Study of the impacts of systemic insecticides and their environmental fate in aquatic communities of paddy mesocosms

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Our knowledge of the ecological impact of insecticides on aquatic organisms is lacking at a community level because it requires high research skills, due to the complexity of community interactions. Here, the aquatic community’s response to the residues of two systemic insecticides, imidacloprid and fipronil, with different physicochemical properties was monitored for three years. In this study, four key points are considered for evaluating the ecological impact of the insecticides in relation to biodiversity conservation. These are as follows: (1) environmental fates as explained by their different physicochemical properties, (2) life cycles and habitats of each taxonomic and functional group, (3) indirect effects through the food chain, and (4) long-term field monitoring over the course of a year.

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Introduction

There is growing concern about the negative impact of pesticides on biodiversity because of the dissemination of toxic agrochemicals. However, the use of pesticides is essential for ensuring the quality and productivity of crops. As a first step in evaluating the ecological risks of pesticides, standard toxicity tests have been carried out based on the OECD test guidelines using three standard test organisms (i.e., a zooplankton crustacean, Daphnia magna; a fish, Cyprinus carpio or Oryzias latipes; and an aquatic algae, Pseudokirchneriella subcapitata). Such tests are indispensable; however, their rigid operation with no consideration of environmental uncertainty, including ecosystem complexity and variable weather conditions, may be insufficient for evaluating the ecological safety of pesticides, as those tests do not accurately reflect the toxic impact in the real world. Thus, to understand pesticide risk management and biodiversity conservation, it is essential to evaluate the data not only on acute toxicities at the species level but also on the long-term ecological impact at the population and/or community levels. However, our knowledge about the ecological impact of insecticides on biocenosis is lacking due to the community’s complexity, which requires advanced research skills and high costs. To resolve these problems, the ecological impact of a repeated single-pulse application of two systemic insecticides, imidacloprid and fipronil, that exhibit different physicochemical properties on aquatic communities of experimental paddies was assessed over a three-year period (2010–2012). The community impact was assessed in relation to each residue. Model ecosystems using micro- and mesocosms can be effective tools for more accurately predicting any potential toxic impact on biocenosis.

1. Methodology used in studying paddy mesocosms

Six independent experimental paddies (5.2 m long × 1.6 m wide), consisting of two replicates for each of three treatments (i.e., imidacloprid- and fipronil-treated paddies and control with no chemical treatments) were set up in the early spring of 2010.

The neonicotinoid imidacloprid is highly soluble in water and moderately persistent in soil, whereas the phenylpyrazole fipronil is less soluble in water and more readily adsorbed by soil than is imidacloprid. To study the environmental fate of these insecticides, their soil and water residues were monitored for four months, from mid-May to mid-September (i.e., the planting period) of each year. Previous reports have indicated that the toxicity of fipronil to cladocerans and fish is 100 to 1,000 times higher than that of imidacloprid.

Water (500 mL) and surface soil (<3 cm depth, 500 g) sam-
ple for insecticide analyses were collected at 2-hr (day 0) and then on days 1, 3, 4, 7, 14, 28, 56, 91, and 119 after the application of the insecticides from multiple random sampling spots in each insecticide-treated field. Water and soil samples of imidacloprid were extracted using solid-phase extraction columns (Waters Oasis HLB), and their extracts were analyzed by liquid chromatography coupled with mass spectrometry (LC-MS/MS; Xevo TQ, Waters). Samples of fipronil were extracted using the same procedure as for imidacloprid and analyzed by gas chromatography coupled with tandem mass spectrometry (GC-MS/MS; CP-3800, Varian). In addition, the community response and recovery of zooplankton, benthic organisms, and aquatic insects and the growth of Medaka fish after exposure to insecticide were monitored once a fortnight.

2. The environmental fate of imidacloprid and fipronil

The range of maximum concentrations of imidacloprid in water 2 hr after the initial exposure was narrow during the three years of monitoring (20–50 µg/L). Concentrations of fipronil were less than 1 µg/L soon after the insecticide application each year. The half-lives (DT_{50_{water}}) of both insecticides in water were within one to two weeks of each other between 2010 and 2012, suggesting that the exposure dynamics of imidacloprid and fipronil in water were constant regardless of their successive applications. Residue of imidacloprid, which is characterized by a relatively low absorption by soil, increased with every repeated application and remained at a level above 2 µg/kg soil throughout each experimental period even two years after application of the insecticide. Residue of fipronil in the soil remained for three years but its concentration among samples varied greatly (2 to 200 µg/kg). Although residue concentrations in water and soil of the two insecticides were 10 to 1,000 times lower than those established in the registration withholding standards of imidacloprid (8,500 µg/L) and fipronil (19 µg/L) in Japan, we should recognize that those residue concentrations lead to drastic changes in aquatic community structures as shown below.

3. Community response and recovery after insecticide exposure

This three-year study clarified that the impact of the two insecticides on aquatic biocenosis, particularly the fipronil-treated mesocosm, was still found two years after the initial insecticide exposures; additionally, successive applications caused an evident and long-term impact on the community structure. These results suggest that the negative effects of the first exposure pulse may have influenced the community response and the recovery process after a subsequent pulse. On the other hand, the resilience of communities after insecticide exposure was clearly different among the taxonomic groups studied, particularly zooplankton, benthic organisms, and aquatic insects. Zooplankton and benthic organisms, which were dominated by Chironomidae sp. larvae and Tubificidae sp., decreased in abundance but rapidly recovered within two or three months after application of the insecticides in each of the three years. The impact of both insecticides on aquatic insects was very small in the first application of 2010. However, pronounced variations in community structure were found two years after exposure to fipronil, and then their resilience decreased with successive applications of the same insecticide. Among aquatic insects, the high sensitivity of dragonfly nymphs, in particular Aeschnidae sp. and Crocothemis servilia mariannae, to fipronil was noticed. Susceptibility to pesticides among species may depend on differences in their life-cycle strategies and habitats. Aquatic insects and benthic organisms, which are active at the soil-water interface, are more affected over time by persistent residue of fipronil in the soil as compared to the residue of imidacloprid. The rapid recovery of zooplankton and benthic organisms after insecticide exposure can be explained by the short life cycles of these organisms, whereas the recovery process of aquatic insects, which have longer life cycles, cannot be accurately assessed unless they are monitored for at least two years.

The growth of adult Medaka fish and their juveniles was periodically lower in both insecticide-treated mesocosms than in the controls over the three years, suggesting indirect effects through the decline in their food source (such as zooplankton) or increased use of energy to detoxify/metabolize the insecticides.

Conclusions

The results obtained during these three years clarified that community responses to insecticides in experimental paddies strongly fluctuated from year to year. However, mesocosms are more powerful tools than are laboratory acute toxicity tests, as they can evaluate the risks of pesticides and relate the findings to four key points as follows: (1) the environmental fate of pesticides with different physicochemical properties, (2) life cycles and habitats of each taxonomic and functional group, (3) indirect effects through the food chain, and, most importantly, (4) the essential nature of long-term field monitoring experiments over the course of a year for obtaining data on the cumulative ecological impact of pesticides for a more realistic assessment of risk to ecosystems.