Comparison of ecological risks of insecticides for nursery-box application using species sensitivity distribution

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The ecological risks to aquatic organisms posed by insecticide use were compared using species sensitivity distribution (SSD) to determine if nursery-box application is ecologically safer than surface-water application. The targeted insecticides were imidacloprid and ipronil for nursery-box application and fenitrothion as a reference for surface-water application. Ecological risks were quantified as the potentially affected fraction (PAF) of species calculated using SSD and the pesticide concentration in river and paddy water. The PAF value was the highest for fenitrothion in both river and paddy water, indicating that substituting nursery-box for surface-water application reduces the ecological risk. The validity of our SSD approach for risk quantification was confirmed with comparisons in mesocosm studies. The comparisons suggest that the PAF values successfully correspond to the magnitude of the pesticide effect on ecosystems. The actual ecosystem appeared to have strong recovery potential, even when more than 50% of the species were affected. © Pesticide Science Society of Japan

Keywords: risk assessment, imidacloprid, ipronil, potentially affected fraction.

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Introduction

In Japan, pesticide registration criteria based on ecological risk assessment are set by the Japan’s Ministry of Environment under the Pesticide Regulation Law. Under the risk assessment scheme, acute toxicity tests are conducted for fish (Cyprinus carpio), daphnids (Daphnia magna), and algae (Pseudokirchneriella subcapitata), and then the acute effect concentration (AEC) is determined as the minimum value of the 50% effect concentration (EC50) or 50% lethal concentration (LC50) divided by an uncertainty factor (10 for fish and crustaceans and 1 for algae). Subsequently, the predicted environmental concentration (PEC), which is the peak concentration in river water at the time of pesticide application, is calculated using an environmental model based on a standard scenario in a model basin. Finally, if the PEC is less than the AEC, the short-term aquatic risk is deemed to be insignificant and the pesticide is considered to fulfill the criteria.

Various measures are taken by farmers for the protection of biodiversity, such as reducing pesticide use, substituting to safer pesticides, and preventing of pesticide runoff into river water.

However, the efficiency of the risk management options has not been evaluated. The present risk assessment scheme is deterministic, and therefore does not allow the comparison of risks under the various risk management options. Insecticide application in rice paddy fields in Japan has gradually shifted from surface-water application to nursery-box application in light of its many advantages such as reduced labor, long-term effect, and low runoff and drift. However it is necessary to determine if nursery-box application is ecologically safer than surface-water application. Therefore, quantitative risk assessment is essential.

Probabilistic analysis is a useful tool for quantifying risks. Nagai et al. conducted probabilistic ecological risk assessment of several paddy herbicides and compared the risks. In their studies, the species sensitivity distribution (SSD) was used as the key concept for the probabilistic analysis. Species sensitivity to environmental contaminants varies markedly, and this variation can be described by the statistical distribution (often a log-normal distribution) estimated from sampled toxicity data (EC50 or LC50) and visualized as a cumulative distribution function. SSD has been used to determine hazardous concentrations for the protection of ecosystems and to reveal ecological risks. The 5th percentile of a distribution (called the 5% hazardous concentration, HC5) has been used in the United States and Europe for deriving threshold concentrations that protect most species in a community. The SSD has also been used for quantitative ecological risk assessment of pesticides, such as
diazinon\textsuperscript{6)} and aldicarb\textsuperscript{7)} (insecticides), atrazine a (herbicide),\textsuperscript{9)} and pesticide mixtures.\textsuperscript{9)} The potentially affected fraction (PAF) was used as an index of the magnitude of ecological risk. The PAF represents the effect on species diversity, which is a quantitative index of the biodiversity effect.

In this study, the ecological risks to aquatic organisms posed by insecticides for nursery-box application were compared using the SSD. Imidacloprid (a neonicotinoid insecticide) and fipronil (a phenylpyrazole insecticide), typical insecticides for nursery-box application, were chosen for risk assessment. Fenitrothion (an organophosphate insecticide) is a typical insecticide for surface-water application and was chosen as a reference insecticide for risk comparison. In the assessment, all ecological risks were quantified as PAF values derived by the SSD and exposure analysis. Moreover, the validity of our SSD approach for risk quantification was confirmed by comparing the results of mesocosm studies with the PAF values.

**Materials and Methods**

1. Problem formulation

We applied the method of ecological risk assessment by comparing the values of EC\textsubscript{50} or LC\textsubscript{50} based on acute toxicity testing and the PEC as the peak concentration of pesticide application. Specifically, species are considered to be affected by a pesticide when the PEC is greater than the values of EC\textsubscript{50} or LC\textsubscript{50}. Ecological risks were characterized using PAF values calculated by the SSD based on the values of EC\textsubscript{50} or LC\textsubscript{50} and the pesticide concentration.

The evaluation point is generally set at a river or a pond, and the PEC in Japan’s pesticide registration criteria is calculated at a downstream point of a first-grade river. However, species richness in agro-ecosystems has recently received attention, especially in rice paddy fields in Japan.\textsuperscript{10)} Therefore, the river ecosystem as well as the paddy ecosystem was selected for ecological risk assessment. For the risk assessment of the paddy ecosystem, the maximum pesticide concentration in paddy water was used instead of the PEC.

2. Effect analysis

Information on the acute (defined as test duration of 1–7 days) effect of the insecticides imidacloprid and fipronil on freshwater aquatic organisms was collected from published literature. The reliability of the information was separated into four categories according to the Organization for Economic Cooperation and Development (OECD) Manual for the Assessment of Chemicals\textsuperscript{11)}: 1 = reliable without restrictions, 2 = reliable with restrictions, 3 = unreliable, and 4 = not assignable. Toxicity testing in accordance with OECD test guidelines and the principles of Good Laboratory Practice (GLP) was evaluated as reliability “1.” Toxicity data used in the pesticide registration criteria concerning toxicity to aquatic organisms\textsuperscript{11)} was evaluated as reliability “1” according to expert examinations. Data in assessment reports published by the government was evaluated as reliability “2.” Data in the Pesticide Handbook\textsuperscript{12)} and Pesticide Manual\textsuperscript{13)} was evaluated as reliability “2,” given the expert knowledge and long experience of the editors. The reliability of data in original papers in scientific journals was evaluated according to the method proposed by Hobbs et al.\textsuperscript{14)} In their method, the quality of data presented in published research papers is assessed by awarding scores based on a series of criteria or questions, designed to ascertain the scientific rigor of the testing. Their method is robust and independent of the assessors for evaluating the quality of aquatic toxicity data.\textsuperscript{14)} The reliability of a paper is classified as unacceptable (equivalent to reliability “3”), acceptable (equivalent to reliability “2”), or high quality (equivalent to reliability “1”) depending on the total quality score. Collected acute toxicity data (EC\textsubscript{50} and LC\textsubscript{50}) was entered in a database.

SSD analysis was conducted using the collected datasets on toxicity. Only data evaluated as reliability “1” or “2” was used for SSD analysis. The data was separated into arthropods and other species, because arthropods are the most sensitive to insecticides among taxonomic groups and the SSD showed a clear separation of arthropod species from other species.\textsuperscript{15)} All data was reduced to genus-level data according to the U.S. EPA guideline,\textsuperscript{16)} and converted to interval data according to Naito et al.\textsuperscript{17)} Multiple data on the same species and same genus was treated as interval data using the minimum and maximum data of a dataset. If only one data item was available in the same genus, for example a value of 10, the data was treated as interval data of 9.5–10.5. If the data was reported as “greater than” values, it was treated as interval data from the minimum value to 10 times the minimum value. Each interval dataset on arthropods and other genera was fitted to a log-normal distribution using the maximum likelihood method.\textsuperscript{17)} Maximum likelihood parameters of the distribution, log mean and log standard deviation (logSD), were obtained by fitting.

The parametric bootstrap method was used to estimate the confidence interval (CI) associated with the SSD.\textsuperscript{18)} Random sampling by the number of genera (n) used for SSD analysis was conducted from the estimated maximum likelihood SSD. The SSD parameters, log mean and log SD, were again calculated from the sampled values. These calculations were repeated 10,000 times, and the 90% CI (5–95 percentile) of SSD was determined. The statistical software R (ver. 2.5.1) was used for bootstrap analysis.

The SSD for fenitrothion was also analyzed as a reference to compare the ecological risks with insecticides for nursery-box application. Maltby et al.\textsuperscript{15)} estimated the SSD for fenitrothion using acute toxicity data on freshwater arthropods and reported 5 and 10 percentiles of SSD with CI. SSD parameters were estimated from the reported values. The number of data was estimated from the reported confidence limit of the 5 percentile of SSD using the relationship between the CI and n established by the above bootstrap method.

3. Exposure analysis and risk assessment

PEC was calculated using an environmental model based on a standard scenario in a model basin, which is used in Japan’s
pesticide registration criteria. Details of the PEC calculation model were described by the Ministry of Environment\(^1\) and the Ministry of Agriculture, Food, and Fisheries. The PEC of each insecticide was calculated based on Tier 2, ground application in paddy field, absence of a static period, and a toxicity study period of 2 days. These conditions for PEC calculation are based on actual conditions as much as possible. To calculate the Tier 2 PEC, data from a paddy field lysimeter test is needed. The lysimeter test is used to examine the temporal variation of the pesticide concentration in paddy water after 2 weeks of pesticide application using a small-scale simulated paddy field (generally \(1 \times 1 \) m). Based on the test results, the PEC values in river water were calculated considering pesticide mass discharge through surface runoff and seepage. The highest insecticide concentration in the lysimeter test was regarded as the peak concentration in paddy water.

PEC values and peak concentrations in paddy water were used to quantify the ecological risk. The potentially affected fraction (PAF) of species was calculated from the concentrations and each SSD. Thus, PAF in river and in paddy water was calculated separately. The 90% CI (5–95 percentile) of PAF was also calculated using the CI of each SSD.

4. Evaluation of mesocosm study

Data from mesocosm studies, which can examine the community-level effect of pesticides under simulated outdoor field conditions, was collected from open literature. Indirect effects through species interaction can be evaluated, because many different organisms live in a mesocosm test system, which is a more realistic condition than that obtained in a standardized laboratory toxicity test. Moreover, the long-term effects and recovery process after pesticide application can also be evaluated. However, the community-level effect under field conditions is highly complex, and therefore multivariate statistical methods, such as the principal response curve method\(^{20}\), are generally used to analyze mesocosm test data. According to a European guidance document on aquatic ecotoxicology\(^{21}\), effects under each tested concentration were categorized in five classes: Class 1, no effect; Class 2, slight effect usually on a single sampling date immediately after application; Class 3, clear short-term effect (recovery within 8 weeks post last application); Class 4, clear effect duration unknown; Class 5, clear long-term effects (no recovery within 8 weeks post last application). In the present study, the no-observed-effect concentration on the ecosystem (NOEC\(_{eco}\)) was determined as the concentration at which the effect corresponding to Class 1 was observed. Similarly, the lowest-observed-effect concentration (LOEC\(_{eco}\)) and the recoverable concentration (RC\(_{eco}\)) on the ecosystem were determined as concentrations at which the effects corresponding to Class 2 and 3 were observed, respectively.

The ecological relevance of PAF values under field conditions was examined using mesocosm evaluation. The PAF values were calculated using the values of NOEC\(_{eco}\), LOEC\(_{eco}\), and RC\(_{eco}\) by each SSD. Moreover, in order to evaluate the validity of the predicted no-effect concentration on aquatic organisms, AEC, HC\(_5\) derived by SSD analysis, and NOEC\(_{eco}\) were mutually compared. AECs for imidacloprid and fipronil were derived from the assessment report\(^1\) by Japan's Ministry of Environment, and since AEC for fenitrothion has not been reported,\(^1\) it was derived from the \(Daphnia\) EC\(_{50}\) value\(^2\) divided by an uncertainty factor of 10.

Results and Discussion

1. Effect analysis

Acute toxicity data on imidacloprid was obtained for 27 genera of freshwater organisms. The values of EC\(_{50}\) and LC\(_{50}\) ranged from 32,800 to \(>119,000 \mu\text{g/L}\) for 3 aquatic plants, 1.0 to 85,000\(\mu\text{g/L}\) for 7 crustaceans, 0.65 to 76.8 for 8 aquatic insects, \(>87,000\) to 237,000 for 5 fish, 6.2 for 1 oligochaete, 56,000 to \(>100,000\) for 3 snails, and 82,000 to 129,000 for 1 amphibian (Fig. 1). Sensitivity to imidacloprid differed dramatically among arthropods (crustaceans and aquatic insects) and other species. Moreover, the difference in sensitivity of crustaceans among taxonomic groups was very large (more than 10,000 times). Ostracods were highly sensitive (EC\(_{50}\) of \(1~\text{to}~10\mu\text{g/L}\)) to imidacloprid,\(^{22}\) but \(Daphnia\) magna, which is the standard species for the toxicity testing of arthropods, was much less sensitive (EC\(_{50}\) of \(>85,000\mu\text{g/L}\)).\(^1\)

Acute toxicity data on fipronil was obtained for 27 genera of freshwater organisms. The values of EC\(_{50}\) and LC\(_{50}\) ranged from
68 to $>19,000 \mu g/L$ for 5 aquatic plants, 2.24 to 3,800 $\mu g/L$ for 7 crustaceans, 0.153 to 699.6 for 10 aquatic insects, 85.2 to 560 for 4 fish, and $>2,000$ for 1 bivalve (Fig. 1). The difference in sensitivity of arthropods among taxonomic groups was large (more than 1,000 times). The EC$_{50}$ value for *D. magna* (190 $\mu g/L$) was 1,200 times higher than that for the most sensitive aquatic insect, *Cheumatopsyche brevilineata* (0.153 $\mu g/L$).

The SSD of imidacloprid and fipronil showed a clear separation between arthropods and others (Fig. 2). The SSD parameters of imidacloprid were determined to be log mean of 3.43 and log SD of 2.60 for arthropods ($n=15$), and log mean of 11.8 and log SD of 0.668 for others ($n=12$). The SSD parameters of fipronil were determined to be log mean of 1.36 and log SD of 2.33 for arthropods ($n=17$), and log mean of 6.11 and log SD of 1.00 for others ($n=10$). The SSD parameters of fenitrothion were estimated to be log mean of 2.32 and log SD of 1.91 for arthropods ($n=32$). The HC$_5$ values for arthropods were calculated to be 0.43 (90% CI of 0.073–2.4) $\mu g/L$ for imidacloprid, 0.084 (90% CI of 0.021–0.37) $\mu g/L$ for fipronil, and 0.44 (90% CI of 0.20–1.1) $\mu g/L$ for fenitrothion. The toxicity of fipronil is greater than that of imidacloprid and fenitrothion.

2. Exposure analysis and risk assessment

The parameters used to calculate PEC, organic carbon normalized soil partition coefficient ($K_{ow}$), half-life in water (DT$_{50}$), and lysimeter test are summarized in Table 1. The calculated PEC was 0.171 $\mu g/L$ for imidacloprid, 0.00178 $\mu g/L$ for fipronil, and 0.839 $\mu g/L$ for fenitrothion. The maximum insecticide concentration in paddy water derived from lysimeter tests was 66.3 $\mu g/L$ for imidacloprid, 0.52 $\mu g/L$ for fipronil, and 505 $\mu g/L$ for fenitrothion. These concentrations were used to quantify the ecological risk as PAF. The river and paddy water concentrations of fenitrothion were the highest. This is because the application rate of fenitrothion (50 g/10 a) is higher than that of imidacloprid (20 g/10 a) and fipronil (10 g/10 a), and most insecticides for nursery-box application were distributed in paddy sediment and do not dissolve in paddy water.

The PAFs of arthropods in river water were 2.3% (90% CI of 0.1–8.0%) for imidacloprid, <0.1% (90% CI of <0.1–0.6%) for fipronil, and 9.6% (90% CI of 3.7–16.8%) for fenitrothion (Fig. 3A). The PAFs of arthropods in paddy water were 61.6% (90% CI of 44.6–78.7%) for imidacloprid, 19.5% (90% CI of 7.1–32.6%) for fipronil, and 98.0% (90% CI of 94.6–99.6%) for fenitrothion (Fig. 3B). The ecological risk of fenitrothion was the highest in both river and paddy water, indicating that substituting nursery-box application for surface-water application reduces the ecological risk. This is due to the higher concentration of fenitrothion in river and paddy water. The maximum likelihood estimates of ecological risk of imidacloprid and

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**Table 1.** Values of $K_{ow}$, DT$_{50}$, maximum insecticide concentrations in paddy water derived from lysimeter test, their reference, and calculated PEC

<table>
<thead>
<tr>
<th></th>
<th>$K_{ow}$ (mL/g)</th>
<th>DT$_{50}$ (day)</th>
<th>Parameter reference</th>
<th>Maximum paddy concentration ($\mu g/L$)</th>
<th>Lysimeter test reference</th>
<th>PEC ($\mu g/L$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imidacloprid</td>
<td>276</td>
<td>0.42*</td>
<td>1)</td>
<td>66.3</td>
<td>34)</td>
<td>0.171</td>
</tr>
<tr>
<td>Fipronil</td>
<td>825</td>
<td>0.33</td>
<td>33)</td>
<td>0.52</td>
<td>35)</td>
<td>0.00178</td>
</tr>
<tr>
<td>Fenitrothion</td>
<td>1376</td>
<td>1.1</td>
<td>12)</td>
<td>505</td>
<td>36)</td>
<td>0.839</td>
</tr>
</tbody>
</table>

* Converted value under spring sunlight in Tokyo.
fipronil in river water were lower than the standard threshold level (5%).

The SSD approach has been applied to the evaluation ecological risk in river or pond ecosystems but not in paddy ecosystems. Our study is the first to compare ecological risks in paddy ecosystems using the SSD concept. Hayasaka et al. investigated the effect of imidacloprid and fipronil on paddy ecosystems using small experimental paddy mesocosms. The effect of imidacloprid was higher than that of fipronil, that is, zooplankton, benthic, and neuston communities in imidacloprid-treated fields had a significantly lower abundance of species than in the control and fipronil fields. The results were consistent with our assessment, indicating that the SSD concept is useful for comparing the ecological risks not only in river or pond ecosystems but also in paddy ecosystems.

3. Evaluation of mesocosm study

Literature on aquatic mesocosm and microcosm tests was collected, and data from four studies on imidacloprid was obtained. Pestana et al. investigated the effects of imidacloprid on a benthic macroinvertebrate community for 20 days after application using outdoor stream mesocosms. No significant difference from the control experiment was observed at 1.6 µg/L exposure, however there was a difference at 17.6 µg/L exposure. Sánchez-Bayo and Goka investigated the effects of imidacloprid on communities in rice agro-ecosystems using outdoor paddy mesocosms. The maximum concentration of imidacloprid in paddy water was 240 µg/L, and a significant difference in the diversity index from the control experiment was observed for one month, followed by recovery. A 19-week tank-type mesocosm study was conducted at concentrations of 0, 2, 6, 20, 60, and 180 µg/L imidacloprid. No significant effect on population and taxonomic richness of macroinvertebrates was observed, however the effect on amphipod abundance in some samples was significant at 2 µg/L exposure. According to a European risk assessment report, the effect of imidacloprid on a community was investigated using outdoor mesocosms with sediment. No effects on chironomids and mayflies, which are the most sensitive taxa, were observed at a concentration of 0.6 µg/L, however some were observed at a concentration of 1.5 µg/L. The results for imidacloprid were evaluated as NOECeco of 0.6–1.6 µg/L, LOECeco of 1.5–17.6 µg/L, and RCeco of 240 µg/L (Table 2).

Data on fipronil was obtained from one mesocosm study. Wirth et al. conducted a tank-type mesocosm study at concentrations of 0, 0.15, 0.355, and 5 µg/L fipronil for 7 weeks. Shrimp were the most sensitive, displaying an effect at 0.355 µg/L exposure during the first two sampling times. The effect was greater at 5 µg/L exposure, but complete recovery was observed at the end of the 7-week experiment. The results for fipronil were evaluated as NOECeco of 0.15 µg/L, LOECeco of 0.355 µg/L, and RCeco of 5 µg/L (Table 2).

Van Wijngaarden et al. reviewed freshwater mesocosm studies to determine the threshold levels of several insecticides. The data from four studies on the effect of single fenitrothion application was evaluated: Class 1 effect was observed at 1.1 µg/L exposure, and Class 3–5 effects were observed at 18.7, 30.8, 80, and 460 µg/L exposure. Clear recovery was not observed at the highest concentration. The results for fenitrothion were evaluated as NOECeco of 1.1 µg/L and RCeco of 18.7–80 µg/L (Table 2).

4. Ecological relevance of potentially affected fraction

The HC5 values, which correspond to the predicted no-effect concentration on aquatic ecosystems, AEC (pesticide registration criteria), and NOECeco derived from mesocosm studies were compared (Table 2). Although HC5 and NOECeco showed similar values for three insecticides, AEC showed much higher values (127–14,167 fold) than NOECeco for imidacloprid and fipronil. These results suggest that HC5 is a more appropriate index of the threshold level for aquatic ecosystems than the present Japanese pesticide registration criteria. Maltby et al. and van den Brink et al. also showed that the values of HC5 based on acute toxicity were protective against adverse ecological effects under single short-term exposure in freshwater semi-field (microcosm/mesocosm) experiments. Their results

Table 2. Comparison between AEC, HC5, and the evaluations of mesocosm studies (NOECeco, LOECeco, and RCeco)

<table>
<thead>
<tr>
<th>Insecticide</th>
<th>AEC (µg/L)</th>
<th>HC5 (µg/L)</th>
<th>NOECeco (µg/L)</th>
<th>LOECeco (µg/L)</th>
<th>RCeco (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imidacloprid</td>
<td>8500</td>
<td>0.43</td>
<td>0.6–1.6</td>
<td>1.5–17.6</td>
<td>240</td>
</tr>
<tr>
<td>Fipronil</td>
<td>19</td>
<td>0.084</td>
<td>0.15</td>
<td>0.35</td>
<td>5</td>
</tr>
<tr>
<td>Fenitrothion</td>
<td>0.45</td>
<td>0.44</td>
<td>1.1</td>
<td>—</td>
<td>18.7–80</td>
</tr>
</tbody>
</table>
are consistent with ours, indicating the validity of our approach. Fish, daphnids, and algae, which are the standard test species for ecological risk assessment, are much less sensitive to imidacloprid and ipronil than aquatic insects. Therefore, using the toxicity data on only the three standard species would lead to an underestimation of ecological risk. Toxicity testing using aquatic insects, such as the caddisfly\(^23\) is essential for assessing these types of insecticides.

The PAF values for the three insecticides under the exposure of NOEC\(_{eco}\), LOEC\(_{eco}\), and RC\(_{eco}\) were calculated to understand the ecological relevance of the PAF values (Fig. 4). The PAFs of arthropods were 6.5–12.7% (average 9.9% and 90% CI of 0.8–24.9%) for NOEC\(_{eco}\), 12.2–41.8% (average 23.0% and 90% CI of 2.9–59.2%) for LOEC\(_{eco}\), and 54.3–86.0% (average 70.4% and 90% CI of 38.0–93.7%) for RC\(_{eco}\). The average PAF values for NOEC\(_{eco}\), LOEC\(_{eco}\), and RC\(_{eco}\) were significantly different (analysis of variance, \(p<0.01\)). These results suggest that the PAF values correspond to the magnitude of the pesticide effect on ecosystems. Moreover, it was found that the actual ecosystem had strong recovery potential, even when no less than 70% of the species in the ecosystem were affected. Recovery from temporal effects is important for ecosystem management but has not been considered in laboratory toxicity testing. Our results suggest that laboratory toxicity data might be applicable for predicting community recovery using the SSD approach.

The PAFs of arthropods in paddy water were estimated to be 19.5–98.0% for the three insecticides (Fig. 3B). These ecological risks were much higher than the standard threshold level (5%). Here, we discuss the protection level and management goal in agro-ecosystems from the viewpoint of integrated biodiversity management (IBM) concept. IBM proposed by Kiritani\(^32\) is the theory that insect pest control and conservation are reconciled and made compatible with each other. In other words, IBM aims to control the population density between the outbreak level (economic injury level) and a specific extinction threshold. Agricultural land is a place for crop production, and therefore the protection of all organisms at all times is unrealistic in actual agriculture where pest control is essential. Therefore, the population density of target and non-target organisms is reduced by pesticide application during cultivation periods to prevent injury to agricultural production, but the density must be managed so as to remain above a specific extinction level. This enables the population density to recover after the cultivation period (Fig. 5).

Thus, protection of all individuals at all times is not deemed necessary considering the recovery potential of ecosystems from occasional adverse effects. A similar principle has been applied in the United States to develop water quality criteria for the protection of aquatic organisms.\(^16\) We compared the results from SSD analysis and mesocosm experiments, and found that the temporary and recoverable effects were equivalent to PAF values of 54.3–86.0%. An adequate protection level in agro-ecosystems will be revealed through the accumulation of these comparisons.

5. Application and perspective

Recently, there have been concerns that some insecticides for nursery-box application adversely affect specific organisms. However, the solution is not simply to prohibit the use of such insecticides, because risks are always a tradeoff. In our study, substituting surface-water application with fenitrothion for nursery-box application with imidacloprid or ipronil would increase the ecological risk. Therefore, risk tradeoff must be considered whenever proposing alternative actions. Moreover, overemphasis on a specific species is dangerous to ecosystem protection, because the effects on other species may be neglected. A good action for the protection of the specific species may cause side-effects on other species. This is another kind of risk tradeoff. Therefore, the effect on biodiversity covering a wide range of species must be evaluated. Our approach using SSD is very useful for comparing the ecological risks of insecticides considering a wide range of species. Moreover, this approach is widely applicable not only in river and pond ecosystems but also in agro-ecosystems. The features of our approach are summarized as (1) quantitative, (2) predictable, (3) targeting a wide range of species, and (4) easier and less costly than the field experiment. Therefore, our approach is expected to be useful for planning effective risk management.
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