



Costs and benefits of aerial 1080 operations to Western weka (*Gallirallus australis australis*)

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Abstract: The impact of aerially applied 1080 poison on a Western weka (*Gallirallus australis australis*) population was assessed at Tennyson Inlet, Marlborough Sounds, between September 2010 and June 2016. We estimated mortality and the incidence of sublethal poisoning as a direct consequence of two aerial 1080 operations and examined the differences in nest success, chick survivorship and adult survivorship. Most weka in the treated block appear to have been sublethally poisoned but only one of 58 (1.8%) radio-tagged weka died as a direct consequence of 1080 application. Both adult and chick survivorship were higher in the treated block, but nest success was unaffected by the observed reduction in rat and stoat abundances following the 1080 operation. The net effect of aerial 1080 application on this weka population was positive when the operation followed a beech (*Nothofagaceae*) mast and stoat (*Mustela erminea*) irruption, as adult and chick survivorship after the operation exceeded adult mortality during the operation. However, 1080 operations carried out when stoats are uncommon may have a minor negative impact on weka populations due to the risk of primary poisoning without compensatory increases in survivorship.

Keywords: compound 1080, *Gallirallus australis*, mortality, nest success, non-target species, pest control, sodium fluoroacetate, weka

Introduction

The aerial application of sodium fluoroacetate (1080) has been a common method for the control of introduced mammals in New Zealand forests since the late 1950s. In the past, the majority of aerial 1080 operations targeted brushtail possums (*Trichosurus vulpecula*; Eason et al. 1993) in an effort to reduce the transmission of bovine tuberculosis from possums to dairy cattle (Livingstone 1994). More recent operations have targeted ship rats (*Rattus rattus*; Innes et al. 1995) with the aim of reducing predation of native fauna (Innes & Barker 1999). Pest control operations that target rodents have most often been undertaken during beech (*Nothofagaceae*) masts, to prevent rodents reaching plague-like proportions in response to the increased food availability (King 1983). The shift to rodent control in response to beech masts, and an accumulation of knowledge on the application of 1080, has led to an increased frequency in 1080 operations over conservation land and changes in the method of application (Eason et al. 2006; Elliott & Kemp 2016).

Individuals of many native New Zealand bird species are known to have been killed during 1080 operations (Veltman & Westbrooke 2011). Despite these deaths, the populations of several forest bird species have been shown to benefit from 1080 because of reduced predator abundances (Miller &

Anderson 1992; Powlesland et al. 1999, 2000; Schadowinkel et al. 2014). The net effect of 1080 use, weighing non-target mortality against the effects of reduced predation, has not been adequately monitored for many native species (Veltman & Westbrooke 2011), including weka (*Gallirallus australis*).

Weka are particularly vulnerable to 1080 poisoning (Spurr 1979), because they are omnivorous and known to ingest the type of pellets used in poison operations (Spurr 1993; Hartley et al. 2000). For this reason, weka were identified as a high priority species for additional research (Spurr & Powlesland 1997). Despite their inquisitive nature, several studies have indicated that the number of adult weka killed by 1080 is low (Miller & Anderson 1992; Spurr & Powlesland 1997; Walker 1997; van Klink & Tansell 2003; van Klink 2008), although only one study (van Klink 2013) has monitored radio-tagged birds through a pre-fed cereal bait operation to accurately estimate mortality when 1080 is applied using the most recent protocols (Veltman et al. 2014).

Direct mortality of weka caused by primary and secondary poisoning is only part of the picture (Innes & Barker 1999). The other aspect is the effect of a reduction in predator abundance on the weka population. This second aspect has not been adequately studied. Anecdotal reports and earlier studies suggest the presence of mustelids (*Mustela* spp.) and cats (*Felis catus*) can reduce adult weka survivorship (Beauchamp

et al. 1998; TSRP 2009) and reproductive success (Bramley 1996). Since secondary poisoning will reduce the number of mustelids and cats in a treated area (Gillies & Pierce 1999; Murphy et al. 1999), a positive effect of 1080 on weka is likely. To determine the net impact of current aerial 1080 application methods we monitored a weka population through two aerial 1080 operations in Tennyson Inlet, Marlborough Sounds. We studied (1) the mortality of adult weka, (2) the incidence of sublethal poisoning, (3) nest success, (4) chick survivorship and (5) survivorship of adult weka before and after 1080 operations.

Methods

Study site

The study was conducted in the area around Tennyson Inlet in the Marlborough Sounds, approximately 45 km northeast of Nelson and 30 km northwest of Picton. The study site was divided into a treatment block (approx. 3900 ha) centred around Mt. Stanley (41°06'5" S 173°49'0" E) and an adjacent non-treatment block (approx. 2500 ha) centred around Opouri Saddle (41°08'2" S 173°43'5" E) (Fig. 1). The site features coastal mixed podocarp and hard beech (*Fuscospora truncata*) forest at sea level, which gives way to predominantly red beech (*Fuscospora fusca*), silver beech (*Lophozonia menziesii*) and mountain beech (*Fuscospora solandri*) at higher altitudes of up to 1000 m a.s.l.

Average annual rainfall for the area is approximately 1750 mm and ambient temperatures range from -4.5° to 28°C, with an annual average temperature of 13.5°C (CliFlo, National Institute of Water of Atmospheric Research Ltd.).

Substantial flowering was observed in all beech species in the spring of 2013, followed by very heavy seeding in

2014. In addition to the beech mast, many other plant species also produced noticeably large quantities of fruit/seed in the summer of 2014.

Poison operations

Two aerial 1080 operations were conducted in the treatment block during this study. Both operations included a non-toxic pre-feed bait drop 13 days prior to the toxic bait drop. Non-toxic 0.3% cinnamon-lured cereal pellets (16 mm, 6 g RS5) were sown at a rate of 1 kg ha⁻¹ during pre-feed operations. Pellets of the same type containing 0.15% 1080 were dyed green and sown at 1 kg ha⁻¹ for toxic operations. No baits were sown in the non-treatment block. The first 1080 operation occurred on 2 November 2013 and the second operation on 23 November 2014. Both operations covered approximately the same area (4300 ha and 3939 ha in 2013 and 2014, respectively) (Fig. 1).

It took approximately 35 days after each poison operation for rainfall to exceed 100 mm (CliFlo, National Institute of Water of Atmospheric Research Ltd.), after which baits were considered non-toxic (Bowen et al. 1995).

Pest abundance

Rat and stoat abundances were assessed using the protocols of Gillies and Williams (2007). Ten tracking tunnel lines were set out randomly, although constrained by a minimum distance of 500 m, in each of the treatment and non-treatment blocks and each line contained ten tunnels, spaced at 50 m intervals.

Rat abundance was measured four times per year (February, May, August and November) from November 2010 until August 2016 using tracking cards lured with peanut butter for one night. Stoat abundance was measured on five occasions between September 2013 and January 2015, by leaving tracking cards out for three consecutive nights lured with fresh rabbit meat. After January 2015, our stoat index protocol was altered and

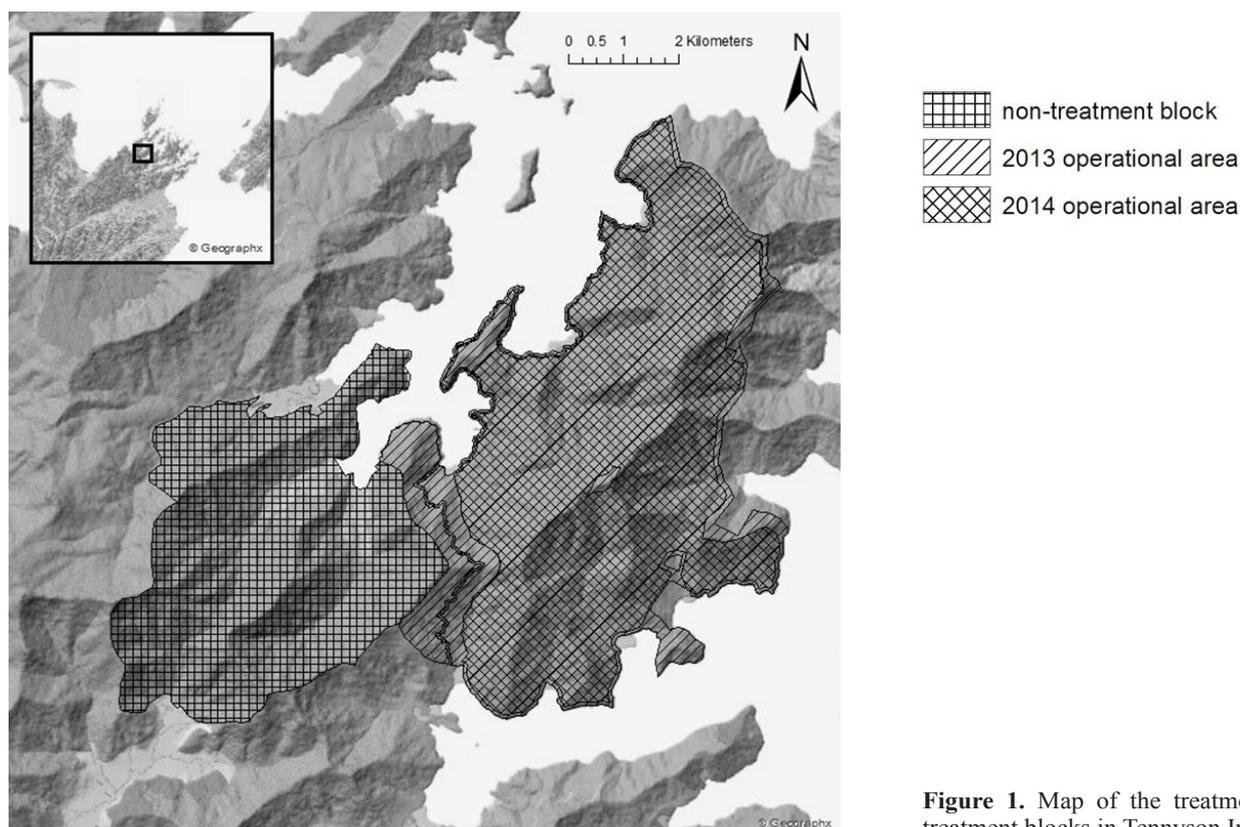


Figure 1. Map of the treatment and non-treatment blocks in Tennyson Inlet.

tracking cards were left out for 14 consecutive nights lured with salted rabbit meat. Stoat abundance was measured on five more occasions using the altered method, with the last survey conducted in August 2016.

Weka capture & identification

A total of 191 adult and juvenile weka were caught between September 2010 and June 2016. Recordings of weka calls were used to locate and attract birds, and hand nets, cage traps and hand nooses were used to capture them.

Adult weka were fitted with a metal leg band, three colour bands and a radio transmitter attached with a flying-bird harness (Karl & Clout 1987). Juveniles were fitted with a metal leg band only. Weight and bill length measurements (Beauchamp 1998) were used to identify the sex of adult birds.

Several types of transmitters were used during this study. The latest model (Sirtrack™, version 9.2) had three pulse rates and determined if birds were alive, dead or incubating, as well as a diagnostic output for determining recent activity and time of death.

Sublethal poisoning

Sublethal poisoning from 1080 was first reported by Walker (1997), when a weka was confirmed to have been poisoned by 1080, showed symptoms and subsequently recovered. The diagnostic transmitters used in our study recorded the activity rate from selected individuals directly before and after the 2014 application of 1080. This data set was used to determine the proportion of birds with such large changes in activity patterns that they may have been adversely affected by the poison.

Mortality and long-term survivorship

From September 2010 until June 2016 the pulse rate of each bird's transmitter was checked regularly to determine whether birds were alive or dead. Radio-tagged birds that could not be located over the course of several weeks were assumed to have died. Weka that died without having been in contact with 1080 were located and a cause of death determined where possible.

Radio-tagged weka that died within 35 days of the poison operations in the treatment block were collected and sent to the Institute of Veterinary, Animal and Biomedical Sciences at Massey University in Palmerston North for autopsy. Muscle tissue samples from these same birds were sent to Manaaki Whenua - Landcare Research in Lincoln, Canterbury, to be assayed for the presence of 1080 using Gas Liquid Chromatography. The likelihood of direct poisoning was assumed to be negligible after 35 days post-operation, when rainfall had exceeded 100 mm. The risk period for secondary poisoning was considered to be similar, judging from calculations made with regard to deer and possum carcass monitoring (McIntosh et al. 1959, 1966; Meenken & Booth 1997; Ross & McCoskery 2012). These studies suggest that beyond a carcass age of 25 days, a weka would need to consume considerably more than its daily food intake of possum/deer stomach to show symptoms of 1080 poisoning.

Direct mortality figures were calculated as a point estimate with 95% confidence intervals (CI). The Clopper-Pearson Exact Binomial method (Clopper & Pearson 1934) was used for calculating confidence intervals.

Factors affecting long-term adult weka survivorship were examined using generalised linear models (GLMs) with binomial errors and complementary log-log link functions using methods from Rotella et al. (2004) and Bolker (2014).

GLMs were run in the statistical program R version 3.4.1 (R Core Team 2016). A suite of 11 plausible models variously including and excluding possible explanatory covariates for year, sex, block, stoat abundance and 1080 treatment were compared using AICc (Burnham & Anderson 2002).

Nest success & chick survivorship

Weka activity was monitored by observers using a Yagi aerial (Sirtrack™) and Telonics™ TR4 hand-held receiver. Although weka in the Marlborough Sounds are known to breed year-round (Beauchamp 1987), we intensively monitored the pairs in this study during the months of spring and summer (September–January) between January 2011 and January 2016.

During the spring and summer monitoring periods, we collected diagnostic outputs (which provided an index of average daily activity) of all females at weekly intervals, in an attempt to acquire a complete picture of nesting activity. Since females incubate during daylight hours, a sharp drop in activity occurred when nesting started. When the diagnostic output indicated a pair was nesting we located the nest and installed a motion-triggered camera (Ltl Acorn®-5210 series), which recorded hatch date, number of chicks hatched, predation attempts and parental attendance. Once the family left the nest area, 2–3 days after hatching, they were visited weekly until the pair had either lost all chicks or until the chicks were considered independent. Weka chicks are known to stay with their parents until 55 days old (Beauchamp 1987) so any chick that could not be located using parental transmitters before 55 days old was assumed to have died.

Factors affecting nest success and chick survivorship were investigated with the same methods used to examine long-term survivorship, except that for chick survivorship we accounted for the possibility that survivorship of each chick in the same brood may not have been independent of the others using generalised linear mixed models (GLMMs) with a random effect for brood. GLMMs were run in R version 3.4.1 (R Core Team 2016) using the package lme4 version 1.1-15 (Bates et al. 2014). For both nesting success and chick survivorship we explored the possibility that survival might vary with nest or chick age and days since the beginning of the field season (timing) by incorporating linear, second order and third order polynomial relationships between age, timing and nesting success or chick survivorship.

To explore the relationship between nest success and 1080 operations we assessed via model selection 11 GLMs to determine whether our data supported a treatment effect after the 2013 operation or a year after the 2014 operation in 2015. For 2013, we measured nest success in the same season before and after the 1080 operation and thus had a BACI design (Stewart-Oaten et al. 1986). We compared models with and without an interaction effect between site and before/after to determine whether the data supported a treatment effect in 2013. We could not carry out the same sort of BACI analysis in 2014 because we found no nests in our non-treatment block after the 1080 operation that year. Instead we simply compared models with separate terms for before and after the 1080 drop in 2014 with models where before and after had been combined. For 2015, we had no before/after measures in the same year, so we compared nest success in the treatment and non-treatment blocks.

To explore the relationship between chick survivorship and 1080 operations we compared a suite of GLMMs to determine whether our data supported a treatment effect after the 1080 operations in 2013 and 2014 or a year later in 2015. For 2013

and 2014, we measured chick survivorship in the same season before and after the 1080 operation and thus had a BACI design (Stewart-Oaten et al. 1986). We compared models with and without an interaction effect between site and before/after to determine whether the data supported a treatment effect. For 2015, we had no before/after measures in the same year, so we compared the survival rates between our treatment and non-treatment blocks.

Results

Rat and stoat abundance

Before the 1080 operations, the rat tracking indices in the non-treatment block were consistently higher than in the treatment block (Fig. 2). In 2013, after the 1080 operation,

rat indices dropped from low (<20%) to undetectable levels in the treatment block, but then rose quickly during the beech mast in 2014. The 1080 operation in 2014 lowered rat indices from very high (94%) to low (12%) levels, followed by quick recovery to levels of around 35%. For both 2013 and 2014, the 1080 operations maintained stoat tracking rates at low levels (<5%) for at least 12 months. Stoat tracking rates then increased in the non-treatment block in January 2015 (Fig. 3) and remained high compared to the tracking rates in the treatment block for over a year.

Direct mortality

In the treatment block, 58 adult birds were monitored for a minimum of 35 days after the 2013 and 2014 aerial 1080 applications and 39 adult birds were monitored for the same period in the non-treatment block (Table 1). Due to the

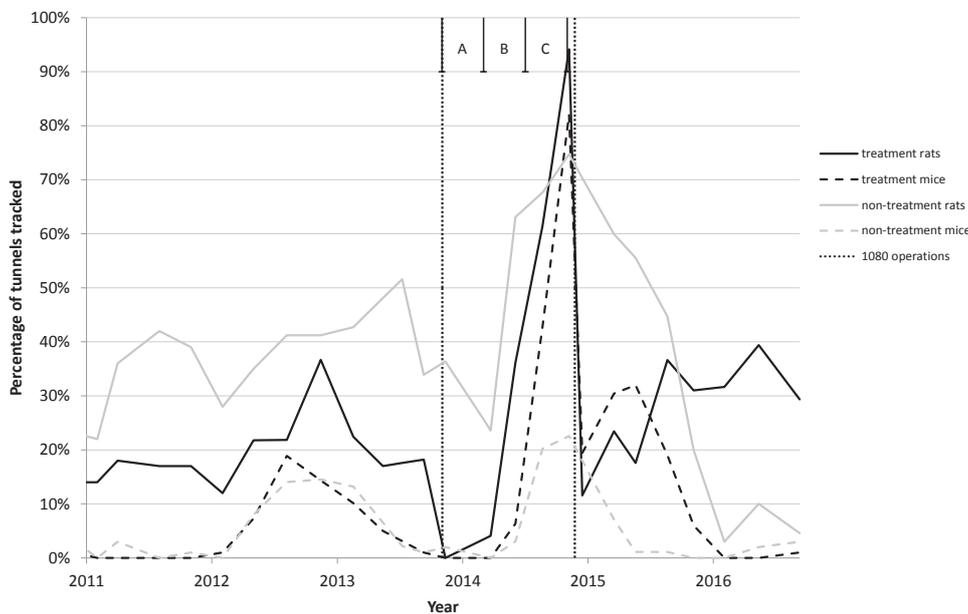


Figure 2. Tracking tunnel indices for rats in Tennyson Inlet with vertical bars denoting the poison operations that occurred on the 2nd of November 2013 and the 23rd of November 2014. Time block ‘A’ represents the period when beech flowering was observed and seeds began to develop, ‘B’ when the seeds fell to the ground and ‘C’ when seeds lay dormant on the forest floor before germinating.

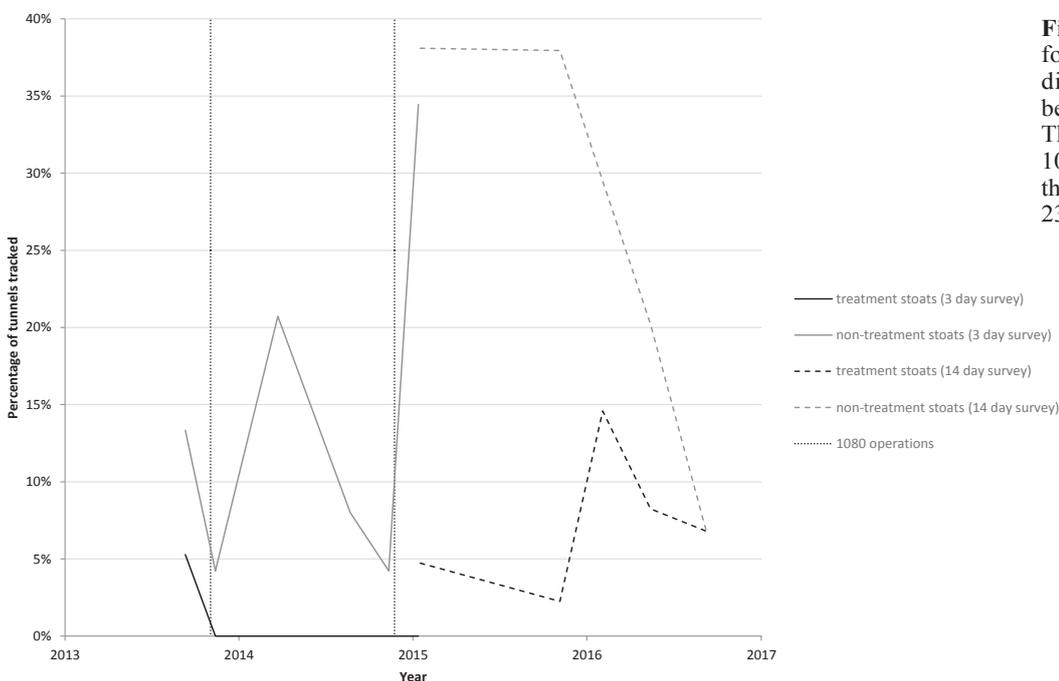
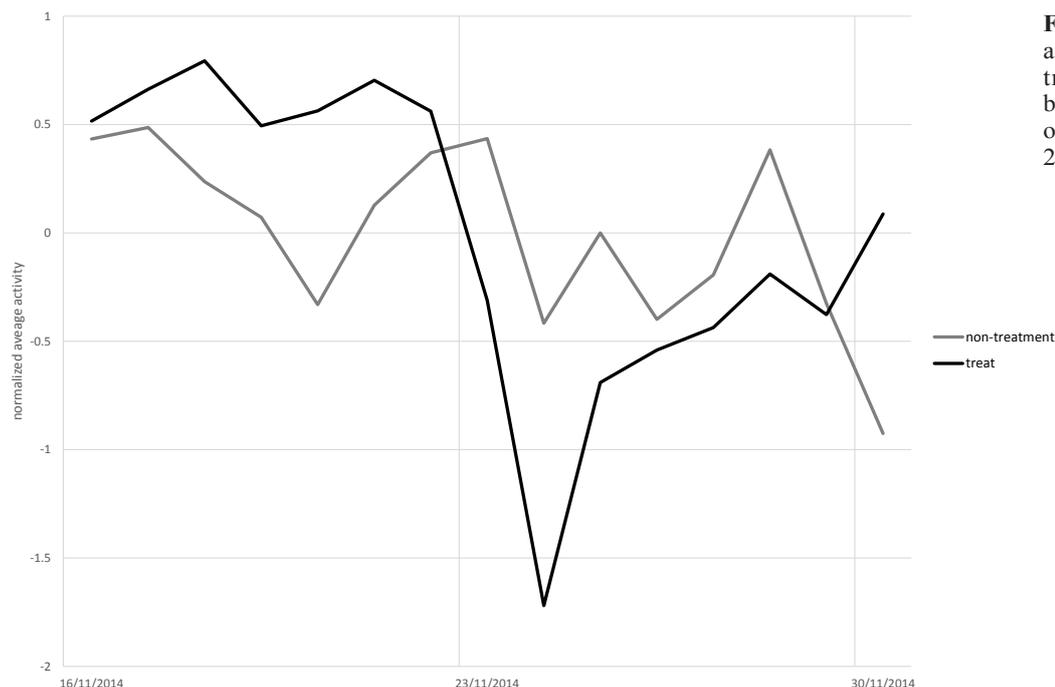


Figure 3. Tracking tunnel indices for stoats in Tennyson Inlet with different index measurements before and after January 2015. The dotted vertical bars denote the 1080 operations that occurred on the 2nd of November 2013 and the 23rd of November 2014.

Table 1. Mortality of weka monitored in treatment and non-treatment blocks during the 2013 and 2014 aerial 1080 operations in Tennyson Inlet.

Year	Block	Number of weka monitored	Risk period	Number of dead	1080 concentration in tissue ($\mu\text{g g}^{-1}$)
2013	Treatment	26	35 days	1	1.23
2013	Non-treatment	21	N/A	0	N/A
2014	Treatment	32	35 days	0	N/A
2014	Non-treatment	18	N/A	2	N/A

**Figure 4.** Normalized average activity levels of weka in the treatment and non-treatment blocks. The 1080 operation occurred on the 23rd of November 2014.

accuracy associated with GPS guided delivery of 1080 baits, it is assumed that 1080 pellets would have been present within the home range of each weka in the treatment block. Three weka were found dead in the treatment block soon after the 1080 operations and their times of death were determined from their transmitters.

One adult male weka (1250 g) died the day after the aerial 1080 operation in 2013 and was found to have $1.23 \mu\text{g g}^{-1}$ of 1080 in its muscle tissue. It was almost certainly killed by 1080. One adult female weka (745 g) died 4 days after the 2014 aerial 1080 operation and was found to have traces of 1080 ($0.004 \mu\text{g g}^{-1}$) in its muscle tissue. However, the NOEL (no observed effect level) of 1080 in gavaged weka has previously been reported as $4.5\text{--}6.75 \mu\text{g g}^{-1}$ (McIntosh et al. 1966) and it seems unlikely that the level of 1080 found in the muscle tissue of this bird was sufficient to kill it. There was no visible sign of dyed bait remnants in its gut. The bird had some bruising, indicating that it had been grabbed before death and it was found down a long-drop toilet near a public hut together with another weka. The transmitter of the second weka found in the long-drop toilet (soon after the 2014 operation) revealed that it had died several weeks before the aerial 1080 operation. We think both birds found in the toilet had been killed by humans though one had consumed a small amount of 1080 before it was killed. Both weka were excluded from our estimates of mortality caused by 1080. We have assumed

that only the male weka found dead was killed by 1080 baits and therefore the mortality rate of weka monitored for both aerial 1080 operations combined was 1.8% (0.04–9.24% CI).

Of the 39 birds in the non-treatment block, two died during the same 35-day post-operation period. Their cause of death could not be determined. Both these birds were found approximately 4.5 km from the edge of the treatment block. The death rate of the monitored birds not exposed to 1080 baits was higher but not significantly higher than those exposed to 1080 baits.

Sublethal poisoning

There was a significant difference in the activity of our study birds after the 1080 operation in the treatment block compared with the non-treatment block (Fisher's exact test $P = 0.018$). In the 3 days following the 1080 operation, the average daily activity of weka with diagnostic transmitters dropped by $31.2\% \pm 4.6\%$ (standard error of the mean) ($N = 10$) and $8.0\% \pm 4.3\%$ ($N = 6$) in the treatment and non-treatment block respectively. All individuals in the treatment block had a pronounced drop in activity during the 3 days following the poison operation compared to 7 days immediately prior to the operation, but seemed to revert to normal daily activity levels within approximately 7 days (see Fig. 4).

Long-term survivorship

We monitored the long-term survivorship of 157 radio-tagged adult weka. Model selection for long-term survivorship identified four highly ranked models with similar AICc values. All four models had terms for stoat plague and 1080 treatment and differed only in their inclusion of sex and the interaction between stoat plague and 1080 treatment as explanatory terms (Table 2). We conclude that the stoat plague substantially reduced adult survival in 2015, but that 1080 baiting eliminated the effect of the stoat plague in the treatment block (Fig. 5). We are uncertain whether the survival of males and females differs, and whether 1080 was more effective at increasing adult weka survivorship during stoat plagues, than at other times.

Estimated annual survival of weka during the first 5 years of our study when stoats were rare was 63% (55–70% CI) similar to the 62.5% observed by Beauchamp (1987) in nearby Double Cove, Marlborough Sounds. In 2015, when stoat numbers were high in our non-treatment block, estimated annual survival of adult weka was only 12% (4–24% CI). In contrast, estimated annual survival in the treatment block in 2015 was similar to, or better than, that during the first 5 years of the study: 71% (55–82% CI).

Table 2. AIC_c for 11 candidate GLMs of the relationship between adult survivorship, year, sex, block, stoat plagues and 1080 treatment.

	K	AIC _c	ΔAIC _c
plague × treat	4	947.88	0.00
plague + treat	3	948.13	0.25
sex + plague × treat	5	948.14	0.25
sex + plague + treat	4	948.48	0.60
sex + year × block	13	956.18	8.29
year × block	12	956.25	8.36
treat	2	973.86	25.97
sex + treat	3	974.22	26.33
plague	2	975.57	27.68
sex + plague	3	976.28	28.41
null	1	981.51	33.63

Nest success

We monitored 93 weka nests, 11 of which failed. Two failures were caused by the death of one of the parents, two by infertility, one by lack of parental attendance and one by predation by another weka. The cause of the remaining five nest failures could not be determined, but we had no evidence of any nest failing due to interference by introduced mammals.

The inclusion of linear terms for nest age and timing in the models improved the GLMs and these terms were included in all the models exploring the effect of 1080 operations (Table 3).

Although nesting success was higher after the 1080 operations in 2013 and 2014, and lower in the treatment block in 2015 than it was in the non-treatment block (Fig. 6), models without these effects better fitted the data than did models that included them (Table 3). AIC_c ranked a simple model with only time and age effects much higher than any of the other plausible models (Table 3). This analysis provides no evidence that nesting success was affected either positively or negatively by predators or their control.

Chick survivorship

Between January 2011 and January 2016, we monitored 234 weka chicks from 102 broods, equally split between the treatment and non-treatment blocks. Seventy chicks disappeared before they were 55 days old and were assumed to have died. Before chicks grew adult feathers (at approximately 35 days of age) mortality rates were relatively high with a daily death rate of 1.15%, dropping to 0.34% at ages over 35 days. These death rates equate to a survival probability of 66.6% for the period between hatching and 35 days and 93.4% for chicks between the age of 36 days and independence, set at 55 days.

During the stoat irruption in 2015, chick survival was 12% in the untreated block and 80% in the treated block.

The inclusion of a quadratic relationship with chick age and a third order polynomial relationship with timing substantially improved the GLMMs and these terms were included in all the models exploring the effect of 1080 operations.

The best models of the relationship between chick survival and treatments have strong support for treatment effects in 2013 and 2015, and lesser support for a 2014 treatment effect

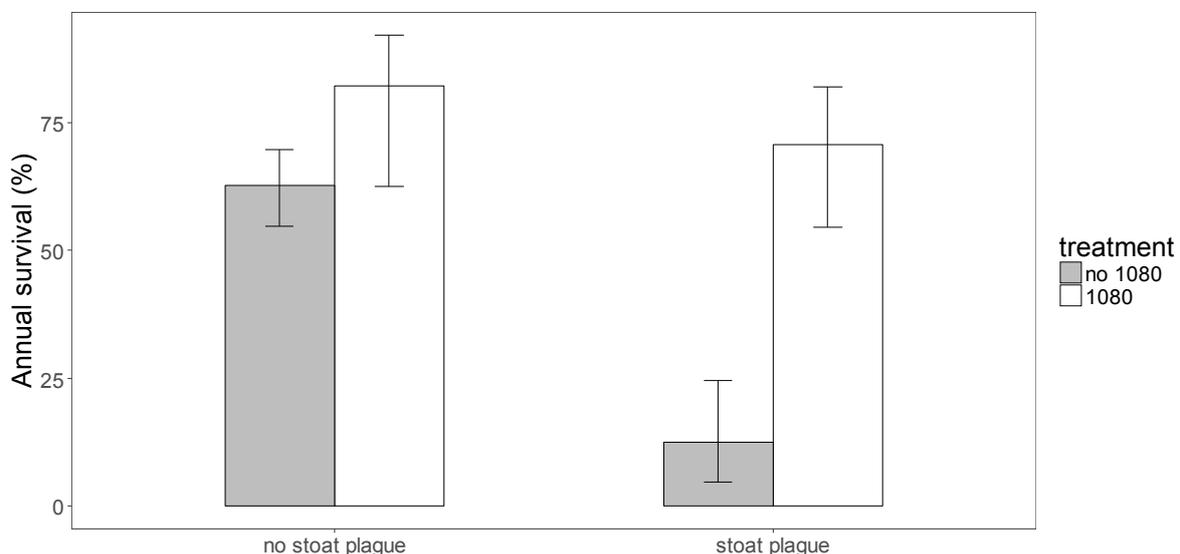
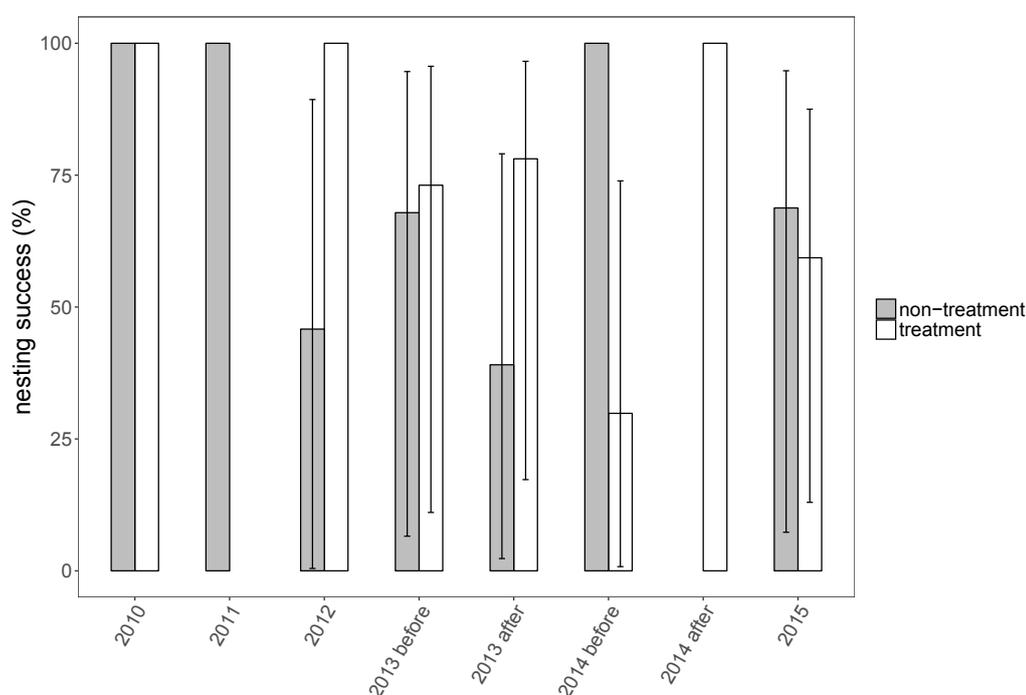


Figure 5. Estimated annual survivorship of adult weka (± 95% CI) in stoat and non-stoat-plague years with and without 1080 treatment.

Table 3. AIC_c for 11 candidate GLMs of the relationship between nest success, year, block, and treatment effects in 2013, 2014 and 2015. All models include linear effects for nest age and timing.

	K	AIC _c	ΔAIC _c
Null	3	110.68	0.00
block	4	112.64	1.96
year	8	117.60	6.92
year + block	9	119.62	8.94
year + block + treat2013	10	120.32	9.64
year + block + treat2014	10	121.51	10.82
year + block + treat2015	10	121.52	10.84
year + block + treat2013 + treat2014	11	122.13	11.45
year + block + treat2013 + treat2015	11	122.35	11.67
year + block + treat2014 + treat2015	11	123.42	12.74
year + block + treat2013 + treat2014 + treat2015	12	124.17	13.49

**Figure 6.** Estimated nest success of weka ($\pm 95\%$ CI) in the treatment and non-treatment blocks. Data are shown for each year, with 2013 and 2014 subdivided into before and after the 1080 operations. No nests were monitored in the treatment block in 2010 and 2011. No confidence intervals are shown when nest success is 100%.

(Table 4). In 2015, nearly a year after the last 1080 operation, chick survivorship was substantially lower in the non-treatment block than in the treatment block (Fig. 7). In 2013, chick survivorship in the treatment block dropped sharply after the 1080 operation, while in 2014 chick survivorship in the treatment block increased relative to the non-treatment block.

Discussion

Pest indices

In 2013, rat numbers were reduced to undetectable levels after the 1080 operation, but following the 2014 beech mast, rat numbers rose to 94% tracking rate in the treatment block. The 1080 operation in 2014 achieved only a moderate rat kill which might be a consequence of the very high rat abundance before the 1080 operation. With very high rat densities and low poison sowing rates (1 kg ha^{-1}) we speculate that there may not have been enough 1080 bait, or that bait was not sufficiently evenly distributed, for all rats to come in contact with it.

Our study suggests high rat abundance does not directly affect weka survivorship, but there may be means by which high rat abundance could affect nest success (see ‘other population impacts’). Rodent abundance has an indirect effect on weka survivorship, because when rodents are abundant they constitute a large part of stoats’ diets (King et al. 1996; Murphy et al. 1998) and stoat numbers increase. As a consequence of sustained high rat numbers in the non-treatment, stoat abundance peaked in the summer of 2014/2015. Stoat abundance remained high for over a year after the 2014/2015 peak, after which the first signs of decline became evident, coinciding with a drop in rodent abundance.

Direct mortality and sublethal poisoning

Our result suggests sublethal poisoning of weka is ubiquitous during a 1080 operation. Of the 32 adult birds monitored for mortality in the 2014 operation, 66% (21) were also monitored the previous year and were likely to have been sublethally poisoned during the 2013 operation. These birds might have biased our estimate of mortality because they may have learned

Table 4. AIC_c values for eight candidate GLMMs of the relationship between chick survivorship, block, year and treatment effects in 2013, 2014 and 2015. All models included a second order polynomial term for chick age and a third order polynomial term for timing.

	K	AIC _c	ΔAIC _c
block+year+treat13+treat15	17	459.30	0.00
block+year+treat13	16	460.90	1.60
block+year+treat13+treat14+treat15	18	461.23	1.93
block+year+treat13+treat14	17	462.91	3.61
block+year+treat15	16	465.14	5.84
block+year+treat14+treat15	17	466.60	7.29
block+year	15	469.76	10.45
block+year+treat14	16	471.47	12.16

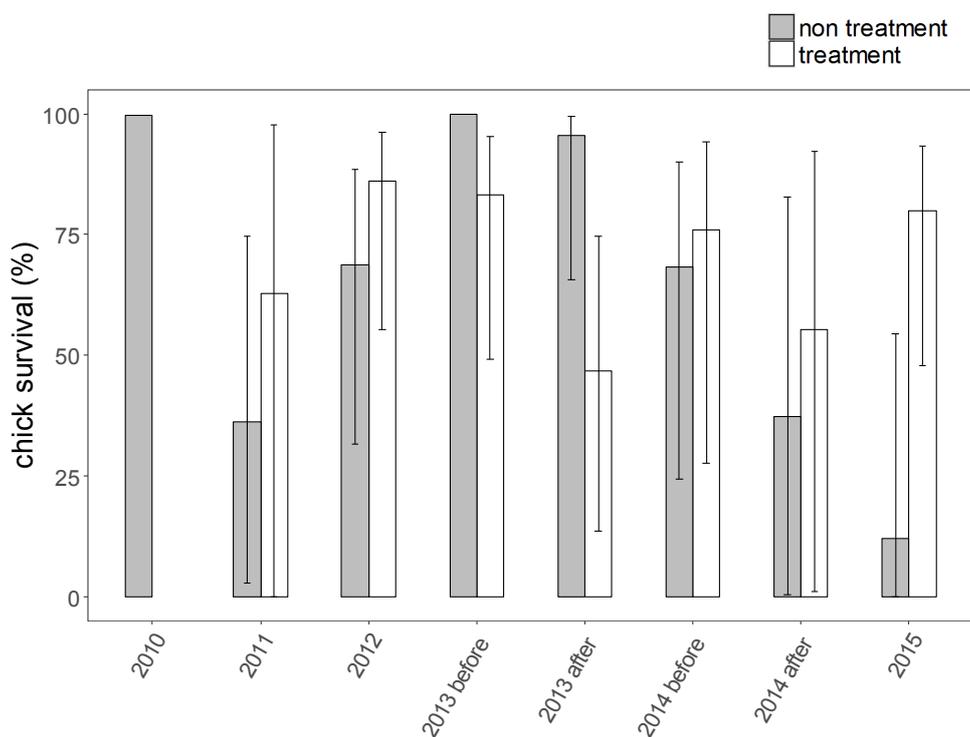


Figure 7. Estimated weka chick survival from hatching to independence ($\pm 95\%$ CI) in the treatment and non-treatment blocks. Data are shown for each year, with 2013 and 2014 subdivided into before and after the 1080 operations. No chicks were monitored in the treatment block in 2010. No confidence intervals are shown when chick survival was 100%.

to avoid the 1080 pellets. However, seven of the ten birds monitored for sublethal poisoning in 2014 were known to have been alive during the previous 1080 operation, yet they clearly had not learned to avoid 1080 pellets as they all showed signs of sublethal poisoning during their second exposure to 1080. Therefore, we conclude that we can reasonably treat mortality rates from both poison operations as independent.

Combining our study with another, the pooled mortality rate from monitoring 90 birds across four 1080 operations is 3.3% (0.7–9.4% CI). These data combine our mortality data (1.8%, 0.04–9.2% CI) with that gathered by van Klink (2013; 6.2%, 0.8–20.1% CI) during two 1080 operations using similar protocols. However, the operations described by van Klink used 12 g pellets and a sowing rate of 2 kg ha⁻¹ toxic pellets.

During the 1080 operation in 2014, all 10 birds monitored for sublethal poisoning had a sharp drop in activity soon after the 1080 was sowed, followed by rapid recovery. It seems that most weka that eat 1080 baits are sublethally poisoned.

Weka have an estimated LD₅₀ of 8.1 mg kg⁻¹ (McIntosh et al. 1966), meaning a single 6 g 0.15% w/w 1080 pellet contains sufficient poison to kill 50% of weka weighing 1.1 kg. Weka are generally regarded as neophilic and clearly

eat 1080 pellets (Spurr 1993; Hartley et al. 2000). In our study area, the average adult male weight was 1138 g (N = 76) and adult female weight was 784 g (N = 66). Therefore, their low mortality is surprising. Walker (1997) offered three possible explanations for the low mortality rates of weka during 1080 operations:

1. Weka can detect 1080, dislike the smell and ignore the pellets.
2. Weka only peck at pellets, receive a sublethal dose, and subsequently avoid pellets.
3. The LD₅₀ for weka is higher than existing information suggests.

The speed with which weka show symptoms of 1080 poisoning has not been studied, but studies on other bird species suggest that the latency period could be between 1 to 18 hours (McIntosh et al. 1966; McIlroy 1984; Ataria et al. 2000). It is possible that some physiological effects might be noticed by birds before symptoms occur, a notion that has been explored in mice (Fisher et al. 2009). Fisher et al. (2009) suggest that a water-soluble, rapidly absorbed and metabolised poison such as 1080 could have subtle aversive effects on mice in minutes, rather than hours. However, since weka activity, as measured

by transmitters, dropped dramatically after 1080 exposure, we have compelling evidence that weka with transmitters ate a sublethal amount of 1080. We hypothesise that they neither avoided the pellets nor detected the 1080 after only a small asymptomatic dose. Assuming the LD₅₀ of 1080 for weka estimated by McIntosh et al (1966) is approximately correct, then weka must either have pecked at the baits and become ill before consuming a lethal dose, or they must have eaten a whole bait and regurgitated it before they absorbed a lethal dose.

Long-term survivorship

Weka survivorship was improved by the 1080 application in 2014, but not in 2013. We speculate that the difference is related to stoat abundance as indexed by tracking rates. In 2013 there were relatively few stoats, weka survival was high and the poisoning of a few stoats by 1080 made little difference. In contrast, after the 2014 operations stoats were abundant and weka survival was low, except in our treatment block where the poisoning of stoats with 1080 caused a substantial decrease in stoat abundance and a substantial increase in weka survivorship.

Although we know that at least one weka was killed by 1080 in 2013, our statistical analysis did not support the notion that 1080 operations had an adverse effect on the long-term survivorship of weka. It seems that although weka can be killed by 1080, the low mortality is undetectable when measured on an annual timescale.

Previous studies suggest that at national or regional scales, habitat loss and drought are major contributing factors to a reduction in weka populations (Beauchamp 1987, 1997; Beauchamp et al. 1998). No habitat was lost during our study and the difference in weka survival between the treatment and non-treatment blocks excludes drought as an explanation for the decline we observed in our non-treatment block. In our study, stoat predation is the most likely explanation for the reduction in weka we observed.

Nest success and chick survivorship

Statistical analysis of nest success data did not support the notion that 1080 affected nest success after either the 2013 or 2014 1080 operations. During this study, automatic cameras recorded a variety of mammals including mice, rats, possums, stoats and cats investigating weka nests, but none of these nests failed. The only observed predation was caused by another weka. Predation of weka nests by introduced mammals (perhaps excluding dogs *Canis familiaris*) seems to be rare. Perhaps because weka are relatively large and aggressive birds they are able to protect their nests from most predators. Since weka nests are rarely preyed upon by mammalian predators there is little scope for an improvement in nest success following 1080 bait application.

A sublethally poisoned adult weka could conceivably neglect its nesting duties, but the three pairs of weka that were incubating at the time of the 2013 and 2014 1080 operations continued incubating successfully. 1080 did not adversely affect nest success in our study. Our analysis indicated that chick survival was probably negatively affected by 1080 operation in 2013 and positively affected by the 2014 operation. During the period when stoats were abundant in 2015, a year after the last 1080 operation, there was a substantial decrease in chick survival in the non-treatment block, which did not occur in the treatment block. These results suggest that during 2013 when there were no predator plagues, the 1080 operation

had a negative effect on chick survival, perhaps because some chicks died either when they were fed poison by their parents, or when their parents became ill for a short time after eating 1080. After the 2014 operations there may have been a similar impact, but it was overshadowed by the positive effect of killing stoats. In 2015 no aerial 1080 baiting occurred, and in the non-treatment block chick survivorship was low, probably because the chicks were eaten by stoats which were at a high density. In the treatment block stoat numbers were still suppressed following the 1080 drop a year before, and chick survivorship was high.

Other population impacts

We may have overestimated nesting success because we were unable to detect nest failures that occurred during laying. Most of the nests we monitored were found when the diagnostic transmitters indicated that the female was incubating and using this method we were unable to find nests before incubation started. The only nest we found during laying was found by chance. A camera showed that the female on this nest spent approximately 50% of her time attending the nest during 2 days between the laying of the first and fourth eggs. Subsequent parental attendance rose from 90% over the following 2 days to 100% for the remainder of the incubation period. The low nest attendance during laying means nests are more vulnerable to predation during laying than they are during incubation, yet any failures during laying would be undetected.

Only a few published studies report on the long-term impact of sublethal poisoning with 1080 and most of these are concerned with the effect of long-term dosing on developmental and reproductive toxicology in mammals (ERMA 2007). The effects of a single sublethal dose of 1080 in birds, as might occur after a 1080 operation, has only been studied once (Ataria et al. 2000). This study showed that although 1080 residues were quickly excreted in live mallards (*Anas platyrhynchos*), histopathological abnormalities sometimes occurred, particularly in heart and skeletal muscle tissue. Single dose studies on sheep (*Ovis aries*) also showed effects on heart, brain and lung tissue, but were without clinical significance (O'Connor et al. 1999; Gooneratne et al. 2008). Weka might also suffer tissue damage from a sublethal dose of 1080, although how this would affect their long-term health is unknown. The adult survival rate of weka that we recorded before the first 1080 operation suggests a median life-expectancy of approximately 1.6 years. Weka are relatively short-lived and any 'long-term' effect on their health would have to occur within 1–2 years for it to have any impact on their population dynamics. Weka survival in the treatment block in the 2 years following the first 1080 operation was higher than in the non-treatment block. 1080 had had no detectable 'long-term' effect on the population at the end of our study by which time more than half the birds that were exposed to 1080 in 2013 had already died from other causes.

The net effect of 1080 on weka

Weka may readily eat 1080 pellets, but for an unknown reason the mortality rate from 1080 poisoning is low and undetectable when compared with other causes of weka mortality over a whole year. We could detect no effect of 1080 on nest success, chick or adult survival in the years of the 1080 operations, but the treatment appears to have prevented a substantial decrease in chick and adult survivorship in the 12 months after the 1080 operation in 2014, which coincided with a stoat

irruption. Adult survival was 71% in the block treated with 1080 compared to 12% in the untreated block. Chick survival was 12% in the untreated block and 80% in the treated block. The improvement in adult survival associated with 1080 is clearly enough on its own to compensate for the small mortality, and the increase in chick survival means that the benefit to weka is even greater. It is important to note that we detected an improvement in adult and chick survivorship in the treatment block only after the second 1080 operation, not the first. We conclude that it is only when stoats are abundant that 1080 use has the potential to benefit weka through reduced stoat predation: at times when stoats are not abundant they have relatively little impact on weka.

Although we monitored weka through two aerial 1080 operations, the circumstances of the two operations were very different. The second operation was after a beech mast when rodent and stoat numbers had risen substantially, while there was no such rise in predator numbers at the time of the first operation. The best available evidence suggests that 1080 operations that are timed to pre-empt stoat irruptions will benefit weka populations, while those that are not timed to pre-empt stoat irruptions will have a small, even negligible, negative impact on weka populations.

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