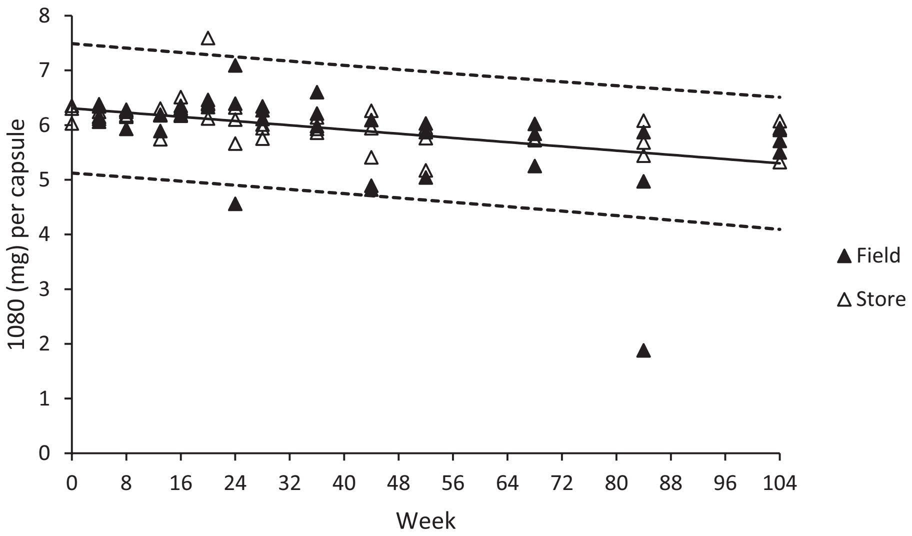


FIGURE 3 | Fitted model for the mean degradation of 1080 (solid line) and 95% confidence limits (dashed lines) for individual capsules kept in storage (hollow markers) or deployed under field conditions (solid markers) in Queensland.

location for the shed storage of the ejector capsules, the rainfall during the study was 362.9 mm. This is around the average for the region (Table S2).

The average minimum and maximum temperature at the Gascoyne field site is much higher than all other sites at 27.2 (±8)°C–37.0 (±5.8)°C. At the storage location, 18.9 (±5.4)°C–33.3 (±7.7)°C were the minimum and maximum temperatures. No temperature data were available from inside the storage facility during the trial; however, during the same period in 2024 an iButton (DS1925L-F5# Thermochron iButton, United States) demonstrated the chemical facility temperature averaged 20°C (range = 6.5°C–39°C).

3.2 | Toxin Content, Degradation and Leakage of Capsules

3.2.1 | 1080—Queensland

The mean (±SE) content of 1080 capsules at Week 0 (control) ($n = 3$) was 6.23 mg (0.10), approximately 4% greater than the nominal dose at manufacture (6 mg). The content of 1080 was significantly influenced by time (week, $F_{1,73} = 18.63$, $p < 0.001$) but not treatment ($F_{1,73} = 1.346$, $p = 0.250$), the interaction between treatment and time ($F_{1,74} = 1.50$, $p = 0.225$), or the initial weight of the capsule ($F_{1,73} = 0.849$, $p = 0.360$). As a result, treatments were pooled to model the decay rate over time from Week 0 (Figure 3), which generally conformed ($F_{1,79} = 19.79$, $p < 0.001$, adjusted $r^2 = 19\%$) to a linear trend:

$$1080\ (\text{mg}) = 6.30\ (\text{SE} = 0.10) - 0.01\ (\text{SE} = 0.002) \times \text{week} \quad (1)$$

Equation (1) was used to estimate the time (weeks) that capsules could be stored and remain lethal to wild dogs. The oral lethal dose (LD_{50}) for 1080 in wild dogs is considered to be 0.11 mg kg^{-1} (McIlroy 1981), equating to 1.76 mg for an average ~16 kg wild dog (Allen and Leung 2014). If the degradation of 1080 continued at the same modelled rate, the average capsule would remain lethal for approximately 470 weeks (95% CI = 301–855 weeks)—or over 9 years.

Only 4/150 (~2.6%) 1080 capsules showed any barely noticeable signs of (potential) leakage or seepage of solution. Subsequent assays of three of these capsules deployed during the trial showed that one contained 4.56 mg 1080 when field sampled at Week 24, falling outside 95% confidence limits for 1080 content in a capsule at this period (Figure 3). The remaining two capsules were assayed at 5.17 and 5.44 mg when sampled from storage at 52 weeks and 84 weeks, respectively, suggesting little loss of 1080 content. Paradoxically, the capsule that contained the lowest 1080 content (1.88 mg at week 84, field treatment) did not present any noticeable signs of leakage.

3.2.2 | 1080—Western Australia

Capsules sampled prior to treatment at Week 0 (control, $n = 3$) contained a mean 1080 (±SE) content of 6.01 mg (0.12). The 1080 content of capsules in Western Australia was significantly influenced by time ($F_{1,115} = 4.70$, $p < 0.001$) and treatment ($F_{1,115} = 8.61$, $p < 0.001$) but not their interaction ($F_{1,115} = 0.18$, $p = 3.09$). As a result, the rate of decline from Week 0 for field and storage treatments was modelled and presented separately (Figure 4).

For capsules in storage, the rate of decline followed a linear trend ($F_{1,60} = 23.97$, $p < 0.001$, adjusted $r^2 = 0.27$):

$$1080\ (\text{mg}) = 6.12\ (\text{SE} = 0.07) - 0.01\ (\text{SE} = 0.002) \times \text{week} \quad (2)$$

Field-deployed capsules similarly followed a linear trend ($F_{1,61} = 19.17$, $p < 0.001$, adjusted $r^2 = 0.23$)

$$1080\ (\text{mg}) = 5.82\ (\text{SE} = 0.13) - 0.02\ (\text{SE} = 0.005) \times \text{week} \quad (3)$$

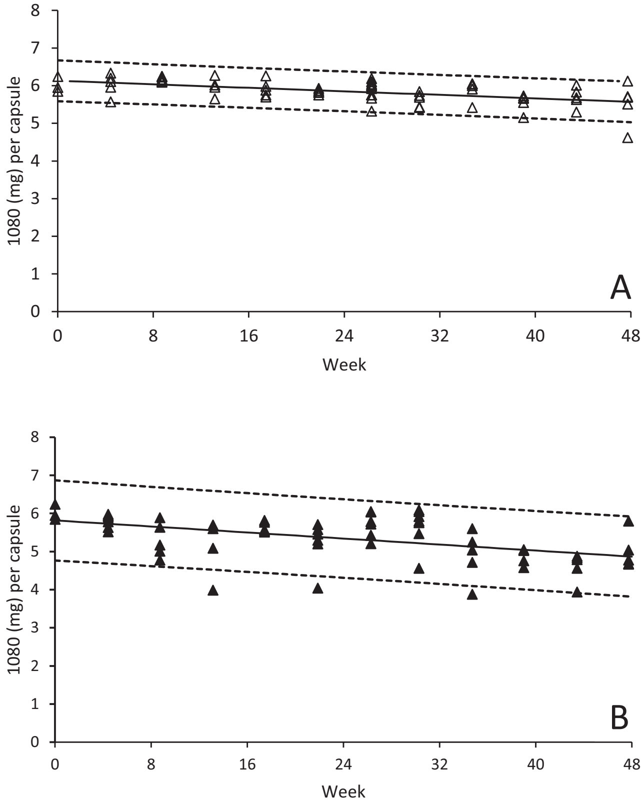


FIGURE 4 | (A, B) Fitted models for the mean degradation of 1080 (solid line) and 95% confidence limits (dashed lines) for individual capsules (A) kept in storage (hollow markers) or (B) deployed under field conditions (solid markers) in Western Australia.

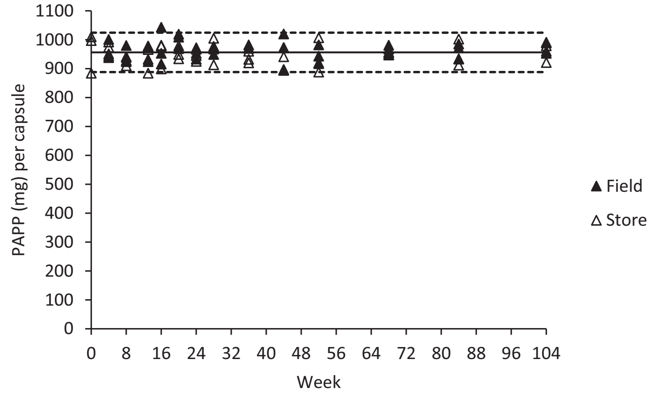


FIGURE 5 | The mean PAPP (mg) content (solid line) and 95% confidence limits (dashed lines) for individual capsules kept in storage (hollow markers) or deployed under field conditions (solid markers) in Queensland.

The 1080 content in capsules deployed in the field or store treatments was compared between Queensland and Western Australian sites (up to and including 52 weeks). Time ($F_{1,86}=5.47$, $p<0.001$) and site ($F_{1,86}=10.67$, $p<0.001$) significantly influenced 1080 content in field capsules, but there was no interaction between the two ($F_{1,86}=0.07$, $p=0.61$). After accounting for time (week), field-deployed capsules in Western Australia contained less 1080 ($\beta=-0.73$, $t=-6.36$, $p<0.001$) than those in Queensland. Similarly, 1080 content in stored capsules was influenced by time ($F_{1,85}=32.40$, $p<0.001$) and site ($F_{1,85}=12.99$, $p<0.001$) but not their interaction ($F_{1,85}<0.001$, $p=0.93$). Again, the 1080 content was lower in stored capsules in Western Australia ($\beta=-0.24$, $t=-3.63$, $p<0.001$).

Modelled regressions (Equations 2 and 3) indicated that the average capsule in storage or field-deployed would remain lethal (1.76 mg 1080) to wild dogs for approximately 374 weeks (>7 years, 95% CI = 266–622 weeks) or 205 weeks (~4 years, 95% CI = 133–372 weeks), respectively, under Western Australian conditions.

3.2.3 | PAPP—Queensland

No damage to capsules or leakage of powder from PAPP capsules was evident during field deployment or sampling. The mean content (±SE) of week 0 capsules was 963.7 mg (40.0) for PAPP ($n=3$, Table 1). This is approximately 4% less than the nominal content at manufacture (1000 mg). There was no significant difference in PAPP content over time ($F_{1,73}=0.480$, $p=0.49$) or between treatments ($F_{1,73}=1.31$, $p=0.257$) or their interaction ($F_{1,72}=0.350$, $p=0.556$). The initial weight of the capsule had a significant interaction with treatment ($F_{1,73}=6.54$, $p=0.01$) to influence the PAPP content at sampling. Subsequent investigation showed that initial capsule weights differed between treatments ($W=1054$, $p=0.003$). The mean PAPP content and 95% confidence limits (956.2 ± 68.1 mg) for individual capsules for store and field treatments over the 104-week period are presented in Figure 5.

PAPP content (mg) was regressed ($F_{1,79}=148.9$, $p<0.001$, adjusted $r^2=64.9\%$) against initial capsule weight (g) to provide the predictive model:

$$\text{PAPP (mg)} = 0.812\ (\text{SE} = 0.06653) \times \text{initial capsule weight (mg)} - 909.7\ (\text{SE} = 152.92) \quad (4)$$

Equation (4) was used to plot the predicted PAPP content and 95% confidence limits for the initial capsule weight (Figure 6).

3.2.4 | PAPP—Western Australia

Six capsules (including one capsule kept in storage) from 137 tested during the WA trial (~4.4%) had missing end caps or sealant wax, and no visible capsule contents remaining. These empty capsules were subsequently assayed to contain only trace amounts of PAPP (mean = 0.58 mg, range = 0–1.4 mg, Table 2), which represented less than 0.2% of the nominal dose at manufacture (~1000 mg). Given that this represents total loss from capsule failure, data from these capsules (see Table 2) were thereafter excluded from formal analysis of degradation rates of (intact) capsules (Table 3).

The PAPP content of intact capsules was significantly influenced by the interaction between time and treatment ($F_{1,117}=4.76$, $p=0.03$), so the rate of decay was analysed separately for each treatment.

For capsules in storage (Figure 7A), there was a small ($\beta=0.5$, $t=3.56$, $p<0.001$) linear increase in PAPP content over time (i.e., week) ($F_{1,64}=12.69$, $p<0.001$):

$$\text{PAPP (mg)} = 980.71\ (\text{SE} = 3.95) + 0.50\ (\text{SE} = 0.14) \times \text{week} \quad (5)$$

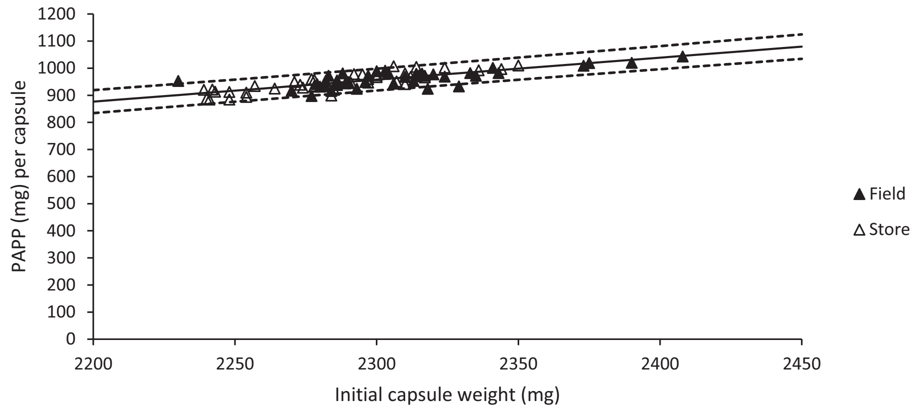


FIGURE 6 | The relationship between initial capsule weight (mg) and mean PAPP (mg) content (solid line) and 95% confidence limits (dashed lines) for individual capsules assayed from the Queensland trial (all treatments).

TABLE 2 | PAPP (mg) content (±SE) of leaked (empty) capsules ($n = 6$) during the Western Australian trial.

Day	Week	Treatment	PAPP (mg)
92	13.1	Field	1.4
153	21.9	Field	0.44
153	21.9	Field	0.11
184	26.3	Field	0
184	26.3	Field	0.71
184	26.3	Store	0.8
		Mean (SE)	0.58 (0.19)

For capsules deployed in the field, there was no significant effect of time ($F_{1,63} = 0.32$, $p = 0.57$) with PAPP (mg) content per capsule estimated at 994.75 ± 40.5 mg ($t = 398.9$, $p < 0.001$) over the ~48-week study (Figure 7B).

The PAPP content in capsules in the Western Australian site was significantly greater ($\beta = 38.69$ SE = 3.95, $t = 9.79$, $p < 0.001$) than those in the Queensland study. Initial capsule weights were not recorded during the Western Australian study to compare to toxin content or between study sites.

4 | Discussion

This is the first study quantifying the longevity of field-deployed and stored ejector capsules containing the toxins 1080 or PAPP for wild dog control. Our study data demonstrate that, in Queensland, 1080 capsules (field-deployed or stored) showed low susceptibility for leakage, and minimal loss of 1080 content over the 2-year study period. Degradation of 1080 in capsules was significantly greater in the Western Australian study, and field-deployed capsules had a higher rate of loss than those kept in storage. Regardless, if degradation continued at the same modelled rate, the average field-deployed capsule would still contain a lethal dose for a wild dog for ~4 years, and > 7 years if kept in storage. Intact PAPP capsules were relatively more resistant to degradation, with neither stored or field-deployed PAPP capsules showing any significant loss in PAPP content at either study area during the examined period (up to 24 months). However, a low proportion (4%) of PAPP capsules deployed in the field in Western Australia physically failed, leaving only trace amounts of toxin remaining. These capsules would be easily identified and rejected by the practitioner. Importantly, the stability of intact PAPP and 1080 capsules provides valuable information to inform users on the effective, safe and efficient use (and re-use) of toxins in ejectors for wild dog control.

Very few (~2.6%) 1080 capsules sampled in Queensland during the trial showed any signs of potential leakage, and only one of the three capsules assayed contained less 1080 than expected (i.e., 4.56 mg at Week 24, outside 95% confidence limits). Interestingly, one field-deployed capsule with no obvious signs of leakage only contained 1.88 mg 1080 (at Week 84). Further investigation showed that the solution only assayed at a concentration of 1.97 mg/mL (in contrast to the nominal 6 mg/mL), suggesting loading with a low concentration solution at manufacture, rather than subsequent leakage, was primarily responsible. However, the possibility of unobserved leakage and subsequent dilution of the remaining solution in the capsule contents from rainwater cannot be excluded, particularly given the high (above average) rainfall during field deployment at Nambour (Table S1). Regardless, these capsules still contained more 1080 than required for a lethal dose to a wild dog (~1.76 mg, as calculated above), suggesting little practical effect on field toxicity. Manufacturer guidelines for ejector use also reinforce the need for appropriate storage and precautions for re-use of capsules given ‘capsules exposed to very high temperatures may leak’ (ACTA, n.d.-a). In Queensland, 1080 capsules were exposed to a maximum ambient temperature of 37.9°C in the field and 39.4°C in the chemical store and appear resistant to leakage at these ambient temperatures. Our results indicate, at least over the conditions experienced during the 24-month trial period in the Queensland study area, a low probability of capsule leakage and negligible practical implications on the toxicity of capsules to wild dogs.

There was no evidence of any decline in PAPP content in intact, undamaged capsules during the study, suggesting that capsules that remain sealed are highly resistant to toxin loss and degradative processes. No leakage from PAPP capsules was evident during the Queensland trial. In contrast, 4% of PAPP capsules at the Western Australian site leaked their

TABLE 3 | Mean (SE±) PAPP (mg) or 1080 (mg) content for entire capsules under each treatment (Field, Store or Control) for each sampling period (Week) at Western Australia.

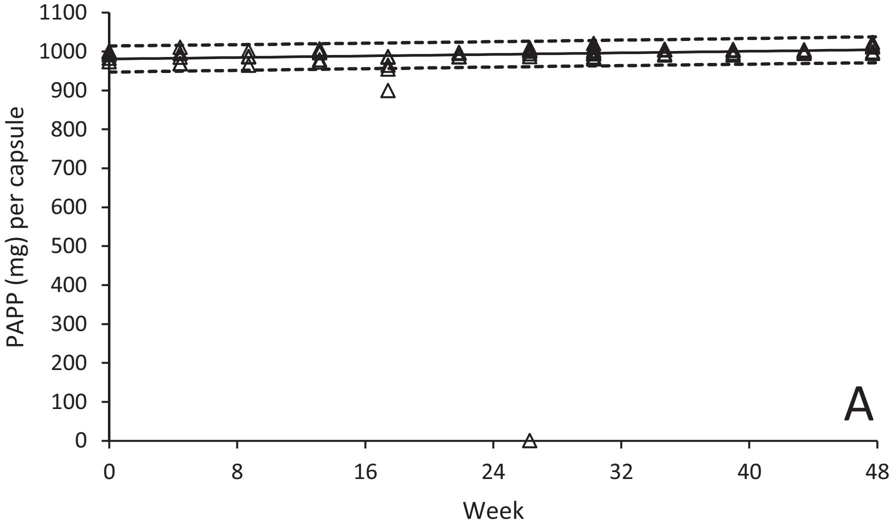
		PAPP				1080					
Day	**Week**	**Field**	***n***	**Store**	***n***	**Control**[a]	***n***	**Field**	***n***	**Store**	***n***
0	0	989.80 (13.63)	5	989.60 (4.97)	5	6.01 (0.12)	3				
31	4.4	1004.80 (8.27)	5	985.80 (8.01)	5			5.81 (0.07)	5	6.03 (0.13)	7
61	8.7	983.0 (5.65)	5	985.40 (5.90)	5			5.30 (0.20)	5	6.17 (0.03)	5
92	13.1	1001.50 (8.42)	6	991.20 (6.48)	5			5.10 (0.39)	4	5.98 (0.13)	4
122	17.4	991.80 (6.16)	5	958.40 (15.80)	5			5.64 (0.06)	5	5.91 (0.10)	5
153	21.9	990.10 (5.47)	10	991.50 (2.96)	4			5.22 (0.25)	5	5.84 (0.03)	6
184	26.3	997.25 (13.80)	4	1000.14 (2.77)	7			5.67 (0.12)	10	5.87 (0.08)	7
212	30.3	998.0 (0.84)	5	996.70 (4.00)	10			5.66 (0.20)	5	5.63 (0.08)	7
243	34.7	999.0 (1.67)	5	999.80 (3.04)	5			4.90 (0.29)	5	5.89 (0.12)	5
273	39	985.60 (9.47)	5	999.80 (2.71)	5			4.86 (0.11)	5	5.55 (0.11)	4
304	43.4	987.40 (8.73)	5	1000.0 (1.61)	5			4.60 (0.17)	5	5.69 (0.12)	5
334	47.7	1012.60 (15.17)	5	1009.0 (5.24)	5			4.99 (0.21)	5	5.53 (0.25)	5
Total *n*			65		66		3		62		60

[a]Control capsules used for both Week 0 Store and Field 1080 treatments.

entire capsule contents with only trace amounts (< 0.2% of nominal dose) remaining. Observations suggest that the wax-like seals on the capsule ends "melted", resulting in a total loss of capsule contents (T. Kreplins, personal observations). This is likely due to the consistently higher (minimum to maximum) ambient temperatures that capsules were exposed to under field conditions in Western Australia (see Figure 2A–C), although one capsule in storage also failed. This also suggests that temperature, rather than exposure to visible or UV light (i.e., to field capsules) per se, was responsible for the leakage, although long-term exposure to light may also contribute to capsule or toxin degradation. The 42°C ambient temperatures are common in summer months in both Western Australian locations, while measured temperatures in Queensland remained < 40°C. Soil temperatures in the Gascoyne field sites, on the red soil, would be even higher. Some capsules used in the Queensland study were observed to display clumping and/or darkening of the originally beige-coloured powder (capsule contents) (M. Gentle and L. Harriott, personal observations), possibly due to the intrusion of moisture, contaminants, or exposure to the air or light, but this did not appear to correspond with any reduction in expected PAPP content. This colour change may indicate a reduction in physical stability (i.e., changes to the physical properties) of the PAPP powder rather than chemical stability (e.g., loss of potency) (Loftsson 2014), the latter of more importance for toxin efficacy. Nevertheless, any absorption of moisture into capsules is unwanted and may still result in deleterious performance outcomes, for example, clumping or 'caking' of powder which may be more easily rejected (i.e., 'spat out') by the wild dog. The total failure of capsules (clearly evident by the lack of contents) or the potential contamination (colouration change or clumping) supports the careful examination of capsules for damage prior to use (and re-use), with affected capsules disposed of as per label specifications. This can also be considered the foundation of guidelines on shelf-life to support such usage recommendations.

Differences in degradation rates between toxins can be a result of many factors, including form and chemical composition. Chemical or drug formulations in solid (e.g., powder) form are more resistant to degradation than corresponding aqueous solutions (Loftsson 2014), thus the formulation may be at least partly responsible for the high stability of PAPP (powder) compared to 1080 (viscous liquid). Chemical composition is also important, with 1080 considered to be readily biodegradable, while PAPP has been shown to be more resistant to environmental degradation (e.g., Gentle et al. 2017; Fleming and Parker 1991).

Under chemical use regulations, the use of any toxin for vertebrate pest control must comply with the label conditions. The 1080 capsule label (APVMA 69620/61260) provides directions to dispose of 'damaged or unusable capsules', specifically 'from non-activated ejectors... if damaged or showing signs of wear' (ACTA 2019), but no further guidance is provided for their re-use. Our data strongly supports the disposal of damaged capsules given the almost complete loss of toxin may occur (demonstrated in this study with PAPP capsules). However, the PAPP capsule label (APVMA 87033/117419) specifically states that capsules 'can be re-used if undamaged' (ACTA, n.d.-b), but no further guidance is provided to assist users on the suitable lifespan of such capsules. Undamaged, intact PAPP capsules did not show any loss of PAPP in either site, including up to 2 years in Queensland, supporting almost unlimited use when undamaged. Based on average lethality to the target species, if degradation continued at the same modelled rates as those studied here, 1080 capsules are estimated to remain lethal to a 16 kg wild dog for ~4–9 years. However, recommending such a long



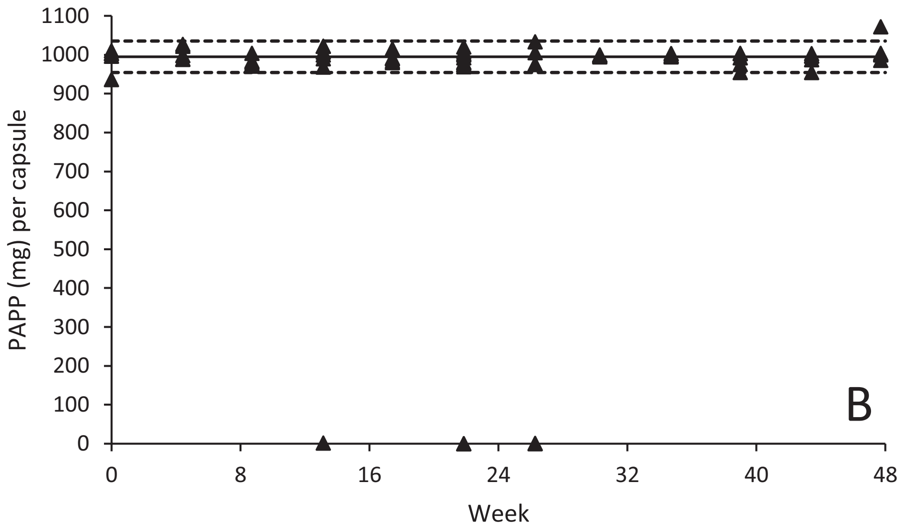


FIGURE 7 | (A, B): The mean* PAPP (mg) content (solid line) and 95% confidence limits (dashed lines) for individual capsules (A) in storage (hollow markers) or (B) deployed under field conditions (solid markers) in Western Australia. *Excluding capsules ($n = 6$) that leaked during the study (<2 mg PAPP per capsule).

period is not supported given these ignore other potential areas of toxin degradation (e.g., defluorination, microbes, etc.) or capsule failure (e.g., perishing of the plastic capsule) that could not be measured in the study term (12–24 months). More conservatively, the recommended shelf-life of chemical or drug products is often defined as the time to reach 90% or 95% of original potency (Loftsson 2014). Given the average 1080 loss per week from stored capsules (−0.01 mg, Equations 1 and 2), if capsules contained the nominal 1080 content of capsules at manufacture (6 mg 1080), the recommended shelf-life 1080 capsules would be 30–60 weeks (>6–12 months) to maintain the 90%–95% potency threshold (5.4–5.7 mg, respectively). For capsules deployed in field conditions similar to Western Australia (−0.02 mg/week, Equation 3), the recommended shelf-life to maintain 90%–95% potency is halved to 15–30 weeks (~4 to >6 months). These are extremely conservative estimates given the nominal capsule loadings (6 mg 1080 or 1000 mg PAPP) represent an average lethal dose to an average wild dog (~1.76 or 416 mg, Gentle et al. 2017), which would be obviously maintained for extended periods well below 90% potency. Conservative interpretation of the modelled data, therefore, supports the use of undamaged, intact, and non-activated PAPP or 1080 capsules stored or deployed under the climatic conditions to those during this study for at least 24 months (2 years), following careful inspection. These guidelines will help to minimise the operating expenses associated with ejector programmes, optimise toxin use, and reduce unnecessary waste and the premature disposal of capsules.

Data from the Queensland site demonstrated that the initial weight of the capsule was positively correlated with toxin content for PAPP, but not 1080. The PAPP content in capsules in the Western Australian site was significantly greater than those in the Queensland study. Differences in the amount of PAPP loaded into capsules at manufacture are probably responsible, but formal comparison between sites is not possible given initial capsule weights were not recorded during the Western Australian study. Capsule weight may have an application to help determine the relative toxicity of PAPP capsules prior to deployment, to help identify those that contain insufficient quantities of PAPP, although none were identified during the study.

This study has provided useful data on the degradation and loss of 1080 and PAPP toxins used in ejector capsules under field and storage conditions under two differing climates. This provides users with evidence-based recommendations on the longevity of capsules to estimate shelf-life and usable lifespan. Collectively, this information adds to that available for the use and efficacy of ejectors in arid rangelands (Kreplins et al. 2018, 2022) and the optimal spatial deployment of ejectors in sub-tropical peri-urban areas (Harriott et al. 2021) to provide best-practice guidelines for their use in Australia.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data from this study may be shared upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Rainfall (mm) that fell during the trial period (9 April 2021–7 April 2023) at Maroochy Research Station, Nambour, Queensland relative to the long-term median. **Table S2:** Rainfall (mm) that fell during the trial period (1 August 2021–1 July 2022) at the store (Northam) and in the field (south of Gascoyne Junction) in Western Australia, relative to the long-term median.