

# Ecological Risk Assessment and Risk-Benefit Analysis Using ‘Expected Loss of Biodiversity’

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## Abstract

Ecological risk from the development of a wetland is assessed quantitatively by means of a new risk measure, ‘Expected Loss of Biodiversity (ELB)’. ELB is defined as the weighted sum of the increments in the probabilities of extinction of the species living in the wetland due to its loss. With regard to the weighting for a particular species, this is calculated according to the length of the branch on the phylogenetic tree that will be lost if the species becomes extinct. The length of the branch on the phylogenetic tree is regarded as reflecting the extent of contribution of the species to the taxonomic diversity of the world of living things. The increments in the probabilities of extinction are calculated by a simulation used for making the Red List for vascular plants in Japan. The result of the assessment is combined with the economic costs for conservation of the wetland to produce a value for the indicator of the ‘cost per unit of biodiversity saved’.

## 1. Necessity of Ecological Risk Assessment and Measure of Biodiversity

Quantitative risk assessment has been well-established so far as adverse effects of environmental pollution on human health are concerned, and risk management based on quantitative risk assessment is becoming more and more widely used in policy-making. Quantitative risk assessment is also needed for the ecological effects of environmental degradation in order to ensure that the management of the ecosystem is based on more rational grounds. Nakanishi (1995) proposed to adopt the extinction of species as the endpoint for

ecological risk assessment, in that the extinction should be an event that everyone wants to prevent. Our study is an attempt to actualize this proposal for the issue of land-use conversion.

The necessity of a measure of biodiversity for the issue of conservation of particular lands is another background to our study. Conservation of local ecosystems has been treated as a separate issue from conservation of global biodiversity. It is certainly easy to envisage that the existence of local ecosystems contributes to global biodiversity, but it has been the intrinsic values of local ecosystems that have pushed forward their conservation. When the biodiversity of local ecosystems is concerned, it is often measured by an indicator which can be defined within the ecosystems independently from the world outside of it. The number of species present on a certain area of land, for instance, is often used as a measure of diversity. But this measure does not quantify the contribution of the land to global diversity. Our study is an attempt to combine the issue of local ecosystems with that of global biodiversity.

## **2. The Case of the Development of Nakaikemi Wetland**

The case to which we are attempting to apply our method of ecological risk assessment is the development of Nakaikemi Wetland.

Nakaikemi (Tsuruga, Japan) is a wetland of about 25 ha, which is characterized by its unique geomorphic feature of pouched valley aggraded with mud. Most of the area has been used as rice paddy for hundreds of years but recently more than two third of the land lie fallow according to a set-aside policy because this area has the lowest rice-growing productivity. Abandoned rice fields have been found to support a remarkable biodiversity there.

In this area live many species of aquatic plants which are regarded as declining nationwide, including 13 of the 'threatened' and 2 of the 'nearly threatened' species according to the Red List published by the Japanese Environment Agency in 1997. There are also many species of fish including 'threatened' cyprinodont and insects including more than 60 kinds of dragonflies and several kinds of declining diving beetles.

Osaka Gas Company made a plan for the construction of a liquefied natural gas (LNG) plant on this area in 1992. The procedure for the environmental impact assessment was completed in 1996, whereby the plan was allowed on condition that threatened and rare plant species be transplanted to the 'protected conservation area' of 3.3ha and that a transplantation test be conducted for three years.

A protection movement opposed to the development plan was organized as soon as the plan was made public. The Ecological Society of Japan issued a statement calling for the preservation of the whole area of this wetland in 1996.

Osaka Gas Company argues that the natural life on this wetland is a secondary one created as a by-product of human cultivation, that the diversity of this land will be reduced if left to nature, and that, therefore, the protection of the 'conservation area' is necessary for the natural life on this land. Ecologists oppose this argument by asserting that the transplant will not succeed owing to the complexity of the relationship among the species living in the wetland, that no one can judge

the success of the transplant in three years, that human-controlled nature in such a small area is not the same as what existed before, and that, therefore, the whole area should be conserved for the traditional utilization of the land (Kadono 1997).

### **3. Expected Loss of Biodiversity (ELB)**

Our framework for combining a local ecosystem with global biodiversity and for expressing the risk from the loss of a local ecosystem in terms of the increments in the probability of extinction is as follows.

1. Loss of a local ecosystem means loss of one habitat of the species living there. It would thereby raise the probability of their nationwide extinction.
2. Extinction of species would reduce global biodiversity. The impact is measured by the reduction in the contribution of the species to global biodiversity.
3. The sum of the increments in the extinction probability weighted by the reduction in the contribution to biodiversity for all the species living on the land can be called 'Expected Loss of Biodiversity (ELB)'.

We have estimated the ELB for the development of Nakaikemi.

#### **3.1 Increases in the Extinction Probability**

Our estimate of the extinction probability is based on the simulation used in making the Red List for vascular plants in Japan. The Red List was created in 1997, following the categories and the criteria of IUCN's Red List of 1994, and adopted the quantitative assessment of the probabilities of extinction for each of the vascular plants. Among the five criteria, the so called criterion 'E' is based on the quantitative assessment of the extinction probability. This criterion classifies the threatened species into:

1. CR (critically endangered), if the probability of extinction is larger than or equal to 50% in 10 years or 3 generations,
2. EN (endangered), if the probability of extinction is larger than or equal to 20% in 20 years or 5 generations, and
3. VU (vulnerable), if the probability of extinction is larger than or equal to 10% in 100 years.

In actual classification, other criteria, namely criteria A,C and D, was used along with the criterion E, and the criterion that gave the most severe result was made effective.

The assessment of the extinction probabilities was made by a simulation based on the data on the number of sites where a species exists, the population size at each site and the nationwide distribution of the reduction rates of the population in the past 10 years (Yahara et al., 1998). The data were collected from about 400 researchers. The simulation assumed the distribution of the reduction rate in the past 10 years would hold in the future, and conducted 1,000 trials to assess how many times a species would become extinct within the next 100 years.

This simulation produces the mean time for the extinction of each species. By using this simulation, the increment in the mean time for the extinction when one habitat is lost can be calculated. The reciprocal of the mean time for the extinction means the probability of extinction per year, if the extinction in each year is assumed to occur independently from that in other years. If we let  $T$  represent the mean time for the extinction of a species, our proposal is to adopt  $\Delta(1/T)$  as a measure of risk.

The result concerning the impact of the loss of land on the extinction probabilities for the vascular plants in Nakaikemi is shown in Table 1. For this calculation, it is necessary to know the number of habitats by population size and the number of habitats by rate of population decline. These figures are to be published in the *Red Data Book*. Information on the population of each species at Nakaikemi is also necessary, and this has been provided in the research done by Kadono.

Table 1: Increments in the extinction probabilities of vascular plants due to the loss of Nakaikemi

No.	Species	Family	Red list category	Time for extinction (T)		$\Delta(1/T)$
				Before the loss (year)	After the loss (year)	
1	Isoetes japonica	Isoetaceae	VU	89.96	89.89	$8.90 \times 10^{-6}$
2	Marsilea quadrifolia	Marsiliaceae	VU	32.32	32.26	$6.43 \times 10^{-5}$
3	Salvinia natans	Salviniaceae	VU	54.57	54.56	$5.71 \times 10^{-6}$
4	Azolla japonica	Azollaceae	VU	52.76	52.65	$4.10 \times 10^{-5}$
5	Persicaria foliosa	Polygonaceae	VU	54.00	53.87	$4.26 \times 10^{-5}$
6	Trapa incisa	Trapaceae	VU	85.08	84.06	$1.42 \times 10^{-4}$
7	Eusteralis yatabeana	Lamiaceae	VU	35.99	35.54	$3.56 \times 10^{-4}$
8	Prenanthes tanakae	Asteraceae	VU	119.59	118.87	$5.10 \times 10^{-5}$
9	Sagittaria aginashi	Alismataceae	NT	162.02	161.91	$4.38 \times 10^{-6}$
10	Najas japonica	Najadaceae	EN	37.73	37.51	$1.53 \times 10^{-4}$
11	Monochoria korsakowii	Pontedariaceae	VU	56.44	56.23	$6.68 \times 10^{-5}$
12	Iris laevigata	Iridaceae	VU	102.22	102.15	$6.32 \times 10^{-6}$
13	Sparganium erectum	Sparganiaceae	NT	185.15	185.08	$1.90 \times 10^{-6}$
14	Sparganium japonica	Sparganiaceae	NT	202.22	201.77	$1.10 \times 10^{-5}$
15	Habenaria sagittifera	Orchidaceae	VU	81.80	81.79	$1.49 \times 10^{-6}$

### 3.2 Contributions to Biodiversity

Some taxonomists (and an economist) have proposed that *taxonomic diversity*---a term including both inter- and intra-specific diversity--- can be measured by using phylogenetic information (Williams et al., 1991, 1994; Weitzman, 1992; Faith, 1995). We have developed a practical method to apply their proposal to the assessment of the risk from land use conversion.

The basic idea is to regard the length of the branch of the phylogenetic tree that would be lost if a species were extinct as the contribution to the global diversity of the species. It would be desirable if we could determine the branch length by the length of the real time that has passed since the species  $i$  diverged from its sister. It is, however, quite rare that this is known. Therefore, we treated the reciprocal of the number of nodes between the terminal node of a species and the root as a surrogate for the length of the time that has passed since the divergence

from its sister species.

In addition to the problem of the lack of knowledge about the ages of species, there is another problem, that is to say, a fully resolved phylogenetic tree is not always available for a group of species. Faced with this problem, we adopted the approach of using a phylogenetic tree from the root to a certain upper taxon including the species in question, and to estimate the expected value of the reciprocal of the number of nodes between the terminal node for the species and the root, on the basis of the number of nodes above the upper taxon and the number of species included in the upper taxon.

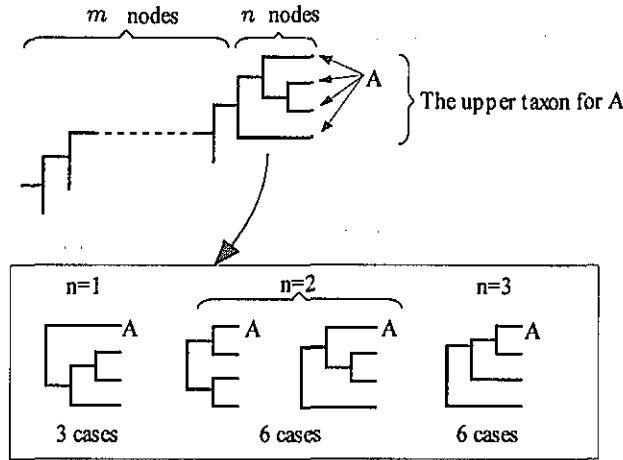


Fig. 1: Node counting when there are four species in the upper taxon

For instance, when there are four species within an upper taxon, 15 phylogenetic trees can occur within the upper taxon. In three cases, a species, say A, has one node between the root of the upper taxon and itself, in six cases, A has two nodes between the root and itself, and in six cases it has three nodes. Hence, when the upper taxon itself has  $m$  nodes between itself and the root of the whole tree (Fig.1), the expected mean value of the reciprocal of the number of nodes between the terminal node for species A and the root of the whole tree is  $3/[15(m+1)]+6/[15(m+2)]+6/[15(m+3)]$ .

When there are  $n$  species within an upper taxon, the number of phylogenetic trees in which a species A has  $k$  nodes between itself and the root of the upper taxon is represented by  $f_k(n)$  that forms the equation:

$$\begin{cases} f_1(n) = f(n-1) \\ f_k(n) = \sum_{i=1}^{n-k} {}_{n-1}C_i f(i) f_{k-1}(n-i), \quad k = 2, 3, \dots, n-1 \end{cases}$$

where  ${}_nC_i$  is the combination of  $n$  things taken  $i$  at a time and  $f(n)$  represents the total number of phylogenetic trees when there are  $n$  species, i.e.,

$$f(n) = \sum_{i=1}^{n-1} f_i(n).$$

The expected mean value of the reciprocal of the number of nodes between the terminal node for species A and the root of the whole tree is, therefore,

$$E_n[1/(m+k)] = [1/f(n)] \sum_{k=1}^{n-1} f_k(n)/(m+k)$$

where  $m$  is the number of nodes between the upper taxon and the root of the whole tree.

To obtain the value of  $E_n[1/(m+k)]$  using these equations requires huge amounts of calculations when  $n$  is large. Hence, in practice, when  $n$  is larger than 100, we used  $(m+1/E_n[1/k])^{-1}$  as an approximation for  $E_n[1/(m+k)]$ , where  $E_n[1/k]$  is equal to  $E_{n-1}[1/k](2n-4)/(2n-3)$ .

We applied this approach to the species listed in Table 1.

For the relationships among Psilotopsida, Lycopodiopsida, Equisetopsida, Polypodiopsida and Spermatopsida, we assume the tree shown in Fig. 2 according to Bremer et al. (1987) and Bremer (1985). The relationship among the three families of Lycopodiopsida, i.e., Isoetaceae, Lycopodiaceae and Selaginellaceae, is based on the molecular analysis by Manhart (1995), although the molecular analysis has not produced stable results for this level of taxa.

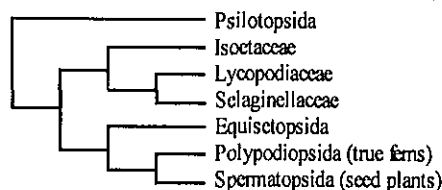


Fig. 2: Phylogenetic tree for higher taxa of vascular plants

As a result, the number of nodes for Isoetaceae between the terminal and the root is three, which is shown in the column 'number of nodes above the upper taxon' for *Isoetes japonica* in Table 2 (Isoetaceae is the selected upper taxon for *Isoetes japonica*).

For the true ferns, we determined the number of nodes above the families according to the molecular phylogenetic tree from Hasebe et al. (1995, p.146). The nodes for the seed plants were counted according to the phylogenetic tree presented by Chase et al. (1993). The resulting numbers of nodes are shown in the column 'number of nodes above the upper taxon'. The numbers for the flowering plants were not determined uniquely because the phylogenetic tree we used contains unresolved relationships between some taxa and because the tree does not include all the families of flowering plants.

The numbers of species within the upper taxa were obtained from Cronquist (1981) for the dicotyledons, from Dahlgren et al. (1985) for the monocotyledons and from Kramer and Green (1990) for the ferns and fern allies respectively. The resulting values of  $E_n[1/(m+k)]$  or  $(m+1/E_n[1/k])^{-1}$ , depending on whether  $n \leq 100$  or  $n > 100$ , are also presented in the sixth column

in Table 2. When  $m$  is not determined uniquely, the value of  $E_n[1/(m+k)]$  or  $(m+1/E_n[1/k])^{-1}$  is calculated by using the probability of a particular value of  $m$ . The average value of  $(m+1/E_n[1/k])^{-1}$  with these probabilities as weights can also be seen in Table 2.

Table 2: Contribution to biodiversity and ELB of the plant species in Nakaikemi

No.	Species	Selected upper taxon	No. of nodes above the upper taxon	No. of species within the upper taxon	Contribution to biodiversity		ELB $\Delta P_i Y_i$ (year)
					$E_n[1/(m+k)]$ or $(m+1/E_n[1/k])^{-1}$	$Y_i$ (year)	
1	Isoetes japonica	Isoetaceae	3	68	0.07332	29328994	261
2	Marsilea quadrifolia	Marsiliaceae	9	67	0.04879	19514737	1254
3	Salvinia natans	Salviniaceae	10	10	0.07070	28278915	161
4	Azolla japonica	Azollaceae	10	6	0.07720	30881499	1267
5	Persicaria foliosa	Polygonaceae	20-21	1000	0.01775	7101914	303
6	Trapa incisa	Trapaceae	25-29	15	0.03085	12341354	1755
7	Eusteralis yatabeana	Lamiaceae+Verbenacea	29-33	580	0.00852	3406671	1214
8	Prenanthes tanakae	Asteraceae	28-29	20000	0.00531	2124976	108
9	Sagittaria	Aginashi Alismatales	17-19	249	0.02771	11085960	49
10	Najas japonica	Najadales	17-19	205	0.02905	11618822	1782
11	Monochoria	Pontedariaceae	22-26	34	0.03003	12010897	802
12	Iris laevigata	Iridaceae	18-18	1400	0.01574	6297533	40
13	Sparganium erectum	Sparganiaceae	22-27	20	0.03147	12588373	24
14	Sparganium japonica	Sparganiaceae	22-27	20	0.03147	12588373	139
15	Habenaria sagittifera	Orchids	17-21	20115	0.00557	2226034	3
							9163

### 3.3 Expected Loss of Biodiversity

Let us define the unit of biodiversity as the distance on the tree of the vascular plants from any terminal nodes to the root node, and let us express the contribution to diversity of a species  $i$  in terms of this unit as  $B_i$ . The values of  $B_i$  are equal to the values for  $E_n[1/(m+k)]$  or  $(m+1/E_n[1/k])^{-1}$  in Table 2. We may express the contribution of a species to biodiversity in terms of year on the assumption that, say, the first diversion of vascular plants occurred 400 million years ago. Let  $Y_i$  represent the contribution of species  $i$  in this term, and then  $Y_i = B_i \cdot 4 \times 10^8$ .

Provided  $\Delta P_i$  is the increase in the reciprocal of the survival expectancy of species  $i$ , namely  $\Delta(1/T)$  for the species  $i$ , the expected loss of biodiversity (ELB) is represented by:

$$\sum_i \Delta P_i Y_i.$$

The values for  $\Delta P_i Y_i$  are presented in the last column of Table 2. The resulting ELB is about 9,200 years. This means Nakaikemi has a heritage of 9,200 years of the history of speciations and this will be lost if this wetland disappears.

### 4. Risk-Benefit Analysis

Using ELB as a measure of the ecological risk from land-use conversion, we can conduct risk-benefit analysis. Depending on the judgment concerning the success of the 'conservation area' in protecting the biodiversity of Nakaikemi, the risk-benefit analysis can have two scenarios.

The first one is to suppose the diversity is perfectly protected by the conservation area of 3.3 ha. In this scenario, the cost for the construction and the maintenance of the conservation area is regarded as the benefit lost by the conservation effort to maintain the expected diversity of 9,200 years. The initial and the running costs of the conservation area are 1 billion yen and 60 million yen per year, respectively, from which the annual value of the cost is calculated to be 120 million yen under a discount rate of 3% and a depreciation period of 25 years. The resulting benefit/risk ratio (B/R ratio) is 13,000 yen/year-ELB.

The second scenario is to suppose the diversity is completely lost in the development in spite of the conservation area. In this scenario, the benefit from the LNG plant is regarded as being enjoyed at the expense of the ELB of 9,200 years. The benefit of the LNG plant in Nakaikemi, estimated in terms of the increments in the construction costs when the plant has to be located in another place, ranges from 27 billion yen to 100 billion yen, the annual value of which is in the range of 1.0 to 3.9 billion yen. The resulting B/R ratio for this scenario is 110,000 to 420,000 yen/year-ELB.

## 5. Acknowledgments

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