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Using gamma distribution to determine half-life of rotenone, applied in freshwater

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HIGHLIGHTS

- We investigated the use of the gamma model to calculate the half-life of rotenone.
- Physical and environmental variables can be incorporated into the model.
- A method for calculating the range around a mean half-life is presented.
- The model is more flexible than the traditionally used first-order kinetic model.

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ABSTRACT

Following the use of rotenone to eradicate invasive pest fish, a dynamic first-order kinetic model is usually used to determine the half-life and rate at which rotenone dissipated from the treated waterbody. In this study, we investigate the use of a stochastic gamma model for determining the half-life and rate at which rotenone dissipates from waterbodies. The first-order kinetic and gamma models produced similar values for the half-life (4.45 days and 5.33 days respectively) and days to complete dissipation (51.2 days and 52.48 days respectively). However, the gamma model fitted the data better and was more flexible than the first-order kinetic model, allowing us to use covariates and to predict a possible range for the half-life of rotenone. These benefits are particularly important when examining the influence that different environmental factors have on rotenone dissipation and when trying to predict the rate at which rotenone will dissipate during future operations. We therefore recommend that in future the gamma distribution model is used when calculating the half-life of rotenone in preference to the dynamic first-order kinetics model.

1. Introduction

Rotenone is a natural toxin derived from the roots and stems of several tropical and sub-tropical plants of the pea (Leguminosae) family (Ling, 2003). It is used as a terrestrial insecticide, and being highly toxic to fish, with 24 hour 50% Lethal Concentration (LC_{50}) values commonly between 5 and 100 μg/L, as a non-specific piscicide. It has been used as a piscicide to control and eradicate invasive species, restore native species and to manage recreational fisheries in North America (e.g. Finlayson et al., 2010, 2014; Vasquez et al., 2012), Europe (e.g. Norwegian Ministry of the Environment, 2007; Mo et al., 2008; Britton et al., 2010), Africa (Weyl et al., 2014), Pacific Islands (Nico and Walsh, 2011; Nico et al., 2015), Australia (e.g. Rayner and Creese, 2006; Morgan et al., 2014; Pearce, 2014), and New Zealand (Chadderton et al., 2001; Studholme, 2003; Pham et al., 2013).

Rotenone was first trialled as a piscicide in New Zealand in 1981 (Rowe and Champion, 1993). It was not used again until 2001 when koi carp (*Cyprinus carpio*) and gambusia (*Gambusia affinis*) populations were found for the first time in the South Island (Shaw and Studholme, 2001). Between 2001 and 2012, sixty-nine sites, mostly small ponds and dams, throughout New Zealand were treated with rotenone to prevent the spread of invasive fish species. The majority of these operations successfully eradicated the fish being targeted. However, some sites have had to be re-treated after the eradication attempt failed or fish were illegally re-introduced.

Rotenone has a low water solubility (0.2 mg/L at 20 °C, Ling, 2003), and is broken down in water to non-toxic products via hydrolysis, oxidation and photochemical conversion. The rate at which these processes occur is dependent upon factors such as temperature, pH, water hardness, and sunlight but typically persistence in natural waters ranges

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from a few days to several weeks (Ling, 2003). It is important to monitor the rate of dissipation of rotenone from the waterbody following its use as a piscicide to confirm that sufficient rotenone was used to achieve a complete fish kill (Finlayson et al., 2014); and determine when desirable fish can be restocked (Gilderhus et al., 1988), water can be taken for drinking (ERMA NZ, 2008, 2009; Finlayson et al., 2014) and recreational activities can resume (Finlayson et al., 2014).

The data collected on the rate of dissipation can be used to determine the half-life ($t_{1/2}$) of rotenone in waterbodies. Determining the half-life is important because as it can be used to estimate the rate at which rotenone will dissipate during future pest fish control operations. The environmental fate of pesticides is of concern to regulatory authorities and the public, and if pest control tools are to be maintained they must be shown to have minimal long term impacts on the environment. Therefore, information about the half-life of rotenone is valuable when applying for approval to use it from consenting authorities (Dawson et al., 1991; Finlayson et al., 2014) and designing water sampling protocols (Gilderhus et al., 1986, 1988; Finlayson et al., 2014). It is also important in determining the correct amount of rotenone to apply and for maintaining public confidence in the use of rotenone by showing that it does not persist in the environment (Finlayson et al., 2001, 2014; Vasquez et al., 2012).

A dynamic first-order kinetics model is commonly used to calculate dissipation rates and half-lives of organic chemicals in aqueous solutions, including rotenone (e.g. Gilderhus et al., 1988; Dawson et al., 1991; Siepmann and Finlayson, 1999; Finlayson et al., 2001, 2014; Vasquez et al., 2012). Unfortunately, the use of the first-order kinetics model to calculate $t_{1/2}$ has a number of issues. Firstly, while the original scale can usually be meaningfully interpreted, in some cases log transformation of the original scale may not be. For example, rotenone concentration is always positive; whereas the log transformed rotenone concentration may be a negative value. Secondly, environmental variables such as temperature, pH, water hardness and sunlight, and random variation among operations are unaccounted for in the model.

Since the concentration of rotenone in ponds is expected to decline to zero over time, it can be interpreted as a study of survival time of rotenone. The two parameter gamma model is widely used for analysing life-time data. We consider it a suitable candidate for analysing the dissipation of rotenone because (i) the response variable has a constant coefficient of variation rather than a constant variance, (ii) the response variable can be modelled without transformation, (iii) the range of parameter values allow for a flexible range of distributions, and (iv) environmental variables can be built into the model, making it easy to fit the model to the data. The density of the gamma distribution is given by:

$$f(y) = \frac{1}{\lambda^{\alpha}\Gamma(\alpha)} y^{\alpha-1} e^{-\frac{y}{\lambda}} \quad ; y \geq 0 \tag{1}$$

where α and λ are the distribution parameters, describing shape and scale respectively. The first part of the above expression is constant. The gamma distribution provides considerable flexibility with non-negative response variables because the scale parameter and especially the shape parameter allow for a range of distribution patterns (Faraway, 2006). The mean and the variance for the gamma distribution are:

$$\begin{aligned} &\text{mean} = E(y) = \mu = \alpha\lambda; \text{and} \\ &\text{variance} = \text{Var}(y) = \alpha\lambda^2. \end{aligned} \tag{2}$$

The parameters are commonly unknown, but can be estimated using the equations:

$$\begin{aligned} &\text{shape parameter} = \alpha = \text{mean}^2/\text{variance}; \text{and} \\ &\text{scale parameter} = \lambda = \text{variance}/\text{mean}. \end{aligned} \tag{3}$$

Apart from life-time distribution, the gamma distribution also has applications in fields such as hydrology and engineering (Aksoy, 2000; Gupta and Kundu, 2001).

In the present study, we investigate the use of the stochastic gamma model for determining the rate of dissipation and half-life of rotenone using data collected during invasive fish eradications in New Zealand. We then compare the results from the gamma model with the traditional first-order kinetics model to determine which model fits the data better and provides a better estimate of the half-life of rotenone. We also provide a preliminary estimate of the half-life of rotenone in New Zealand waterbodies.

2. Methods

2.1. Study sites and treatment

Twenty one sites where the dissipation of rotenone was comprehensively monitored were used in this study (Table 1). All the sites, with the exception of upper reservoir in the Karori Sanctuary, were small (75–15,000 m^2 area, 0.5–4 m deep) man-made earth bottomed ponds and dams built for irrigation or ornamental purposes. The Karori Sanctuary

Table 1
Location of operations where water samples were collected.

Site	Region	Date piscicide applied	Water temperature recorded
Waiwhero pond 1	Nelson-Marlborough, South Island	3 April 2002	
Waiwhero pond 2	Nelson-Marlborough, South Island	3 April 2002	
Waiwhero pond 3	Nelson-Marlborough, South Island	3 April 2002	
Bensemann pond 1	Nelson-Marlborough, South Island	5 April 2002	
Bensemann pond 2	Nelson-Marlborough, South Island	5 April 2002	
Bensemann pond 3	Nelson-Marlborough, South Island	5 April 2002	
Devlin's pond	Nelson-Marlborough, South Island	11 April 2002	
Hansen's pond	Nelson-Marlborough, South Island	11 March 2003	
Wood's pond	Nelson-Marlborough, South Island	11 March 2003	
Hansen's pond	Nelson-Marlborough, South Island	25 April 2008	✔
Urquhart pond 2	Nelson-Marlborough, South Island	16 March 2010	
Urquhart pond 3	Nelson-Marlborough, South Island	16 March 2010	
Urquhart pond 4	Nelson-Marlborough, South Island	16 March 2010	
Hansen's pond	Nelson-Marlborough, South Island	17 March 2010	✔
Waipu big pond	Northland, North Island	3 June 2010	✔
Waipu small pond	Northland, North Island	3 June 2010	✔
Upper Reservoir, Karori Sanctuary	Wellington, North Island	22 February 2011	
Wharawhara pond	Bay of Plenty, North Island	3 March 2011	
Ahiaruhe pond	Wellington, North Island	11 October 2011	
Kauri Point pond A	Bay of Plenty, North Island	6 March 2012	✔
Kauri Point pond B	Bay of Plenty, North Island	6 March 2012	✔