

Supporting Information 1

Trophic transfer of anticoagulant rodenticides while managing rodent pests: the fine line between predator-prey regulation and pesticide-pest regulation

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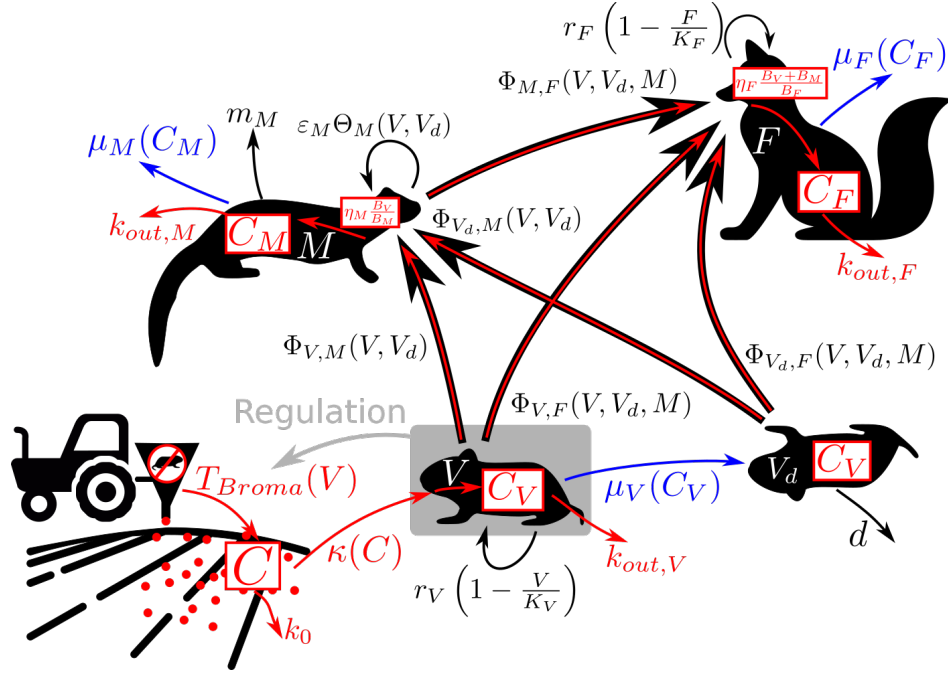


Figure S1 – Dynamics of mustelids (bold grey line) and red foxes (bold black line) after 50 years of simulation (10 years of burn-in period, shaded area, and 40 years considered here for the compute of results, estimation of cost functions, etc.). Letters at the top-right part of each sub-graph corresponds to the results obtained from each farmer functional response. FR (dashed line) and MR (dotted line) indicate the farmer-regulated and mustelid-regulated periods of vole population dynamics.

1 Model derivation

1.1 Dynamic of populations for the tri-trophic dynamic

The population dynamics of a tri-trophic system is commonly described as follow:

$$\begin{cases} \frac{dV}{dt} = r_V V \left(1 - \frac{V}{K_V}\right) - \Phi_{V,M}(V)M - \Phi_{V,F}(V, M)F \\ \frac{dM}{dt} = \varepsilon_M \Phi_{V,M}(V)M - m_M M - \Phi_{M,F}(V, M)F \\ \frac{dF}{dt} = F r_F \left(1 - \frac{F}{K_F}\right) \end{cases} \quad (S1)$$

As described in the manuscript, the vole population, V followed a logistic growth rate, with r_V the maximal reproduction rate, fixed at $r_V = \ln(2 \times 600)/365$ in $[\text{day}^{-1}]$, since montane water vole populations can increase from 0 to 600 individuals ha^{-1} or more in a year [Giraudoux et al., 1997] resulting in the equilibrium density being fixed at $K_V = 600$ individuals.

26 1.1.1 About the logistic model

27 The idea behind this parametrization is the use of a classical Malthusian equation with r_V in
28 $[\text{day}^{-1}]$ and V in $[\text{ind ha}^{-1}]$:

$$\frac{dV}{dt} = r_V V \Rightarrow V(t) = V(0) \exp(r_V t) \Rightarrow r_V = \ln \left(\frac{V(t)}{V(0)} \right) \times \frac{1}{t} \quad (\text{S2})$$

29 So to have the maximal growth rate r_V , we need the greatest $V(t)$ (measured at 600 ind
30 ha^{-1} but supposed to be more in theoretical optimal condition) obtained in the minimum of
31 time (less than a year). Then, to add the carrying capacity K_V in $[\text{ind}^{-1}]$, we use the logistic
32 equation and assumed the carrying capacity to be the one measured in the environment:

$$\frac{dV}{dt} = r_V V \left(1 - \frac{V}{K_V} \right) \quad (\text{S3})$$

33 The estimation of r using the Malthusian function and then applying the carrying capacity
34 K can be seen as non consistent because of the dependency of r_V to K_V . For instance, in
35 Ginzburg [1992], the author says that going from $dV/dt = r_V V$ to $dV/dt = r_V V(1 - V/K_V)$
36 would be correct if r was independent of resource limitation K_V :

37 *"Two populations of a species live in environments identical in all respects, that is, they have*
38 *the same resource availability and any other imaginable characteristics. One of the two is subject*
39 *to higher mortality. There is no doubt that the population growth curves in these two cases will*
40 *be different. Are the final equilibrium abundances different? Most ecologists will answer that the*
41 *equilibrium values should be the same and that the higher rate of reproduction just means that*
42 *the population will 'get there faster', but reach the same level nevertheless".*

43 Then, Ginzburg [1992] states that there is two ways to reflect the extra mortality: either
44 assuming (a) $dV/dt = r_V V(1 - V/K_V) - m_V V$ or (b) $dV/dt = (r_V - m_V) V(1 - V/K_V)$. In
45 equation (a), the equilibrium depend on r : $V^* = (r_V - m_V) K_V / r_V$, so is wrong with the
46 un-changed equilibrium assumption. And re-writing (b) gives: $dV/dt = r_V V(1 - V/K_V) -$
47 $m_V V(1 - V/K_V)$. Since $-m_V V(1 - V/K_V)$ reflects an environmental pressure, it should not
48 be positive when $V > K_V$. Meaning, when the population is over it's carrying capacity, we are
49 going to growth even faster and to infinity. In the present manuscript, we made assumption
50 (a), and we assume that r is not independent of resource limitation K_V . It is for instance well
51 known that vole reproduction rate is linked to the state of resource at the time of reproduction
52 [?].

53 Many authors respond to Ginzburg [Olson, 1992, Watkinson, 1992, Mackenzie, 1992,
54 Berryman, 1992] and later [Gabriel et al., 2005].

55 In his response, Olson [1992] says: *"While the logistic model is often defined as non-*
56 *mechanistic, it has the attractive feature of describing population growth with only two pa-*
57 *rameters, K and r . K is universally defined as the population-carrying capacity. However, there*
58 *is much disagreement about the definition of r and this disagreement has affected conclusions*

59 *derived from the use of the logistic equation.*" Olson [1992] suggests that the problem is the
60 intuition assigned to the r-independence to equilibrium density K . Again in our line, Watkin-
61 son [1992] argues that *"Most ecologists, he asserts, would believe that the equilibrium values of*
62 *these two populations should be the same. In that case I must be one of the minority who does*
63 *not believe this to be so."*

64 Another answer by Berryman [1992] proposed to rewrite the model in order to see the
65 link between r and K . The approach by Berryman [1992] is interesting as it introduces
66 a relevant effect of considering the exploitation rate (link to the growth rate) within the
67 carrying capacity, meaning a carrying capacity with its on dynamic (e.g., with its resilience
68 depending on how exploitation happen), and non an extra-system static one.

69 1.1.2 Predation of voles, and predator dynamics

70 The vole population was preyed upon by mustelid and fox populations, denoted M and F
71 respectively in (S1). The vole consumption rate at different vole densities was described by
72 functional responses ($\Phi_{V,M}$ for mustelids, $\Phi_{V,F}$ for foxes).

$$\begin{aligned}\Phi_{V,M}(V)M &= \frac{a_M V}{1 + h_M a_M V} \\ \Phi_{V,F} &= \frac{a_{VF} V}{a_{VF} V + a_{MF} F} \times \frac{(a_{VF} V + a_{MF} M)^2}{1 + h_F (a_{VF} V + a_{MF} M)^2} \\ \Phi_{M,F}(V, M)F &= \frac{a_{MF} V}{a_{VF} V + a_{MF} F} \times \frac{(a_{VF} V + a_{MF} M)^2}{1 + h_F (a_{VF} V + a_{MF} M)^2}\end{aligned}\tag{S4}$$

73 We treated small mustelids as vole specialist predators [King and Powell, 2006], assuming
74 a Holling Type 2 functional response with attack rate a_M in [day^{-1}] and handling time h_M
75 in [day] (equation (S4)). We then represented foxes feeding on voles and mustelids by a
76 multi-species functional response derived from Holling Type 3, referring to generalist feeding
77 behaviour [Baudrot et al., 2016]. For that, we denoted a_{VF} and a_{MF} (both in [day^{-1}]) the
78 fox attack rate on voles and mustelids respectively. The parameter h_F was the handling time
79 for foxes in [day].

80 Consequently, the functional responses $\Phi_{X,Y}$ are all in [day^{-1}]. And the functions:
81 $\frac{dV}{dt} = r_V V \left(1 - \frac{V}{K_V}\right) - \Phi_{V,M}(V)M - \Phi_{V,F}(V, M)F$ and $\frac{dF}{dt} = F r_F \left(1 - \frac{F}{K_F}\right)$ are also
82 consistent, all part being in [$\text{ind ha}^{-1} \text{ day}^{-1}$].

83 1.1.3 Conversion efficiency and mortality rate in mustelid population

84 The parameterization of the conversion efficiency of ingested food into new born, ε_M in
85 [n.d.] (non dimensional), and the mortality rate, m_M in [day^{-1}], in equation (S1) is not
86 straightforward since we have to take into account the mortality rate due to starvation. In the
87 situation of no starvation, ageing, diseases and predation of mustelids are the main reason

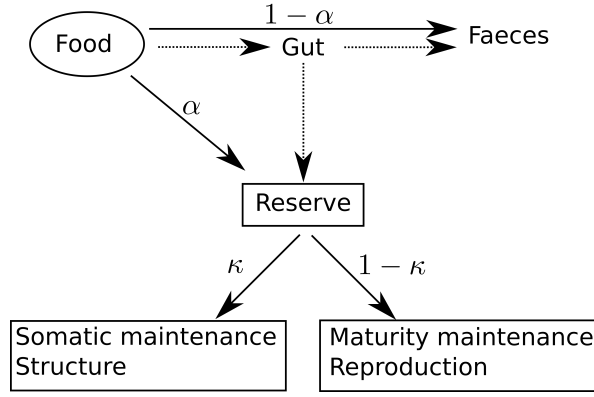


Figure S2 – Representation of the standard dynamic energy budget (DEB model [Sousa et al., 2010])

of death. In the situation of no prey availability at initial condition, then the mortality rate of mustelids should be equal to the mortality rate without food. Using the simplest scheme of Dynamic Energy Budget (DEB) theory (see Figure S2), the ingested food is assimilated for a part, we denote α and non-assimilated for another part, $(1 - \alpha)$. Then, the assimilated part goes to a reserve (or directly use) in either the somatic maintenance or in the maturity maintenance (to produce reproductive tools). In DEB, a proportion κ from the reserve is the part allocated to somatic maintenance [n.d.] and a proportion $1 - \kappa$ is addressed to the maturity maintenance.

Figure S2 represents the standard dynamic energy budget (DEB) model [Sousa et al., 2010]. Then, assuming the generic functional response $\Phi_{V,M}(V)$, the reproduction rate of the predator is like:

$$\Phi_{V,M}(V)\alpha(1 - \kappa)\varepsilon' \quad (\text{S5})$$

where ε' in [n.d.] is the conversion efficiency of daily assimilated food for one individual, dedicated for reproduction into newborn mustelids.

Then, $\alpha\kappa\Phi_{V,M}$ is the part allocated to somatic maintenance structure. Parameters α and κ are non-dimensional [n.d.].

We can then take into account the starvation process in the mortality rate, with a food-independent mortality rate $m_{M,-\Phi}$ in $[\text{day}^{-1}]$ and a part depending on food availability $m_{M,+\Phi} = \sigma\alpha\kappa\Phi_{V,M}$ in $[\text{day}^{-1}]$, with σ [n.d.] a conversion parameter.

Then, the dynamic of Mustelid given in the manuscript equation (S1) could be rewritten as:

$$\frac{dM}{dt} = \Phi_{V,M}(V)\alpha(1 - \kappa)\varepsilon'M - (m_{M,-\Phi} + \sigma\alpha\kappa\Phi_{V,M})M - \Phi_{M,F}(V, M)F \quad (\text{S6})$$

Which is equal to:

$$\frac{dM}{dt} = (\alpha(1 - \kappa)\varepsilon' - \sigma\alpha\kappa)\Phi_{V,M}(V)M - m_{M,-\Phi}M - \Phi_{M,F}(V, M)F \quad (\text{S7})$$

Therefore, if we set the food-independent mortality rate $m_M = m_{M,-\Phi}$ and the conversion efficiency of ingested food $\varepsilon_M = \alpha((1 - \kappa)\varepsilon' - \sigma\kappa)$, we get back to the equation provided in model (S1) but with a clearer definition of ε_M .

This is why we parameterized m_M in $[\text{day}^{-1}]$ as the inverse of life expectancy in $[\text{day}^{-1}]$, and ε_M in $[\text{n.d.}]$ as an unclear parameter derived from the null model (i.e., without AR) to reflect observed population dynamics.

In any case, the dimension of the equation $\frac{dM}{dt} = \varepsilon_M \Phi_{V,M}(V)M - m_M M - \Phi_{M,F}(V, M)F$ is well defined, since $\varepsilon_M \Phi_{V,M}(V)$ is in $[\text{day}^{-1}]$.

1.2 Dynamic of populations with AR

After spreading by farmer, in the model AR is degraded or transferred to voles, which are exposed to the environmental contaminant mainly through ingestion of contaminated food-stuffs (i.e., trophic transfer), and AR accumulates in their tissues and is release with rate $k_{out,V}$. Contaminants in an individual, the body burden, are commonly measured in concentration per mass of individual, $[\mu\text{g g}^{-1} \text{ ind}^{-1}]$ (equivalent to $[\text{mg kg}^{-1} \text{ ind}^{-1}]$ and denoted $[\text{ppm ind}^{-1}]$). Predators are only exposed to contaminant through the consumption of voles, a trophic transfer, so as a function of functional response.

To consider both toxicological and population dynamics within the same equation, we convert population dynamics into dynamics of their biomasses as in [Huang et al., 2015, Baudrot et al., 2018].

We denote V, V_d, M, F the densities of voles, dead voles, mustelids and foxes respectively ; B_V, B_{V_d}, B_M and B_F the mean biomass of an individual of those species in $[\text{g ind}^{-1}]$, and $B_{T,V}, B_{T,V_d}, B_{T,M}$ and $B_{T,F}$ the total biomass of the population in the space unit we used, so in $[\text{g ha}^{-1}]$. In other words, $B_{T,X} = B_X \times X$. The notation C_V, C_{V_d}, C_M and C_F holds for the mean concentration of the contaminant in one individual, commonly called the body burden of the prey in ppm $[\text{mg kg}^{-1}]$. The growth function of the prey population is a function $g_X(X, C_X)$ in $[\text{day}^{-1}]$ depending on the population density X and the concentration of the contaminant C_X . The dose-response curve $\mu_X(C_X)$ is defined by a log-normal cumulative distribution function as in Loos et al. [2010].

Variables for the population dynamics To convert individual dynamics into biomass dynamics, we just multiplied the variable density X in $[\text{ind ha}^{-1}]$ with a constant B_X in $[\text{g ind}^{-1}]$, so that the derivative as just to be multiplied by this constant:

$$\frac{dB_{T,X}}{dt} = \frac{dB_X X}{dt} = B_X \frac{dX}{dt} \quad \text{and so we have} \quad \frac{dX}{dt} = \frac{1}{B_X} \times \frac{dB_{T,X}}{dt} \quad (\text{S8})$$

141 **Variable for the toxicant dynamics** For the dynamic of toxicants, we consider an homoge-
 142 neous population.

143 We set a new variable $w_X = C_X B_X X$ which is in $[\mu\text{g g}^{-1}] \times [\text{g ind}^{-1}] \times [\text{ind ha}^{-1}]$, so
 144 that: w_X is in $[\text{mg ha}^{-1}]$ or $[\text{mg population}^{-1}]$, which is the quantity of contaminant within
 145 the population.

146 The dynamic of the new variable is defined with:

$$w_X = C_X B_X X = C_X B_{T,X} \Rightarrow \frac{dw_X}{dt} = B_X \frac{dX C_X}{dt} = B_X \left(X \frac{dC_X}{dt} + C_X \frac{dX}{dt} \right) \quad (\text{S9})$$

147 As a consequence, $\frac{dw_X}{dt}$ is in $[\text{mg ha}^{-1} \text{ day}^{-1}]$.

148 1.2.1 Dynamic of the contaminant in the environment

149 In the agro-ecotoxicological system, we consider an environmental concentration of contam-
 150 inant denoted by w_{ext} in $[\text{mg ha}^{-1}]$ in order to reflect the spatially explicit spreading of AR
 151 following determined in baits per area. From the Figure S1, we can directly provide the
 152 dynamic of this concentration:

$$\frac{dw_{ext}}{dt} = T_{Broma}(V) - k_0 w_{ext} - \kappa(w_{ext}) V B_V \quad (\text{S10})$$

153 with $T_{Broma}(V)$ the farmer input of AR in $[\text{mg ha}^{-1} \text{ day}^{-1}]$ depending on vole density
 154 denoted V in $[\text{ind ha}^{-1}]$. AR concentration in baits is $50 \mu\text{g g}^{-1}$ (or mg kg^{-1}). So when
 155 farmer spread in grasslands at quantity 7.5 to $20 \text{ kg ha}^{-1} \text{ day}^{-1}$, its an amount of 375 to
 156 1000 mg ha^{-1} of AR spread (i.e., $\text{mg kg}^{-1} \times \text{kg ha}^{-1} \text{ day}^{-1}$).

157 The disappearance of AR in the field, denoted k_0 , in $[\text{day}^{-1}]$, so that $k_0 w_{ext}$ is in $[\text{mg ha}^{-1}$
 158 $\text{day}^{-1}]$. Such quantity, w_{ext} , was available in the literature, and a proportion disappeared in
 159 the environment at rate $k_0 = 0.0815 \text{ day}^{-1}$ [Sage et al., 2008].

160 The function $\kappa(w_{ext})$, in $[\text{mg kg}^{-1} \text{ day}^{-1}]$, reflects the transfer of contaminant from the en-
 161 vironmental compartment to the vole compartment. As a consequence, the term $\kappa(w_{ext}) V B_V$
 162 is in $[\text{mg ha}^{-1} \text{ day}^{-1}]$ ($[\text{mg kg}^{-1} \text{ day}^{-1}] \times [\text{kg ha}^{-1}]$).

163 This rate $\kappa(w_{ext})$ was assumed to be an increasing function characterized by a maximum
 164 intake rate M_{in} in $[\text{mg kg}^{-1} \text{ day}^{-1}]$, and a half-saturation constant for ingestion D_{in} in $[\text{mg}$
 165 $\text{ha}^{-1}]$ since w_{ext} is in $[\text{mg ha}^{-1}]$:

$$\kappa(w_{ext}) = M_{in} \times \frac{w_{ext}}{D_{in} + w_{ext}} \quad (\text{S11})$$

166 So the dimension of the ingestion rate $\kappa(w_{ext})$ is the same as M_{in} that is $[\text{mg kg}^{-1} \text{ day}^{-1}]$.

1.2.2 Dynamics of contaminant within populations

With the previous assumption, the general model is described as follow:

Population dynamics From the equation (S8), we have: $\frac{dB_{T,X}}{dt} = B_X \frac{dX}{dt}$

Conversion of w_V into C_V

$$\frac{dC_V}{dt} = \frac{dw_V/B_{T,V}}{dt} = \frac{1}{B_{T,V}^2} \left(\frac{dw_V}{dt} B_{T,V} - w_V \frac{dB_{T,V}}{dt} \right) \quad (\text{S12})$$

$$\left\{ \begin{array}{l} \frac{dw_{ext}}{dt} = T_{Broma}(V) - k_0 w_{ext} - \kappa(w_{ext}) B_{T,V} \\ \frac{dB_{T,V}}{dt} = B_{T,V} g_V(V, C_V) - \mu_V(C_V) B_{T,V} - B_V \Phi_{V,M}(V) M - B_V \Phi_{V,F}(V, M) F \\ \frac{dw_V}{dt} = \kappa(w_{ext}) B_{T,V} - k_{out,V} w_V - w_V \mu(C_V) - C_V B_V \Phi_{V,M}(V) M + \gamma_V w_V g_V(V, C_V) \\ \frac{dB_{T,V_d}}{dt} = \mu_V(C_V) B_{T,V} \\ \frac{dw_{V_d}}{dt} = \frac{dw_V}{dt} \\ \frac{dB_{T,M}}{dt} = B_{T,M} (\varepsilon_M B_V \Phi_{V,M}(V) M - m_M - \mu_M(C_M)) - B_M \Phi_{M,F}(V, M) F \\ \frac{dw_M}{dt} = -k_{out,M} w_M - w_M (m_M + \mu(C_M)) + \eta_M C_M B_M \Phi_{V,M}(V) M - \\ C_M B_M \Phi_{M,F}(V, M) F + \gamma_M w_M g_M(M, C_V) \\ \frac{dB_{T,F}}{dt} = B_{T,F} g_F(F, C_F) - \mu_F(C_F) \\ \frac{dw_F}{dt} = -k_{out,F} w_F - w_F \mu(C_F) + \eta_F C_M B_M \Phi_{M,V} F + \eta_F C_V B_V \Phi_{V,V} F + \gamma_F w_F g_F(F, C_F) \end{array} \right. \quad (\text{S13})$$

Thus, it is straightforward to express the dynamics as:

$$\left\{ \begin{aligned}
 \frac{dV}{dt} &= \overbrace{r_V V(1 - V/K_V)}^{\text{growth rate}} - \overbrace{\mu_V(C_V)V}^{\text{poisoning}} - \overbrace{\Phi_{V,M}(V, V_d)M + \Phi_{V,F}(V, V_d, M)F}^{\text{predation}} \\
 \frac{dV_d}{dt} &= \overbrace{\mu_V(C_V)V}^{\text{new dead voles}} - \overbrace{\Phi_{V_d,M}(V, V_d)M + \Phi_{V_d,F}(V, V_d, M)F}^{\text{predation}} - \overbrace{dV_d}^{\text{degradation}} \\
 \frac{dM}{dt} &= \overbrace{(\varepsilon_M \Theta_M(V, V_d) - m_M)M}^{\text{growth rate}} - \overbrace{\mu_M(C_M)M}^{\text{poisoning}} - \overbrace{\Phi_{M,F}(V, V_d, M)F}^{\text{predation}} \\
 \frac{dF}{dt} &= \overbrace{r_F F(1 - F/K_F)}^{\text{growth rate}} - \overbrace{\mu_F(C_F)F}^{\text{poisoning}} \\
 \frac{dC}{dt} &= \overbrace{T_{Broma}(V)}^{\text{treatment}} - \overbrace{k_0 C}^{\text{degradation}} - \overbrace{\kappa(C)}^{\text{consumption}} \\
 \frac{dC_V}{dt} &= \overbrace{\kappa(C)}^{\text{intake}} - \overbrace{C_V \left(k_{out,V} + r_V \left(1 - \frac{V}{K_V} \right) \right)}^{\text{excretion}} \\
 \frac{dC_M}{dt} &= \overbrace{\eta_M \frac{B_V}{B_M} (\Phi_{V,M}(V, V_d, M) + \Phi_{V_d,M}(V, V_d, M)) C_V}^{\text{intake}} - \overbrace{C_M (k_{out,M} + \varepsilon_M \Phi_{V,M}(V, V_d, M))}^{\text{excretion}} \\
 \frac{dC_F}{dt} &= \overbrace{\eta_F \frac{B_V}{B_F} ((\Phi_{V,M}(V, V_d, M) + \Phi_{V_d,M}(V, V_d, M)) C_V + \Phi_{M,F}(V, V_d, M) C_M)}^{\text{intake}} - \overbrace{k_{out,F} + r_F \left(1 - \frac{F}{K_F} \right)}^{\text{excretion}}
 \end{aligned} \right. \tag{S14}$$

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