Ecological Risk-Benefit Analysis of DDT Regulation

Mayuko Nakamaru[1,2] Yoh Iwasa[1,3] Toshihiro Oka[1,4] Junko Nakanishi[1,5]

1. CREST, Japan Science and Technology Corporation (JST)
2. Department of Systems Engineering, Shizuoka University, Hamamatsu, 432-8561, JAPAN
3. Department of Biology, Faculty of Sciences, Kyushu University, Fukuoka 812-8581, JAPAN
4. Fukui Prefectural University, Kenjojima, Matsuoka-cho, Fukui, 910-1195, JAPAN
5. Institute of Environmental Science and Technology, Yokohama National University, Yokohama 240-0067, JAPAN

Abstract

Here we report the ecological risk-benefit analysis of DDT based on the enhanced extinction risk of a wild population of sparrowhawk. Raptors such as sparrowhawk are vulnerable to the exposure to DDTs (DDT and its metabolites) and show many symptoms including eggshell thinning. Estimating the extinction risk of raptors is important from a conservation viewpoint as well. We evaluated the mean extinction time based on the canonical model, and calculated the risk equivalent, i.e. the decrease in the carrying capacity causing the same enhancement of the population extinction risk as the chemical exposure. The equivalent habitat losses in the population with 50-250 females were 23-34% when the DDTs concentration in eggs was 11.9 ppm. We also calculated the benefit of DDT by evaluating economical cost of an alternative policy of preventing malaria by using pyrethroid-impregnated bednets. Combining these two, we are able to carry out the ecological risk-benefit analysis.

1, Introduction

Risk-benefit analysis has been used in evaluating alternative policies of environmental chemical management (Oka, 1999). However in these attempts only the human health risk of environmental chemicals is considered, and ecological hazard is neglected. Here we report an attempt of the ecological risk-benefit analysis of DDT regulation, in which we evaluate the ecological risk of toxic chemicals based on the enhancement of population extinction risk.

DDT is notorious for its biological magnification through food chains and causing harm to birds. On the other hand, DDT has little acute toxicity and is a pestiside effective in controlling malaria vectors. Hence there is conflict between the tropical countries where malaria is still a serious problem and the "northern" countries where malaria is not prevalent. Risk-benefit analysis can help us to handle the trade-off between these two aspects.

Risk-Benefit Analysis

In the risk-benefit analysis of controlling a toxic environmental chemical at a low concentration, we need to evaluate the amount of risk reduced (ΔR) and the amount of benefit of using the chemical (the benefit of the chemical), or the cost of controlling it (ΔB). Then the ratio of the costs relative to the reduced risk helps us in environmental policy choice.

An alternative method of controlling mosquitos as a malaria vector is to use organophosphate insecticide, which does not show biomagnitication, but it is volatile and may cause human health damage. Vaccination to malaria is more expensive than DDT, and it becomes ineffective very quickly because malaria parasites evolve resistance. Pyrethroid causes significant

damages neither to ecosystem nor to human, but more expensive than DDT, though the price has become lower recently. When pyrethroid-impregnated bednets became widely used in Solomon Islands, the malaria incidence dropped to 44.4% in 1995 from 1993 (Ikeshoji & Bakotee 1996).

Here we calculate the benefit of using DDT by comparing the policy of using DDT and an alternative policy of using pyrethroid-impregnated bednets. The endpoint of the ecological risk is chosen to be the extinction of a wild population of animals or plants, especially a bird which would be the most sensitive to the DDT exposure.

2, The extinction risk assessment

The birds who are top predators in the food web are very vulnerable to DDTs (DDT and its metabolites) because of the biomagnification. Many studies have shown that DDTs cause population decline of raptors and water birds, exemplified by the egg thinning of peregrine falcon (*Falco peregrinus*) and sparrowhawk (*Accipiter nisus*) in England (e.g. Newton, 1986). A high concentration of DDTs was accumulated in the body of herring gulls in the Long Island, NY, USA. Gilman *et al.* (1977) reported that the reproductive rate of herring gulls in the Great Lakes was reduced by the exposure to DDTs, PCB, and other environmental chemicals.

In the workshop of the last year, we presented the estimate of extinction risk of DDT to herring gull populations (Nakamaru *et al*., 2000, 2001). However the herring gull is not an endangered species, and in fact they increase rapidly in number. Evaluating extinction risk of herring gulls may be a good exercise of extinction risk estimate, but it is not directly meaningful to conservation. On the other hand, raptors are often endangered, and the extinction risk evaluation of raptors are important from the conservation viewpoint as well. Hence we here calculate the extinction risk of sparrowhawk living in eastern England. We adopted the same method as used for the herring gull last year (Nakamaru *et al.*, 2000, 2001). All the data needed for extinction risk estimate of sparrowhawk were available, which is much better than the situation for estimating extinction risk of herring gulls, in which we had to use the data of the sensitivity to DDTs taken for other species (black duck).

It is reported that the eggshell thinning of sparrowhawk began in 1947 because of the spread of DDT usage (Newton, 1986). The number of sparrowhawks declined in 1957-1963. In the west England the population size became less than half of the previous level. In the eastern England, some populations became extinct. Newton (1986; 1995) said that the population declining came from HEOD which is the derivative of aldrin and dieldrin, agricultural chemicals. After prohibiting aldrin and dieldrin in 1962, the sparrowhawk population began to recover. The exposure to DDE made the reproductive success decline, but the population recovered even without controlling the DDE. From this, Newton concluded that DDE had only a small effect to the population trend. He also said that PCB and other chemicals also didn't bring the population to decline.

However we believe that the exposure to DDE should have caused significant enhancement of population extinction risk of sparrowhawk. According to our estimate of the extinction risk of herring gulls reported in the last year, the population growth rate was still positive after the

exposure to DDTs at the level observed in the Long Island, NY in 1969's, and hence immediate population extinction was not predicted. However DDTs exposure reduced the mean extinction time have reduced by several orders of magnitude (Nakamaru *et al.*, 2000, 2001). We expect that the same should be true to sparrowhawk populations. Exposure to DDTs, PCB and other environmental chemicals greatly reduces the mean extinction time of sparrowhawk populations, but did not cause their immediate extinction.

To present the magnitude of extinction risk caused by environmental toxic chemical at a low concentration, we calculate "*risk equivalent*", the amoung of loss in carrying capacity (or habitat size) that causes the equivalent enhancement of population extinction risk (Hakoyama *et al.*, 2000). The risk equivalent is much better than other methods of presenting the damage to the ecosystem in a intuitively clear manner.

2-1, The calculation of the extinction risk

We calculated the mean extinction time using the integral equation derived from the canonical model (Hakoyama & Iwasa, 2000; see also Eq. (1), (2) in Iwasa *et al.* (2001)) in this volume for the explanations). The canonical model contains four parameters: the intrinsic rate of population growth (r), the carrying capacity (K_0), the intensity of the environmental fluctuation (σ_e^2) and the decrease of the population growth rate caused by the exposure to DDTs. We estimated these values from the data about sparrowhawk in England.

According to Hakoyama & Iwasa (2000), when the population is exposed to DDTs, both the intrinsic rate of population growth and the carrying capacity decrease. When the exposure causes the decrease in growth rate of α per generation, we can simply replace r and K_0 in the integral equation for mean extinction time by $(r-\alpha)$ and $(K_0(r-\alpha)/r)$, respectively (see also Eq. (3) in Iwasa *et al.* (2001)).

The intrinsic rate of population growth (r)

The intrinsic population growth rate is the growth rate in a low-density population. We used the population data after the control of organophosphate pesticide. The population growth rate was observed in four areas, but some of these populations receive the heavy immigration and their data need to be excluded. Then we can get the intrinsic growth rate per year is about 0.4, which is about 9-10 times higher than one of herring gulls in the Long Island, NY, USA (0.0462).

The decrease of population growth rate caused by DDTs (α)

From eq (1, 2) in Newton (1986), we can obtain the relationships between DDE concentration in egg and the decrease rate of the young per clutch as follow;

$$[\text{shell index}] = 1.81 - 0.31 \times \log[\text{DDE}] \quad (1)$$

$$\begin{pmatrix} \text{\%reduction in number of} \\ \text{youngs raised per clutch} \end{pmatrix} = 160.7 - 113.7 \times [\text{shell index}]. \quad (2)$$

Eq. (1) can be used when [DDE] is 4-10 ppm. We can combine these equations, the age-specific fertility (i.e. the number of youngs per female), and the age-specific survivorship (Newton & Rothery, 1997) by an age-structured matrix model, and then we can obtain the population growth rate when exposed to DDTs. The maximum life span of females was 10 years and the generation time was 2.6 years. Then the intrinsic growth rate per generation (r_g) of a population not exposed to DDTs was estimated as 1.04 ($= 0.4 \times 2.6$). This is about three times higher than that of herring gulls reported in the last year (Table 1).

Hence we can obtain the relationship between the concentration of DDTs in egg and the intrinsic growth rate per generation (Fig. 1). The regression line is as follows.

$$r_g = 1.04 - 0.020[DDE]. \qquad (3)$$

Hence, the decrease of survivorship is $\alpha = 0.020[DDE]$.

The environmental fluctuation and the carrying capacity (K_0)

During 1972-1984, the number of clutches and the number of nestings were observed in Eskdale, England. The population size was very stable and the CV of the population size was 0.00643. However this stability can be explained by immigrants from other populations. Pimm *et al.* (1988) concluded that, when the estimated CV of the population size is very small, we should use the general average values of CV, rather than the estimated one. Hence we set CV = 0.2, which Nakamaru *et al.* (2000, 2001) adopted in estimating the extinction risk of herring gulls. Using the magnitude of population size fluctuation as given by the CV, we can estimate the magnitude of environmental fluctuation σ_e^2 (Hakoyama and Iwasa, 2000).

We estimated the extinction risk for the cases with carrying capacity of K_0 = 50, 100, and 250, measured in terms of the number of breeding females. These values were used for herring gull populations.

2-2, The result of the extinction risk of sparrowhawk

Figure 2 shows the relationship between the CV of population size and the mean extinction time, and Figure 3 shows that the decrease of the logarithm of the mean extinction time when the population is exposed to DDTs. We converted these into the fraction of reduction in the carrying capacity that causes the same enhanced extinction risk (or risk equivalent, see Iwasa, 2001) (Figure 4). For example, when the concentration of DDTs is 11.9ppm, which is the same as that of herring gulls in the Long Island, NY, the equivalent loss of habitat is 34.0% in K_0=250; 29.2% in K_0=100; and 23.9% in K_0=50 (Table 1).

2-3, Discussion

The equivalent loss of habitat or the extinction risk equivalent of sparrowhawk obtained in this paper was higher than that of herring gulls, although they are of the same order of magnitude (Table 1). In general, the risk of exposure to toxic chemicals expressed as the equivalent loss of

habitat tends to be larger for stable populations with long mean extinction time than for endangered populations (Hakoyama *et al.*, 2000) -- hence it is larger when (1) K_0 is larger, (2) CV is smaller and (3) r is larger. Risk equivalent is useful in evaluating the hazard received by sparrowhawks and herring gulls and as a population extinction risk in a manner easily understandable. The same measure of risk is applicable to other risk factors, such as the spread of disease, the habitat fragmentation, and the genetically deterioration, which reduce the population growth rate. Using this currency, we can easily compare the hazard caused by exposure to environmental chemicals and land exploitation. Risk equivalent also suggests the magnitude of the habitat improvement for a wildlife population to be made as the compensation of inevitable exposure to toxic chemicals at a low level (J. Giesy, personal comm.).

3, Ecological Risk/Benefit Analysis

Now we explain the method of calculating risk-benefit analysis ($\Delta B/\Delta R$).

The reduction of ecological risk achieved by the control of DDTs is given by

$$\Delta R = \begin{bmatrix}\text{Extinction risk}\\ \text{caused by DDTs}\end{bmatrix} - \begin{bmatrix}\text{Extinction risk caused by pyrethroid}\\ \text{impregnated bednets}\end{bmatrix}.$$

There is no report of the harm to wildlifes by pyrethroid, except Mittal *et al.* (1991) who concluded it has some effect to aquatic life. If we measure the effect to a sparrowhawk population, we can assume that there is no extinction risk caused by pyrethroid.

We have to consider DDTs remaining in the environment long after the application of DDT because of its long half life. Therefore we assume the difference in the ecological risk such as,

$$\Delta R = \begin{bmatrix}\text{Extiction risk}\\ \text{before the DDT control}\end{bmatrix} - \begin{bmatrix}\text{Extiction risk}\\ \text{after the DDT control}\end{bmatrix}$$

We used the concentration of DDTs in the area in which the DDT is currently used as the concentration before control. We regarded the DDTs level in USA and other "northern" contries as the concentration after control. We can estimate the DDTs concentration in the environment using the time series data of DDTs level for lake trout and herring gull (Nishikawa, 1999; Giesy & Snyder, 1998).

There are a number of species in the area exposed to DDTs, but no data is available for all of these species, and hence we cannot estimate the extinction risk of each species separately. In the beginning of this assessment, we simplify the assumption and focus on birds. We assumed that the risk to other waterfowls is the same as the risk to herring gulls and that risks to other raptors are the same as the risk to sparrowhawks. We weightd the species using the phylogenetic information -- the loss of a species is regarded more serious if it is an phyloginetically isolated than the loss of another species which has a number of similar species (Oka, 1999).

We assumed that the benefit of using the chemical (ΔB) is equal to the enhanced cost per person per year when DDTs is replaced by pyrethroid-impregnated bednets to control the mosquitos.

The price of a pyrethroid-impregnated bednet is assumed to be the prices of a bednet and a cost of the treatment of pyrethroid. In Cameroon the price of a bednet for two persons was US$23.3/sheet (Brinkmann & Brinkmann, 1995). When this is used for three years, it costs US$ 3.87/person/year. We have no full data about the treatment in Cameroon, but it was said that it cost US$ 0.63/person/year to do the treatment in Solomon Islands (Kere & Kere, 1992). Therefore we use the price of bednets in Cameron and of the treatment in Solomon Islands when we estimate the cost of pyrethroid-impregnated bednet in Africa. The estimated cost was US$ 4.50/preson/year.

When the unit price of DDT is US$ 5.90 /kg, the total cost of DDT, which includes not only the price of DDT but also the cost of transport and operations, is US$ 4.37/person/year. The unit price of DDT is between US$ 3.00 /kg and US$ 8.00 /kg. We assume that this varies uniformly. From these data, the total cost is US$ 3.44 (or US$ 5.04) /person/year when the unit price is US$ 3.00 (or US$ 8.00) /kg. When the total cost of DDT is US$ 4.50/person/year, the increase of the cost from DDT to betnets is US$ 0.26/person/year (= ((4.50 - 5.04)+(4.50 - 3.44))/2) .

When we consider a specific area in Africa as an illustrating example, the cost of control (or the benefit of the chemical) is

$$\Delta B = [\text{The population in this area}] \times \text{US\$}0.26.$$

4, Summary

We can estimate the ecological risk and the benefit of the chemical if we adopt the assumptions as explained above. However there are a number of problems in this procedure. The canonical model we used in estimating the ecological risk has only four parameters. However it is often the case that we don't have enough data to estimate these parameters with confidence, as shown by the attempt for herring gulls. The situation was better for sparrowhawk, but it is a rare case. When we estimate the extinction risk of a bird, we may have to use the data on other birds. Therefore the extinction risk itself may not be very reliable. First we supposed that the best alternative policy when DDT is replaced is to use pyrethroid impregnated bednets. We calculated the benefit of DDT (ΔB) assuming that all of people in the area use the bednets. However some people refuse to use bednets because they are not very comfortable to sleep in. Therefore the simultaneous use of both bednets and DDT, rather than completely replacement , might be more realistic. Second we assumed that the specific area was exposed by DDTs, however DDT can disperse and may become spread over a much wider area.

Even if the reliability of the ecological risk-benefit analysis is rather limited, we often cannot wait the decision until we have sufficient amount of data to predict the risk with confidence.

However, without quantitative estimates of ecological risk, the management of environmental chemicals will keep focusing on the human health risk and neglecting the ecological hazard.

We tentatively conclude that the risk equivalent is the best measure for ecological hazard of environmental chemicals. Calculating risk equivalent for various chemicals and for various species assuming a standard value of CV and standard values of the carrying capacity would be a good start point of introducing ecological risk-benefit analysis of environmental chemicals. The improvement of the methodology by many researcher based on the experience through many tries and errors will follow soon.

5, Reference

Brinkmann U, Brinkmann A. (1995) *Bulletin of the World Health Organization* 73: 651-658.
Gilman AP, Fox GA, Peakall DB, Teeple SM, Carroll TR, Haymes GT. (1977) *J. Wildl. Manage.* 41: 458-468.
Hakoyama H, Iwasa Y. 2000. *J Theor Biol*. 204: 337-359
Hakoyama, H., Iwasa, Y., Nakanishi, J. 2000. *J. Theor. Biol.* 204: 327-336.
Ikeshoji T. & Bakotee B. (1996) *Med. Entomol*. Zool. 47: 331-337.
Iwasa Y, Hakoyama H, Nakamaru M, Nakanishi J. (2001) The proceedings of the third international workshop on risk evaluation and management of chemicals, In The 4th international workshop on risk evaluation and management of chemicals, Yokohama National University, Yokohama, January 30 - 31, 2001. (in print)
Kere JF, Kere NK, (1992) *Health Policy and Planning* 7: 382-386.
Mittal PK, Adak T, Sharma VP (1991) Indian Journal of Malariology, 28, Sep. 167-170.
Mindell DD. (edit). (1997) Avian Molecular evolution and systematics. Academic Press.
Nakamaru M, Iwasa Y, Nakanishi J. (2000) The proceedings of the third international workshop on risk evaluation and management of chemicals,155-162pp. In The third international workshop on risk evaluation and management of chemicals, Yokohama National University, Yokohama, January 27 - 28, 2000.
Nakamaru M, Iwasa Y, Nakanishi J. (2001) *Kankyo-kagaku-kaishi* Vol. 14 (1) (in press)
Newton I.(1986) *The Sparrowhawk*. Poyser, Carlton
Newton I.(1988) "Age and Reproduction in the Sparrowhawk". In *Reproductive Success*. edi.T. H. Clutton-Brock. University of Chicago Press.
Newton I. (1989) *Lifetime Reproduction in Birds*. Academic Press.
Newton I, Wyllie I. (1992) *J. Applied Ecology* 29: 476-484.
Newton I. (1995) *J. Anim. Ecol*. 64: 675-696.
Newton I, Rothery (1997) *Ecology* 78: 1000-1008.
Nishikawa Y (1999) Aromatics **51**:(9, 10) 35-47 (In Japanese)
Oka T. (1999) *Kankyo-seisaku-ron*. Iwanami Publ. Com, Tokyo (In Japanese)
Perrins CM, Leberton JD, Hirons GJM. (1991) *Bird Population Studies*, Oxford UP.
Pimm SL, Jones HL, Diamond J. (1988) *Am Nat* 132: 757-785.

Table 1 The equivalent fraction of reduction of the carrying capacity to the given decrease in *T*

	herring gull	sparrowhawk
the intrinsic growth rate (r)	**0.372**	**1.04**
environmental fluctuation (CV)	**0.2**	**0.2**
the carrying capacity (K_0)	**50, 100, 250**	**50, 100, 250**
The equivalent loss of habitat (DDTs in egg = 11.9 ppm)	**13.5%, 19.5%, 26.4%**	**23.9%, 29.2%, 34.0%**

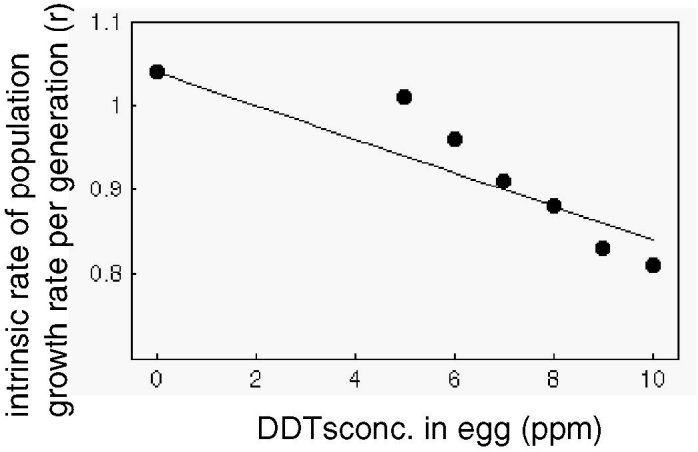

Fig. 1 The intrintsic rate population growth per generation when the population is exposed to environmental DDTs.

The horizontal axis is for the DDTs concentration, and the vertical axis is the growth rate, r. The black circles are calculated through the consecutive equations and data. The solid line is the regression calculated with the value for unexposed population fixed.

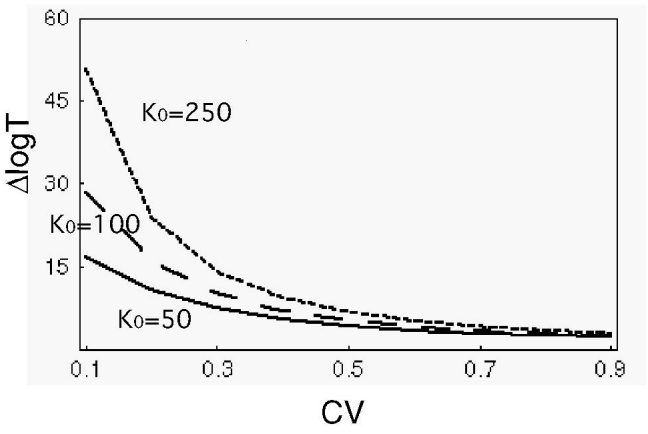

Fig. 2 The estimated mean extinction time under some environmental fluctuations.

The horizontal axis is the coefficient of variation, CV, of the population size. The small dotted curve indicates for K_0=250 expressed in the number of females. The broken curve is for K_0=100, and the solid curve is for K_0=50.

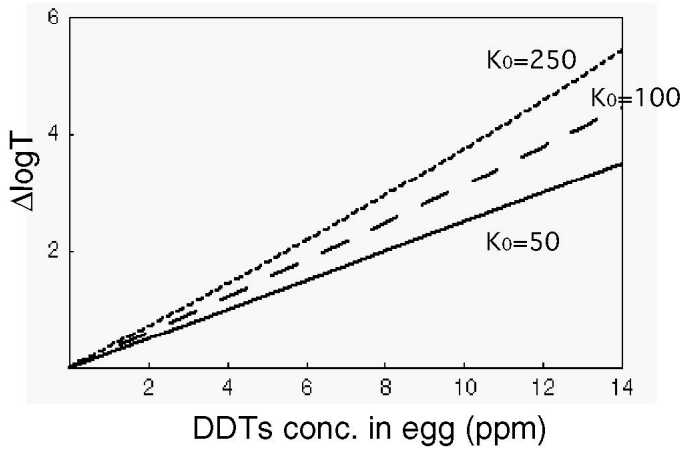

Fig. 3 The decrease of logarithm of T when the population is exposed to environmental DDTs.

The intrinsic rate population growth per generation when the population is exposed to environmental DDTs. The horizontal axis is for the DDTs concentration, and the vertical axis is the decrease of logarithm of T. The small dotted curve indicates for K_0=250 expressed in the number of females. The broken curve is for K_0=100, and the solid curve is for K_0=50.

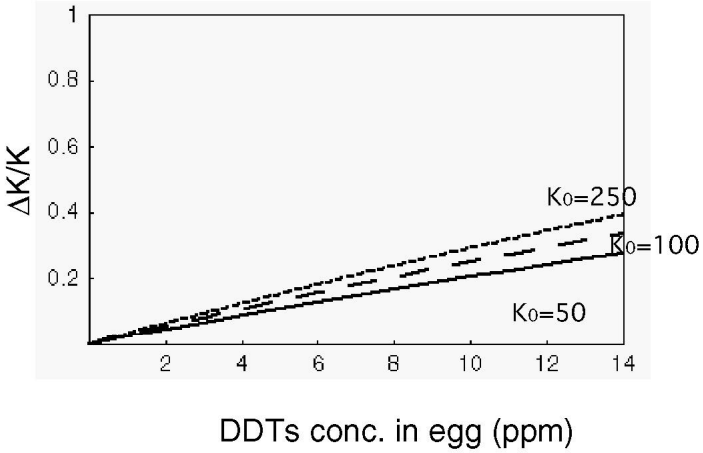

Fig. 4 The equivalent habitat size loss.

The horizontal axis is for the DDTs concentration in water (ppm), and the vertical axis is for the equivalent loss of carrying capacity that causes the same reduction to the mean extinction time as the exposure to DDTs concentration in water. The small dotted curve indicates K_0=250 (the number of females). The broken curve is for K_0=100, and the solid curve is for K_0=50.