Aquatic Refugia: Relevance and Significance in Ecological Risk Assessment

Kayla Campasino, Jeffrey Giddings, David Campana
Introduction

- Pesticides may enter aquatic environments via spray drift, runoff, erosion, etc.\(^1, 2, 3\)
  - National Pesticide Loss database indicates runoff concentrations exceed toxicity thresholds for fish in numerous areas
  - Pyrethroids detected in 73% of sediment samples collected from water bodies adjacent to agricultural fields in CA Central Valley\(^4\)

- Pyrethroids
  - Synthetic insecticides (bifenthrin, cypermethrin, permethrin, etc.)
  - Hydrophobic (log \(K_{ow}\) 6.40 - 7.48)\(^5\)
  - Ecological risk assessment part of registration review process
Ecological Risk Assessment (ERA)

- Estimating the likelihood that adverse effects will occur from exposure

- EPA framework
  - Problem formulation: product use and assessment endpoints
  - Exposure analysis: modeling to estimate exposure concentrations
  - Effects analysis: derived from ecotoxicology studies
  - Risk characterization

- Current models assume a homogeneous distribution of the chemical within the water body
Refugia

- Places or times where the negative effects of disturbance are lower than in affected areas or times

- Variables that influence refugia
  - Environmental heterogeneity: vegetated sections, sediment organic carbon gradients
  - Physicochemical properties: hydrophobicity → sorption to organic matter
  - Environmental fate: degradation, transport
Environmental heterogeneity creates spatial and temporal refugia

- Runoff simulation in a vegetated 650 m drainage ditch
- Sorption of bifenthrin and lambda-cyhalothrin to aquatic macrophytes reduced downstream water concentrations
  - Aquatic vegetation acts as a sink
  - Rapid aqueous dissipation

---

Table 4: Estimated mass (g) of bifenthrin and lambda-cyhalothrin in the water, sediment, and plant compartments relative to each sampling time (*total active ingredient amended to ditch at time zero). E-02, E-03, and E-04 represent 10^-2, 10^-3, and 10^-4, respectively, for significant digit purposes.

<table>
<thead>
<tr>
<th>Time</th>
<th>Water</th>
<th>Plants</th>
<th>Sediment</th>
<th>Total</th>
<th>Time</th>
<th>Water</th>
<th>Plants</th>
<th>Sediment</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 h</td>
<td>1.11E-02</td>
<td>1.11E-02</td>
<td>1.11E-02</td>
<td>3.33E-02</td>
<td>0 h</td>
<td>1.11E-02</td>
<td>1.11E-02</td>
<td>1.11E-02</td>
<td>3.33E-02</td>
</tr>
<tr>
<td>3 h</td>
<td>5.78</td>
<td>6.29</td>
<td>3.85E-02</td>
<td>12.1</td>
<td>3 h</td>
<td>3.10</td>
<td>6.13</td>
<td>6.24E-02</td>
<td>9.29</td>
</tr>
<tr>
<td>12 h</td>
<td>0.718</td>
<td>7.22</td>
<td>3.23E-02</td>
<td>7.97</td>
<td>12 h</td>
<td>0.353</td>
<td>3.76</td>
<td>1.12E-02</td>
<td>4.13</td>
</tr>
<tr>
<td>24 h</td>
<td>0.191</td>
<td>4.03</td>
<td>1.13E-02</td>
<td>4.24</td>
<td>24 h</td>
<td>0.106</td>
<td>1.59</td>
<td>3.68E-03</td>
<td>1.70</td>
</tr>
<tr>
<td>7 d</td>
<td>0.134</td>
<td>1.93</td>
<td>6.31E-02</td>
<td>2.13</td>
<td>7 d</td>
<td>4.05E-02</td>
<td>6.74E-02</td>
<td>1.79E-02</td>
<td>0.126</td>
</tr>
<tr>
<td>14 d</td>
<td>4.48E-02</td>
<td>3.00</td>
<td>5.25E-02</td>
<td>3.10</td>
<td>14 d</td>
<td>6.90E-03</td>
<td>2.09E-01</td>
<td>1.29E-02</td>
<td>0.229</td>
</tr>
<tr>
<td>30 d</td>
<td>4.37E-03</td>
<td>0.199</td>
<td>1.93E-03</td>
<td>0.206</td>
<td>30 d</td>
<td>1.05E-03</td>
<td>3.41E-02</td>
<td>4.24E-02</td>
<td>7.75E-02</td>
</tr>
<tr>
<td>44 d</td>
<td>8.82E-04</td>
<td>4.89E-02</td>
<td>8.31E-04</td>
<td>5.07E-02</td>
<td>44 d</td>
<td>6.22E-03</td>
<td>9.10E-02</td>
<td>5.04E-02</td>
<td>0.148</td>
</tr>
</tbody>
</table>
Environmental heterogeneity creates spatial refugia

- Pyrethroid runoff from nursery application into a sedimentation pond and 260 m drainage channel.  
- Sorption of bifenthrin and permethrin to sediment resulted in increasing sediment concentrations with increasing distance from sedimentation pond.
  - Offsite transport
  - Lower bioavailability in water column

### Table 2. Concentrations of bifenthrin and permethrin in sediments along a runoff path.

<table>
<thead>
<tr>
<th>Distance from the sedimentation pond (m)</th>
<th>Concentration mg kg⁻¹</th>
<th>OC (mg kg⁻¹)</th>
<th>Clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bifenthrin</td>
<td>cis-Permethrin</td>
<td>trans-Permethrin</td>
</tr>
<tr>
<td>0</td>
<td>0.33 ± 0.01 (1.0)†‡</td>
<td>0.77 ± 0.07 (1.0)</td>
<td>0.20 ± 0.03 (1.0)</td>
</tr>
<tr>
<td>104</td>
<td>2.27 ± 0.09 (6.9)</td>
<td>1.10 ± 0.03 (1.4)</td>
<td>0.28 ± 0.05 (1.4)</td>
</tr>
<tr>
<td>145</td>
<td>10.64 ± 2.82 (32.2)</td>
<td>4.45 ± 0.03 (5.8)</td>
<td>0.92 ± 0.22 (4.6)</td>
</tr>
<tr>
<td>166</td>
<td>10.06 ± 0.18 (30.5)</td>
<td>2.73 ± 0.12 (3.5)</td>
<td>0.82 ± 0.09 (4.1)</td>
</tr>
<tr>
<td>210</td>
<td>8.47 ± 1.10 (25.7)</td>
<td>6.10 ± 0.26 (7.9)</td>
<td>1.26 ± 0.20 (6.3)</td>
</tr>
</tbody>
</table>

† Organic carbon content.
‡ Numbers in parentheses are relative enrichment ratios.
Environmental processes create spatial and temporal refugia

- Degradation of deltamethrin and fenvalerate exposed to UV light\textsuperscript{9}
- > 95% degradation after 160 seconds
- Photoproducts (3-phenoxy benzaldehyde and 3-phenoxyenzoic acid) suggest photo-oxidation is the primary reaction
- Limited light penetration in water body $\Rightarrow$ more rapid degradation at water surface
Environmental processes create spatial and temporal refugia

- Microrganisms (*Pseudomonas* and *Serratia* spp.) were cultured with cypermethrin or flumethrin\(^\text{10}\)
- ≥ 50% of the pyrethroids were degraded after 20 days
- Average pyrethroid concentration in cultures after 20 days
  - With microorganisms: ~15mg/L
  - Without microorganisms: ~34 mg/L
- Pyrethroid degradation may be more rapid in sediments harboring abundant microbial communities compared to environments with less microbial biodiversity
Habitat refugia contribute to ecosystem recovery after pesticide contamination

- Rainfall-induced parathion-ethyl and fenvalerate runoff into a headwater stream on agricultural land
- Eight out of 11 macroinvertebrate species eliminated after three high contamination runoff events
- 9 out of 11 populations recovered within 11 months despite no observed in stream emergence
- No observed in stream emergence; uncontaminated stream located 500 m from study site
- Population recovery likely due to recolonization from less affected sites
Habitat refugia contribute to ecosystem recovery after pesticide contamination
Habitat refugia contribute to ecosystem recovery after pesticide contamination

- Macroinvertebrate abundance measured in streams subjected to agricultural runoff\textsuperscript{12}
- SPEAR = Species At Risk
  - Sensitivity to pesticides
  - Life history traits influencing recovery
- Ten months after the peak pesticide concentrations, SPEAR were more abundant in affected stream sites when forested sections were less than 4,000 m from study sites and greater than 200 m in length
- Upstream forested sections allowed in-stream recolonization
Effect of refugia on aquatic recovery after exposure to pesticides may vary with species

- Invertebrate recovery in covered vs. open pond mesocosms after deltamethrin treatment\textsuperscript{13, 14}

- Caquet et al. (2007)
  - Open mesocosms $\rightarrow$ faster benthic macroinvertebrate recovery
  - Aerial recolonization probably had a significant influence on recovery

- Hanson et al. (2007)
  - Closed mesocosms $\rightarrow$ faster zooplankton recovery
  - Recovery likely due to sediment egg bank and predation release

- Internal vs. external recovery mechanisms in different species groups
Effect of refugia on aquatic recovery after exposure to pesticides may vary with species

- Benthic vs. water column zooplankton recovery in covered vs. open pond mesocosms after deltamethrin treatment
- Recovery of benthic organisms was slower than recovery of organisms found in the water column
- Different species groups utilize refugia differently with a water body

**Water column**

**Sediment surface**

![Graph showing recovery in 28 d and 42 d for different species.](image)

13
Refugia in ERA

- Mathematical models supported by empirical evidence\(^6\)
  - Simulated population changes after disturbance events
  - Refugium size, proportion of individuals lost, time between disturbances

- Simulated short term movements of individuals into and out of refugia
  - Population persistence with 10% vs. 40% refugia
  - Total area of refugia had a greater impact on population persistence than proportional loss or disturbance frequency
Refugia in ERA

- Quantifying refugia\textsuperscript{15}
  - Relationship of macrophyte structure and macroinvertebrate abundance and species richness
  - Surface convolution and refuge space correlated to macroinvertebrate distribution

- Population modeling\textsuperscript{16}
  - Comparison of ecological models applicable to risk assessment
  - Suitable aquatic ecosystem models
    - AQUATOX
    - IFEM
    - CASM

Warfe et al. (2008)
Conclusions

- Models assume homogeneous distribution
- Sorption to sediment, vegetation, and other organic matter reduces aqueous concentrations
- Pyrethroid concentrations are highly dynamic within a water body across small temporal and spatial scales
- Invertebrate populations exhibit faster recovery when refugia are present; may be variable depending on internal vs. external refugia
- Refugia may have a smaller effect on species without dispersal capabilities
- Development of methods to incorporate quantifying refugia and population modeling into ERA should lead to more realistic estimates of exposure and effects
References


