Aquatic Pesticide Best Management Practices and Relational Database for the Protection of NOAA Trust Species

by
Kelsey L. Gianou

PROJECT PAPER

Submitted to

Marine Resource Management Program
College of Earth, Oceanic, & Atmospheric Sciences
Oregon State University
Corvallis, OR 97331

2012

In partial fulfillment of the
requirements for the
degree of

Masters of Science

Presented April 20, 2012
Commencement June, 2012

Acknowledgements

I would like to thank my major professor, Dr. Samuel Chan, for giving me guidance and freedom for creativity throughout the project. I also thank the other members of my committee, Dr. Robert Emanuel for his continued support and Dr. Paul Jepson who stimulated several ideas for this project. I would also like to thank my team of Oregon Sea Grant scholars Amanda Slade, Sue Xiong, and especially Jennifer Lam, for without their help the project could not have been completed.

Thank you to the program managers who participated in interviews. The quality and details of the case studies would not be so if they hadn't participated.

Last, but certainly not least, I thank my family. Thank you to my parents, who have supported and believed in my ambitions my entire life. And thank you to my husband, Jason Gianou, for his unwavering support, selfless sacrifices, and unconditional love.

Contribution of Authors

Drs. Samuel Chan, Robert Emanuel, and Paul Jepson have provided guidance and editorial assistance throughout the project. Drs. Chan, Emanuel, and Jepson as well as Jennifer Lam contributed to writing the technical synthesis report for NOAA included in this project paper. Jennifer Lam, Amanda Slade, and Sue Xiong contributed to the database.

Abstract

Pesticides are widely used to control undesirable pests and may be applied directly to water or lands directly adjacent to water. There can be unintended consequences, however, to native, threatened, and endangered species. There is little information on the impacts of aquatic pesticides and best management practices (BMPs) to NOAA Trust Species. The goal of this project is to provide a set of resources and examples of aquatic pesticide toxicity to NOAA Trust Species and BMPs to NOAA Fisheries Service agents and private and public resource managers. The products produced by this project are 1) an aquatic pesticide and NOAA Trust Species database, 2) a technical report synthesizing case studies and an aquatic pesticide BMP framework for aquatic pest control, and 3) an aquatic pesticide BMP framework applied to salmon habitat restoration programs for peer reviewed publication. The products produced by this project are to assist NOAA Fisheries agents in consulting on the issuance of the EPA's 2011 National Pollutant Discharge and Elimination System (NPDES) Pesticide General Permit and to continue to provide assistance to NOAA Fisheries in determining entity eligibility and helping managers apply for inclusion under the 2011 NPDES Pesticide General Permit. The project products can also be used by private and public resource managers when developing and implementing aquatic pest control action plans with regards to the use of aquatic pesticides. The database highlights substantial gaps in ecotoxicity data of aquatic pesticides impacts to NOAA Trust Species. Taking a BMP approach to pesticide uses can help compensate for these gaps. Pest control managers, habitat restoration managers, and NOAA Fisheries Service agents will benefit from easily accessible, synthesized information on aquatic pesticides, their potential toxicity to NOAA Trust Species, and pesticide BMPs specific to aquatic pest control. Tools that could be utilized by all of these stakeholders could increase communication between these parties. This may lead to increased discussion and evaluation of the current knowledge of pesticide impacts and aquatic pesticide BMPs.

Table of Contents

Part II: List of Tables:

Part III List of Tables:

Part IV List of Tables:

Part I: Introduction and Summary

A. Background

Pests are a major concern in the United States and around the world. Pests can cause impacts to human health, agriculture, and natural resources and cost billions of dollars in damage and control (Pimentel, Lach, Zuniga & Morrison, 2000). For example, Pimentel et al. (2000) estimated that non-native species of pests cost the United States about 137 billion dollars per year. Non-native pests also impact endangered species. It is estimated that almost half of the species listed under the United States Endangered Species Act are threatened by non-native species (Pimentel, Lach, Zuniga & Morrison, 2000; Sanderson, Barnas & Rub, 2009). Aquatic non-native species can alter habitat, hydrological flows, nutrient cycling within streams, compete with native species for food and space, and displace and predate upon native and endangered organisms (Pejchar & Mooney, 2009; Pimentel, Lach, Zuniga & Morrison, 2000; Sanderson, Barnas & Rub, 2009; Urgenson, Reichard & Halpern, 2009). It is estimated that non-native aquatic species may rival the threats to endangered and threatened salmon posed by other commonly cited impacts such as habitat, hydropower, hatcheries, and harvest (Sanderson, Barnas & Rub, 2009). Although some non-native species can be removed through physical, cultural, or mechanical methods, some pest control programs require the use of pesticides for effective control or eradication (Kerr, 2010; Patten, 2002; Silver & Hutten, 2004).

Chemicals are widely used across the United States for pest control (Grube, Donaldson, Kiely & Wu, 2011). Biological and chemical pesticides may be applied directly to water, or to lands directly adjacent to water to control aquatic, riparian, marine, and estuarine pests. In 2009, the U.S. Sixth Circuit Court of Appeals held that Clean Water Act National Pollutant Discharge Elimination System (NPDES) permits are required for all biological and chemical pesticide point source discharges into the waters of the United States. This includes pesticides that are applied directly to, over, or near waters of the United States due to the nature of a pesticide residue after the pesticide has completed its intended action (*National Cotton Council, et al. v. EPA*, 2009). The EPA issued a NPDES Pesticide General Permit in 2011 that applies to pesticide applied in, near, or over waters for mosquito and other flying insect control, weed and algae control, animal pest control, and forest canopy pest control. This permit applies to areas where the EPA has permitting authority including Massachusetts, Alaska, Idaho, New Hampshire, New Mexico, Oklahoma, Washington D.C., most U.S. territories and Indian country lands, and federal facilities. When applying for the EPA's NPDES Pesticide General Permit and inclusion under the permit, decision makers and applicators are required to implement best management practices (BMPs) in order to minimize the amount of pesticides discharged into the waters of the United States (USEPA, 2011b). BMPs have been defined as practices that aim to reduce water pollution in the waters of the United States (Protection of Environment, 2007). Integrated pest management (IPM) strategies are a form of BMP, and they include multiple strategies to control pests, including prevention, early detection, and physical, mechanical, cultural, biological, and chemical control (Kogan, 1998).

BMPs specific to point source discharges of pesticides into waters of the United States may differ from those BMPs specific to pesticide applications for terrestrial use, such as agriculture. Agricultural BMPs for pesticide uses aim to reduce pesticides entering the waters of the United States from nonpoint sources since the majority of pesticide application actions do not result in direct point source discharges of pesticides into water. Although the goal of reducing water pollution from pesticide use actions is the same between terrestrial and aquatic pesticide use, the specific pesticide BMPs may be different due to the nature of where the pesticide is applied. Aquatic pesticides can be defined as pesticides that are to be applied directly to, over, or near waters of the United States. One of the reasons that the U.S. Sixth District Court of Appeals ruled that pesticides that are to be applied directly to, over, or near waters of the United States are considered under the Clean Water Act to be a pollutant with a point source discharge is because pesticides may linger in the water after the pesticide action has been completed (*National Cotton Council, et al. v. EPA*, 2009). Pesticides applied to aquatic habitats can be very difficult to contain. They become diffuse in the water and therefore may result in aquatic non-target organism exposure. Aquatic organisms, such as fish and invertebrates, are particularly vulnerable to pesticides in the water due to gill exposure. Dermal and ingestion exposures are also significant routes of exposure to aquatic organisms. In addition, due to movement of water, pesticides can be transported far downstream from the original application site. Pesticides can be toxic to non-target aquatic organisms, including endangered and threatened species listed under the Endangered Species Act (ESA) (USEPA, 2011a; Wan, Watts & Moul, 1989). Therefore, a large concern with the use of pesticides directly in or near aquatic habitats is their effect on protected species. Pesticide BMPs specific to aquatic-use pesticide applications need to consider the efficacy of the pesticide action, as well as potential effects to non-target organisms that are present or downstream of the aquatic habitat in which the pesticide is applied. Because of this concern to protected species listed under the ESA, the National Oceanic and Atmospheric Administration (NOAA) Fisheries Service is required to counsel on activities, such as the issuance of the EPA's NPDES Pesticide General Permit, and the potential impact to NOAA Trust Species (protected marine species that are listed under the ESA). Federal agencies are required to consult with NOAA Fisheries to deem if their actions jeopardize marine protected species or their critical habitat as listed under the ESA (1973). This determination is called a Biological Opinion. NOAA Fisheries is responsible for suggesting reasonable and prudent alternatives to an action if an action is deemed to jeopardize NOAA Trust Species or their critical habitat (ESA, 1973). NOAA is not only responsible for consulting on whether or not a permit may be issued, but also for determining if an entity is eligible for coverage under a NPDES permit with regards to the protected species provisions (USEPA, 2011b).

Advising on NPDES permits for the consideration of NOAA Trust Species can be a challenging and daunting task. This is exacerbated by the limited data on aquatic pesticide toxicity to NOAA Trust Species and lack of common reference material for aquatic pesticide BMPs. This is also a challenge for pest managers, including those that are responsible for the decisions and use of pesticides in aquatic habitats. These managers are attempting to conform to NPDES permit regulations while effectively controlling pests for the protection of human health, recreation, water services, and habitat restoration. This is of particular concern when using pesticides in order to restore habitat for endangered species, such as stream, shoreline, and coastal habitat for salmon. There are tradeoffs between using the pesticides to eradicate non-native species in order to improve habitat function, and the pesticide effects to the salmon. This is because some pesticides can be directly toxic to salmonids (USEPA, 2011a; Wan, Watts & Moul, 1989). Pest control managers, habitat restoration managers, and NOAA Fisheries Service agents would benefit from easily accessible, synthesized information on aquatic pesticides, their potential toxicity to NOAA Trust Species, and pesticide BMPs specific to aquatic pest control. Tools that could be utilized by all of these stakeholders could increase communication between these parties. This may lead to increased discussion and evaluation of the current knowledge of pesticide impacts and aquatic pesticide BMPs.

B. Goals and Objectives

The goal of this project is to provide a set of resources and examples of aquatic pesticide toxicity to NOAA Trust Species and Best Management Practices (BMPs) to NOAA Fisheries Service agents and private and public resource managers. The products produced by this project were to assist NOAA Fisheries agents in consulting on the issuance of the EPA's NPDES Pesticide General Permit in 2011 and to continue to provide assistance to NOAA Fisheries in determining entity eligibility and helping managers apply for inclusion under the 2011 NPDES Pesticide General Permit. The project products can also be used by private and public resource managers when developing and implementing aquatic pest control action plans with regards to the use of aquatic pesticides.

In order to achieve this goal, three main objectives were identified:

1. Build a database with general aquatic pesticide information, aquatic pesticide toxicity to NOAA Trust Species, NOAA Trust Species' life histories, and general IPM strategy examples for resource manager and NOAA Fisheries use.

This database includes 26 commonly used aquatic pesticides that are included in the EPA's NPDES Pesticide General Permit and 61 NOAA Trust Species designated population segments and evolutionarily significant units. The database is synthesized and presented in such a way to encourage use by both aquatic resource managers and NOAA Fisheries agents.

2. In a report to NOAA, synthesize a variety of aquatic pesticide best management practices (BMPs) case studies and present these case studies through a developed aquatic pesticide BMP framework.

The framework aims to guide decisions for pesticide use in NOAA Trust Species habitat. NOAA Fisheries agents can use this framework when consulting on NPDES permitting applications and aquatic resource managers can also use the framework as a decision making tool for pesticide use in aquatic habitats.

3. Publish the aquatic pesticide BMP framework in a peer reviewed journal in order to broaden potential user exposure to the framework.

This article was written based on the framework developed in objective 2. The framework was presented through a salmon habitat restoration context and supported by two case studies from the technical report. Salmon represent commercially, culturally, and economically important NOAA Trust Species. Salmon also have the most toxicity information with regards to aquatic pesticides, and may be the most likely species to be exposed to pesticide use due to their anadromous life histories. It is therefore useful to present an aquatic pesticide BMP framework through a salmon focused lens in order for users to gain exposure to the framework and its potential uses.

The products resulting from the above objectives are presented in Parts II, III, and IV of this thesis. Executive summaries of each product are provided below followed by a description of lessons learned from the entire project.

C. Executive Summaries

1. **Part II:** Aquatic Pesticide and NOAA Trust Species Toxicity Database

In order to assist with the EPA's National Pollutant Discharge Elimination System (NPDES) Pesticide General Permit approval, application, and eligibility of inclusion decisions from a NOAA Trust Species perspective, an aquatic pesticide and NOAA Trust Species database was compiled. This database includes information on 26 commonly used aquatic pesticides and their effects on 61 NOAA Trust Species' distinct population segments and evolutionarily significant units. The database is unique because it is a comprehensive database that synthesizes information on toxicity, life history, integrated pest management (IPM) strategies, and includes an aquatic pesticide BMP framework. This database is meant to be used by resource managers and NOAA Fisheries agents to help determine if pesticide actions will result in the jeopardy of NOAA Trust Species. The data is presented in a format that attempts to address some user based issues with highly detailed databases. Data for the database was collected using a variety of methods, including searching pesticide labels, extension agency literature, government publications, trade organization websites, other grey literature, and published literature. Included is a version of the user guide that accompanies the database. A summary analysis of the data reveals substantial data gaps in pesticide toxicity information to NOAA Trust whales, pinnipeds, marine turtles, marine invertebrates, marine fish, and a marine plant. Toxicity results for NOAA Trust anadromous fish reveal that adulticides and piscicides are generally the most toxic to fish and there can be high variation in toxicity ranges within pesticides. A smartphone application is being developed to broaden the accessibility and use of this database. Future recommendations include analysis of data gaps within the NOAA Trust anadromous fish, analysis of within and among variation in toxicity ranges of pesticides, and the inclusion of surrogate species and synergistic data.

2. **Part III:** A Selected Synthesis of Literature and Case Studies on Best Management Practices for Reducing the Impacts of Pesticides in Aquatic Environments and Protecting NOAA Trust Species

Best Management Practices (BMPs) are important strategies for dealing with uncertainty. Pesticides, although a useful tool for pest control, may be toxic to endangered and threatened species and there is relatively little knowledge of their impacts. There is also a lack of common reference literature on aquatic pesticide BMPs. In an effort to compile information on aquatic pesticide BMPs, the National Oceanic and Atmospheric Administration (NOAA) requested a synthesis document to accompany the database presented in Part II of this thesis. The goal of the document is to highlight cases of BMPs for pesticide use in aquatic or riparian environments. This synthesis was to be used to assist NOAA Fisheries in establishing a biological opinion for the EPA's proposed NPDES pesticide general permit (PGP) and provide a tool for informing public or private managers about the proper use of pesticides in aquatic ecosystems with consideration of NOAA Trust Species. This synthesis is a compilation of case studies from five aquatic pest control efforts representing several types of uses of aquatic registered pesticides and associated application types from across the United States. These case studies are:

1. Demonstration Project on *Hydrilla* and *Hygrophila*, FL
2. Hoh River Knotweed Project, WA
3. Invasive *Spartina* Project, CA
4. Cheney Lake Restoration Project, AK and,
5. New York City Comprehensive Mosquito Surveillance and Control Plan, NY

These case studies were synthesized through reviews of treatment reports, gray literature, and scholarly articles. Key program contacts were also interviewed in each case. Each BMP case study is accompanied by a description of an example pesticide that was used within the corresponding project. Through the formation of the case studies, it became apparent that several key aquatic pesticide BMP elements were shared among the projects. These elements were identified and developed into an aquatic pesticide BMP framework. The elements within the framework are: Alternative Non-Chemical Methods, Pesticide and Product Choice, Adjuvants, Licensing and Certification of Applicators and Professional and Trade Associations, Application Method, Equipment and Calibration, Application Rates, Application Timing, Application

Conditions, Mitigation, Monitoring, Storage of Chemical, and Disposal of Chemical and Equipment. Each case study is organized and presented through this framework. Presenting aquatic pesticide BMPs through a common framework is advantageous because it allows for comparisons between projects that are highly site specific and has the potential to be adapted into an evaluation framework in the future. The BMP framework also provides a decision and presentation tool that highlights transparent tradeoff decisions that go into each key component of aquatic pesticide use planning. I suggest that NOAA Fisheries recommend the use of this framework to resource managers who are applying for a NPDES permit. Although this document presents examples of aquatic pesticide BMPs that will limit exposure risk to NOAA Trust Species, this document does not assess risk of each pesticide to individual NOAA Trust Species. This document also does not compile a comprehensive list of all possible BMPs for individual pesticides or their variations in application types; rather it presents examples of effective aquatic pesticide BMPs within a framework that could be used in the future to catalog the aquatic pesticide BMPs currently in practice. This document provides NOAA Office of Protected Resources with a tool that supports the mission of NOAA to develop policies and assist other public agencies for the protection of ocean and coastal resources.

The report is presented as was written when submitted to NOAA in 2011 and has the following contributing authors: Dr. Robert Emanuel, Jennifer Lam, Dr. Paul Jepson, and Dr. Samuel Chan.

3. **Part IV:** A Best Management Practice Framework for Aquatic Pesticide Management to Limit Impacts to Salmon

This section presents a BMP framework to guide the process of developing and implementing BMPs for pesticide use in aquatic habitats for invasive species control and salmon habitat restoration. Two of the five case studies and the aquatic pesticide BMP framework developed in the synthesis document in Part III of this thesis were used as a foundation to present an aquatic pesticide BMP framework specific to the protection of endangered and threatened salmon. The key elements of the framework have been grouped into the following six categories: Integrated Pest Management (IPM), Products, Applicator Knowledge, Field Practices, Monitoring, and Off-Site Practices. The category groups, key elements, and main questions related to each category are presented in a summary, while each of the key elements is supported with examples from two case studies. The two relatively successful invasive species control/habitat restoration project case studies that are presented to support this framework are: the Hoh River Knotweed Project, and the Invasive *Spartina* Project. Case studies were synthesized from publicly available technical reports and supplemented with personal communications from program managers. This pesticide BMP framework could be used as a tool by managers to clearly present BMPs and the tradeoff decisions that go into each invasive species control program. This framework can be tailored for other restoration programs and is not limited to salmon habitat restoration. The framework also has the potential to be adapted to catalog and possibly evaluate the efficacy of pesticide BMPs for invasive species control and impacts to non-target organisms. This section is intended for peer review publication and has been written to the specifications of the journal *Restoration Ecology*. This section will be submitted to *Restoration Ecology* within 2012. It is useful to focus in on a particular topic and related case studies in order to engage an audience. By presenting this aquatic pesticide BMP framework through a salmon habitat restoration focused lens, it provides specific examples of tradeoffs between using pesticides to restore critical habitat and the potential risks that pesticides directly pose to endangered and threatened species. It is anticipated that by publishing in a peer reviewed journal, the framework will gain exposure to restoration managers, scientists, and other professionals since salmon health is such a prevalent topic.

D. Lessons Learned

There are several lessons to be learned from this project. The first is project management, including prioritization of the more challenging tasks, for projects that have several variables coming from different sources. The database had several different types of data that was requested to be included. Every effort was made to include the most pertinent information within the database by the deadline requested. I am proud of the quantity and quality of the data included within the database, but I would recommend an expansion of the Integrated Pest Management (IPM) and Best Management Practices (BMPs) sections. These sections were the “black box” at the beginning of the project, and the most challenging. As more information was discovered about them, it became increasingly clear that providing a catalog of all aquatic pesticide BMPs within the deadline was not possible. Therefore, case studies of exemplary aquatic pesticide BMPs were chosen to highlight the details and site specific decisions that are made between programs. One option that I may choose if I were to approach this differently is to address the BMPs earlier on in the project timeline in order to provide a more complete set of BMPs for NOAA’s use.

Another lesson that was learned when developing the case studies was that all BMP elements were not necessarily included in program plans or treatment reports. Many of the decision details were excluded due to time and money constraints. It therefore became clear that a thorough review of BMPs required interviews of key members of the program who can provide decision details and context to each program. These interviews extend the process of case study development, therefore restricting the number of case studies to be completed within a prescribed period of time. However, I found the interviews necessary in order to provide a complete representation of the programs’ BMPs; just because a particular BMP element was not in the program reports does not mean that the program managers had not addressed it. In order to deal with this problem when attempting to catalog a large number of BMPs, I recommend using the aquatic pesticide BMP framework that I have developed and cataloging a sample set of aquatic pesticide BMPs without conducting personal interviews. This may reveal a set of common gaps in reports in addressing particular BMP elements, which could then be used to encourage those who write these reports to at least briefly address these elements to show that the program has indeed considered them. I would also recommend the encouragement of the use of the framework when developing pesticide BMPs to ensure that each program does not miss key elements of reducing risk to endangered and threatened species. NOAA, EPA, or state agencies could even go so far as to require the use of this framework when entities are applying for inclusion into pesticide permits. Pesticide BMPs that present their decisions and practices in a clear, common framework may also improve public perception of these projects if the public can see that multiple key elements are addressed in reducing risk to endangered or threatened species.

A third lesson was the integration of several types of highly detailed data into one, user friendly database that presented the data in a unique format. When organizing the data, I wanted to be sure that the data was easily accessible to the user. I wanted to present the data in a way that summarized the results without overwhelming the user with data and without losing crucial details. In addition, as it became clear that several sections had gaps in information, I set up the database in such a way that made the data gaps apparent. The organization of the database can allow users to analyze the data gaps, some of which are explored in Part II of this report. One thing I may have done differently, if possible, is set up a second database in which each data result is presented separately and not grouped into the same cells by pesticide, species, and life stage as was done in the final current version of the database. I would then link the separated, detailed data of that database into the current version of the database. This would allow for a user to conduct a more quantitative and detailed analysis of the toxicity data results, if desired, beyond the grouped data. This may also make it easier to keep the database current and updated once, and if, the project was passed onto another person for future maintenance.

The final main lesson learned from this project comes from the main result of the database which is the lack of data for the included 26 aquatic pesticide toxicities to many of the NOAA Trust Species. In order to address this issue and expand the usability of this database, I recommend including potential surrogates for the marine mammals, reptiles, marine fishes, and marine plant. While the goal would not be to detract from the fact that the effects of these included aquatic pesticides on many NOAA Trust Species is unknown, it would provide users perhaps some idea of the potential effects, if indeed any surrogates or surrogate information existed for these pesticides. This idea of surrogates can also be extend to the pesticides themselves. Some of the pesticides may have related chemicals that were not included. The inclusion of similar or related chemicals may help to partially fill some of the data gaps. It is also important, however, to recognize distinctions between related chemicals, for example 2,4-D acid and 2,4-D esters. It the current form of the database, all of the 2,4-D pesticides were grouped into just 2,4-D. Although distinctions were made between toxicity results, perhaps a more thorough distinction of the pesticide information differences in environmental fate, for example, may be useful. This is an issue with the pesticides that have several formulations and adjuvants included under the pesticide. Also, some of the toxicity studies that were included were conducted on formulations that may not be approved for aquatic use or may no longer be sold. A distinction between these products and those that are currently available for aquatic use may be a helpful improvement to the database. Lastly, I recommend the inclusion of any synergistic information that may be available for these 26 aquatic pesticides. How to create a user friendly database that presents all of the synergistic combinations and highlights those data gaps remains a challenge, but I do believe that it is an important subject to address and deserves attention.

This project was highly challenging, yet greatly rewarding. While I have presented several suggestions for an improvement to the project products, I do believe that I was successful in providing NOAA and resource managers with products that will aid in reducing aquatic pesticide risk to NOAA Trust Species. I am excited at the prospect that the database, case studies, and framework may be utilized and improved upon by various stakeholders, agencies, and scientists in order to further advance the protection of coastal and ocean resources.

E. Literature Cited

Endangered Species Act of 1973 (16 U.S.C. § 1531 et seq.)

Grube, A., Donaldson, D., Kiely, T., & Wu, L. U.S. Environmental Protection Agency, Biological and Economic Analysis Division, Office of Pesticide Programs. (2011). *Pesticides industry sales and usage: 2006 and 2007 market estimates*. Retrieved from U.S. Environmental Protection Agency website: http://www.epa.gov/opp00001/pestsales/07pestsales/market_estimates2007.pdf

Kogan, M. (1998). Integrated pest management: Historical perspectives and contemporary developments. *Annual Review of Entomology 43*, 243-270.

Kerr, D. San Francisco Estuary Invasive *Spartina* Project (2010). *Aquatic Pesticide Application Plan for the San Francisco Estuary Invasive Spartina Project*. California State Coastal Commission, Berkeley, CA. Retrieved from http://www.spartina.org/project_documents/2010_APAP_FINAL_ALL.pdf.

National Cotton Council of America et al. v. EPA, 553 F.3d 927 (6th Cir. 2009).

Patten, K. (2002). Smooth cordgrass (*Spartina alterniflora*) control with imazapyr. *Weed Technology*, *16*, 826-832.

Pejchar, L., & Mooney, H. (2009). Invasive species, ecosystem services and human well-being. *Trends in Ecology and Evolution*, *24*(9), 497-504. doi:10.1016/j.tree.2009.03.016

Pimentel, D., Lach, L., Zuniga, R., & Morrison, D. (2000). Environmental and economic costs of nonindigenous species in the United States. *BioScience*, *50*(1), 53-65.

Protection of Environment, 40 C.F.R. pt. 122.2 (2007).

Sanderson, B. L., Barnas, K. A., & Wargo Rub, A. M. (2009). Nonindigenous species of the Pacific Northwest: An overlooked risk to endangered salmon? *BioScience*, *59*, 245-256.

Silver, J., and Hutten, M. (2004). *Knotweed control on the Hoh River: Summary report-2002 to 2004.* 10,000 Years Institute, Port Townsend, WA. Retrieved from website: http://www.10000yearsinstitute.org/10k_asp/knotweed.asp.

Urgenson, L., Reichard, S., & Halpern, C. (2009). Community and ecosystem consequences of giant knotweed (*Polygonum sachalinense*) invasion into riparian forests of western Washington, USA. *Biological Conservation*, *142*, 1536-1541.

U.S. Environmental Protection Agency, Office of Research and Development. (2011a). *ECOTOXicology database system. Version 4.0.* Retrieved from website: http:/www.epa.gov/ecotox/

U.S. Environmental Protection Agency, Office of Wastewater Management. (2011b). *Pesticide general permit (PGP) for discharges from the application of pesticides: Authorization to discharge under the National Pollutant Discharge Elimination System*. Retrieved from: http://www.epa.gov/npdes/pubs/final_pgp.pdf

Wan, M. T., Watts, R. G., & Moul, D. J. (1989). Effects of different dilution water types on the acute toxicity to juvenile pacific salmonids and rainbow trout of glyphosate and its formulated products. *Bulletin of Environmental Contamination and Toxicology*, *43*, 378-385.

Part II: Aquatic Pesticide and NOAA Trust Species Toxicity Database

Abstract

Pesticides are widely used to control undesirable pests and may be applied directly to water or lands directly adjacent to water. There can be unintended consequences, however, to native, threatened, and endangered species. There is little information on the impacts of aquatic pesticides and best management practices (BMPs) to NOAA Trust Species. In order to assist with National Pollutant Discharge Elimination System permitting approval, application, and eligibility of inclusion decisions from a marine protected species perspective, an aquatic pesticide and NOAA Trust Species database was compiled. This database includes information on toxicity, life history, integrated pest management (IPM) strategies, and a pesticide BMP framework for 26 aquatic pesticides and 61 NOAA Trust Species. Resource managers and NOAA Fisheries agents can use this database to help determine if pesticide actions will result in jeopardy or take of NOAA Trust Species. A user guide is presented to explain the data collection methods and organization within the database. Results from the database highlight major data gaps in ecotoxicity information for all of the listed Trust Species with the exception of anadromous fish. Toxicity results indicate that adulticides and piscicides are the most toxic to fish, and there can be a wide range of toxicity levels within pesticides. In order to broaden the accessibility and use of this database a smartphone application is being developed. This database is unique because it is a comprehensive, NOAA Trust Species specific database that synthesizes information for the benefit of managers and NOAA Fisheries stakeholders. It is anticipated that an increase in accessibility to aquatic pesticide and BMP information will result in cooperative actions that will lead to successful aquatic pest control programs that pose low risk to NOAA Trust Species. Future recommendations include a more detailed analysis of the data gaps within the anadromous fish, analysis of toxicity ranges between pesticide formulations and organism life stages, the inclusion of surrogate species for the marine mammals and reptiles, and inclusion of synergistic studies.

A. Introduction

Chemical control of pests is a strategy commonly employed by land and water managers throughout the United States. The U.S. Environmental Protection Agency (EPA) has estimated that 1.1 billion pounds of pesticides were used in the United States in 2007 (Grube, Donaldson, Kiely & Wu, 2011). The application of pesticides may overlap with endangered or threatened species habitat. This is of concern because pesticides may be toxic to endangered species, such as salmon (USEPA, 2011a; Wan, Watts, & Moul, 1989). However, the use of pesticides in aquatic environments may be necessary in order to control or eradicate aquatic pests (Kerr, 2010; Patten, 2002; Silver & Hutten, 2004).

The use of pesticides in aquatic environments poses some unique problems compared with terrestrial pesticide use. Pesticides applied in or near aquatic systems result in direct exposure to aquatic organisms, including non-target organisms. Also, pesticides become more diffuse within the water and are more difficult to contain. Pesticides that are to be used or discharged into aquatic environments require a National Pollutant Discharge and Elimination System (NPDES) permit. There are also special criteria for when pesticides will be discharged into water containing species listed under the Endangered Species Act, including determinations of whether or not the pesticide-use action will have a significant effect on the listed species or if there is a declared pest emergency situation. NPDES permits often require consultation with the National Oceanic and Atmospheric Administration's (NOAA) Fisheries Service to determine if negative effects resulting from a permit approval are probable. When applying for a NPDES permit and inclusion under a permit, decision makers and applicators are required to implement best management practices (BMP) (USEPA, 2011b). BMPs are practices that include prevention, physical and cultural control methods, integrated pest management strategies (IPM) and actions of pesticide use. The goal of using BMPs is to reduce water pollution in the waters of the United States (Protection of Environment, 2007).

In order to provide public and private resource managers and decision makers with information about the proper use of aquatic pesticides for aquatic pest control with consideration to NOAA Trust Species (marine and anadromous organisms listed under the Endangered Species Act), a database of 26 commonly used aquatic pesticides and their effects on NOAA Trust Species was complied. This database is meant to be used as a tool by resource managers and NOAA Fisheries Service agents when dealing with application, eligibilities of inclusion, and advising for the 2011 EPA NPDES Pesticide General Permit under the Clean Water Act (1973).

B. Why a Database of This Kind is Needed

Information on the effects of aquatic pesticides on NOAA Trust Species is generally lacking (Raimondo, Vivian, Delos & Barron, 2008), as are common reference materials for aquatic pesticide BMPs. However, there are online, publicly accessible databases that have information on pesticides and their toxic effects to a wide variety of organisms. Examples include the EPA's ECOTOX (http:/www.epa.gov/ecotox/) and OPP pesticide ecotoxicity databases (http://www.ipmcenters.org/Ecotox/index.cfm). These databases present data in great detail by each specific result. These databases are organized to present results with a high level of study detail, including water temperature, water hardness, length and weight of organisms, pH, etc. It is fortunate to have such databases publically available, since some of the toxicity results are presented in these databases are not readily available in the published literature. Other resources, such as the National Pesticide Information Center (http://npic.orst.edu/) provide pesticide fact sheets that include general information about a pesticide, such as what it does, major restrictions, and potential health concerns to humans and wildlife.

The database developed in this project attempts to synthesize and present data on 26 commonly used aquatic pesticides and their potential impacts specific to NOAA Trust Species, as well as provide resources for aquatic pesticide BMPs into one comprehensive database. This database presents four major categories of data: general pesticide information, toxicity to NOAA Trust Species, NOAA Trust Species life history, and IPM/BMP strategies for aquatic pesticide uses in one database that is easily accessible and user friendly for managers and NOAA Fisheries stakeholders. The format and presentation of the data attempts to address some of the user-based challenges posed by extensively detail-oriented toxicity databases. This is done by presenting data on aquatic pesticides and their potential effects on NOAA Trust Species in a synthesized way. For example, the toxicity data is grouped by endpoint yet still filtered by species and pesticide. Therefore, a user can look at all of the data produced for a particular species and pesticide formulation in a comprehensive format, rather than one result per data endpoint. The disadvantage of this approach is that not all of the study details, such as water hardness, temperature, pH, etc. are included with each data point. The critical details, such as what the endpoint is, the duration of the test, and the age of the animal are all still included when available. Also, each data point is referenced so any user that is interested may refer to the original source if they would like more detail about how the study was conducted. A user-friendly database that synthesizes aquatic pesticide toxicity information on NOAA Trust Species is highly valuable to resource managers that are tasked with deciding which pesticides to use for controlling aquatic and marine pests. It will assist in determining if the pesticides are potentially toxic to NOAA Trust Species, which will help managers in the NPDES Pesticide General Permit eligibility application process. NOAA Fisheries Service agents can also use this database as a tool for determining if a proposed pesticide use in a NPDES permit will result in potential take of NOAA Trust Species. This will be advantages to NOAA Fisheries agents when consulting for permits and user eligibility under these permits as well as advising resource managers through the application process. Additionally, if the two stakeholder groups are using the same database, greater communication and engagement between these stakeholders may occur which may result in increased success of aquatic pest control programs and the protection of NOAA Trust Species. The organizational format of this database presents where data is not available or was not found, which highlights the data gaps and uncertainty of the pesticide impacts on NOAA Trust Species.

Incorporated into this database is general pesticide information, which includes a variety of synthesized information on human toxicity, modes of action, bioaccumulation, etc. allowing the user to gain a broad picture of what the pesticide is and how it may affect organisms other than NOAA Trust Species, including humans. Because this database focuses on NOAA Trust Species, it also includes a section which presents synthesized information on the life history, biogeography and seasonal pattern of each NOAA Trust Species. This is to provide the user with basic information about whether or not a species may be present in the habitat to receive pesticide treatment, when they are present, and at what life stage. This is important to consider since presence effects the risk of exposure and life stage may influence toxic effect. In addition, example IPM strategies are given in an IPM section of this database, to encourage users to brainstorm about how to use other control methods in order to reduce or eliminate the need for pesticides. A BMP framework to be used for pesticide use decision making is also included.

Because this database includes example IPM strategies and an aquatic pesticide BMP framework for decision making, managers can use this as a tool to put together a well thought out BMP and action plan section for a pesticide permit application. Also, through reviewing the example IPM strategies and BMP framework, managers may discover alternative methods for pest control that are affordable and achievable, and thus may result in a reduction of pesticide use.

C. Data Collection and Organization

This database is a synthesis of information on aquatic-use pesticides, toxicity, NOAA Trust species, example IPMs, and BMP decisions. Information was collected for 26 aquatic-use pesticides including adulticides, larvicides, herbicides/algaecides, and aquatic nuisance pesticides (Table 1) and 61 NOAA Trust Species distinct population segments and evolutionary significant units (ESU) (Table 2). The database is currently in a Microsoft Office Excel format and is planned to be published as a smartphone application. The 26 aquatic-use pesticides were chosen based on their frequency of use and consideration of inclusion into the EPA NPDES Pesticide General Permit that was issued in 2011 (USEPA, 2011b). There are several categories and sub-categories within the database and the methods of data collection varied by information type. The following information is a version of the database user guide that was created for the database and smartphone application. Within this user guide are descriptions of what is included in each category and sub-category along with the methods used to collect the data.

Table 1: Pesticides evaluated in this database, associated Chemical Abstract Service (CAS) numbers, and anadromous fish acute toxicity ranking.

		Toxicity Level[a,b,c]				
Pesticide	CAS #	Practically Non Toxic	Slight	Moderate	High	Very High
ADULTICIDES						
Resmethrin	10453-86-8					X
Pyrethrin	8003-34-7					X
Sumithrin	26002-80-2					X
Permethrin	52645-53-1				X	X
Malathion	121-75-5				X	X
Naled	300-76-5				X	X
LARVICIDES						
Temephos	3383-96-8		X	X	X	
Methoprene	40596-69-8	X	X	X	X	
Monomolecular Film	52292-17-8		X			
Bacillus thuringiensis israelensis[d]	68038-71-1					
Bacillus sphaericus[d]	143447-72-7					

AQUATIC HERBICIDE/ALGICIDES						
Copper sulfate	7758-98-7	X	X	X	X	X
2,4-D	94-75-7	X	X	X	X	
Endothall	145-73-3	X	X	X	X	
Glyphosate	1071-83-6	X	X	X	X	
Triclopyr	55335-06-3	X		X	X	
Fluridone	59756-60-4		X	X		
Diquat	85-00-7	X	X	X		
Imazapyr	81334-34-1	X				
Copper chelate[d]	14025-15-1					
AQUATIC NUISANCE						
Antimycin A	1397-94-0				X	X
Rotenone	83-79-4			X		X
TFM (3-trifluoromethyl-4-nitrophenol)	88-30-2		X	X	X	X
Sodium chlorate	9-9-7775	X				
Chlorine[d]	7782-50-5					

[a]Rankings are based on Zucker (1985).
[b]Rankings are based on acute 96 hour LC50 data for NOAA Trust Species salmon, steelhead, and Shortnose sturgeon, as well as rainbow trout as a surrogate species.
[c]Data in this table include any associated formulations, metabolites, or other adjuvants integrated under each pesticide within the database.
[d]No 96 hour LC50 data was available for ranking.

Table 2: NOAA Trust Species included in this database and their status.

Common Name (Distinct Population Segment or Evolutionarily Significant Unit)	Scientific Name	Status
Cetaceans		
Beluga whale	*Delphinapterus leucas*	Endangered
Blue whale	*Balaenoptera musculus*	Endangered
Bowhead whale	*Balaena mysticetus*	Endangered
Fin whale	*Balaenoptera physalus*	Endangered
Humpback whale	*Megaptera novaeangliae*	Endangered
Killer Whale (Southern Resident)	*Orcinus orca*	Endangered
North Atlantic right whale	*Eubalaena glacialis*	Endangered
North Pacific right whale	*Eubalaena japonica*	Endangered
Sei whale	*Balaenoptera borealis*	Endangered
Sperm whale	*Physeter macrocephalus*	Endangered

Pinnipeds		
Hawaiian monk seal	*Monachus schauinslandi*	Endangered
Steller sea lion (Eastern)	*Eumetopias jubatus*	Threatened
Steller sea lion (Western)	"	Endangered
Marine Turtles		
Green sea turtle (Florida & Mexico's Pacific coast colonies)	*Chelonia mydas*	Endangered
Green sea turtle (All other areas)	"	Threatened
Hawksbill sea turtle	*Eretmochelys imbricate*	Endangered
Kemp's ridley sea turtle	*Lepidochelys kempii*	Endangered
Leatherback sea turtle	*Dermochelys coriacea*	Endangered
Loggerhead sea turtle	*Caretta caretta*	Threatened
Olive Ridley sea turtle (Mexico's Pacific coast breeding colonies)	*Lepidochelys olivacea*	Endangered
Olive Ridley sea turtle (All other areas)	"	Threatened
Anadromous Fish		
Chinook salmon (California coastal)	*Oncorhynchus tschawytscha*	Threatened
Chinook salmon (Central Valley spring-run)	"	Threatened
Chinook salmon (Lower Columbia River)	"	Threatened
Chinook salmon (Upper Columbia River spring-run)	"	Endangered
Chinook salmon (Puget Sound)	"	Threatened
Chinook salmon (Sacramento River winter-run)	"	Endangered
Chinook salmon (Snake River fall-run)	"	Threatened
Chinook salmon (Snake River spring/summer-run)	"	Threatened
Chinook salmon (Upper Willamette River)	"	Threatened
Chum salmon (Columbia River)	*Oncorhynchus keta*	Threatened
Chum salmon (Hood Canal summer-run)	"	Threatened
Coho salmon (Central California coast)	*Oncorhynchus kisutch*	Endangered
Coho salmon (Lower Columbia River)	"	Threatened
Coho salmon (Southern Oregon & Northern California coast)	"	Threatened
Coho salmon (Oregon coast)	"	Threatened
Green sturgeon (Southern)	*Acipenser medirostris*	Threatened
Shortnose sturgeon	*Acipenser brevirostrum*	Endangered
Pacific eulachon/smelt	*Thaleichthys pacificus*	Threatened
Sockeye salmon (Ozette Lake)	*Oncorhynchus nerka*	Threatened
Sockeye salmon (Snake River)	"	Endangered

Steelhead (Central California coast)	*Oncorhynchus mykiss*	Threatened
Steelhead (California Central Valley)	"	Threatened
Steelhead (Lower Columbia River)	"	Threatened
Steelhead (Middle Columbia River)	"	Threatened
Steelhead (Northern California)	"	Threatened
Steelhead (Puget Sound)	"	Threatened
Steelhead (Snake River)	"	Threatened
Steelhead (South-Central California Coast)	"	Threatened
Steelhead (Southern California)	"	Endangered
Steelhead (Upper Columbia River)	"	Threatened
Steelhead (Upper Willamette River)	"	Threatened
Marine Fish		
Bocaccio	*Sebastes paucispinis*	Endangered
Canary rockfish	*Sebastes pinniger*	Threatened
Smalltooth sawfish	*Pristis pectinata*	Endangered
Yelloweye rockfish	*Sebastes ruberrimus*	Threatened
Marine Invertebrates		
Black abalone	*Haliotis cracherodii*	Endangered
Elkhorn coral	*Acropora palmata*	Threatened
Staghorn coral	*Acropora cervicornis*	Threatened
White abalone	*Haliotis sorenseni*	Endangered
Marine Plants		
Johnson's seagrass	*Halophilia johnsonii*	Threatened

1. Caution Statement

For all data references are given as numbers in parenthesis which correspond to references listed by section within the smartphone application or in a downloadable Reference Document. You should consult the original document/scientific paper to ensure an understanding of the context of the data retrieved from the database. While care has been taken to ensure that the information in the database is as accurate as possible at the last date of updating, we take no responsibility for any errors or omissions in the original data source. Data sources may have changed since they were last incorporated into the database, and may need updating.

Always refer to the pesticide label for application rates, uses, and restrictions.

The pesticide active ingredients in this database have been approved for aquatic use and are included in the EPA's NPDES Pesticide General Permit (USEPA, 2011). However, the specific formulations or adjuvants may not be approved for aquatic use. Please view the label of each formulation and adjuvant and consult with the permit that the pesticide will be applied under to determine if it is approved for aquatic use within the region of its intended use.

Rainbow trout (*Oncorhynchus mykiss*) is not a NOAA Trust Species. Rainbow trout has been included in the NOAA Trust Species ecotoxicity data because it is a common surrogate for coldwater fish species (Dwyer et al., 2005).

2. Pesticide Information

Pesticide information was collected by searching the National Pesticide Information Center (NIPC), U.S. Environmental Protection Agency (EPA) publications, pesticide labels, and other published literature. This information can be used to get a broad depiction of each pesticide, such as what it is used for, human toxicity concerns, and restrictions. Information was organized into the following categories for each pesticide: General Pesticide Information, Human Acute and Chronic Toxicity, Environmental Fate, Ecotoxicity Studies, Regulatory Guidelines, and Bioaccumulation.

2a. General Pesticide Information

This section includes CAS numbers, trade names, application rates, EPA registration number, chemical class, specific use, modes of applications, mode of action, general impacts to non target organisms, common adjuvants, and current EPA restrictions. This information gives managers information about what the pesticide is, how it is used, what is commonly used with the pesticide, and any major restrictions.

2b. Human Acute and Chronic Toxicity

This section gives information about what is known about acute and chronic toxicity levels and symptoms each pesticide may have on humans. The categories in this section are acute toxicity, signs of toxicity, chronic toxicity, carcinogenicity, and fate in the human body.

2c. Environmental Fate

The environmental fate section includes information about how the pesticide active ingredient behaves in the environment, including half-lives and environmental fate of metabolites when available. Categories in this section are soil, water, air, plants, and indoor. How long a pesticide or its metabolite persists in the environment under different conditions may influence pesticide choice.

2d. Ecotoxicity Studies

This section includes general information on the results of ecotoxicity studies on three categories of organisms: fish and aquatic life, birds, and terrestrial invertebrates. This section provides general ecotoxicity information that is not specific to species listed as NOAA Trust Species. This information may be useful when NOAA Trust Species toxicity information is limited or when managers are considering potential impacts to non-target organisms other than NOAA Trust Species.

2e. Regulatory Guidelines

This section has information regarding EPA evaluations of pesticide toxicity in the form of chronic reference dose, acceptable daily intake, and U.S. EPA Classification. U.S. EPA classifications include, for example, whether or not the pesticide active ingredient is classified as carcinogenic or not. Chronic reference dose is calculated from No Observable Adverse Effect Levels in test organisms and from uncertainty factors (Newman, 2010). Reference doses are used in risk analyses. Acceptable daily intake doses are the amount of chemical (in this case a pesticide) that an adult can consume every day of their lives without an appreciable health risk (Extension Toxicology Network, 1989).

2f. Bioaccumulation

Bioaccumulation information and bioaccumulation potential of each pesticide is given in this section. Pesticides with high bioaccumulation pose a risk of accumulating in human and other non-target organism tissues. There is the potential for pesticides with high bioaccumulation to transfer up the food chain to predators and pose a risk of biomagnification (Newman, 2010).

3. Toxicity of Pesticide to NOAA Trust Species

This information was compiled by conducting searches in the OSU libraries database, the EPA Office of Pesticide Program's Pesticide Ecotoxicity Database (http://www.ipmcenters.org/Ecotox/index.cfm), and the EPA's ECOTOX database (http://cfpub.epa.gov/ecotox/). Toxicity information is given, when available, for each pesticide and NOAA Trust Species.

Toxicity information is separated by pesticide formulation, active ingredient, metabolites, and common surfactants when available because each of these may result in a different toxic effect. Toxicity information is broken down into the following sections: Acute LC50 (96h), Toxicity Level, Chronic LC50, Sublethal/Behavior, and Field Studies. In addition, information is separated by life stage, when possible, to show any potential differences in susceptibility between juvenile and adult organisms.

3a. Acute LC50 (96h)

The toxicity information in this section is given mainly as acute LC50 (Lethal Concentration of 50% of the sample population) values and No Observable Effect Levels (NOEL). Most of the values are acute values determined after 96 hours of exposure. These values are used to determine how toxic an acute (short term) exposure will be to the NOAA Trust Species of interest. They are used to determine the toxicity level of each pesticide or pesticide formulation. When values are derived from other exposure times, such as 24 or 48 hours, this information will be noted. Notes such as the age of the chemical, pH of the water, water hardness, and percent of active ingredient in the formulation tested, or the exact age, length, or weight of the organism may be given in parentheses after the corresponding LC50 value. This information is often included because abiotic factors such as water hardness and temperature as well as biotic factors such as organism size can influence the toxicity of a compound to the organism tested. NOELs are given when available and are often determined along with acute LC50 values. NOELs are the level of pesticide or formulation that was tested that showed no observable effect, and so in this case, the highest level at which there was no death of the tested sample population (Newman, 2010). Some acute lethal results are not expressed as LC50 or NOEL values, and these are described accordingly.

3b. Level of Toxicity

Toxicity levels for fish are based off of 96 hour acute LC50 concentrations. The EPA uses the guidelines as described in Zucker (1985). For fish, the toxicity levels are as follows: < 0.1 mg/L Very highly toxic; 0.1- 1 mg/L Highly toxic; >1 to < 10 mg/L Moderately toxic; > 10 to < 100 mg/L Slightly toxic. Anything >100 mg/L is considered to be practically nontoxic (Zucker, 1985). This is a way to compare the acute toxicity of pesticides and pesticide formulations to each other.

3c. Chronic LC50

Chronic LC50 values are based on long-term tests on the organism either covering an important life stage (such as early life stage), at least 10% of the organism's life span, or the entire life of the organism. The definition of chronic LC50 is the concentration that is lethal to 50% of the sample population over a relatively long period of the organism's life. Many of the chronic LC50 data for fish are actually early life stages tests, in which the early life stage (in this case egg to fry) is tested and is considered to be the most sensitive stage. These data are used to determine what concentrations of pesticide have a lethal impact to organisms exposed for chronic (long) periods of time relative to the organism's live span (Newman, 2010).

3d. Sublethal/Behavior

This section has information on sublethal and/or behavioral effects that a pesticide or pesticide formulation may have on the tested organism. Sublethal studies may range from tissue bioaccumulation, weight, and length outcomes. Behavioral studies may include changes in behavior such as swimming direction, olfactory detection, and lethargy. Sublethal and behavior studies are important for providing insights to which concentrations a pesticide may alter the physical fitness or survival behavior of an organism but without causing direct mortality from the pesticide itself (Newman, 2010).

3e. Field Studies/Effects

This section provides information on any studies conducted that tested a pesticide's effect on a specific or multiple life stages in the field. These studies are rare, but can give insight to pesticide impacts in the field.

3f. Life Stage Categories

The pesticide toxicity information is also separated by life stage categories. This is because there may be a difference in toxic effects of chemicals among organism life stages. For example, juveniles are often considered to be more sensitive that adults (Newman, 2010). The life stages for the fish, with emphasis on salmonids, are separated into the following categories:

3f-1. Adult

Salmonids are classified as adults when they are in the saltwater stage or are returning to freshwater to spawn. Rainbow trout (a common species used to represent other salmonids in toxicity studies) are classified as adults when indicated in the study literature.

3f-2. Egg

Salmonids are classified in the egg stage when they are either in the egg, or have hatched from the egg to alevin during the duration of the toxicity test. This is common in chronic or early life stage testing.

3f-3. Juvenile

This stage can encompass any stage between, but not including, egg and smolt. This includes egg sack fry, swim up fry, fingerling, and parr.

3f-4. Smolt

This stage includes salmonids that are in the life stage when they are capable of first entering estuarine and saltwater conditions.

4. NOAA Trust Species Life History

Information on the life cycle, biogeography, and seasonal pattern for each NOAA Trust Species was collected by searching the Office of Protected Resources Website (http://www.nmfs.noaa.gov/pr/), federally listed organism status update documents, and the published literature. NOAA Trust Species' life histories were separated by species and ESU when available. General life histories are also given for each species with several ESUs and "see general" is given in cells where specific ESU information could not be found.

The purpose of this section of the database is to provide information on the life history of each NOAA Trust Species, including where and when they can be found within their designated habitat. This can assist managers, landowners, and organizations in determining whether or not NOAA Trust Species are present or adjacent to the area of proposed pest control and at what times of the year. Presence and life stage timing of these species may influence the management practices associated with applying pesticides in an area, especially if the pesticide is toxic to the species or if there are indirect influences of concern. Be sure to contact local experts to gain more information about a NOAA Trust Species' presence, seasonal behaviors, life stages, and population status before beginning any pesticide use.

4a. Life Cycle

Life cycle information is given for each NOAA Trust Species or ESU. This is broken up into sections depending on the life cycle of the organism, usually falling into categories of adult, juvenile, and general attributes.

4b. Biogeography

The biogeography will indicate each NOAA Trust Species' distribution. Biogeography information is given for each life cycle stage for each NOAA Trust Species when available. For example, salmon, which are anadromous, have a freshwater distribution when they are juveniles and will then migrate out to sea to mature into adults. Adult spawning salmon return to their home streams to spawn (Good, Waples & Adams, 2005).

4c. Seasonal Pattern

The seasonal pattern will give the approximate seasons or months that a NOAA Trust Species is in a particular life stage. Seasonal pattern information is separated into life cycle stage because many anadromous species migrate, spawn, hatch, and smolt in different seasons (Good, Waples & Adams, 2005).

5. General IPM Strategies

Information for integrated pest management strategies was collected by searching all extension service publications (peer-reviewed) given through the following website: http://www.extension.org/search. Other searches included using the American Mosquito Control Association website (http://www.amca.memberclicks.net), and resources provided by the Integrated Plant Protection Center at Oregon State University. General IPM strategies are presented for each group of pesticide: Mosquito, Aquatic Nuisance Fish, Aquatic Nuisance Mollusc, Aquatic Nuisance Lamprey, and Aquatic Plant/Algae. These IPM strategies are a brief look into the possibilities for pest control, with considerations to alternatives to pesticides. IPM strategies are intended to be used as a first step in pest management before application of pesticide is needed. The goal of IPM is to use ecologically sound and effective strategies in order to reduce pesticide use (Kogan, 1998). References are to be used as a resource to gain a better understanding of the options and to discover more IPM strategies and BMPs associated with pest control. The IPM strategies presented are designed to get users brainstorming and provide general strategies per pest group. However, each pest and infested location will require site specific choices therefore each IPM/BMP must be tailored to each local program in order to achieve the best results.

Also associated with the IPM strategies is a list of available aquatic-use approved pesticides that are included in the database. Selecting a pesticide in the IPM portal will take the user to the aquatic pesticides portal when using the smartphone application.

6. BMP Framework

Through the synthesis of several case studies of aquatic pest control projects from around the United States, a pesticide BMP framework was developed (for further information, see Parts III and IV of this thesis). This pesticide BMP framework is meant to be used as a BMP decision making tool for managers who are faced with having to use aquatic-use pesticides to control aquatic pests. Included in the framework presented within the database are several suggested questions and some practices that will guide managers through the development of BMPs with the goal of reducing risk to NOAA Trust Species while maintaining pest control efficacy.

7. Abbreviation and Definition Key

An abbreviation and definition key (Table 3) is provided to assist with user understanding and interpretation of the data. It includes definition of categories, as well as definitions of terms and abbreviations that the user will encounter in the database.

Table 3: Abbreviation and Definition Key

Title	Description
Acute LC50 (96h)	This value is the concentration at which 50% of the test organisms have died (lethal concentration) after 96 hours. If the LC50 was reported for a time other than 96 hours (for example 24 or 48 hours) it will be noted in parentheses. Other acute lethal values that are not reported as LC50s are also presented in the LC50 column.
Level of Toxicity	This is based off of the Acute LC50 (96h) and is as follows: < 0.1 mg/L Very highly toxic; 0.1- 1 mg/L Highly toxic; >1 to < 10 mg/L Moderately toxic; > 10 to < 100 mg/L Slightly toxic. Anything >100 mg/L is considered to be practically nontoxic (Zucker, 1985).
Chronic LC50	This value is the concentration at which 50% of the test organisms have died (lethal concentration) after a chronic period of time. Time will be noted with the data when available. Other chronic lethal values that are not reported as LC50s are also presented in the Chronic LC50 column.
Sublethal/Behavior	Results from tests of sublethal or behavioral endpoints such as estrogenic activity and avoidance behaviors.
Field Studies	Results from field studies or observed effects on organisms from pesticide applications in the field applications as a result of pesticide application/exposure.
Formulations	Formulations and market products of the pesticide. Will often have some percentage of active ingredient along with a surfacant, adjuvant, and other inert ingredients when available. Some formulations, ester, amine, and salt forms of the pesticide have different CAS numbers from the ones presented here, but ecotoxicity data is included for these formulations as well.
Surfactant	Chemical species that acts as wetting agents to lower the surface tension of a liquid and allow for increased spreadability.
Life Stages	Toxicity data is separated by life stage when data is available; otherwise, it is grouped as 'All Life Stages'. Life stages were often estimated by sizes given in the literature, when life stage could not be accurately estimated, it is categorized by N.R. or All Life Stages.
Metabolite	A substance produced from the metabolism of the compound (in this case the pesticide).
N.R.	Not Recorded
LD50	Median Lethal Dose
LOEC	Lowest Observed Effect Concentration
NOEC	No Observed Effect Concentration
NOEL	No Observable Effects Limit
LOEL	Lowest Observed Effect Limit
IC50	Concentration that produces 50% inhibition
IC10	Concentration that produces 10% inhibition
IC25	Concentration that produces 25% inhibition

n/f	Data not found or not available
EC	Emulsifiable Concentration
A.I.	Active Ingredient
Conversions	ppm (Parts per Million)= mg/L=mg/kg; ppb (Parts per Billion)= µg/L=µg/kg; 1 mg/L=1,000 µg/L=1,000,000 ng/L Note: ppm and mg/L are often used synonymously within this database
LC90	This value is the concentration at which the compound is lethal to 90% of the test organisms.
LC10	This value is the concentration at which the compound is lethal to 10% of the test organisms.
LC2	This value is the concentration at which the compound is lethal to 2% of the test organisms.
A.E.	Acid Equivalent
Ucrit	The speed at which a fish can no longer propel itself forward and becomes exhausted.
mg/l	milligrams per liter
µg/L	micrograms per liter
ng/L	nanograms per liter
mmol	millimole
mM	millimolar
meq	milliequivalents
µM	micromolar
ppm	Parts Per Million

8. General Notes for Users

There are many NOAA Trust Species for which toxicity data could not be found. In fact, with the exception of sturgeon, salmonids are the only NOAA Trust Species for which there is ecotoxicity data for the species or a surrogate species (rainbow trout). When information in any category of the database was unavailable or could not be found by the methods described, an "n/f" is denoted. The lack of data for non-salmonid NOAA Trust Species is also the reason why the user guide continuously uses salmonids as an example, since detailed descriptions of toxicity expression or life stages for the other species is not relevant if there is no data.

Another important note for users is that some of the toxicity data will have additional information in parentheses behind the main data point, such as temperature, pH, hardness, weight of organism, etc. or will have a range of toxicity values within one reference. This is because all of these factors may influence the toxicity concentration of a chemical to an organism (Newman, 2010). The data presented in the database attempts to walk a fine line between keeping ecotoxicity study result details in the database, without overwhelming the user with additional details that may not be directly pertinent to the overall interpretation of the results. When users need or desire to know the exact details of the study, it is encouraged that they consult the original data source.

D. Results

This database houses a wealth of information. Although a thorough review and interpretation of all of the data presented within the database is not within the scope of this study, two of the main results from this database are summarized here 1) data gaps and 2) pesticide acute toxicity rankings.

1. Data Gaps

One of the most apparent results from the formulation of this database was the lack of ecotoxicity data for the 26 pesticides on NOAA Trust Species. In fact, no data was able to be found for any of the 26 pesticides on the listed cetaceans, pinnipeds, marine turtles, marine fish, marine invertebrates, or marine plants (Table 4). The only group of NOAA Trust Species included in this database to have any type of ecotoxicity data for any of the 26 pesticides was the anadromous fish. A count of how many pesticides (including any toxicity data found for formulations, metabolites, or common adjuvants) had at least one toxicity study per anadromous fish species was performed to illuminate how many pesticides have gone untested for these NOAA Trust Species. Included in the table are rainbow trout, a common cold water fish surrogate species (Dwyer et al., 2005), which were included for that very reason, in addition to having the same species name as steelhead (*Oncorhynchus mykiss*). Accordingly, rainbow trout had the most number of pesticides tested, but even rainbow trout did not have all 26 pesticides (Table 4). In fact, some pesticides had no ecotoxicity data for anadromous fish, including rainbow trout (Table 5). This could be due to a number of reasons, but one such explanation is that the data may not be publicly available and therefore could not be found by the methods used to create this database. The NOAA Trust salmon with the highest number of pesticides tested (out of the 26 included in this database) were coho (*Oncorhynchus kisutch*) and chinook salmon (*O. tschawytscha*). Green sturgeon (*Acipenser medirostris*) and Pacific eulachon (*Thaleichthys pacificus*) had no ecotoxicity studies for the 26 pesticides.

There was also a lack of comprehensive data present for the majority of the 26 pesticides. Using the toxicity data for anadromous fish, each pesticide was evaluated to either have present or absent data in each of the four toxicity data categories: acute, chronic, sublethal, and field. This data includes all associated formulations, metabolites, and common adjuvants that may be integrated under each pesticide. Only Rotenone and Copper sulfate had at least one study present in each of the four categories. This may be because both rotenone and copper sulfate are commonly applied directly to water and can be highly toxic to fish (Table 1) and therefore may have more need or more opportunity for published acute, chronic, sublethal, and field studies for endangered species or rainbow trout. In addition, Rotenone is a piscicide, and has been used to eradicate rainbow trout in some streams in Australia (Lintermans, 2000); therefore will likely have several comprehensive studies for its use, particularly to endangered fish. However, Antimycin A is also a highly toxic piscicide (Table 1), but is missing available chronic data for anadromous fish and rainbow trout.

Table 4: Frequency of pesticides with data for each NOAA Trust Species and rainbow trout.

NOAA Trust Species Common Name	# of Pesticides with Ecotoxicity Data[a,b]
Cetaceans[c]	**0**
Pinnipeds[c]	**0**
Marine Turtles[c]	**0**
Anadromous Fish	
Chinook salmon	14
Chum salmon	3
Coho salmon	15
Green sturgeon	0
Shortnose sturgeon	2
Pacific eulachon/smelt	0
Sockeye salmon	4
Steelhead	5
Rainbow Trout[d]	21
Marine Fish[c]	**0**
Marine Invertebrates[c]	**0**
Marine Plants[c]	**0**

[a]Out of a total of 26 total pesticides.
[b]Data in this table include any associated formulations, metabolites, or other adjuvants integrated under each pesticide within the database.
[c]Includes all species listed under the indicated group in Table 2.
[d]Rainbow trout is not listed as a NOAA Trust Species; it is a surrogate species for cold water fish (Dwyer et al., 2005).

The most common category of toxicity studies is acute studies. This is not surprising since acute toxicity studies are a common measure of pesticide toxicity, can be ranked into nontoxic to highly toxic categories (Zucker, 1985), are used by the EPA to develop acute water quality criteria, required the use of a salmonid in the development of the criteria (Stephen, Mount, Hensen, Gentile, Chapman & Brungs, 2010), and are relatively simple tests logistically compared to chronic, sublethal, and field studies. The sublethal category of studies is the second

Table 5: Data type present for each pesticide.

Pesticide	Data Type[a,b] Acute	Chronic	Sublethal	Field
ADULTICIDES				
Resmethrin	X	X		
Permethrin	X		X	
Malathion	X		X	
Pyrethrin	X			
Sumithrin	X			
Naled	X			
LARVICIDES				
Bacillus thuringiensis israelensis	X		X	
Methoprene	X		X	
Monomolecular Film	X			
Temephos	X			
Bacillus sphaericus[c]				
AQUATIC HERBICIDE/ALGICIDES				
Copper sulfate	X	X	X	X
2,4-D	X	X	X	
Endothall	X	X	X	
Imazapyr	X	X	X	
Triclopyr	X	X	X	
Glyphosate	X		X	X
Diquat	X		X	X
Fluridone	X		X	
Copper chelate[c]				
AQUATIC NUISANCE				
Rotenone	X	X	X	X
TFM (3-trifluoromethyl-4-nitrophenol)	X	X	X	
Antimycin A	X		X	X
Sodium chlorate	X	X		
Chlorine[c]				

[a]Includes all NOAA Trust anadromous fish species listed in Table 2, plus rainbow trout.
[b]Data in this table include any associated formulations, metabolites, or other adjuvants integrated under each pesticide within the database.
[c]No data were found.

most commonly tested for these 26 pesticides on anadromous fish and includes endpoints such as metabolism, fate in body, behavior, and growth. Sublethal studies are important because they may indicate an effect of reduced fitness, such as reduced growth or altered behavior, which may have implications at a population level. The frequency of sublethal studies on anadromous fish for these 26 pesticides may be due to the wide range of included studies. Chronic lethal studies are the third most frequent category (Table 5). Chronic studies are longer term, therefore can be more difficult to perform than acute studies and even acute sublethal studies. As with acute studies, chronic studies are also used for developing water quality criteria. Some water criteria calculations, however, require chronic data for only at least one species of fish (Stephen, Mount, Hensen, Gentile, Chapman & Brungs, 2010), therefore a different species than the species listed in Table 4 may have been tested, thereby at least partially explaining the lack of chronic data for some of these 26 pesticides. Field studies testing these 26 pesticides on the anadromous fish listed in Table 4 are the rarest in frequency (Table 5). Field studies are more complex, are difficult to reproduce, and are cost intensive compared to laboratory studies, and therefore are not a feasible requirement for developing national water quality criteria (Stephen, Mount, Hensen, Gentile, Chapman & Brungs, 2010). Studies that monitor and then go on to publish field results of effects from pesticide applications are seemingly rare. Many factors can contribute to salmonid survival therefore confidently attributing an impact to pesticide application may only be done in at least semi-controlled conditions.

Three of the 26 pesticides reviewed had no data that fell within the four categories for anadromous fish listed in Table 4 (Table 5). As mentioned earlier, this may be because data may simply not be available through the methods used to collect the data.

2. Acute Toxicity Rankings

Other apparent results from the formation of this database were the values and ranges in acute toxicity rankings both between and within the 26 pesticides. Anadromous fish acute toxicity results from the database were ranked from practically non-toxic to highly toxic based on Zucker (1985) for each pesticide including any formulations, metabolites, or associated compounds that may have been integrated under each pesticide and are summarized in Table 1. Adulticides are consistently the most toxic group of pesticides to anadromous fish; they are also the group with the least amount of toxicity ranges. Larvicides are less toxic than adulticides, but have a wider range of toxicity values (Table 1). The two biological larvicides, *Bacillus thuringiensis israelensis* (Bti) and *B. sphaericus* had no available 96 hour LC50 toxicity values to be ranked, but other acute values for Bti suggest that Bti has low toxic risk to fish when applied according to the label (Wipfli, Merritt, and Taylor 1994). Many pesticides within the aquatic herbicides/algaecides have toxicities ranging from practically non-toxic to highly toxic, and Copper sulfate ranges from nontoxic to very highly toxic (Table 1). These ranges may be due to variation between within studies, or perhaps due to differences in toxicities between formulations, isomers, surfactants, and other adjuvants which are common in herbicides. The aquatic nuisance group has a wide range of acute toxicities within the group. The two piscicides, Rotenone and Antimycin A, are highly toxic to anadromous fish (Table 1), as would be expected. The lampricide TFM ranged from slightly toxic to very highly toxic to anadromous fish, while sodium chlorate, a molluscicide, is practically nontoxic to fish (Table 1).

E. Smartphone Application Development

A smartphone application is being developed to broaden the accessibility and use of the database. This adds a unique element to the database, because as of yet no smartphone application exists for this type of data. A mobile version of this database would allow managers, NOAA Fisheries agents, scientists, and other stakeholders to access this database at their convenience. Also, because smartphone applications are greatly gaining in popularity due to advances in publicly available technology (Clouston, 2010) users may find it to be a satisfying alternative to the traditional website access.

There are several considerations when developing a smartphone application of this type, including making sure that the application is easy to for the user to navigate and understand. Also, aesthetics may play an important role in encouraging people to continue to use the database. These considerations must be taken into account through the development process. The steps involved in developing a smartphone application include: creating a wireframe, programming, beta testing, final edits, and launch. A wireframe is a mockup of the database. It includes diagrams that indicate how it will look, how users will navigate through the database, their options, what happens when categories or options are chosen by the user, and how the data will be presented. Accompanying the wireframe is a concept map. This maps out how the database is navigated through, which portals link to one another, and how many layers are within each category. This is used by the application programmers when they are programming code for what options and data will be presented on selected screens. Once the programming is complete, the application will be made available for beta testing on a webpage that allows users to navigate through the application by accessing it from their computer or from their smartphone. Users to be involved with the application beta testing will include professionals from Oregon Sea Grant, water resource managers, aquatic pest managers, and NOAA employees. A special effort will be made to contact aquatic pest control project managers that contributed to case studies synthesized as part of a BMP framework development (see Parts III and IV in this thesis) to get their feedback on the database and application. Once feedback has been received and analyzed, the smartphone application will be adjusted accordingly, and then launched as a downloadable application. It is anticipated that the smartphone application will be completed and launched by June 2012. The application will be available for download on the iTunes and Android marketplaces and be promoted through the Oregon Sea Grant website and other sites.

Some additional challenges that arise with this type of database include dealing with jargon and industry standard definitions. Because this application is available to managers, scientists, policy makers, stakeholders, and the public, any user can download and navigate through the database. Some users will have a better understanding of the terms and definitions that are used throughout the database, but other users would benefit from clear, simple definitions. The challenge is to create a database that doesn't exclude users based on their knowledge, but also isn't clouded with definition and extra side information. While some of the main terms are defined within the user guide and/or the terms and definitions table (Table 3), many still may remain cryptic for some users. A possible solution for this is to hyperlink jargon to websites that define the term, allowing for increased understanding of users without overloading the information actually contained within the database. The use of hyperlinks is being considered. Whether or not this method is used will be dependent upon the availability of suitable definitions from reputable sources on the internet.

F. Conclusion and Recommendations

This database presents data on 26 commonly used aquatic pesticides, potential toxicities to NOAA Trust Species, and provides some resources to engage managers and decision makers about the practices and decisions of pesticide use in aquatic environments. It is unique to other databases in that it is a comprehensive, NOAA Trust Species specific database that synthesizes information for the benefit of managers and NOAA Fisheries stakeholders. The presentation and organization of the data within the database has yielded some major knowledge gaps in ecotoxicity effects of these 26 aquatic pesticides to NOAA Trust Species, particularly listed cetaceans, pinnipeds, marine turtles, marine fish, marine invertebrates, and a marine plant (Table 4). A recommendation for the use of this database is to draw attention to the ecotoxicity study data gaps for NOAA Trust species. Only species listed under the anadromous fish group had any ecotoxicity data from the 26 pesticides (Table 4). This highlights the challenges of testing the toxic effects on endangered species, particularly large animals where ethics of testing the lethal concentration of a compound on an endangered species is an obvious issue. Many of the available data on potential pesticide impacts on whales, pinnipeds, and marine turtles come from tissue samples (Andreani, Santoro, Cottignoli, Fabbri, Carpene & Isani, 2008; Sydeman & Jarman, 1998; Tilbury, Adams, Krone, Meador, Early & Varanasi, 1999), but there was no overlap of the NOAA Trust Species and the 26 aquatic pesticides included in this database. Surrogates are commonly used to derive how sensitive an endangered species may be to a pesticide (Raimondo Vivian, Delos & Barron, 2008; Stephen, Mount, Hensen, Gentile, Chapman & Brungs, 2010). Branching out into using other mammals and reptiles as surrogates, or using similar chemicals or metabolites such as elemental copper with regards to the copper sulfate and copper chelate pesticides included within this database, may be a useful future update to the database. However, there are limitations to using surrogates (Dwyer et al., 2005), so understanding those limitations and applying BMPs to limit the exposure of pesticides to aquatic and marine endangered species will assist in dealing with the toxicity uncertainty emphasized by these data gaps. I would also recommend direct testing of these pesticides to the marine invertebrate and marine plant NOAA Trust species if feasible in order to understand any potential impacts.

There are also apparent gaps in the comprehensiveness of the data in listed anadromous fish for many of the pesticides, with acute studies being the most common and field studies the least common (Table 5). As mentioned in the results section, there may be several reasons why acute studies are the most common type, followed by sublethal, chronic, and then lastly field studies. A future recommendation is the analysis of the types of acute, sublethal, chronic, and field studies. A method for quantifying either the number and types of studies or number of types of data values for each category could be developed and used to determine if, for example, how consistent the types of sublethal studies are, or how many acute studies there are compared to chronic studies for each pesticide and each NOAA Trust Species. The current evaluation presented here only uses presence or absence of a study type groups with all listed fish plus rainbow trout. A more detailed, quantitative analysis of the data could yield an assessment of data quality for each pesticide and species. Also, further analysis could separate the active ingredient, field grade, formulation, metabolite, surfactant, and other adjuvant data that may be integrated under each pesticide. Pesticides with several formulations tested may have an increased likelihood of having a more comprehensive (data in more categories) than a pesticide with just the active ingredient tested. Analyzing the formulation, adjuvant, etc. data separately could yield informative results. Likewise, separating data by life stage could also yield study frequency trend differences among life stages within species or taxonomic groups and illuminate data gaps that may have been missed by combining all life stages together.

Acute toxicity values ranked based on Zucker (1985) allowed for the comparison of the toxicity and the ranges in toxicity of most of the 26 pesticides to NOAA Trust anadromous fish species, plus rainbow trout. Results varied, from the consistent highly to very highly toxic adulticides to the wide ranges of toxicity within the aquatic herbicides/algaecides (Table 1). The ranges in toxicity, particularly within the same pesticide, may be due to differences between species, differences in life stage of the species tested, or due to toxicity differences between formulations, metabolites, or other forms of the pesticide. An example of differences in toxicity between active ingredient forms is the pesticide 2,4-D. 2,4-D acid and 2,4-D dimethylamine salt (DMA) are practically non-toxic to juvenile rainbow trout (2011a), but 2,4-D butoxyethyl ester (BEE) is highly toxic to juvenile rainbow trout (Wan, Watts, & Moul, 1990), all of which were included under 2,4-D within the database. A future recommended analysis in order to determine the cause of ranges within and between pesticides is to analyze acute toxicity data with distinctions between formulations and other forms that may be integrated within each pesticide. An analysis between the life stages of each species tested could determine if the observed ranges in toxicity are due to differences in life stage sensitivity. In addition, separating generally by species may illuminate which species may be most sensitive to which pesticides, and if there is a general consistency between the listed fish species. Understanding the ranges of toxicity within each pesticide will lead to more certainty of the toxicity differences between pesticides which will make for more informed choices of which pesticide to use in the field where endangered anadromous fish are present. It also has implications for which products, formulations, or isomers should be used.

One important aspect addressing potential pesticide toxicity to NOAA Trust Species is the potential synergistic effects of pesticides. Multiple pesticides are present in our nation's waters and these chemicals may have synergistic effects on endangered species (Laetz, Baldwin, Collier, Hebert, Stark & Scholz, 2009). This database does not include any data on synergistic effects. Incorporating synergistic effects into a toxicity database remains a challenge, but it is very important when considering the real world impacts that the suite of pesticides in the environment may have on NOAA Trust Species. A future direction of the database could be an attempt to include and effectively present synergistic data.

Another future recommendation for the use of this database is to adapt the included pesticide BMP framework and use it as a catalog and evaluation tool for pesticide BMPs. BMPs can take many forms under many categories and may not even be labeled as BMPs, making them not easily found or recognized. If pesticide BMPs were written and organized using a common framework, the BMPs may have increased recognition and it would be easier to share, compare, and evaluate these practices between pest control programs. A catalog of pesticide BMPs, specifically pertaining to aquatic pesticide use, would be very useful for aquatic pest managers looking for ideas on how to approach the problem of environmentally safe pesticide use within aquatic systems. Sharing and evaluating aquatic pesticide BMPs may also encourage discussion and improvements of pesticide use practices among pest control programs and other stakeholders. The development of this database into a smartphone application will hopefully encourage use throughout many stakeholder groups and may help achieve increased communication between stakeholders. The smartphone application could potentially be used as a catalog tool for managers to upload their pesticide BMPs into the framework within the database.

As one final note, it is important to recognize that this database is mostly pesticide centric and assumes that resource managers in charge of aquatic pest control have sufficiently researched alternative pest control actions, including the possibility of no action. Pesticides may not always be the best solution. In some cases, pest control actions may pose more of a risk to the environment and ecosystem services than no pest control. Alternative, non-chemical methods such as physical, cultural, or biological control methods may pose less risk to humans, endangered species, and the environment. This should be considered before and during the development of any pest control plan.

G. Literature Cited

Andreani, F., Santoro, M., Cottignoli, S., Fabbri, M., Carpene, E., & Isani, G. (2008). Metal distribution and metallothionein in loggerhead (*Caretta caretta*) and green (*Chelonia mydas*) sea turtles. *Science of the Total Environment*, *390*, 287-294.

Clouston, D. (2010, January 10). App economy has smartphones growing in popularity. *The Salina Journal (Kansas).*

Dwyer, F.J., et al. (2005). Assessing contaminant sensitivity of endangered and threatened aquatic species: Part I. acute toxicity of five chemicals. *Archives of Environmental Contamination and Toxicology, 48*, 143-154.

Extension Toxicology Network. (1989, January). *Ecotox net: Toxicology information briefs, standards*. Retrieved from http://extoxnet.orst.edu/tibs/standard.htm

Good, T. P., Waples, R. S., & Adams, P. (editors) U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. (2005). *Updated status of federally listed ESUs of West Coast salmon and steelhead.* (NMFS-NWFSC-66) U.S. Department of Commerce.

Grube, A., Donaldson, D., Kiely, T., & Wu, L. U.S. Environmental Protection Agency, Biological and Economic Analysis Division, Office of Pesticide Programs. (2011). *Pesticides industry sales and usage: 2006 and 2007 market estimates*. Retrieved from U.S. Environmental Protection Agency website: http://www.epa.gov/opp00001/pestsales/07pestsales/market_estimates2007.pdf

Kerr, D. San Francisco Estuary Invasive *Spartina* Project (2010). *Aquatic Pesticide Application Plan for the San Francisco Estuary Invasive Spartina Project*. California State Coastal Commission, Berkeley, CA. Retrieved from http://www.spartina.org/project_documents/2010_APAP_FINAL_ALL.pdf.

Kogan, M. (1998). Integrated pest management: Historical perspectives and contemporary developments. *Annual Review of Entomology 43*, 243-270.

Laetz, C., Baldwin, D., Collier, T., Hebert, V., Stark, J. & Scholz, N. (2009). The synergistic toxicity of pesticide mixtures: Implications for risk assessment and the conservation of endangered Pacific salmon. *Environmental Health Perspectives*. 117(3), 348-353.

Lintermans, M. (2000). Recolonization by the mountain galaxias (*Galaxias olidus*) of a montane stream after the eradication of rainbow trout (*Oncorhynchus mykiss*). *Marine & Freshwater Research* 51(8), 799-804.

Newman, M. (2010). *Fundamentals of ecotoxicology*. (3rd ed., pp. 135-367). Boca Raton, FL: Taylor and Francis Group.

Patten, K. (2002). Smooth cordgrass (*Spartina alterniflora*) control with imazapyr. *Weed Technology*, *16*, 826-832.

Protection of Environment, 40 C.F.R. pt. 122.2 (2007).

Raimondo, S., Vivian, D.N., Delos, C. & Barron, M.G. (2008). Protectiveness of species sensitivity distribution hazard concentrations for acute toxicity used in endangered species risk assessment. *Environmental Toxicology and Chemistry*, *27*(12), 2599-2607.

Silver, J., and Hutten, M. (2004). *Knotweed control on the Hoh River: Summary report-2002 to 2004.* 10,000 Years Institute, Port Townsend, WA. Retrieved from website: http://www.10000yearsinstitute.org/10k_asp/knotweed.asp.

Stephen, C. E., Mount, D. I., Hensen, D. J., Gentile, J. R., Chapman, G. A., & Brungs, W. A. United States Environmental Protection Agency, Office of Research and Development. (2010). *Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses* (PB85-227049). Retrieved from United States Environmental Protection Agency website: http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/upload/85guidelines.pdf

Sydeman, W., & Jarman, W. (1998). Trace metals in seabirds, Stellar Sea lion, and forage fish and zooplankton from central California. *Marine Pollution Bulletin*, *36*(10), 828-832.

Tilbury, K. L., Adams, N., Krone, C., Meador, J., Early, G., & Varanasi, U. (1999). Organochlorines in stranded pilot whales (*Globicephala melaena*) from the coast of Massachusetts. *Archives of Environmental Contamination and Toxicology*, *37*, 125-134.

U.S. Environmental Protection Agency, Office of Research and Development. (2011a). *ECOTOXicology database system. Version 4.0.* Retrieved from website: http:/www.epa.gov/ecotox/

U.S. Environmental Protection Agency, Office of Wastewater Management. (2011b). *Pesticide general permit (PGP) for discharges from the application of pesticides: Authorization to discharge under the National Pollutant Discharge Elimination System*. Retrieved from: http://www.epa.gov/npdes/pubs/final_pgp.pdf

Wan, M. T., Watts, R. G., & Moul, D. J. (1989). Effects of different dilution water types on the acute toxicity to juvenile pacific salmonids and rainbow trout of glyphosate and its formulated products. *Bulletin of Environmental Contamination and Toxicology*, *43*, 378-385.

Wan, M. T., Watts, R. G., & Moul, D. J. (1990). Acute toxicity to juvenile pacific salmonids and rainbow trout of butoxyethyl esters of 2,4-D, 2,4-Dp and their formulated product: Weedone Cb and its carrier. *Bulletin of Environmental Contamination and Toxicology* *45*, 604-11.

Wipfli, M. S., R. W. Merritt, and W. W. Taylor. (1994). Low toxicity of the black fly larvicide Bacillus thuringiensis var. israelensis to early stages of brook trout (*Salvelinus fontinalis*), brown trout (*Salmo trutta*), and steelhead trout (*Oncorhynchus mykiss*) following direct and indirect exposure. *Canadian Journal of Fisheries and Aquatic Sciences.* 51.6, 1451-58.

Zucker, E. U.S. Environmental Protection Agency, Office of Pesticide Programs. (1985). *Hazard evaluation division, standard evaluation procedure: Acute toxicity test for freshwater fish* (Report No. 540/9-85-006). Washington, DC: US Environmental Protection Agency.

Part III:

A Selected Synthesis of Literature and Case Studies on Best Management Practices for Reducing the Impacts of Pesticides in Aquatic Environments and Protecting NOAA Trust Species

Principal Investigators:
Dr. Robert Emanuel
Dr. Samuel Chan

Co-Authors:
Kelsey Gianou
Jennifer Lam
Dr. Paul Jepson

September 2011
Updated October 2011

This document was produced by **Oregon State University and Oregon Sea Grant** with funding from the National Oceanic and Atmospheric Administration. **Reference No. NFFKPR00-11-05375**

Abbreviations and Terms

LC_{50}	This value is the concentration at which 50% of the test organisms have died (lethal concentration) after a specified period of time such as 96 hours.
Acute toxicity	Adverse effects that result from a single dose or single exposure of a chemical; any poisonous effect produced within a short period of time, usually 96 hours or less.
A.I.	The active ingredient of a pesticide formulation.
A.E.	Acid equivalent. This term in used to normalize the differences in forms such as salts, amine or esters to the acid form of the compound. Often toxicity or application rates are expressed as acid equivalents when the pesticide comes in several different formulations.
LOEC	Lowest Observed Effect Concentration. This is the lowest concentration tested that resulted in an observable effect.
NOEL	No Observed Effect Level. This is the highest concentration tested that did not produce an observable effect.
ppm	Parts per million (mg/L or mg/kg)
ppb	Parts per billion (µg/L or µg/kg)
lbs ai/A	Pounds of active ingredient per acre

I. Introduction

1. Project Background

Pesticides are an important tool for the management of a variety of organisms that affect ecosystems, businesses, land management activities, and human health. As such, they may be used in situations where trade-offs between effective control of a pest organism is in conflict with environmental concerns—such as damage to native endangered or threatened organisms or their habitat. This document is designed to highlight situations where these chemical controls are applied in aquatic or riparian environments and harm to a non-target species is possible. In so doing, these cases highlight the complex inter-relationships between applications of pesticides, decision points for use, and best management practices that are designed to minimize harm to non-target species while remaining effective for pest control.

This document was written by researchers at Oregon State University, under contract with the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS). The goal of the document is to highlight cases of best management practices for pesticide use in aquatic or riparian environments. It draws on examples of several types of uses of aquatic registered pesticides and associated application types. It is meant to accompany a database produced on the same contract for NMFS. That database, entitled Aquatic Pesticide, NOAA Trust Species and General BMP/IPM Strategies Database, compiled information on chemistry, toxicology, uses and integrated pest management practices of 26 aquatic registered pesticides and their application types as applied to waters of the U.S. where NOAA Trust species may be present.

This project directly addresses two NOAA program priorities:

1. Protect, restore, and manage the use of coastal and ocean resources through an ecosystem approach to management and;
2. Provide critical support for NOAA's Mission. Serve society's needs for water information and more specifically, serve NMFS stakeholders.

This BMP Project aids NOAA in both of these goals by providing the Office of Protected Resources as well as other related programs within NOAA a tool for informing public or private managers about the proper use of pesticides in aquatic ecosystems with consideration of Endangered Species Act-listed species. In so doing, it aids the agency in providing valuable guidance based on an ecosystem approach to management (EAM) of aquatic resources within its jurisdiction. The most important feature of EAM is the role of humans in the maintenance of productive, resilient, and healthy marine resources while protecting the species and habitats within that ecosystem. A basic tenet of EAM is that conserving ecosystem functions and integrity will be, or should be, a fundamental vehicle for sustainable development (13). The simultaneous treatment of aquatic nuisance species (which include best management practices where pesticides are used) and the preservation of healthy populations of native organisms are two aspects of maintaining ecosystem functionality and integrity while addressing human uses. The products of this project provide NOAA Office of Protected Resources with tools that support the mission of NOAA to develop policies that protect ocean resources and assist other public agencies and the public itself with information about water and the protection of coastal resources.

The types of pesticides and associated application types include:

1. Mosquitoes and nuisance insects
2. Aquatic weeds and nuisance algae
3. Aquatic nuisance animals
4. Forest canopy applications (in riparian settings)

The database and synthesis document were requested to assist NOAA's NMFS in establishing a biological opinion for the Environmental Protection Agency's (EPA) proposed general permit that will cover the use of pesticides that will result in point-source discharges to waters of the U.S. under the National Pollution Discharge Elimination System (NPDES) of the Clean Water Act. The Federal Clean Water Act (CWA 1973) regulates discharges of pollutants--including pesticides --to waters of the United States from both point sources and nonpoint sources. The National Pollutant Discharge Elimination System permitting program was developed to control the discharge of point and certain nonpoint sources (e.g. pesticides and associated toxins either through direct application or runoff) of pollution to the nation's waters. CWA compliance standards for nonpoint source discharges are usually in the form of "best management practices" (BMPs) that are implemented to be effective to the "maximum extent practicable" (MEP). The biological opinion informs the EPA and other federal agencies consulted in the creation of the Pesticides General Permit (PGP) as to the potential for risk to threatened and endangered species protected by the Endangered Species Act and placed into trust status by statute. The creation of the PGP has motivated this research into best management practices (BMPs) that would lessen that potential for harm to aquatic organisms. The pesticides evaluated within this project are listed in Table 1.

Table 1: Pesticides to be evaluated by this project.

ADULTICIDES *Ranked*	**LARVICIDES**
Naled	*Bacillus thuringiensis israelensis*
Permethrin	Methoprene
Resmethrin	Temephos
Malathion	*Bacillus sphaericus*
Sumithrin	Monomolecular Film *(not ranked)*
Pyrethrin (*not ranked*)	
AQUATIC HERBICIDE/ALGICIDES	**AQUATIC NUISANCE**
Sodium carbonate peroxyhydrate	Rotenone (Fish)
Endothall	Antimycin A (Fish)
2,4-D	Sodium chlorate (Mollusk)
Copper sulfate	TFM (3-trifluoromethyl-4-nitrophenol) (Lamprey)
Copper chelate	Chlorine or Bromide (Mollusk)
Diquat	
Glyphosate	
Fluridone	
Triclopyr	
Imazapyr	

The Endangered Species Act (ESA 1973) requires federal agencies, in consultation with the U.S. Fish and Wildlife Service and/or the NOAA Fisheries Service, to ensure that actions they authorize, fund, or carry out are not likely to jeopardize the continued existence of any listed species or result in the destruction or adverse modification of designated critical habitat of such species. The law also prohibits any action that causes a "taking" of any listed species of endangered fish or wildlife. NOAA Trust Species protected under the ESA and considered in this project are listed in Table 2.

Table 2: Species Listed as Threatened and Endangered within the Action Area for EPA's Pesticide General Permit.

Common Name (Distinct Population Segment or Evolutionarily Significant Unit)	Scientific Name	Status
Cetaceans		
Beluga whale	*Delphinapterus leucas*	Endangered
Blue whale	*Balaenoptera musculus*	Endangered
Bowhead whale	*Balaena mysticetus*	Endangered
Fin whale	*Balaenoptera physalus*	Endangered
Humpback whale	*Megaptera novaeangliae*	Endangered
Killer Whale (Southern Resident)	*Orcinus orca*	Endangered
North Atlantic right whale	*Eubalaena glacialis*	Endangered
North Pacific right whale	*Eubalaena japonica*	Endangered
Sei whale	*Balaenoptera borealis*	Endangered
Sperm whale	*Physeter macrocephalus*	Endangered
Pinnipeds		
Hawaiian monk seal	*Monachus schauinslandi*	Endangered
Steller sea lion (Eastern)	*Eumetopias jubatus*	Threatened
Steller sea lion (Western)	"	Endangered
Marine Turtles		
Green sea turtle (Florida & Mexico's Pacific coast colonies)	*Chelonia mydas*	Endangered
Green sea turtle (All other areas)	"	Threatened
Hawksbill sea turtle	*Eretmochelys imbricate*	Endangered
Kemp's ridley sea turtle	*Lepidochelys kempii*	Endangered
Leatherback sea turtle	*Dermochelys coriacea*	Endangered
Loggerhead sea turtle	*Caretta caretta*	Threatened
Olive Ridley sea turtle (Mexico's Pacific coast breeding colonies)	*Lepidochelys olivacea*	Endangered
Olive Ridley sea turtle (All other areas)	"	Threatened

Anadromous Fish		
Chinook salmon (California coastal)	*Oncorhynchus tschawytscha*	Threatened
Chinook salmon (Central Valley spring-run)	"	Threatened
Chinook salmon (Lower Columbia River)	"	Threatened
Chinook salmon (Upper Columbia River spring-run)	"	Endangered
Chinook salmon (Puget Sound)	"	Threatened
Chinook salmon (Sacramento River winter-run)	"	Endangered
Chinook salmon (Snake River fall-run)	"	Threatened
Chinook salmon (Snake River spring/summer-run)	"	Threatened
Chinook salmon (Upper Willamette River)	"	Threatened
Chum salmon (Columbia River)	*Oncorhynchus keta*	Threatened
Chum salmon (Hood Canal summer-run)	"	Threatened
Coho salmon (Central California coast)	*Oncorhynchus kisutch*	Endangered
Coho salmon (Lower Columbia River)	"	Threatened
Coho salmon (Southern Oregon & Northern California coast)	"	Threatened
Coho salmon (Oregon coast)	"	Threatened
Green sturgeon (Southern)	*Acipenser medirostris*	Threatened
Shortnose sturgeon	*Acipenser brevirostrum*	Endangered
Pacific eulachon/smelt	*Thaleichthys pacificus*	Threatened
Sockeye salmon (Ozette Lake)	*Oncorhynchus nerka*	Threatened
Sockeye salmon (Snake River)	"	Endangered
Steelhead (Central California coast)	*Oncorhynchus mykiss*	Threatened
Steelhead (California Central Valley)	"	Threatened
Steelhead (Lower Columbia River)	"	Threatened
Steelhead (Middle Columbia River)	"	Threatened
Steelhead (Northern California)	"	Threatened
Steelhead (Puget Sound)	"	Threatened

Steelhead (Snake River)	"	Threatened
Steelhead (South-Central California Coast)	"	Threatened
Steelhead (Southern California)	"	Endangered
Steelhead (Upper Columbia River)	"	Threatened
Steelhead (Upper Willamette River)	"	Threatened
Marine Fish		
Bocaccio	*Sebastes paucispinis*	Endangered
Canary rockfish	*Sebastes pinniger*	Threatened
Smalltooth sawfish	*Pristis pectinata*	Endangered
Yelloweye rockfish	*Sebastes ruberrimus*	Threatened
Marine Invertebrates		
Black abalone	*Haliotis cracherodii*	Endangered
Elkhorn coral	*Acropora palmata*	Threatened
Staghorn coral	*Acropora cervicornis*	Threatened
White abalone	*Haliotis sorenseni*	Endangered
Marine Plants		
Johnson's seagrass	*Halophilia johnsonii*	Threatened

2. Likelihood of NOAA Trust Species Exposure

Of the organisms listed in Table 2, the research team estimated that nearly all of the pesticides and application types posed the greatest direct risk to anadromous and in some cases, estuarine fish. Therefore, the study focused on practices that posed greatest jeopardy to salmonids and sturgeon.

The likelihood of exposure of any organism to pesticides is dependent on the biogeography and habitat of the organism, the pesticide application, the persistence of the pesticide in the environment, the bioavailability of the pesticide, and route of exposure (dermal, inhalation, or oral) (89). The organisms with the greatest risk of direct exposure for any application of aquatic pesticides for mosquito control, aquatic nuisance plants and aquatic nuisance animals are those that spend at least some part of their life cycle in freshwater, estuaries and nearshore habitats or prey upon organisms that have pesticides in their tissues. Of the NOAA Trust species, anadromous fish are of greatest concern for exposure.

Table 3 presents the NOAA Trust species that are most likely to be at greatest risk of exposure to aquatically approved pesticides. Anadromous fish are considered to have a higher risk of pesticide exposure compared to other NOAA trust species such as whales and turtles because anadromous fish reside in habitats that may receive pesticide applications or are downstream of pesticide applications in a watershed. In addition, anadromous fish life stages that occur in freshwater (eggs, larvae, juveniles, smolts and spawners) are presumably the most sensitive to lethal and sublethal effects from chemical exposures (89). In addition, NOAA Trust species that prey upon anadromous fish may be exposed through habitat (foraging in nearshore and estuarine habitats) and diet. However, dermal exposure of marine mammals is likely not a significant pathway. Exposure through diet is mainly a concern when the pesticide is lipid soluble (low water solubility) and persists in animal or plant tissues (89). The toxicity sections of this report focus on the toxicity of selected aquatic pesticides to anadromous fish because there was no toxicity studies found for NOAA Trust cetaceans, pinnipeds, sea turtles, marine invertebrates or marine plants listed in Table 2. When available, toxicity levels of pesticides to anadromous fish will be compared with the application rates recommended on the pesticide label for comparison.

Table 3: NOAA trust species considered to be at greatest risk for aquatic pesticide use exposures.

NOAA Trust Species	Reason for Potential Exposure
Highest Exposure Risk	
Chinook salmon *(Oncorhynchus tschawytscha)*	Anadromous
Coho salmon *(Oncorhynchus kisutch)*	Anadromous
Chum salmon *(Oncorhynchus keta)*	Anadromous
Sockeye salmon (*Oncorhynchus nerka)*	Anadromous
Steelhead trout (*Oncorhynchus mykiss)*	Anadromous
Green Sturgeon *(Acipenser medirostris)*	Anadromous
Shortnose Sturgeon *(Acipenser brevirostrum)*	Anadromous
Pacific eulachon/smelt *(Thaleichthys pacificus)*	Anadromous
Limited Exposure Risk	
Smalltooth Sawfish (*Thaleichthys pacificus)*	Nearshore, mangrove and everglades habitat
Steller Sea Lions *(Eumetopias jubatus)*	Diet
Killer Whale *(Orcinus orca)*	Diet
Beluga Whale *(Delphinapterus leucas)*	Diet
Johnson's Seagrass (*Halophilia johnsonii)*	Intertidal zone and bay habitat
Black Abalone *(Haliotis cracherodii)*	Intertidal zone habitat

3. Introduction to Pesticide and BMP Database

The Aquatic Pesticide, NOAA Trust Species and General BMP/IPM Strategies database that accompanies this BMP case study synthesis includes chemical information on each of the 26 listed pesticides in Table 1, as well as available toxicity data to NOAA Trust Species, NOAA

Trust Species life histories and biogeography, and general IPM strategies based on pest category. The following is a summary on how the authors suggest that the database could be used by managers and how information for each part of the database was compiled.

3a How to use the Aquatic Pesticide, NOAA Trust Species and General BMP/IPM Strategies database

This database is meant to be used as a tool for managers who are deciding to use pesticides for effective pest control purposes with the goal of reducing exposure or impact to NOAA Trust Species. The general pesticide information provides managers with information about the pesticides' modes of action, chemical class, application rates, general toxicity to humans and other organisms, bioaccumulation potential and environmental fate. The NOAA Trust Species life history information should be used to determine if the trust species are present in an area of application for some or all stages of their development and what times of the year they are present. Life history also gives information on life cycle and breeding habits. The NOAA Trust species toxicity data gives what is known about effects of each pesticide on particular life stages of each organism. Managers can use this information to determine which pesticide is least toxic to the organism of concern and at what concentrations. Information may also be given for different pesticide formulations which may have different toxicities to the organisms. Managers can then compare the most sensitive life stages of the organisms of concern to the proposed pesticide (toxicity data) and compare it with the timing of those life stages and the proposed timing of application (life history: seasonal pattern). Users can then look at general IPM strategies for guidelines on how to control pests by using source remediation and biological control before applying pesticides. The best management practice case studies that are provided in this report can then be used for more specific examples for how to control the pest in an effective and environmentally protective way.

3b Chemical Information

General Pesticide information was collected by searching the National Pesticide Information Center (NIPC), the US Environmental Protection Agency publications, and other published literature. Information was organized into the following categories for each pesticide: General Pesticide Information, Acute and Chronic Toxicity, Environmental Fate, Ecotoxicity Studies, Regulatory Guidelines, and Bioaccumulation. Cells are denoted with "n/f" if no information could be found.

3c Organism Life History

The life cycle, biogeography, and seasonal pattern for each NOAA Trust Species were collected by searching the Office of Protected Resources Website (http://www.nmfs.noaa.gov/pr/), federally listed organism status updates, and the published literature. NOAA Trust Species life histories were separated by species and ESU (evolutionarily significant units) when available. General life histories are also given for each species with several ESUs and “see general” is given in cells where specific ESU information could not be found. Cells are denoted with “n/f” if no information could be found.

3d Toxicity Data

Published literature for toxicity data was searched by pesticide name along with common and scientific names of organisms through the OSU library database, and by pesticide name and formulation in the IPM center toxicity database and the ECOTOX database. Toxicity data was organized by formulation of pesticide, in some cases including surfactant data when available, and also by organism life stage. When no information was found on an organism for a pesticide, cells are denoted with an “n/f”. A list under the tab of ‘key’ lists definitions for categories, symbols and abbreviations used in the toxicity data cells.

3e Integrated Pest Management/Best Management Practices

Information for integrated pest management/best management practices strategies was collected by searching all extension service publications (peer-reviewed) given through the following website: http://www.extension.org/search. Other searches included using the American Mosquito Control Association website (http://www.amca.memberclicks.net), and resources provided by the Integrated Plant Protection Center at Oregon State University. In the BMP tab, general IPM strategies are presented for each group of pesticide, intended to be used as a first step in pest management before application of pesticide is needed.

4. Pesticide Use Background

Chemical control of undesirable pests is widely used by rural and urban land and water managers throughout the United States. Chemical controls are applied to water or lands directly adjacent to water in agriculture, forestry, landscaping, urban or other land management contexts. In many cases, pesticides (including within that term insecticides, herbicides, algaecides, piscicides, rodenticides, and fungicides) may be used to control undesirable pests in areas that overlap with protected species. The U.S. Environmental Protection Agency (EPA) recently estimated that more than 1.2 billion pounds of pesticides are applied to crops, forests, residential areas, public lands, and aquatic areas in the United States each year (67). While pesticides have many beneficial uses, their use can often have unintended effects on native biota including protected species.

In recent decades, pesticide users and manufacturers have stepped up efforts to reduce impacts on non-target, protected or beneficial organisms, and apply the chemicals in a more efficient, less costly, and environmentally sensitive way. These efforts have been concentrated in the Integrated Pest Management approach. The scientific basis of “Integrated Pest Control” evolved during the 1950s and 1960s, mainly among researchers at the University of California, Berkeley and Riverside campuses (68). A variety of Integrated Pest Management (IPM) practices have as their goal, the effective use of pesticides to control the undesirable pests while minimizing damage to non-target species. As part of an IPM strategy, resource managers closely examine the pest population, the resource being managed and the most effective time and type of treatment (including cultural, mechanical, biological and chemical) that would effectively control the pest problems while minimizing pesticide use and impacts to non-target species.

Where managers choose chemical control of the pest, the proper and effective use of the pesticides is dependent on the sound judgment of land/water managers and the pesticide applicators. Although pesticides must be registered and labeled according to appropriate uses pursuant to the Federal Insecticide, Fungicide, and Rodenticide Act (1972), compliance with the pesticides label and its careful use is determined by the applicator. As mandated by the Act, all states test licensed commercial applicators for their ability to effectively follow the restrictions and specific use elements of pesticide registrations supplied with each chemical formulation. Pesticide application licenses and certifications allow for pesticide application tracking, evaluation, and enforcement of disciplinary actions. Each state requirement is different, but most require some type of training course and examination. This ensures that applicators are knowledgeable of pesticide application methods and will reduce human error. Many states required category and subcategory examinations and certifications including aquatic-use pesticide categories. In some cases, however, applicators are left to their professional judgment as to proper methods of treatment in unevaluated situations. In these circumstances, best management practices (BMPs) are utilized by applicators and other users.

Knowledge gaps exist on the fate and transport of pesticides in both terrestrial and aquatic environments. For example, questions have arisen with regard to potentially synergistic effects of chemicals (otherwise referred to as chemical “cocktails”) in aquatic wildlife including Pacific Northwest salmonids (69). A similar set of questions arises from bioaccumulation of legacy pollutants such as pesticides in marine predators such as Southern resident killer whales (24) or other cetaceans (2). The development of new BMPs for application of pesticides to aquatic ecosystems should take into account these and other recent research findings.

Agriculture (including aquaculture) is the predominant user of pesticides throughout the nation, and much research has been directed at controlling pests in agriculture through chemical and other means, and minimizing the drift or dispersal of agricultural pesticides into aquatic environments. However, pesticides are also used in many direct water application situations such as: controlling mosquitoes that can pose a threat to public health or the control of other aquatic nuisance insects (e.g. black flies); the control and management of aquatic weeds and algae in waterways, including uses for invasive plant control and the use of algaecides in ponds and aquaculture facilities; and in the control of invasive or other aquatic nuisance species in water (e.g., fish, lamprey, and mollusks). Whether on land or in water, prevention is the single best management option in most cases, but where the control of aquatic invasive and nuisance plants and animals is necessary, chemical control methods may be the most effective response in controlling the pest problem. The direct application of pesticide products in water poses a unique problem for controlling the exposure of non-target aquatic organisms as compared to the control of pesticide exposure in terrestrial environments to aquatic non-target organisms. In aquatic systems, pesticide dispersal is often diffuse and much more difficult to contain, yet protective measures of varying degrees are employed by state, federal, local and private applicators. In some cases, certain protective actions or best management practices are a requirement of state and local permitting authorities.

5. Defining of Best Management Practice (BMP)

The term Best Management Practice (BMP) is of long standing in the USA in the field of water pollution control and originally referred to the practices and training required of personnel who maintained engineered water pollution control systems. BMP's were however referred to in the broader context of water pollution management practices within the Clean Water Act in 1977. Under its authority to implement this act, EPA defined BMP's within the language that set's up the National Pollutant Discharge Elimination System (21). Under 40 CFR 122.2, the EPA defines BMP's as

"….means, schedules of activities, prohibitions of practices, maintenance procedures, and other management practices to prevent or reduce the pollution of "waters of the United States." BMPs also include treatment requirements, operating procedures, and practices to control plant site runoff, spillage or leaks, sludge or waste disposal, or drainage from raw material storage.' [40 CFR 122.2, as amended March, 2007] (21).

BMP's with respect to water quality in agriculture were first developed as a requirement of the Clean Water Act in 1977 (104). They include suites of soil conservation practices that limited nutrient and soil transport, monitoring practices, such as soil testing, and management practices that adjust targeting and timing of nutrients and pesticides analogous to integrated pest management (IPM).

The USDA Natural Resources Conservation Service (NRCS) defines BMP's as "*Methods that have been determined to be the most effective, practical means of preventing or reducing pollution from non-point sources*" (90).

Pesticide BMPs are found in a variety of nodes, including selection, testing, and regulation of the pesticides themselves by the federal government and states. BMPs also include the proper selection of the most appropriate chemical or pest management practice, which depends upon proper identification of the pest organism to be controlled. The application rate and method of application are also vitally important and can be appropriately controlled by licensure requirements and training programs that are generally regulated, funded and delivered at the state level. In some cases, applicators have their own associations where BMPs may be developed, tested and transferred. Experience, training materials and professional associations and organizations provide applicators broad and specific best management practices (BMPs) for pest control. Professional associations such as vector control associations, state non-crop vegetation associations and aquatic nuisance associations provide managers and applicators with information and collaboration opportunities to share, evaluate and update BMPs.

Arriving at a decision to apply chemical pesticides is one that should be weighed carefully and strategically. This decision process is known as Integrated Pest Management and has been defined as:

…the practice of preventing or suppressing damaging populations of pests by application of the comprehensive and coordinated integration of multiple control tactics. Tactics are the various control methodologies, e.g., chemical, biological, cultural. Strategies are the planned manipulations undertaken to optimize the dynamic integration of control methodologies in the context of their economic, environmental and social consequences. The philosophy is holistic, but deeply rooted in applied ecology (103).

Under IPM practice, the process of escalation of management practices begins with careful avoidance of pests through cultural practices, prevention, early detection, then evaluation of pests before a chemical option is selected. Pesticide BMPs are a set of complex decision points, practices and situations, making it difficult to categorize or present in a database format. Within the context of this report, there is no practical way to present all of the arrays of BMPs for pesticides or particular applications or pest species. The authors of the database and this report therefore intend to present a more complete set of case study examples for how BMPs might be applied in specific application types, pest species and under specific situations.

Although prevention, through non-chemical means, is typically the most widely effective first step in managing invasive and nuisance plants and animals, this project focuses exclusively on those instances where a manager has chosen to use pesticides to control undesirable aquatic species. These pesticides were selected based on their frequency of use in aquatic ecosystems and their inclusion in the soon-to-be-issued EPA General Permit. End-users will want to apply the pesticides that are most effective in controlling the pests in question. If they do, the goal of this document is to highlight those management practices that will yield the best results for control and least amount of risk to NOAA Trust Species. However, this document does not assess risk to individual species resulting from applications. It suggests those BMPs that take steps to minimize environmental impacts while allowing the end-user to reach their pest management goals.

6. Case Study Selection

To compile the case studies, we first selected a representative cross-section of application types and pest organisms, including the following:

1. Application of fluridone and endothall to a freshwater, lentic environment, for control of *Hydrilla verticillata* in Florida.
2. Applications of glyphosate to riparian infestations of woody knotweeds (*Polygonum* spp.) along the Hoh River in Washington State.
3. Application of imazapyr to an estuarine environment in San Francisco Bay for the control of *Spartina alterniflora*.
4. Application of rotenone for control of northern pike (*Esox lucius*) in a freshwater lake of Alaska.
5. Application of adulticides and larvicides to fresh and brackish water environments for the control of West Nile-carrying mosquitoes in New York City.

These case studies were synthesized through review of treatment reports, gray literature, and scholarly articles. We also interviewed the principals in each case, discussing the decision points, processes of monitoring, evaluation and application methods. Where possible, we included sufficient detail to explore the trade-offs presented by the presence of the pest organisms and the potential harm from pesticide exposure to non-target species. We have presented each BMP case study as a series of decision steps, from the consideration of non-chemical methods, to pesticide products, methods, rates, mitigation and monitoring. The decisions for each BMP step are tailored to each pest management program and site. These case studies attempt to highlight the decision making processes involved when developing an environmentally conscious BMP. The goal is to provide examples for the type of framework that is needed when developing and utilizing BMPs, particularly when endangered or threatened species are present.

7. Summary of BMPs Components: Rationale for the Case Study Approach

The goal of the case study approach is to provide a framework for best management practices and examples of how decisions and practices inform each step of the process. BMPs are used to develop comprehensive pest management plans. These plans link decisions about pest control methods (non-chemical versus chemical options), pesticide choice, treatment methods, application rates, mitigation measures, monitoring of efficacy, safe chemical storage and disposal and other components that are part of pesticide BMPs. As managers develop these comprehensive plans, they consider how each practice maximizes the efficacy of pest management while reducing the risk of exposure to non-target organisms. The mandate of NOAA is for its trust resources, and while it is important to consider direct effects a practice may have on NOAA Trust Species, BMPs that reduce exposure to any desirable organism may lead to protection of habitat, diet and the NOAA Trust populations. Maximizing efficacy of pest management directly affects the impacts to non-target species because inefficient applications of pesticides will lead to unnecessary pesticide exposure to the environment as well as likely lead to more pesticide use in the future. Each step of our case studies on BMPs is interpreted with the following screening criteria:

1. How does this decision maximize pest management benefits and reduce risk to non-target species and habitats?
2. Hazards, either general or specific to the particular case study, that managers should be aware of when using the pest control methods are included when appropriate.

While developing this BMP framework and synthesizing the case studies, it became clear that many program- or site-specific practices are not always available in the literature, such as published literature, action plans, or treatment reports. Writing reports that include detailed information of every aspect of decisions and practices can be limited by time, cost and man power and are often not able to be produced every season. Many adaptive management BMPs will evolve and change and therefore recent BMPs may not be currently available in reports. In order to address this issue, as a part of our case study approach, interviews were conducted either by phone or email contact with program directors or experts intimately involved with pesticide practices and decisions. These interviews supplemented our case studies with detailed information on current pesticide use practices and were an important part in contributing to the quality and completeness of these case studies. The case study approach with interviews provide for what we suggest as a suitable representation of how each of these programs consider, develop and use BMPs in their comprehensive management plans.

Below is a description of each component in our interpretation of a BMP framework and how each is important with regard to putting together BMPs. In addition, tables are provided under each component description that briefly summarize the related BMPs identified in each case study in order to provide some details and context to the component descriptions. The detailed descriptions of the BMPs presented in the tables can be found in the case studies. This framework should be used or adapted as a tool for individual pest management programs, depending on goals and environmental risks. While it is presented as a list, the decisions may not always proceed in the presented order. It is critical that each step is addressed and the end result will be overall best management practices. There may be trade-offs associated between the components of the BMPs in regards to pesticide efficacy and environmental exposure risks, and several components will influence the decisions made in other components. Thus, justifying the need for comprehensive pest management plans. Some programs may need to expand this framework further to include subcategories, but we present what we think is representative of components for any best management practice that uses pesticides.

7a Alternative Non-chemical Methods

The first, and arguably the most important step in any best management practice is the consideration of alternative non-chemical methods for pest control or eradication (Table 4a). Cultural, physical, mechanical and biological control methods fall under this category. Any practice that uses pesticides before the proper consideration of non-chemical methods may result in unneeded pesticide use. Many pest species can be prevented or controlled by non-chemical means. That being said, many non-chemical methods may not be effective at desired pest control and are often used in concert with pesticides. Some control projects use non-chemical methods as the primary management tool, and use pesticides if non-chemical means are ineffective, while other projects use pesticides almost exclusively due to cost and practicality. A general precaution for the consideration of non-chemical methods is that each method carries its own risk and must be properly evaluated. Types of physical, manual and chemical control, particularly for invasive plant species, can actually increase the pest problem, and improper use of biological control agents may have unintended consequences including a new pest problem.

Table 4a: Alternative Non-Chemical Methods Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Public Outreach - Mechanical Harvesting - Grass Carp - Biological Control Research	- Public Outreach - Non-chemical methods ineffective	- Public Outreach - Manual methods - Mechanical Methods	- Public Outreach - Gillnetting	- Public Outreach - Source reduction - Biological Control

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7b Pesticide(s) and Product(s) Choice

Once non-chemical methods have been considered or used and the decision to use pesticides has been made in order to achieve pest control, the choice of which pesticide and formulation of that pesticide will be used is crucial (Table 4b). First, one must choose which of the registered products will be effective against the pest. Second, as for the emphasis of this report, it must be approved for aquatic use as well as the use on the site for which it is intended. Third, the formulations chosen should have been considered for their potential impacts to aquatic organisms, most notably fish, aquatic invertebrates and their predators. Choosing between pesticide active ingredients and formulations is important, especially since different formulations of pesticides may have different toxicities to non-target organisms. There may be a tradeoff between effectiveness of the pesticide and the toxicity to non-target organisms. The manager must consider the possibility of using a highly toxic compound which may result in fast, complete control with limited future need of application, or a less toxic alternative which may need several years to decades of repeated chemical applications in order to achieve desired outcomes. All of the other steps in this framework will influence the decision of which pesticide and formulation to choose.

Table 4b: Pesticide(s) and Product(s) Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Aquathol®K (endothall) - Other systemic herbicides in combination	- Aquamaster® or Aquaneat® (glyphosate) - Polaris® or Habitat® (imazapyr)	- Habitat® (imazapyr) - Aquamaster® (glyphosate)	- Legume CFT® (rotenone)	- VectoLex® (*B. sphaericus*) - VectoBac® (Bti) - VectoMax® (mixture)

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7c Adjuvant(s)

Adjuvants (Table 4c) often need to be added to pesticide mixtures and are intended to increase efficacy. Adjuvants include, but are not limited to: surfactants, dispersants, drift reduction and marker dyes. Adjuvants, although often not required to undergo the same testing and registration as pesticide active ingredients, may increase the toxicity of the pesticide mixture and therefore must have equal consideration to their use with a pesticide. The possibility of a required adjuvant use may result in a different pesticide active ingredient or formulation choice, depending on the adjuvant or pesticide/adjuvant mixture toxicity.

Table 4c: Adjuvant(s) Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- No adjuvants are used	- Competitor® surfactant - BlazonBlue® marker dye	- Competitor® surfactant - Liberate® surfactant and drift retardant - LI-34® as pH balance in glyphosate formulations - Blazon® marker dye	- No adjuvants were needed	- No adjuvants are added - Piperonyl butoxide synergist is already a part of the adulticide formulation

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7d Licensing and Certification of Applicators; Professional and Trade Associations

Licensing and/or certification (Table 4d) is almost always required for any non-household pesticide applications, especially for pesticides applied near or in aquatic habitats. Certifications and licenses allow States to permit and track pesticide activity. However, each

State has its own rules and regulations for who must be licensed/certified, for what application types and how they achieve certification. The certification/license programs often involve some sort of training requirement and examination. Re-certifications within prescribed timeframes are also common. Licensing and certification programs ensure that pesticides are applied by knowledgeable and capable applicators to reduce the likelihood of spills, misapplication and poor application judgment. It also allows for accountability and disciplinary action when needed.

Professional associations, such as state non-crop vegetation associations, vector control associations or aquatic nuisance associations facilitate professionals to obtain continuing education on latest developments and BMP's, collaborate, learn and discuss with experts and each other. Many associations provide courses and/or conferences where BMPs are discussed and evaluated. Applicators and managers that are affiliated with pest control professional associations are more likely to employ informed and effective BMPs.

Table 4d: Licensing and Certification of Applicators; Professional and Trade Associations Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- General state pesticide license requirement - Aquatic herbicide category specific certification and license - Affiliation with professional aquatic weed organizations	- Joint NPDES permitting - Commercial applicator state license - Aquatic pesticide endorsement - Member of county noxious weed board	- General state pesticide license requirement - Restricted use pesticide certification state requirement - Project and partners affiliated with professional associations	- State pesticide license requirement - USFW rotenone certification	- Permits issued by NYC DEC - Required state category specific certification of pesticide applicators and technicians - Supervisors and managers associated with the AMCA and the NMCA - Program conducts yearly courses for applicators and technicians

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7e Application Method

The method of how pesticides will be applied (Table 4e) can influence the extent and risk of non-target impact. The methods of how a pesticide may be applied will be dictated by product formulation and method feasibility. Some application methods will result in risk of pesticide drift, while others may have limited applicability and thus reduce effectiveness. Each method should be evaluated for feasibility, ease of access to apply to target pest (therefore influencing efficacy), direct impact to habitat and risk of chemical exposure to non-target desirable organisms.

Table 4e: Application Methods Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Ground applications by submerged direct applications or rarely by spray - Large scale aerial spray applications - Drip applications under evaluation	- Ground low volume spray - Cane injection	- Ground spray - Aerial spray	- Submerged pumps - Riparian spray	- Ground application of larvicides - Helicopter application of larvicides - Ground application of adulticides

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7f Equipment and Calibration

The equipment available for use may influence what methods are available and/or feasible for pesticide application (Table 4f). The use of proper equipment is important to ensure safe and effective distribution of pesticide. Malfunctioning/leaky equipment may cause undue environmental pesticide exposure. Furthermore, equipment that is physically destructive to the environment may cause unintended damage. Proper calibration of equipment is crucial to ensure correct pesticide application rates. Calibration can also influence drift of pesticide spray and droplet size (which may strongly influence efficacy). States require pesticide applicators to have appropriate licenses and/or certifications for pesticide applications, and therefore should have the knowledge of suitable equipment use and calibrations.

Table 4f: Equipment and Calibration Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Boats and airboats with trailing hoses for submersed applications - Volume of water body is used to calibrate application rates - Helicopter is used for aerial sprays	- Hand-held spray bottles for low volumes sprays - JK Injection Tool with a short needle for injections - Nozzles adjusted according to weather conditions - Backpack sprayer used for dense knotweed stands	- Amphibious tracked vehicles Argo, Hydrotraxx and MarshMog - Trucks are parked at levees and upland sites - Aerial applications use a boom sprayer or spray ball attached to a helicopter - Nozzles are calibrated for correct droplet size.	- Small motorboat with submerged venture pumps - Backpack sprayer - Pumps and backpacks calibrated to give desired application rates - Direct shot spray hose instead of mist used for backpack spray	- Larvicides applied by hand are measured by spoon or cup - Larvicides applied by backpack blowers - Helicopter is equipped with Isolair Dry Broadcast System - Adulticides sprayed from Grizzly ULV or Cougar Foggers from trucks - Droplets calibrated by Army Insecticide Measuring System - Larvicide and adulticides equipment calibrated at least twice a year

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7g Application Rates

Application rates (Table 4g) will ultimately affect how much pesticide and adjuvant are entering the environment. Pesticide labels will dictate the range of allowable amount of pesticide to be applied per area per single treatment and/or treatment season. Labels also may include the suggested rates for a particular pest. Managers, in addition to adhering to the label which is required by law, should consider recent research and experience as to what rate is most effective at pest control. This ensures that the pesticide being applied will be most effective. Application rates will also influence what pesticide products are to be used. If the application rate needed for desired pest control overlaps with the toxicity thresholds for a non-target species, especially a present protected species, then a different product may need to be considered. Cost may also be a limiting factor when considering how much pesticide needs to be applied for control.

Table 4g: Application Rates Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- 1 to 3 mg/L endothall	- 4% Aquaneat® - 1% Habitat® or Polaris™ AQ - 1.5% Competitor® - 1% BlazonBlue marker dye - 5 mL injections of Aquaneat® per cane	- 5% or 7.5% Habitat® (6 pints per acre) for aerial applications - 3% Habitat® low volume sprays - 2% Aquamaster® at selected sites	- 1 mg of CTF Legumine™ per liter of water (1 ppm)	- VectoLex® CG 5 to 20 lbs product/A VectoBac® CG 2.5 to 10 lbs product/A - VectoMax® CG 5 to 20 lbs product/A - Anvil® 10+10 ULV 0.21 to 0.62 fluid ounces/A,

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7h Application Timing

The timing of pesticide application (Table 4h) is very important, both for pest control efficacy and for minimizing non-target exposure. Timing of pesticide application will influence pesticide residence time, active ingredient pesticide contact time with target pest(s) and if and at what life and development stages non-target species are present. Improper timing of pesticide application can reduce efficacy as well as possibly increase non-target exposure. Unfortunately, the time when efficacy will be at its peak may overlap with the timing of a protected species. It is then up to the manager to make the decisions of which poses the greatest risk: reduced efficacy which may result in increased pest numbers and longevity of pest occupation, or increased risk to protected species for that season. The answer will be different for each pest program.

Table 4h: Application Timing Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Fall and Winter during cooler temperatures	- Late August through mid-October - Before leaf senescence	- Summer and early fall while plants are actively growing - Applied during a falling tide, to increase contact time with herbicide	- October	- Larviciding starts as early as April if larvae are present - Larvicides applied at least 3 times a season - Adulticides only applied when needed

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7i Application Conditions

Application conditions (Table 4i) will affect pest control efficacy and risk of non-target exposure. Weather conditions, such as precipitation, humidity, wind speed, and temperature all influence the contact time of the pesticide to the target environment, dispersal, persistence and risk of unintended pesticide exposure to non-target organisms. Conditions of organisms, such as health and growth stage, also influence pesticide efficacy. Conditions can influence which application methods can be used and can result in the postponement/halting of applications. Application of pesticides during unfavorable conditions will result in decreased control efficacy. In some cases, decisions may be needed to determine if pesticides should be applied during unfavorable conditions or not at all that year. Again, each program will likely come up with individualized answers.

Table 4i: Application Conditions Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Apply to waters with low BOD - Endothall can be applied to waters with relatively high flow as long as residence time is sufficient	- Apply to healthy plants - Avoid applications to damp leaves or within 6 hours of projected rainfall	- Postpone applications during rain. - Spray in wind less than 10 mph - Cease applications by 1pm to avoid afternoon breezes - Aerial applications avoided during temperature inversion or low humidity	- Cooler water, such as water with ice cover, increases pesticide residence time	- Larviciding when monitoring determines need. - Larvicides applied during low tide and during winds speeds of less than ten miles per hour - Larviciding of catch basins during no rain or when light drizzle is forecasted - Larviciding will cease in conditions of hard rain - Adulticide applications made when adult mosquitoes are most active and during permitting weather conditions

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7j Mitigation

Mitigation (Table 4j) is an important component of minimizing non-target exposure. Mitigation strategies can range from spill prevention and containment measures, to practices used throughout pesticide application. Mitigation can include preventative measures or corrective action measures. Mitigation strategies should be considered and used throughout each step but also should be made clear in a distinct section in order to clearly provide users with precautions and appropriate actions.

Table 4j: Mitigation Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Applicators and distributors follow label for spill mitigation	- The project has a spill mitigation plan	- Site-specific mitigation plans - Has a spill mitigation plan - Has an equipment fueling spill mitigation plan - Mitigation checklist	- Sentinel fish placed in connected stream - Plan to use rotenone neutralizing agent if detections of sentinel fish mortality - Air bladder to block flow into stream from treated lake	- Buffer zones of 300 to 400 feet for adulticides - Has spill mitigation plans - Pesticides transported in small quantities

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7k Monitoring

Monitoring the effectiveness of a pest control effort is vital to any program (Table 4k). Monitoring allows for adjustments of products, rates, methods and timing of applications to increase efficacy. As a part of adaptive management, which is an important aspect of BMPs, it serves as an evaluation and learning tool. Without the proper efficacy monitoring techniques, pesticide use and other control efforts will not be validated. In addition to efficacy monitoring, straightforward monitoring of the pest population also allows for informed control choices as methods, rates and timing may depend on the stage and extent of infestation/problem. This increases application efficacy.

Another type of effectiveness monitoring is from the environmental perspective. In other words, how protective of the environment is the pest control effort and does it have any impacts to non-target organisms? This monitoring can take several forms, from pesticide residue sampling to recording non-target organism kill events as a result of pesticide application (Table 4k). This too allows for adaptive management and learning for the adjustment of pesticides, rates, methods and timing of applications. A program that is able to incorporate this type of monitoring will be able to determine whether or not their practices are protective or harmful to non-target organisms.

Table 4k: Monitoring Summary BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Herbicide efficacy monitoring - Herbicide residue monitoring - Native plant impact monitoring - Water quality monitoring - Vegetation maps - Endothall tolerance monitoring	- Herbicide efficacy monitoring - Vegetation maps - New population monitoring - Native plant response observations	- Herbicide efficacy monitoring - Treatment method monitoring - Pre-treatment sampling - Spartina mapping - Genetic sampling - Herbicide residue monitoring - Water quality monitoring	- Pesticide efficacy monitoring - Macroinvertebrate monitoring - Pesticide residue monitoring	- Larvicide and adulticide efficacy monitoring - Source reduction monitoring - Pesticide resistance monitoring - Year round mosquito surveillance - Mosquito larvae breeding habitat maps - Pesticide residue monitoring - Fish kill and non-target organism die-off monitoring

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7l Storage of Chemical

Although proper methods for the storage of a chemical is included on a pesticide label, and certified pesticide applications should be award of proper storage techniques, it is valuable for every BMP to explicitly state how and where the pesticides will be stored (Table 4l).

Improper storage of a pesticide can lead to spills and environmental and human contamination risks.

Table 4l: Storage of Chemical BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Herbicides stored by distribution companies	- Herbicides stored in Pacific Coast Salmon Coalition's equipment storage facility	- Herbicides storage specified by Action Plans and conducted according to label instructions	- Pesticide stored in a secure facility in Kenai, Alaska and stored according to the label	- Pesticides stored in pesticide distribution and storage center located in Brooklyn and stored according to the labels

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

7m Disposal of Chemical and Equipment

Proper disposal of pesticides is essential for preventing environmental contamination (Table 4m). Each state and jurisdiction will have its own regulations on how to dispose of pesticides and pesticide containers, and the procedures should be made clear in the BMP. Improper disposal of pesticides and their containers may lead to environmental contamination and risk of protected species exposure. Cleaning of equipment should also have its own BMP. Thorough cleaning of pesticide application equipment is necessary to ensure equipment will work properly in the future (reduces occurrence of clogged nozzles, etc). Each BMP should have guidelines for how to rinse equipment as well as how to dispose of the rinsate in an environmentally safe manner.

Table 4m: Disposal of Chemical and Equipment BMPs by Case Study

Hydrilla	Knotweed	Spartina	Northern Pike	Mosquito
- Pesticide distribution companies responsible for disposal of chemical and large containers	- Equipment is triple-rinsed every day after use and rinsate is disposed of away from surface water - Containers are given the DNR for disposal	- Chemical containers are disposed of according to government regulations or are returned to the manufacturer - Containers are triple-rinsed and rinsate emptied into an appropriate receptacle	- Equipment was hosed off back into the treated lake and disposed of at the site - The MSDS protocols were followed for disposal	- FIFRA regulations for the disposal of pesticides, pesticide containers and pesticide waste containing products are followed - Outdated pesticide products are returned to the manufacturer for disposal or with the help of NYC DEC

*See case studies for detailed descriptions of these BMPs and the decisions that led to their use.

8. Limitations of this Project

This document and accompanying database have some important limitations. First, this document does not assess risk of each pesticide to individual NOAA Trust Species. Assessment of risk is a complex process that involves careful evaluation of the pesticide, application rate, application method, applicator skill, weather conditions, water body conditions, geography, habitat, organism health and the assumption that there is adequate knowledge to evaluate risk. It cannot be easily inferred from toxicological data or other proxies. Secondly, as explained earlier, this document does not compile a comprehensive list of all possible BMPs for individual pesticides or their variations in application types. BMPs are very much context specific and therefore difficult to catalogue or reasonably evaluate against each other or the possible harm to ESA-listed species without further substantial time and resources. In addition, without the case study approach with personal interviews of project leaders, evaluations of BMPs may be incomplete, therefore BMP comparison and evaluation of all BMPs for aquatic pesticide use is time intensive. However, we do define effectiveness in terms of controlling the pest (user-perspective) and effectiveness in terms of avoiding harm to non-target species (environment-perspective) when possible. Each case study explains the context for pesticide use and a justification for pesticide use. Lastly, we have worked towards exposing gaps in understanding of pesticide ecotoxicological impacts toward NOAA trust species.

II. Pesticide BMP Case Studies

Chapter 1

Herbicide Use in an Aquatic Restoration Context

Invasive aquatic plants are a worldwide problem and can alter aquatic ecology, trophic interactions, commercial uses, recreational uses, form dense monocultures, increase infrastructure maintenance costs and pose risks to habitat of endangered and valued species, public health and safety. Impacts from invasive aquatic plants can cost millions of dollars annually at local levels in economic losses and control efforts. Herbicides are often used in restoration projects involving invasive plant species invading littoral zones of water bodies. These restoration efforts involve working directly in the water, including the application of pesticides to the water for the control of emergent, floating and submersed plants (15). The BMPs and pesticides implemented in aquatic restorations projects have the potential to significantly impact aquatic habitats and their valuable resources such as endangered and threatened species. This case study on herbicide use in an aquatic restoration context includes the following sections:

1. A case study of the Demonstration Project on Hydrilla and Hygrophila in the Upper Kissimmee Chain of Lakes that highlights their pesticide best management practices for controlling Hydrilla as well as other common Hydrilla best management practices.
2. A description of fluridone, a commonly used aquatic-registered herbicide for submerged plants, and includes available toxicity information on endangered/threatened anadromous fish.
3. A description of endothall, a commonly used aquatic-registered herbicides for submerged plants, and includes available toxicity information on endangered/threatened anadromous fish.

1.1 Osceola County, Florida Case Study: Hydrilla control in Kissimmee Chain of Lakes Florida by Waterway Managers

1.1.1 Background

Hydrilla was introduced to Florida in the 1950’s through the aquarium trade. Extensive fluridone treatments were used in Florida to attempt to control Hydrilla. In the year 2000, Florida Hydrilla resistance to fluridone was noted, and now fluridone is no longer effective at Hydrilla control (92). Hydrilla’s development of fluridone resistance was likely due to lack of BMPs for fluridone application, including not rotating treatments and relying on a single herbicide with one mode of action (88). In 2006, Osceola County, FL was awarded a grant by the EPA to conduct a project to develop new and alternative ways to control Hydrilla and Hydrophila in the

Kissimmee Chain of Lakes. The goal of the Demonstration Project on Hydrilla and Hygrophila in the Upper Kissimmee Chain of Lakes is to develop cost effective and selective control of Hydrilla, Hygrophila and other invasive plants while encouraging growth of native plants. This project has four main components: 1. Development and testing of new herbicides, 2. Evaluation of currently registered herbicides for control of Hydrilla and Hygrophila, 3. Biological control of Hydrilla and Hygrophila, and 4. Developing outreach strategies and demonstrating the results of the project to the public, federal, state, and local government partners, and local herbicide applicators. This case study will focus on the evaluation of currently registered herbicides for control of Hydrilla. The Demonstration Project has been evaluating the use of endothall and other herbicides for large scale treatment in the Kissimmee Chain of Lakes. Over the years, through evaluation of efficacy, longevity and selectivity of herbicide treatments, they have been developing BMPs specific to Hydrilla control in Florida (92). For more information on the other three components of the Hydrilla demonstration project see the website: http://plants.ifas.ufl.edu/osceola/index.html.

1.1.2 Introduction to the Invasive Species: Hydrilla

1.1.2a History

Hydrilla originated from Asia and was introduced to Florida in the late 1950s. There are two different bio-types of Hydrilla, which supports the idea that there were two separate introductions to North America. The monoecious bio-type was the most recent introduction and was found in the Potomac River around the NE of North America in the late 1970s and has shown to be more cold-tolerant than the dioecious biotype. The dioecious Hydrilla was introduced earlier and occurs in the warm southern states of North America. When dioecious Hydrilla showed up in Florida due to the aquarium nursery trade, it quickly spread throughout the country by other plant nurseries and boat trailers. Soon after the introduction in the Potomac River, Hydrilla was placed on the Federal Noxious Weeds List and other states' prohibited plant lists which stopped the sale and transportation of the species; however, it is still being inadvertently spread by boaters and other people moving small plant fragments (15).

1.1.2b Biology

Hydrilla is "a rooted submersed perennial monocot that grows in all types of bodies of water" (15). With the monoecious bio-type, each plant has both male and female flower parts, while with the dioecious bio-type each individual plant has only male or female flowers. Hydrilla has small, "strap-like", "saw-toothed" leaves that are in whorls of four to eight around the stem (15). Hydrilla easily reproduces with just small vegetative fragments and is able to create dense colonies that infest waterways. Although Hydrilla is often confused with Elodea, the differences include the number of leaves in each whorl and saw-tooth leaves. Hydrilla is also the only species in the family Hydrocharitaceae that has the presence of tubers or turions on the roots as reproductive structures. These structures make Hydrilla management difficult because tubers occur in sediment, lie dormant for several years and reproduce rapidly by vegetative reproduction (15).

1.1.2c Problems

Dense populations of Hydrilla can cause many problems including blocked waterways, altered flood control, declines in property value and increased need for mosquito control. Boating and other recreational use is limited because Hydrilla infestations create a thick layer on the upper part of the water, making it difficult to travel through. Hydrilla competes with native plant vegetation in shallow waters, but is also capable of living in deep water with low light conditions where many native species do not grow. Competition with other native plants decreases species diversity (15). Other habitat influences caused by Hydrilla included alterations water flow, temperature, oxygen and pH which can have resulting influences on aquatic animals as well as plants. Another problem of Hydrilla is the control methods that are often needed. A commonly employed method of Hydrilla control is the use of herbicides, but managers must take into account the potential negative impacts these herbicides may have on native plants and animals (15). Hydrilla has invaded freshwater lakes and rivers from Florida to Maine, and overlaps with the habitat of the endangered Shortnose Sturgeon. In addition to infestations in the southeast, New England and parts of the Midwest, Hydrilla is also been found in California and Washington (15), where it may occur in or near habitats of endangered or threatened chinook and coho salmon, steelhead and green sturgeon.

1.1.2d Pathways of introduction

The main current pathways to introduction of Hydrilla are likely boats, boat trailers and plant fragments (15).

1.1.2e Overview of Chemical Control

Herbicides that are registered and commonly used for the control of Hydrilla and are included in the upcoming EPA General Permit are: diquat, endothall, copper sulfate, copper chelate, and fluridone. Contact herbicides, such as endothall, can be used to control Hydrilla with spot treatments or large-scale treatments which are applied before native plants grow in the spring. Applying early in the spring can reduce oxygen depletion from decaying vegetation (15). Slow-acting systemic herbicides are also used to control Hydrilla. Fluridone, for example, can inhibit enzyme activity in Hydrilla when applied to the whole waterway and is effective at low concentration rates when contact can extend over a long period of time from weeks to months. The gradual death of Hydrilla populations is advantageous because the gradual decay in plant material will cause less of an oxygen demand which reduces the risk of a fish kill. A disadvantage is that the treatment needs to occur over the whole lake or pond, or in areas where there is little water movement such as bays (15). Liquid formulations of herbicides for submersed weeds can be applied in several different ways, including surface applications along shorelines and aerial applications. Granular and deep-hose applications are used for deeper waters. Tank mixes and other ways to apply the herbicide depend greatly on the specific layer in the water column that the target plant resides. Because herbicides are used to such a great extent in Hydrilla control, some Hydrilla populations have developed resistance to particular herbicides, such as fluridone, so the monitoring of resistant Hydrilla plants and research into alternative herbicides is crucial (15).

1.1.3 Summary of BMPs

The Osceola County Hydrilla and Hygrophila Demonstration Project in Florida is a good example of a BMP for herbicide applications directly to surface waters of important aquatic habitats. It is also an example of a specific BMP developed in a region where traditional herbicide methods are no longer an option due to development of herbicide resistance. There are several differences between the northern bio-type of Hydrilla and the southern, Florida Hydrilla bio-type. For example, northern type Hydrilla is targeted for eradication, except for New York State. Southern type is targeted for control, because eradication is likely not possible (88). The following case study includes BMPs that are being developed as a result of the Demonstration Project's research and experience in Florida as well as BMPs for general Hydrilla control as it would be in states where Hydrilla has not become resistant to fluridone. The purpose of presenting BMPs for both Hydrilla bio-types is to emphasize the difficulty of Hydrilla control and that BMPs are often site-specific and dependent on local conditions (88). Included in this case study are highlights of how these practices reduce non-target organism risk and maximize efficacy along with hazards associated with herbicide applications.

1.1.3a Alternative Non-chemical Methods

Alternative non-chemical methods for controlling Hydrilla include cultural, physical, mechanical and biological strategies and are an important part of effective BMPs. Cultural control methods include public outreach programs. Public education and outreach provides public education of an invasive species problem which may involve brochures and workshops intended to provide public awareness. Outreach and education can improve prevention and illicit volunteer support for control projects (15). Also, educating the public about pesticide practices can inform public opinions about the use of pesticides. The Demonstration Project is actively involved in public education and outreach regarding invasive aquatic plant species, their pathways for spread and control. One of its main initiatives is to develop outreach strategies to public, federal, state and local government partners. As a part of their outreach program, the Demonstration Project has an interactive website with information, articles, links and expert contacts to provide information about what the public can do to prevent and control the spread of Hydrilla (92). Other cultural control methods include prevention of spread through boat ramp monitoring programs, boat washing stations and education on plant identification (15).

Benthic control barriers, a physical control method, aim to shade out plants, but large-scale barriers are impractical due to high cost and impacts to non-target organisms. Drawdown is a method used to control many submersed plant species, but is mostly ineffective against Hydrilla, especially in southern regions, and cause rapid expansion of Hydrilla populations. Hand removal is labor intensive but can be effective on small, pioneering patches of Hydrilla, although care must be taken to pull up tubers and turions, otherwise rapid regrowth will occur. Mechanical harvesting of Hydrilla can be expensive and results will only last about two months after harvesting. Mechanical harvesting will also harvest native plants and can harm other aquatic organisms (15).

Biological control is a prominent control method compared to mechanical and manual control. There is ongoing research into insect-based control of Hydrilla, but so far applicability has been limited. The majority of biological control of Hydrilla is done through grass carp, *Ctenopharyngodon idella*. Sterile grass carp are released in closed ponds and lakes and can be used with herbicides. The grass carp is mostly a non-selective plant feeder which includes native and invasive species. Grass carp remains an effective biocontrol agent for Hydrilla (15), but concerns over escape of the long-lived grass carp, uncertainty over its sterility and destruction of native aquatic plant communities limits its applications.

Due to the limitations, effectiveness and disadvantages to manual, mechanical and biological control of Hydrilla, herbicides are commonly used (15). A key part in the decision of whether or not to use alternative methods or chemicals is what level of control is desired. Some programs may target for complete eradication, others may simply want to control the level of infestation. Practicality, cost and effectiveness of available methods are all a part of this decision (88). Florida has used and is currently using some mechanical harvesting techniques and grass carp for biological control. The Demonstration Project is currently evaluating the effectiveness of using biological insects and bioherbicides to control Hydrilla and a major element of the project is devoted to this research (92).

How does this practice maximize benefits and reduce risk?

- The use of non-chemical alternatives will inherently eliminate the risk posed by herbicide use.
- Evaluating the use of non-chemical methods provides informed decisions on which may be the best choice; these decisions will be dependent on site and level of control desired.
- Using non-chemical methods in combination with herbicides may increase overall control effort efficacy.

Hazards

- The use of non-chemical methods may not provide the highest efficacy of control, and will seldom eradicate the species.
- Non-chemical methods may pose risks to native plants and animals.
- Some methods may cause more rapid growth of Hydrilla.
- Grass carp are not always sterile and there is concern that they might escape and damage the ecology of water bodies with native plants.

1.1.3b Pesticide(s) and Product(s) Choice

The two most commonly used herbicides for control of Hydrilla are fluridone and endothall. Fluridone is the main herbicide used for Hydrilla control throughout the United States, with the exception of Florida, where Hydrilla has become fluridone resistant. Because of its activity and longevity in water bodies, fluridone is considered to be the primary choice for managers attempting eradication of the Hydrilla. All northern states, with the exception of New York, target Hydrilla for eradication. Fluridone is available in the formulation Sonar® for aquatic use. Fluridone is a systemic herbicide that will translocate to the tubers, but tuber control is limited and requires multiple years (five to ten years) for complete eradication. Fluridone is the most common choice when applying to lakes. For the northern bio-type, endothall is mostly used for spot treatments, particularly for boat channels or areas where timely clearing is most critical (88).

In Florida, however, the dioecious bio-type has become resistant to fluridone, so the Demonstration Project has been developing methods and techniques for the use of endothall, in the formulation Aquathol® K, and other herbicides for the control of Hydrilla (60). Resistance/high tolerance to fluridone by Hydrilla in Florida may be attributable to lack of good BMPs during fluridone's extensive use. The Demonstration Project's goal is no longer eradication, since eradication is likely no longer possible, rather control of Hydrilla in order to enhance the important function of lakes and waterways. Endothall has a faster mode of action, and also has a shorter residence time (two to seven days) in surface water. In order to address multiple modes of action, endothall has been paired with other herbicides, such as imazamox, a systemic herbicide, to try and achieve a quick dieback from the endothall and longer lasting effect with the systemic herbicide (88).

Fluridone is slightly to moderately toxic to salmonids (44,138,139,141), and because of the long water residency and repeated dosings of fluridone, chronic exposure is possible (131). However, the application rates of fluridone for submerged weed control are far below salmon toxicity thresholds. Endothall ranges from highly toxic to practically non-toxic to salmonids depending on formulation. Aquathol® K, the formulation used by the Demonstration Project is slightly to practically non-toxic to salmonids, but has the potential to alter olfactory ability (72,121,138). Salmonids, however, are not present in Florida. Application rates of these products and their applicability to anadromous fish will be discussed in the Application Rate section of this case study.

How does this practice maximize benefits and reduce risk?

- The use of fluridone for the control of northern bio-type Hydrilla is the most effective option for eradication.
- The evaluation of endothall for the control of southern fluridone resistant Hydrilla bio-type provides for control options.
- The use of Aquathol®K, which is an aquatically approved formulation of endothall and less toxic to fish than Hydrothal® decreases risk to fish.
- Combining endothall with other systemic herbicides which work by a different mode of action may increase herbicide efficacy and reduce risk of resistance development.

Hazards

- Improper uses of herbicides can lead to resistant plant populations.
- Non-target plant species may be impacted
- High residence time increases risks of impacting other areas via spill and flows from outlets.

1.1.3c Adjuvant(s)

Surfactants will not increase herbicide uptake in plants that are submerged in water, therefore surfactants are not used for herbicide applications to submerged aquatic plants (88).

1.1.3d Licensing and Certification of Applicators, Professional and Trade Associations

The state of Florida employs numerous contractors from both public and private sectors to apply endothall (88). The Florida Department of Agriculture and Consumer Services (FDACS) requires all persons who apply or supervise the application of restricted use pesticides to be certified and licensed by the Department. The FDACS has established a certification and licensing category for applications of herbicides for aquatic plant management. It is either recommended or required (depending on the employer) to have a FDACS Aquatic Pest Control category certification and license. Both a general and Aquatic Pest Control category exam must be passed in order to receive license and certification. The requirement of certification and testing ensures that each applicator is knowledgeable and capable of appropriate applications methods (61). Licenses and certifications must be renewed every four years. This can be achieved by re-taking the examinations or by obtaining the required amount of Continuing Education Units (98).

The Demonstration Project is affiliated and has contacts with a number of professional associations including the Center for Aquatic and Invasive Plants, Florida Fish and Wildlife Commission, the Aquatic Plant Management Society, the Florida Aquatic Plant Management Society, Florida and Exotic Pest Plant Council, Florida Lake Management Society and others (92).

How does this practice maximize benefits and reduce risk?

- Licensing and certification requirements for applicators for general and Aquatic Pest Control specific categories create an enforceable standard that all applicators have the knowledge for safe and effective general and aquatic pesticide applications.
- Affiliations with professional associations provide managers with up to date BMPs and environmental issues from other professionals.
- Continuing education courses and required renewal assist applicators to minimize human error, increase application efficacy and decrease potential environmental risks.

1.1.3e Application Methods

Application methods of herbicides for the control of Hydrilla vary depending on control goals. Applications of herbicides can be made to whole lakes and large portions of a water body or be more targeted to specific areas for site specific control. Questions to ask before applying herbicides and determining what methods to use include: What is the control objective? Is eradication or a tolerable level desired? Is the extent of infestation: widespread, mature, or new? Is the infestation in a contained lake or pond or a connected water body where pesticides and propagules can travel downstream? What is the proximity of the infestation to other sites? How likely is that an infestation going to spread from the water body to another proximal, connected or distant site due to natural or anthropogenic vectoring? All of these questions will influence the methods used, the extent of the control effort and types of herbicides (88).

Applications of herbicides for Hydrilla control include broadcast sprays, application below the water surface and drip stations. Aerial sprays are prone to drift but allow for treatment on large scales. Florida is currently the only state that utilizes aerial sprays (88). Sprays from boats and airboats also pose a risk of drift, while direct application under the water's surface will not result in drift and is the most commonly used method. Fluridone is usually applied to whole or large portions of water bodies. Endothall, on the other hand, is usually applied to selected strips of shoreline (15). However, in Florida, endothall is applied at a large scale with whole and partial lake treatments by boat and helicopter (45). Flowing water can dilute herbicide, so drip applications are being developed to provide consistent concentrations of herbicide in the water for appropriate periods of time. The Demonstration Project controls Hydrilla in slow moving lakes and is attempting drip applications in low energy, slow moving water for selective treatments at sites with high retention, but these methods are still under evaluation. There are some methods for deep water delivery for herbicide applications for submerged aquatic weeds, but application or delivery to deep zones for Hydrilla herbicide products is generally not an option (88).

Whatever the application method, proper distribution of the herbicide is important for contact herbicides like endothall to be sure that as much of the plant comes into contact with the herbicide as possible in order to achieve maximum efficacy. Lower parts of Hydrilla that do not come into contact with endothall will survive and recover rapidly (15).

How does this practice maximize benefits and reduce risk?

- Identifying what level of control is desired, the state of infestation and the proximity to other water bodies will determine the most efficient and appropriate application methods.
- Direct subsurface applications of herbicide eliminate risk of drift and provide for good distribution of herbicides throughout the water.
- The use of aerial applications in Florida provides for effective large scale applications of endothall; however, aerial applications are unique to Florida and may not appropriate in other states.
- Evaluating the use of drip applications in Florida may result in a new effective application method.
- Application methods that result in even and thorough distribution of herbicide will have the greatest efficacy.

Hazards

- Aerial and boat spray applications may result in drift into adjacent areas and water bodies and increase non-target plant and animal herbicide exposure.

1.1.3f Equipment and Calibration

The main equipment used for herbicide applications for Hydrilla control are boats and airboats with trailing hoses for subsurface applications (88). Herbicides are mixed into solution and injected under the water's surface by trailing hose directly into the water. Rarely, herbicides are sprayed from a boat. When calibrating hose and spray flow rates to achieve target water concentrations, the volume of the thermocline (if present) should be used rather than the whole lake volume since the two layers won't mix (88). Aquathol®K may be applied with no dilution, as long as the resulting application rates are calculated correctly, but some dilution may provide for better distribution (7). The Demonstration Project performs aerial sprays by helicopter. Herbicide volume and equipment is calibrated to achieve desired application rates over the targeted area (45). Equipment for experimental drip stations for the Demonstration Projects remains under evaluation (88).

How does this practice maximize benefits and reduce risk?

- Subsurface hose applications apply herbicide at a controllable rate and allow for direct application to the water without risk of drift as from spray applications.
- Calibration of equipment ensures appropriate application rates are applied which increases efficacy.
- Aerial application by helicopter for the Demonstration Project allows for efficient applications over large water bodies.

Hazards

- Drift from aerial and boat spray applications may result in overspray into adjacent water bodies and native vegetation.

1.1.3g Application Rates

Herbicides used for submerged plant control tend to require lower concentrations than for foliar plants. Fluridone can be used at a range of application rates from 4 to 150 ppb. The lower rates tend to have more specific control of a few species while higher rates have a broader spectrum control (15). Fluridone is most commonly applied at rates of 10 to 20 ppb for northern bio-type Hydrilla eradication. If a thermocline is formed, applicators should calculate application rates based on the volume of the thermocline, not the volume of the entire lake, since the two layers will not mix (88). Application rates of fluridone used for Hydrilla eradication are well below the concentrations that cause acute mortality in juvenile rainbow trout and acute and chronic early life stage mortality in juvenile chinook salmon (44,138,139,141), therefore there are no expected impacts to salmonid mortality as a result of field applications of fluridone.

The southern bio-type of Hydrilla in Florida is now fluridone resistant, so fluridone is not applied by the Demonstration Project. The Project is evaluating application rates of endothall using the product formulation Aquathol®K. Application rates they have been using are 1 to 3 mg/L endothall (A.I. or A.E. not specified). The resulting water concentrations depend on whether the application is over an extensive span or a more closed-in application. Applications of endothall using these rates have been effective at reducing Hydrilla (60,88). The endothall rates applied in the field would have limited acute lethal effects to freshwater salmonids (121,138) but, field application rates of Aquathol® K may inhibit smoltification survival in chinook salmon (72). However, endothall is not used extensively in areas with salmonids; its extensive use is restricted to Florida. Shortnose sturgeon is present in Florida waterways, but is not thought to be impacted by treatments (88). No toxicological information was available on Shortnose sturgeon for endothall or fluridone.

How does this practice maximize benefits and reduce risk?

- Fluridone is the most effective herbicide for Hydrilla control/eradication and is effective at application rates that are non-toxic to anadromous fish.
- Effective application rates of endothall to fluridone resistant Hydrilla provide some measure of Hydrilla control.

Hazards

- Application rates of Aquathol®K may have effects on salmonid smoltification.

1.1.3h Application Timing

For northern bio-type Hydrilla, fluridone should be applied in late spring once a thermocline has formed. Thermoclines usually develop in May or June. Hydrilla doesn't often grow deeper than 15 feet, so it will remain in upper layer of the thermocline. When fluridone is applied, the application rate is measured with the volume of the thermocline. Fluridone applied to thermocline lakes will have high residence time. High residence time is crucial since fluridone needs at least 45 days of contact with the plants in order to have maximum efficacy. Retreatments may be necessary. Lake turnover and mixing will decrease herbicide residency, and increase exposure to non-target organisms in the bottom of the lake. Up to 60 to 70% of the herbicide can be lost to deep water due to mixing. Although fluridone is a slow-acting herbicide and oxygen crashes are less likely due to slow plant die-off, it is recommended that herbicide applications be made before biological oxygen demand (BOD) is high, which occurs typically from mid to late summer. High BOD can cause fish mortality. Retreatment of herbicide over several years is often required to starve tubers of nutrition and energy in order to achieve complete eradication (88).

The southern, fluridone resistant Hydrilla bio-type has different timing recommendations. Endothall is a faster-acting herbicide and can cause large amounts of dead plant material over a short period of time. This can lead to high BOD and fish kills (15). Therefore, in Florida, the Demonstration Project applies endothall during fall and winter when the cooler water temperatures will decrease the risk of high BOD. Cooler water temperatures also increase endothall residence time but doesn't affect uptake by Hydrilla, which increases efficacy. Late fall also has lower flow rates in Florida lakes therefore endothall residence time is increased. Residence time is critical for optimal Hydrilla control. The Florida lakes in the Demonstration Project do not stratify therefore thermocline considerations are not applicable (88).

How does this practice maximize benefits and reduce risk?

- Application of fluridone in the northern bio-type of Hydrilla after the formation of a thermocline in the late spring and early summer increases fluridone residence time which increases efficacy
- Applications before summer will decrease the risk of fish kills due to high BOD.

- Application of endothall in fall and winter increases herbicide residence time in Florida lakes and decreases the likelihood of a fish kill and other impacts of high BOD.

Hazards

- Herbicide treatment, particularly fast-acting herbicide such as endothall, to dense beds of Hydrilla in warm, summer waters will lead to high BOD, causing the oxygen levels in the water to crash resulting in fish kills and other adverse effects to non-target organisms.
- Fluridone must have contact with plants for a minimum of 45 days to be effective, so chronic exposures of fluridone to non-target organisms such as fish may occur.

1.1.3i Application Conditions

Northern bio-type Hydrilla sprouts from tubers, but tubers will not produce sprouts every year. Therefore repeated applications of fluridone are needed for several years (five to ten years) to achieve complete eradication. Fluridone applied to new growth will have good efficacy. Apply to waters with low BOD, although there is less of a concern with fluridone than there is for endothall. For the northern bio-type, it is recommended to wait until lakes are thermally stratified before fluridone applications. As mentioned above, this will increase residence time which is crucial for efficacy. Fluridone should be applied to areas with low flow and high water residence time. Endothall can be applied to areas with higher flow, although maximizing residence time is important (88).

How does this practice maximize benefits and reduce risk?

- Applications of fluridone to new and actively growing Hydrilla sprouts will result in good efficacy.
- Applications of fluridone to thermally stratified lakes will increase fluridone residence time which in turn increases efficacy. Also, it reduces exposure of fluridone to deep, bottom dwelling organisms.
- Applying fluridone to slow moving waters will result in higher efficacy due to increase residence time.
- Application of endothall to higher velocity waters will have greater efficacy than fluridone.
- Application of herbicides when BOD is low will decrease the risk of oxygen levels decreasing to a point which results in fish kills and other adverse effects.

Hazards

- Applications of herbicides, particularly endothall, to dense Hydrilla beds may decrease oxygen levels causing fish kills and other adverse impacts. Warmer waters will have higher BOD.

- While endothall may have greater efficacy in higher velocity waters compared to fluridone, appropriate residence time is still necessary to achieve Hydrilla control.

1.1.3j Mitigation

The distributors and pesticide applicator contractors will follow the label for spill mitigation protocols (88). The Aquathol® K label requires that spills be absorbed with sand or other inert materials and be disposed of properly (7). The distribution companies that provide and transport herbicide to treatment sites have their own spill mitigation plans in addition to the pesticide label (88).

How does this practice maximize benefits and reduce risk?

- Plans for spill mitigation will decrease risk of exposure to non-target organisms if a spill were to take place.

Hazards

- Applicators that are not aware of project specific spill mitigation or prevention plans may lead to increased chance of spills or wrongful mitigation actions due to lack of education.

1.1.3k Monitoring

One of the Demonstration Project's main components is to evaluate the efficacy of extensive endothall and other herbicide applications to the Kissimmee Chain of Lakes in Osceola County. To evaluate herbicide applications, this project conducts large scale field applications of Aquathol®K (endothall), Reward® (diquat), and combinations of those two herbicides and others over different seasons (spring, fall and winter) and monitors the efficacy of the treatment and persistence of herbicide residues in the water. These treatments are applied by helicopter and treatment blocks are mapped by GPS. Treatment areas vary from 80 to 6000 acres. Hydrilla and native vegetation abundance, biomass, percent cover and percent volume are sampled over time. Hydrilla tubers and turions are also sampled. Vegetation samples are conducted using visual surveys, gridlines, and fathometer transects. Herbicide residues and water quality parameters including temperature, dissolved oxygen, pH, and conductivity are also collected and monitored over time. Samples for plant and water quality are taken from both treatment and reference sites. Hydrilla control effectiveness and longevity is compared by season of application, concentration and combination of herbicides. Vegetation maps were created to determine a baseline of native plant abundance and to monitor the impact of herbicide application and Hydrilla reduction (60, 92). Based on the numerous progress reports available on the Demonstration Project's website, large scale applications of endothall have had good efficacy and most sites have been slow to recover providing months of control (92). Sites have also seen relatively good Hydrilla selectivity (60).

The Demonstration Project has started to monitor for potential increased tolerance of Hydrilla to endothall; no work has been done to determine if Hydrilla has developed resistance. Several mesocosm studies were conducted to compare the suspected tolerant population to several other Hydrilla samples from throughout Florida. Monitoring of tolerance and resistance to herbicides is an important part of any BMP, particularly in Florida, where poor management practices may have been the cause of the now fluridone resistant population (88).

How does this practice maximize benefits and reduce risk?

- Monitoring effectiveness of herbicide application allows for adjustment of product, concentration and application methods that are most effective, enhancing the control effort benefit.
- Monitoring longevity of control provides information on which chemical, treatment methods and application rates result in best overall long-term Hydrilla control.
- The use of GPS and GIS equipment allows for reliable maps which increases treatment efficacy.
- Herbicide residue data inform the program of the actual field concentrations of herbicide in the water. This evaluation will increase knowledge if herbicide residues remain at concentrations long enough to illicit Hydrilla control and how long the herbicide persists in the environment which could address non-target organism concerns.
- Water quality data such as pH, dissolved oxygen, temperature and other parameters will help determine if herbicide control of Hydrilla is resulting in habitat quality alterations.
- Quantitative sampling methods provide accurate evaluation.
- Testing Hydrilla populations for herbicide tolerance development provides insight to current BMP effectiveness and allows for product and application rate adjustments.

1.1.3l Storage of Chemical

Herbicides used by the Demonstration Projected are stored by distribution companies such as Helena Chemical and their storage facilities have the specific requirements for pesticide storage (88). Herbicides should be stored in facilities that are not subject to excess heat or cold, are sufficiently separated from feed and fertilizer (7), and are in a secure environment.

How does this practice maximize benefits and reduce risk?

- The use of proper pesticide storage reduces the risk of spills and environmental contamination, thereby reducing potential exposure to non-target organisms.

Hazards

- The improper storage of pesticides can lead to human and environmental health risks.

1.1.3m Disposal of Chemical and Equipment

The distribution companies are responsible for the rinsing and re-commissioning of the larger (250 gallon totes) containers. The 2.5 gallon containers are disposed of according to the label (88). The Aquathol® K label requires containers to be triple-rinsed and disposed of in landfill or incinerated (7). Chemicals are disposed of by the distribution companies (88).

How does this practice maximize benefits and reduce risk?

- Proper disposal of herbicide and containers reduces the risk of environmental contamination.

Hazards

- Rinsing equipment in or near surface water can result in environmental contamination.

Acknowledgements: This case study was supplemented with information provided by personal interviews with Dr. Mike Netherland of the US Army Engineer Research and Development Center, Project Coordinator for the Demonstration Project's Element 2: Evaluation of Currently Registered Herbicides for Control of Hydrilla and Hygrophila, and courtesy professor at the University of Florida.

1.1.4 Demonstration Project on Hydrilla and Hygrophila Case Study Details

Descriptions of the Demonstration Project's history, objectives, work plans and progress reports can be found at: http://plants.ifas.ufl.edu/osceola/index.html.

1.2 Example of Pesticide: Fluridone

Fluridone (1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1H)-pyridinone) is used to control aquatic nuisance plants. In susceptible plants, fluridone works by inhibiting the formation of carotene (131).

1.2.1 Application rate

Species susceptibility to the floridone formulation Sonar® A.S. may vary depending on time of year, stage of growth, and water movement. It is recommended to apply Sonar® A.S. prior to initiation of weed growth or when weeds begin active growth. Application to mature target plants may require an application rate at the higher end of the specified rate range and may take longer to control. The maximum application rate for applying fluridone (in the formulation Sonar® A.S.) to ponds is 90 ppb A.I. per surface acre and 150 ppb A.I. per surface acre per annual growth cycle in lakes, reservoirs and static canals. A minimum of 45 days of pesticide contact is required for effective treatment according to the Sonar® A.S. label for water treatments (131).

1.2.2 Degradation rate

The half-life of fluridone by photodegradation in neutral pond water is 34 hours. The half-life for fluridone in water is estimated to be 20 days with a 90 day half-life in hydrosoil. Fluridone is strongly adsorbed to organic material in soil with a half-life of 90 days and is expected to leach slowly (609).

1.2.3 Known toxicity to NOAA Trust Species

1.2.3a Acute LC_{50}

A 96 hour LC_{50} for juvenile chinook salmon was determined to be >5.76 ppm with a NOEL at 0.73 ppm (138). The 96 hour LC_{50s} for rainbow trout range from 4.25 to 12 ppm (44,138,139,141). Fluridone is therefore considered to be slightly to moderately toxic and LC_{50} values are therefore well above the maximum concentration (150 ppb) that is allowed to be applied according to the label. There were no data found for coho, chum, and sockeye salmon or steelhead trout as well as sturgeon, sawfish, Pacific eulachon and rockfish. There were also no data found on endangered or threatened cetaceans, pinnipeds, marine turtles, coral, abalone or Johnson’s seagrass.

1.2.3b Sublethal and Chronic Toxicity

A 75 day early life stage chronic exposure of fluridone to chinook salmon resulted in a >1.71 ppm LOEC and a 1.71 ppm NOEL for growth (138). No alterations of attraction behavior in chinook salmon smolts was observed at 0.09 ppm or 0.9 ppm (ppm A.I. of Sonar® AS). Juvenile rainbow trout also showed no changes in the ability to avoid skin extract when exposed to 0.15 ppm A.I. (formulation Sonar® A.S.) which suggests that it would not alter olfactory behavior in salmonids at maximum application rates (25). There were no chronic or sublethal data found for endangered/threatened coho, chum, and sockeye salmon or steelhead trout, sturgeon, sawfish, Pacific eulachon, rockfish, cetaceans, pinnipeds, marine turtles, marine invertebrates or marine plants listed in Table 2.

1.2.3c Indirect effects

Vegetation along riverbanks and lakes provides habitat for juvenile salmon food sources. Removal of this vegetation may reduce prey availability.

1.2.4 Persistence of pesticide in ambient water

The solubility of fluridone is low at 12 mg/L. The half-life for fluridone in water is estimated to be 20 days, therefore it has moderate persistence. It is stable to hydrolysis which suggests high persistence; also has high persistence under anaerobic aquatic conditions (134). A minimum 45 day exposure to plants is recommended for fluridone to be effective, so often repeated dosings below 150 ppb are used as long as cumulatively they don't exceed a total of 150 ppb per growing season (131) which suggests that non-target species may be exposed to low levels for relatively long periods of time. No chronic or sublethal data, other than growth and olfactory ability, were found for doses below 90 ppb.

1.2.5 Bioaccumulation potential in non-target species

The bioaccumulation potential of fluridone is expected overall to be low with bioconcentration factors in rainbow trout from 2.30 to 90 (85,150). The octanol/water partition coefficient (Log K_{ow}=1.81) is low, suggesting there is a low affinity for non-polar organic solvents (134). There is perhaps a modest potential for bioaccumulation in mammals with repeated exposures (77). Based on the low K_{ow} and low bioconcentration factor, bioaccumulation in fish is unlikely and exposure of endangered pinnipeds and cetaceans through diet therefore is also unlikely.

1.3 Example of Pesticide: Endothall

Endothall, 7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid, is a dicarboxylic acid selective contact herbicide that is used to control both terrestrial and aquatic weeds. Technical endothall is an odorless, white crystal and endothall formulations are available in the form of granules or as a soluble concentrate. Endothall works as an herbicide by interfering with plant respiration, affecting protein and lipid biosynthesis, and disrupting plant cell membranes (22,30,106).

1.3.1 Application rate

The maximum application rate of endothall is 5 ppm A.E./acre for aquatic applications and 2 lbs A.E./acre for terrestrial applications. Endothall acid is not applied directly to sites, rather it is breakdown product of dipotassium salt or an N-dimethylalkylamine (106). The manufacturer's recommended application rates of Aquathol® K (a.i. dipotassium salt of endothall) to ponds and lakes for Hydrilla control are 2 to 4 ppm dipotassium endothall. This equals about 1.4 to 2.8 ppm A.E. and 4 to 8 ppm of Aquathol® K product (1.3 to 2.6 gallons per acre foot) (7). The recommended application rates for Hydrothal® 191 (a.i. Mono(N-dimethylalkylamine) salt of endothall) for the control of Hydrilla in ponds and lakes are 1 to 2 ppm A.E. (4.4 to 8.3 ppm of Hydrothal® 191 liquid formulation at 1.4 to 2.7 gallons per acre foot, and 2.3 to 4 ppm dimethylalkylamine salt) (53).

1.3.2 Degradation rate

Endothall is quickly broken down by microbes in soil or water. Endothall is able to leach through soil into groundwater, but it is thought that the rapid degradation rates will limit the extent of leaching (22). The half-life in soil ranges from four to nine days depending on soil type. In surface water, dipotassium endothall has a half-life of four to seven days and technical endothall has a half-life of about seven days (30).

1.3.3 Known toxicity to NOAA Trust Species

1.3.3a Acute LC_{50}

Endothall appears to exhibit a wide range of toxicity levels to salmonids dependent on formulation. In juvenile rainbow trout, endothall formulations ranged from moderately to practically nontoxic (1.8 ppm to 450 ppm 96 hour LC_{50s}) (138,139). Dipotassium endothall is practically nontoxic (>100mg/L 96 hour LC_{50}) to coho salmon (121), and dipotassium endothall formulations range from slightly to practically nontoxic (32mg/L to 528.7 mg/L 96 hour LC_{50s}) in rainbow trout (138). A 48 hour acute LC_{50} for chinook salmon exposed to disodium endothall was 136 mg/L (121). A seawater challenge study testing chinook smolt exposure to Aquathol® K (A.I. dipotassium endothall) found that 100% of smolts exposed to 16, 38, 46 and 55 ppm A.E. for 14 days then transferred to seawater did not survive past three days of seawater exposure. Only 20% of smolts survived a ten day seawater challenge when exposed to 14 days of 25 ppm A.E. In addition, chinook smolts exposed to 3 ppm A.E. for four days in freshwater exhibited 100% mortality after three days in seawater. There was no difference in the survival between control smolts and smolts exposed to 1.5 ppm A.E. for four or 14 days in freshwater then transferred to a ten day seawater challenge. Also, smolts exposed to 1.5 or 3 ppm A.E. for four days then transferred to clean freshwater for ten days had survival rates no different than controls and smolts exposed to 16, 38, 46 and 55 ppm A.E. for 14 days then transferred to clean freshwater for ten days had little to no mortality. A 14 day LC_{50} with no seawater challenge test was determined to be 62.5 ppm A.E. From this study it appears that exposure to endothall may inhibit chinook salmon smoltification at exposures as low as 3 ppm A.E. for four days (72). The manufacturer's recommended application rates of Aquathol® K to ponds and lakes for Hydrilla control are 2 to 4 ppm dipotassium endothall. This equals about 1.4 to 2.8 ppm A.E. and 4 to 8 ppm of Aquathol® K product (1.3 to 2.6 gallons per acre foot) (7). Based on the acute LC_{50s} for coho and rainbow trout to dipotassium endothall and its formulations, the rates applied in the field would have limited acute lethal effects in freshwater (121,138). However, field application rates of Aquathol® K may inhibit smoltification survival in chinook salmon (72).

The formulation Hydrothol® 191 with the active ingredient dimethylalkylamine salt of endothall was shown to be moderately toxic at a 96 hour LC_{50} of 1.7 mg/L for steelhead trout (84). In addition, the 96 hour LC_{50s} in juvenile rainbow trout exposed to endothall dimethylalkylamine salt ranged from moderate to high toxicity (1.3 ppm (23.36% A.I.), 0.94 ppm (53% A.I.), and 0.56 ppm (53% A.I.) with one study resulting in a 0.16 ppm NOEL (53% A.I.) (138). Recommended application rates for Hydrothal® 191 for the control of Hydrilla in ponds and lakes are 4.4 to 8.3 ppm of Hydrothal® 191 product which results in 2.3 to 4 ppm dimethylalkylamine salt (53). The 96 hour LC_{50s} for steelhead and rainbow trout are both within the range and below the application rates recommended by the Hydrothal® 191 label, therefore application of Hydrothal® 191 (and potentially other dimethylalkylamine salt formulations) to water containing salmonids has the potential to result in fish mortality.

There were no acute data found for chum and sockeye salmon, as well as sturgeon, sawfish, Pacific eulachon, and rockfish. There were also no data found on endangered or threatened cetaceans, pinnipeds, marine turtles, coral, abalone or Johnson's seagrass.

1.3.3b Sublethal and Chronic Toxicity

Sublethal effect studies of endothall on endangered/threatened salmonids focused on chinook and coho smolts. Coho salmon smolts that were subject to a 24 hour seawater challenge after a four day exposure to 5 mg/L technical endothall in freshwater showed plasma sodium concentrations that were within the normal range, suggesting that coho smolts exposed to technical endothall near potential field concentrations have no stress during at least the first 24 hours in seawater (121). A study performed on chinook smolts exposed to Aquathol® K at 10, 16, 38, 46, 55 and 106 ppm A.E. showed hypertrophy of branchial epithelial cells. Smolts exposed to 106 ppm A.E. showed epithelial hyperplasia and lamellar fusion. However, chinook smolts exposed to 1.5 and 3 ppm A.E. showed none of these effects (72).

No other sublethal data for endothall were found on the other endangered/threatened anadromous fish, as well as cetaceans, pinnipeds, marine turtles, marine invertebrates, or marine plants on NOAA trust species listed in Table 2.

No chronic endothall exposure data for NOAA trust species listed in Table 2 could be found. However, an early life stage test on rainbow trout using a 40.3% dipotassium endothall formulation found an egg hatch LOEC to be 12.5 ppm with a NOEC of <12.5 ppm (138).

1.3.3c Indirect effects

Endothall is a defoliant and with any herbicide used to control riparian and aquatic plants, reduction in aquatic plants, especially native plants, could alter habitat and food resources such as prey availability for juvenile salmonids.

1.3.4 Persistence of pesticide in ambient water

Persistence in water is estimated to be short due to its half life of four to seven days and rapid degradation in soil (22,30). The low persistence in water and soil would suggest limited chronic exposure. However, unclear chronic exposure effect thresholds in rainbow trout, a study resulting in chinook smolting inhibition at field application rates of Aquathol® K, and salmonid acute LC_{50} values that are at or below the recommended application for Hydrothal® 191 (72,84,138) suggest that further studies are needed to better understand the acute, chronic and sublethal risks endothall and its commercial products pose to NOAA trust species, particularly anadromous fish, in field situations.

1.3.5 Bioaccumulation potential in non-target species

Endothall is not expected to bioaccumulate due to the <1 whole body bioconcentration factor (BCF) of endothall in bluegill (*Lepomis macrochirus*) and a high water solubility of 100 g/L (133). Therefore, bioaccumulation of endothall in non-target species is unlikely and risk to endangered species through diet is expected to be minimal.

Chapter 2

Herbicide Use in a Riparian Restoration Context

Riparian zones are highly susceptible to invasive plant invasions because they are frequently disturbed by wildlife, domestic animals and changes due to flooding. Riparian zones have a readily available water supply, water flow, and along with disturbance and heavy use, can facilitate for invasive species to easily become established (56). Invasive plants in riparian zones can compete with native species to reduce biodiversity and abundance, and alter litter fall and nutrient cycling which may lead to impacts in terrestrial and aquatic food-webs and further invasions from other species (142). Control of invasive plants is a part of the estimated $20 billion spent in the 1990s to control weeds (56). Herbicides are often used in restoration projects involving invasive plant species invading riparian zones along streams, rivers, lakes and waterfronts. Due to the close proximity and connectivity of riparian zones to aquatic habitats, the BMPs and pesticides implemented in restorations projects have the potential to significantly impact aquatic habitats and their valuable resources such as endangered and threatened species. This case study on herbicide use in a riparian restoration context includes the following sections:

1. A case study of the Hoh River Knotweed Project that highlights their pesticide best management practices for eradicating knotweed and includes other general knotweed control BMPs.
2. A description of glyphosate, a commonly used aquatic-registered herbicide, and includes available toxicity information on endangered/threatened anadromous fish.

2.1 Hoh River, Washington Case Study: Knotweed Management with Pesticides in Riparian Areas

2.1.1 Background

The Hoh River Basin on the west coast of Washington State's Olympic Peninsula is home to a few of the last remaining relatively healthy wild salmon runs in the lower 48 states. This includes spring/summer and fall chinook (*Oncorhynchus tshawytscha*), fall coho (*O. kisutch*), and winter steelhead (*O. mykiss*). Summer steelhead (*O. mykiss*), chum salmon (*O. keta*), and sockeye salmon (*O. nerka*), are also found in the Hoh River and its tributaries (79). In the Pacific Northwest and many other coastal regions of North America, the complex of woody Japanese, Giant, Bohemian and Himalayan knotweed *(Polygonum cuspidatum, sachalinense, bohemicum & polystachyum)* have been invading critical riparian habitats resulting in competition, exclusion and reduction of native plants species, alterations in litter nutrient quality cycling (142), reduction in large woody debris input, and other habitat modifications. The habitat alterations caused by woody knotweed could potentially impact important aquatic species such as salmon. The purpose of the Hoh River Knotweed Project is to eradicate knotweed from 30 river miles of the Hoh River for the protection of functioning ecosystems and salmon habitat (128). A patch of woody knotweed was first discovered within the channel migration zone (CMZ) at river mile 29.5 in 1998. In 1999, a winter storm event transported it down river where it became established all along the river's CMZ to the river's mouth, threatening riparian and river habitat quality. In 2002, the Hoh Tribe began survey, control and effectiveness monitoring efforts to eradicate knotweed from the Hoh River which are ongoing today as a partnership lead by the 10,000 Years Institute, and includes the Hoh Tribe, Hoh River Trust, private landowners, the Department of Natural Resources, Olympic National Park, and the U.S. Forest Service. The Institute and its partners have been largely successful at knotweed control and it is now very difficult to find knotweed along the Hoh River, although control and monitoring efforts continue in order to prevent reinfestation from remaining plants and root material buried in the river floodplain. Throughout the project, the Institute and its partners have striven to use best management practices aimed at reducing pesticide exposure to non target species, such as salmon. These practices have evolved over the ten years of the project as experience and new information on knotweed control and herbicide information have become updated (128).

2.1.2 Introduction to the Invasive Species: Knotweed Complex

2.1.2a History

Woody knotweed, which includes the species Japanese (*Polygonum cuspidatum*), Giant (*Polygonum sachalinense*), Bohemian (*Polygonum x bohemicum*), and Himalayan (*Polygonum polystachyum*), is otherwise referred to as the knotweed complex. All four plants are grouped into the knotweed complex because their biology and the ecological problems they cause are similar. The knotweed complex was introduced to the United States in the late 1800's as ornamental plants and vectors for erosion control from Asia (93). Because of their aggressive behavior, these woody knotweeds have become established in at least 41 states and invade riparian areas, roadsides, and other disturbed habitats (29,142).

2.1.2b Biology

Part of the Polygonaceae family, knotweed is a rhizomatous, herbaceous perennial plant that can grow between five to 19 feet tall. There are two ways to distinguish knotweed from other plants: alternate-growing leaves on the hollow, bamboo-like stems that grow in groups and the nodes have a membranous layer. Between the knotweed complex species themselves, one can distinguish by the leaf shape and the veins on the leaves. New shoots are produced from rhizomes and crowns during the mid-spring to late summer months. Himalayan and Giant knotweeds have perfect flowers with both male and female parts, while Japanese and Bohemian are gynodioecious, so they may have only the female part or be perfect. Knotweeds are considered shade intolerant, so they are most likely to grow in open canopy areas (93).

2.1.2c Problems

Knotweed will produce dense thickets with their canes and outcompete neighboring plants and vegetation, while also changing the nutrients cycle through food webs in waterways. These infestations will also lower property value, posing problems for real estate sales. The strong canes can puncture asphalt, concrete, and brick to reach sunlight and along with rhizome and root- contaminated soil, control can be long and expensive for land and property owners (29). On the banks of rivers, knotweed can form almost impenetrable walls and may impact fisheries and erosion. It often takes multiple growing seasons to eradicate these species (93).

2.1.2d Pathways of introduction

Knotweed was initially introduced by plant growers and gardeners. Once established, it can migrate downstream and across flood plains during flooding events. Also, transportation of root and rhizome contaminated soil can lead to knotweed spread into new areas (29,93)

2.1.2e Overview of Chemical Control

Mechanical control methods are often discouraged because they can induce thicker growth of knotweed. Often, chemical control is the only effective method for knotweed control. Of the herbicides to be included in the soon-to-be-issued EPA General Permit, glyphosate and imazapyr are the two most commonly used and effective herbicides for knotweed control (29). Glyphosate is often used as a stem injection or spray to control knotweed, along with imazapyr broadcast sprays (93). However, using stem injections in dense areas of knotweed may cause the application rate to exceed the maximum label rate. Glyphosate products are most effective from July through October or before the time leaves change color and fall off (senesce) (29,93). Fall application may be most effective because this is when rhizomes will acquire much of the herbicides through translocation (93). Glyphosate or imazapyr are capable of providing more than 80% control of knotweed and a mixture of the two chemicals yields a similar result. Other herbicides, such as triclopyr and 2,4-D, do not provide effective long-lasting knotweed control. To completely control large infestations, herbicide applications are needed over multiple growing seasons (29).

2.1.3 Summary of BMPs

The Hoh Knotweed Project is an example of how herbicide best management practices can be applied to critical aquatic habitat for the protection of important organisms and their habitat. The methods employed by the Institute are consistent with general knotweed herbicide management practices and several protective measures have been taken. The objective of the

Hoh River Knotweed Project is to eradicate knotweed from the Hoh River while using as few herbicide applications as possible (attempts to completely control knotweed as much as possible with each herbicide application) while protecting the valuable habitat and aquatic resources this river provides. Below are some BMPs synthesized from the Hoh Knotweed Project, general knotweed research and practices, highlights of how these practices reduce risk and maximize efficacy and hazards of herbicide application followed by a more detailed description of the evolution and efficacy of the Hoh Knotweed Project.

2.1.3a Alternative Non-chemical Methods

The consideration of non-chemical control methods are a crucial part to any BMP. The Hoh River Knotweed Project considered a number of alternative methods including manual control to knotweed removal, but it was determined that besides public outreach and education, herbicides were the only effective control option for the riverine situation (124). Indeed, chemical control of knotweed is often the only effective method, particularly in areas where knotweed has become firmly established. In fact, cutting, mowing and pulling of knotweed can cause it to grow back in greater density and increase the risk of spread, and is generally discouraged even in combination with herbicide use (29, 129). Some knotweed BMPs have recommended using manual methods such as hand pulling in soft soil conditions such as gardens where there are only a few plants. Cutting must be done with extreme caution as to not allow cut pieces to land on moist soil or into the water where they can resprout. With any manual method of knotweed control, proper disposal of cane and root fragments is crucial to prevent unintended spread (130).

The Hoh River Knotweed Project recommends early detection and rapid response which identifies pathways of infestation and has a watershed user education component that aims at reducing knotweed spread through human activities (129). The Knotweed Project and 10,000 Years Institute delivers presentations to the Olympic Knotweed Working Group, the Pacific Coast Salmon Coalition, the Hoh Tribe, the Hoh River Trust, and the Jefferson County Noxious Weed Board. The Institute has also responded to individual and group inquiries about controlling knotweed and provides information and training. The Institute provides posters and knotweed project information to landowners who allow access for control, and government agencies like the DNR and Olympic National Park (128).

How does this practice maximize benefits and reduce risk?

- The use of effective non-chemical control methods before the use of herbicides inherently decreases the risk of non-target organism exposure to herbicides. The decision to use herbicides in this case was deemed to be the most effective method of eradicating knotweed, as no effective alternative methods currently exists for knotweed management in channel migration zones.

- Early detection and watershed user education can prevent or reduce the need of herbicides by reducing the spread of plant material.
- Public outreach and education can prevent and reduce the spread of knotweed as well as provide education on effective knotweed identification and control.

Hazards

- Manual control methods for knotweed can leave stem fragments that can disperse and grow, are generally ineffective and can make an infestation worse by encouraging more aggressive vegetative growth. Know the plant biology and consequences when attempting a manual control method.

2.1.3b Pesticide(s) and Product(s) Choice

The 10,000 Years Institute has throughout the project continuously worked with Washington State University, the Olympic Knotweed Working Group, and federal, community and state and local agencies to screen which products (herbicides, surfactants and markers dyes) are least toxic to aquatic organisms such as salmon. Even though some of the knotweed stands are hundreds of meters away from the active river channel, the 10,000 Years Institute only uses products approved for aquatic environments in order to reduce potential risks to aquatic organisms. Currently, the Hoh River Knotweed Project is using the glyphosate products Aquamaster® or Aquaneat® and the imazapyr products Habitat® or Polaris™ AQ (129).

Glyphosate itself is considered practically nontoxic to salmonids, although there were some studies suggesting a slight to moderate toxicity to rainbow trout (37,139,149). Imazapyr is practically nontoxic to rainbow trout (138). Imazapyr and glyphosate have been show to be equally effective at controlling knotweed, resulting in 81% and 90% observed injury 12 months after application, respectively, with glyphosate being the more cost effective product due to cost of application (115). In some cases, imazapyr may be the preferred choice, especially in areas with native grasses because imazapyr is not toxic to some native grass species, is more persistent in soils and doesn't translocate or "leak" out of knotweed rhizomes like glyphosate does (51). In the case of the Hoh River, however, the Institute has noted that areas sprayed with a glyphosate mixture show better recovery of native plants, and patches that are sprayed with a glyphosate/imazapyr mixture are occasionally bare of native vegetation the following year (129). Protecting and encouraging the re-establishment of native plants is important for habitat function (115). Glyphosate has been observed to have effected non-target species in floodplains with hyporheic flow below the treated soil surface, where cane injected glyphosate was thought to leak out into the hyporheos and be transferred to native plants nearby and cause significant damage to plants such as Red Alder, which is glyphosate sensitive (129). The use of imazapyr may be a better practice for certain knotweed clumps located above hyporheic zones due to the longer lifespan of imazapyr as compared to glyphosate, but it is important to note that imazapyr is highly toxic to numerous plant species and can persist in water and especially soil (54). See the glyphosate and imazapyr sections (sections 2.2 and 3.2, respectively) for more information on degradation rates and persistence.

Glyphosate and imazapyr can be mixed together in herbicide spray solutions and the mixture efficacy is similar to that of glyphosate or imazapyr alone (29), and may be more effective (129). The Hoh Knotweed Project recommends using a glyphosate/imazapyr mixture in areas where knotweed control access is difficult, and not using imazapyr in areas where it may enter the water through soils or groundwater due to concerns about persistence and toxicity to fish. The addition of imazapyr to the herbicide solution in the Hoh Knotweed Project has helped with controlling large knotweed rhizomes that previously survived multiple treatments of glyphosate and no longer produce enough leaves for the herbicide to be translocated to the roots (129). It is clear that the choice of using glyphosate, imazapyr and a glyphosate/imazapyr mixture is dependent upon local conditions.

How does this practice maximize benefits and reduce risk?

- Use of the most effective agents glyphosate and imazapyr for controlling knotweed that are relatively nontoxic to aquatic organisms such as salmon increases the benefit and reduces the risk of using these herbicides for knotweed control.
- The use of aquatically approved herbicides in all locations of knotweed growth in this project reduces the risk to salmon and other aquatic organisms.
- Some native grasses which are important for ecosystem health are not affected by imazapyr, therefore the use of imazapyr can maximize benefits.
- Glyphosate binds quickly with soil, so using glyphosate can be more protective of non-target plant species, except where hyporheic flow may transport glyphosate out of rhizomes and into root systems of adjacent non-target plants.
- Using a glyphosate/imazapyr mix on knotweed with large persistent rhizomes with small leaves greatly increases efficacy. This reduces the risk of rhizome parts available to establish downstream.

Hazards

- Glyphosate is known to translocate or "leak" out of rhizomes, particularly after stem injections in very dense stands.
- Use of non-aquatic formulations of glyphosate may contain surfactants that are highly toxic to aquatic fauna.
- Imazapyr is persistent in soil and highly mobile in soil and water, so the use of imazapyr should be discouraged near surface and ground water and damp soils.
- Both glyphosate and imazapyr can harm non-target vegetation, so care is needed not to expose desirable vegetation during herbicide applications.

2.1.3c Adjuvant(s)

Many herbicide products require the addition of a surfactant to be added to the spray solution. Surfactants hold the liquid herbicide to the plant surface and are used to increase the amount of herbicide that gets inside of the plant, therefore increasing herbicide efficacy. There are many types of surfactants and they should be chosen based on their approved use with the herbicide and if they are allowed for the environment in which they will be used (51). Within the herbicide solutions used, it is generally the surfactants that are the cause for toxic concern to aquatic organisms, with some surfactants exhibiting moderate to high acute toxicity to salmonids (28,37,122,149). Currently, the surfactant Competitor® and a marker dye BlazeonBlue® are being used in the Hoh River Knotweed Project and have been deemed to be an appropriate, least toxic option by university, community and state agencies working with the 10,000 Years Institute (129).

How does this practice maximize benefits and reduce risk?

- The use of surfactants increases the benefit of knotweed control because they greatly increase the efficacy of the herbicides.
- Coordinating with university, community and state agencies to determine which aquatically approved surfactants and other adjuvants are the least toxic to aquatic organisms reduces risk to non-target aquatic organisms.

Hazards

- Surfactants can be highly toxic to aquatic organism and greatly increase the toxicity of herbicide solutions. Be sure to choose appropriate and least toxic surfactants to use with herbicide applications.

2.1.3d Licensing and Certification of Applicators, Professional and Trade Associations

An Aquatic Plant and Algae Management National Pollutant Discharge Elimination System (NPDES) permit is required for pesticide applications in natural areas. The Hoh River Project is covered through joint permitting with Clallam and Jefferson Counties' Aquatic Noxious Weed Permit. The field crew leader is a commercial licensed pesticide operator with an aquatic endorsement from the Washington State Department of Agriculture (WSDA) (128). The field crew leader has an aquatic endorsement from the WSDA even though in this circumstance an aquatic endorsement is not required (129). The WSDA requires pesticide applicators for the control of aquatic weeds to take an exam for licensing under the category Aquatic Pest Control and well as a core commercial applicators exam (100). Herbicide records for each site and application are maintained by the Institute, and reported through the Clallam County noxious weed board to WSDA. In addition, the Hoh River Project works with the Olympic Knotweed Working Group which provides training workshops for knotweed eradication projects and the project leader is a board member on the Jefferson County Noxious Weed Board (128, 129).

How does this practice maximize benefits and reduce risk?

- Licensing requirements for applicators allow for an enforceable standard that all applicators have the knowledge for safe and effective pesticide applications.
- Affiliations with local associations provide managers with up to date BMPs and environmental issues from other professionals.

2.1.3e Application methods

The herbicides glyphosate and imazapyr can be applied to knotweed by foliar applications made from the air, ground or boat. Stem injection of glyphosate products are also an option. The majority of the Hoh Knotweed Project applications are currently made by ground foliar applications. This is due to the small size of knotweed in the Hoh River CMZ. Stem injections of Aquaneat® or Aquamaster® are made in canes that are 0.5” or larger in diameter, and most stems are now too small to inject. In addition, foliar spray uses less herbicide per stem (129).

Stem injections of glyphosate products are an option but care needs to be taken that the number of stem injections per area does not exceed the maximum rate per unit area allowed by the label. Stem injections of glyphosate have been demonstrated to be as effective as foliar spray, and continued application is often needed for full control, as is also the case for foliar spray. There is a concern that stem injections in areas of sandy soil with hyporheic flow within the plant rooting zone may increase the amount of leaching of glyphosate into the soil which would result in non-target plant exposure as well as other environmental exposure concerns. Therefore, in sandy soil conditions or in areas where knotweed roots may extend to the hyporheos (subsurface water), foliar spray may be a better option (51, 129). Stem injections are useful in areas such as gardens where the method limits the exposure of the other plants while providing direct exposure to the target plant (51). Stem injections of glyphosate in canes that are large enough are also an option when weather conditions such as wind or rain do not allow for foliar spray (43).

Aerial broadcast sprays are recommended in areas where there are vast dense mono-assemblages of knotweed, the weather conditions are correct, and overspray into water can be avoided. Federally mandated aerial buffer zones for imazapyr and glyphosate have not been established, but each state may have its own regulations regarding buffer zones. For example, in Oregon a buffer zone of 60 feet for aerial pesticide application is enforced when near lakes, streams, wetlands and other open areas of water (27). These aerial practices have been evaluated and are considered protective of aquatic biota, human health and water quality (31). Hand and backpack spray are generally more suitable in areas where stands are relatively patchy and treatment can be more localized as to not overspray on native plants or aquatic environments. Aerial applications were not appropriate in the Hoh Knotweed Project; foliar spray by hand or backpack along with stem injections in large stems was deemed to be the most appropriate methods for effective knotweed control. In large dense knotweed stands, the creation of tunnels into the stand every ten feet by bending the canes and NOT breaking them increases access by ground foliar applicators (129).

How does this practice maximize benefits and reduce risk?

- The use of ground foliar spray on plants that are too small for stem injection increases the effectiveness of herbicide application. Also, there is reduced risk of herbicide leaking from rhizomes, as there is with stem injections.
- The preference for foliar spray reduces the amount of herbicide per unit area compared to stem injections and is equally effective.
- The use of stem injections in a limited number of large canes can reduce the risk of drift. Also, it remains an option when weather conditions are poor (rainy, windy) for foliar spray.
- Not using aerial applications in the Hoh River reduces risk of overspray of streams as well as impact to non-target native plants.
- In areas with dense monoculture knotweed infestations, aerial applications with state mandated buffer zones reduce the risk of overspray into aquatic environments, while maximizing herbicide application efficiency.

Hazards

- Using the injection method into knotweed stems that are located in sandy soils or gravel bars may lead to excessive leaching of the herbicide.
- The injection method on knotweed may lead to leakage and leaching of the herbicide when roots/rhizomes extend down to the hyporheos or if the water table will reach the roots/rhizomes within a few weeks after application.
- While applying herbicides, be sure not to break or cut any stems or rhizomes as knotweed can reroot and cutting can stimulate growth.
- Applying herbicides to a small leaf area to knotweed with large rhizomes may reduce herbicide efficacy (129).
- Where a high density of knotweed stems occur, the injection method may lead to over application per unit area.

2.1.3f Equipment and Calibration

Due to the effectiveness of control measures over the past decade, the Hoh Knotweed Project currently uses a hand-held one-liter spray bottle for foliar spray. This is used because the plants are so small and spread out, it is easier to treat just the plant and minimize drift and non-target plant exposure. Also, the small one-liter bottle is easy to use in rough field conditions. A backpack sprayer is used for larger clumps or stands (128). Accurate calibration of equipment is crucial to maintaining appropriate application rates (51). Equipment is calibrated as to give appropriate droplet size to achieve appropriate “spray-to-wet” conditions for foliar spray. Nozzles of spray equipment are adjusted according to weather conditions (temperature and humidity) to give appropriate droplet size. In smaller knotweed stands (50 square feet or less), gaining access as to apply herbicide to tall plants increases application efficacy. A truck tank sprayer where access is possible is used on large infestations and ensures appropriate herbicide coverage on the knotweed (129). The Hoh River applies stem injections of Aquaneat® or Aquamaster® are made in canes that are 0.5” or larger in diameter (128). The equipment used for stem injection is the JK Injection Tool with a short needle, which decreases the occurrence of cane splitting and poking through the entire cane where herbicides can leak out (129). All equipment is triple rinsed at the end of each application day in order to avoid equipment malfunction (128).

The Hoh Knotweed Project does not use aerial spray of their herbicides. Therefore, equipment and calibration recommendations found on the Aquamaster® label are briefly presented in here, due to the importance of proper equipment and calibration in aerial sprays. Nozzles on the boom of the aircraft must not exceed ¾ the length of the wingspan or rotor and must be pointed backward parallel with the air stream. Droplet size is extremely important for increasing efficacy and decreasing drift. Using high flow rate nozzles produces larger droplets which are most practical for aerial sprays. Low spray pressures are recommended to maintain large droplet size. Nozzles type should be taken into consideration and oriented properly (6).

How does this practice maximize benefits and reduce risk?

- The use of hand-held one-liter spray bottle for foliar applications in the Hoh River CMZ maximizes the ability of personnel to transport herbicide to knotweed sites. Also, the use of a spray bottle allows for direct spray to small, scattered knotweed as is currently found in the Hoh River CMZ and therefore minimizes the potential for herbicide drift and environmental exposure risk.
- The use of backpack sprayers in relatively large clumps or stands of knotweed allows for appropriate and even application of herbicide increasing herbicide effectiveness.
- The calibration of adjustment of nozzles for droplet size according to weather conditions increases efficiency of the herbicide application and can reduce non-target exposure.
- Appropriate calibration ensures that the amount of herbicide applied is appropriate and that effective and legal levels are not exceeded.
- Using a short needle with the JK Injection Tool results in a reduction of application difficulties including less stem splitting and not poking through the back of the cane where herbicides can leak out. This increases stem injection herbicide application efficiency and reduces herbicide leakage into the environment.
- The use of appropriate gear and positioning the applicator so they can gain access to dense, tall knotweed stands increases efficacy of herbicide applications.

Hazards

- Inappropriate calibration of foliar spray equipment may lead to herbicide dripping from leaves, which increases risk of environmental exposure especially when dripped into surface water (129).
- Improper calibration and positioning of nozzles for aerial application may lead to increased drift, which increases non-target exposure.

2.1.3g Application Rates

The 10,000 Years Institute always follows the herbicide and surfactant labels and never exceeds the label maximum application rates. During the latest herbicide application in 2010, the Institute used an herbicide solution mix of 3% Aquaneat® (a.i. glyphosate), 1% Habitat® or Polaris™ AQ (a.i. imazapyr), 1.5% Competitor® surfactant and 1% BlazeonBlue® marker dye (128). The concentration of Aquaneat® or Aquamaster® has been increased to 4% in the herbicide solution for 2011. The amount of surfactant used for the Hoh Knotweed Project is usually minimized to 1.5% of the spray solution. The Institute has, in past years, used 6 and 8% glyphosate solutions, but found that these rates were too high and burned the leaves off before the herbicide could be translocated to the rhizomes (129).

Stem injections were applied at 5 mL Aquaneat® per cane in 2010 and will be applied at the same rate in 2011 to any canes that are of appropriate size (great than 0.5”) (128). The label recommends 5 mL injected into the lower node of the plant. An efficacy study found, however, that a 3 mL injection at chest height will produce the equivalent result, which could allow for easier application and less herbicide used (43). Three mL injections of Aquaneat®/Aquamaster® have been tried in previous years in the Hoh Knotweed Project. However, 3 mL has not been as effective as the 5 mL injections on the knotweed in the Hoh River, therefore the Institute has resumed 5 mL injections (129). The evolution of the herbicide solution percentages and the stem injection volumes demonstrates how an effective BMP can use current research and efficacy monitoring to evolve herbicide application practices best suited to the local conditions.

Generally, the maximum recommended rate of herbicide for perennial and woody plant control is recommended for knotweed (51). Some examples of foliar application rates tested to be effective against knotweed are provided in Table 5. The glyphosate application rates recommended for knotweed control are generally well below the 96 hour LC50s for salmonids (149); the imazapyr application rates are well below the 96 LC50s for juvenile rainbow trout and chronic LC50s for rainbow trout eggs (138). See the Glyphosate Known Toxicity to NOAA Trust Species and Imazapyr Known Toxicity to NOAA Trust Species sections of this report (sections 2.2.3 and 3.2.3, respectively) for a more detailed discussion of glyphosate and imazapyr formulation and surfactant toxicity to salmonids and relevance to application rates.

Table 5: Recommended application rates of glyphosate and imazapyr products for the control of knotweed. Adapted from Emanuel et al. (2011).

Trade Name	Active Ingredient	Active Ingredient per Acre	Amount of Product per Acre	Registered for Use Near Water?
Roundup Pro®	Glyphosate	3.75 lb/A	160 oz/A	No
Rodeo®	Glyphosate	3.75 lb/A	120 oz/A	Yes
Arsenal® AC	Imazapyr	1.08 lb/A	34.6 oz/A	No
Stalker®	Imazapyr	1.08 lb/A	69.1 oz/A	No
Habitat®	Imazapyr	1.08 lb/A	69.1 oz/A	Yes
Arsenal® AC + Rodeo®	Imazapyr + Glyphosate	1.08 lb/A + 3.75 lb/A	34.6 oz/A + 120 oz/A	No

How does this practice maximize benefits and reduce risk?

- Never exceeding the legal maximum herbicide application rates reduces risk of exposure to non-target organisms, as determined by the EPA.
- Knotweed is difficult to control, so using the highest recommended herbicide application rate for knotweed control generally increases efficacy, which reduces the need for reapplication in following seasons.
- Monitoring efficacy and adjusting application rates according to experience and field studies, while never exceeded maximum application rates described on the label, allows for increase efficacy of control and reduces risk to non-target organisms by ensuring herbicide is not applied at a rate greater than is needed and also not under applying herbicide so as to reduce efficacy.
- Injecting glyphosate product at the rate recommended by the label (5 mL) maximizes efficacy.

Hazards

- Applying herbicides at high rates will result in leaves “burning” off before the herbicide has been able to translocate to the rhizomes
- Applying herbicides at rates that are too low will reduce efficacy.
- The stem injection method in dense knotweed stand can easily result in exceeding the maximum label rate per acre.

2.1.3h Application Timing

As with other perennial weed control herbicide applications, herbicides are applied in the fall just before the senescence of leaves (approximately 10-30% of leaves yellowed) to ensure that the maximum amount of herbicide is transported throughout the plant, especially to the rhizomes (51). Treatments must also be applied before a killing frost. The Hoh River is located on the west coast of Washington State, and the Institute generally begins herbicide applications in late-August through mid-October to ensure maximum growth of the knotweed for improved identification and control. Applications generally cease in mid-October due to field conditions such as temperature and the onset of the rainy season (128, 129).

How does this practice maximize benefits and reduce risk?

- Applying herbicide in the late summer/fall for knotweed control increases the benefits as it is the best time for maximum herbicide efficacy.
- Ending herbicide applications in October before the rainy season increases efficacy of the herbicide to control knotweed as well as reduces risk of runoff into the Hoh River and its tributaries.

2.1.3i Application Conditions

Herbicide that is applied to stressed plants, such as exposure to drought or epinastic growth from prior herbicide treatment reduces the effectiveness of the herbicide, therefore applying herbicide to stressed knotweed plants should be avoided when possible. However, if it is the end of the season of available application timing and plants are under stress it is recommended that plants still be treated rather than not being treated at all that season (51), unless the knotweed is in a stable location that will not be moved before next treatment (129). Damp leaves or rain shortly after herbicide application will reduce efficacy. The Institute does not apply herbicide to damp leaves and times their applications with weather conditions to increase herbicide efficacy and decrease the risk of runoff (124). It is recommended that glyphosate should be applied on dry leaves six hours before precipitation occurs (111, 129). Cloud cover is not considered to have a significant effect on glyphosate efficacy (51).

Even though aerial application of herbicide is not a suitable option for the Hoh River Project, it can be an option for other knotweed control projects. The weather conditions when applying pesticide by air are extremely influential in pesticide efficacy and non-target exposure. It is recommended that optimal wind speeds are 2-9 mph and that temperatures should be less than 70ºF. Droplets quickly evaporate in hot, dry weather and smaller drops will drift farther. Do not spray in temperature inversion conditions (59).

How does this practice maximize benefits and reduce risk?

- Applying herbicides to dry leaves and avoiding damp leaves or applications within six precipitation increases herbicide efficacy and reduces risk of herbicide runoff into the aquatic environment.
- Applying herbicide to non-stressed, healthy plants increases herbicide efficacy, therefore reducing the amount of herbicide needed to be applied in following seasons.
- Following guidelines for pesticide aerial applications increases herbicide application efficiency and reduces drift.

Hazards

- Spraying wet/damp leaves or right before precipitation will reduce the absorption of the herbicide and its efficacy and increase risk of runoff.
- Spraying with winds greater than 10 mph will increase risk of drift.
- It is generally recommended to treat stressed knotweed than to not treat at all that season.

2.1.3j Mitigation

The Hoh Knotweed Project has mitigation measures in place for if and when a spill happens in the field. After a spill event that occurred far away from the flowing channel and in high organic matter content soil, any material that came into contact with the herbicide as well as plant parts that were pulled away from roots of nearby plants to reduce herbicide exposure was buried (127).

How does this practice maximize benefits and reduce risk?

- A plan for dealing effectively with a spill event reduces the risk of exposure to non-target and aquatic organisms if and when the spill happens.

2.1.3k Monitoring

The 10,000 Years Institute along with their partners monitor knotweed control efficacy by conducting yearly ground surveys to treated sites in the fall late in the growing season and in early summer of the following year prior to beginning treatments. Herbicide application sites are flagged during application and marker dye is used. GIS maps were created from GPS data and are continuously updated with site and density information. New survey sites are located during surveys and are also added due to communications with private landowners about new knotweed infestations. Priority sites are established according to prevalent knotweed stands, persistent large rhizome groups and potential source populations, and are assessed based on winter flow trajectories and extent. Plant height, plant number, cane number and biomass are estimated at each site (128, 129).

How does this practice maximize benefits and reduce risk?

- Monitoring effectiveness of herbicide applications allows for adjustment of product, concentration and application methods that are most effective, enhancing the control effort benefit.
- Surveying every year allows for retreatments when necessary and documents long-term efficacy efforts.
- Working with land owners along the river allows for detection of new infestations and source populations.
- Quantitative methods allow for accurate evaluation.

2.1.3l Storage of Chemical

Herbicides need to be stored in a dry, frost free, well ventilated environment. Currently, the Institute coordinates with the Pacific Coast Salmon Coalition's equipment storage facility and a local private property in a locked protected shed that has some heat in the winter (129).

How does this practice maximize benefits and reduce risk?

- The use of proper pesticide storage reduces the risk of spills and environmental contamination, thereby reducing potential exposure to non-target organisms.

Hazards

- The improper storage of pesticides can lead to human and environmental health risks.

2.1.3m Disposal of Chemical and Equipment

At the end of each day, the crew for the Hoh Knotweed Project triple-rinse equipment such as the injection guns, extra canisters, and hand sprayers, and supplies such as gloves in a gravel driveway miles away from flowing water. The rinsate is captured in a five gallon lidded plastic bucket for use in the spray mixture. Herbicide containers are given to the DNR and triple-rinsed for disposal (124).

How does this practice maximize benefits and reduce risk?

- Rinsing equipment and supplies far away from a flowing water source reduces the risk of pesticide entering the aquatic environment.
- Giving herbicide containers to the Washington DNR for disposal is a safe and responsible practice; the DNR staff are trained and have the logistical means of disposing pesticide supplies and containers, therefore reducing the risk of environmental contamination.

Hazards

- Rinsing equipment in or near surface water can result in environmental contamination.

Acknowledgements: This case study was supplemented with information provided by personal interviews with Jill Silver, Executive Director at 10,000 Years Institute, and Dr. Andy Hulting, Assistant Professor and Extension Weed Management Specialist at Oregon State University. Jill Silver also reviewed this case study.

2.1.4 Hoh River Knotweed Project Case Study Details

The following are Hoh River Knotweed Project details synthesized from project reports and personal communications.

Surveys and maps

The Hoh River knotweed infestation and control efficacy is monitored by surveys using GPS and aerial photographs. Mapping surveys in the CMZ between the river miles 29.5 and 9.5 found 9,600 knotweed canes in 2002 and 18,585 knotweed canes in 2003. The entire CMZ from river mile 29.5 to mouth was resurveyed and mapped in 2004. Surveys are conducted from July to October, late in the growing season, when plants are tall enough to be found in the native riparian complexes (124, 129). Surveys are conducted each year to assess efficacy and update maps. GIS maps were created and continuously updated with density of knotweed plotted on sites (128).

Herbicide treatment

Herbicides were determined to be the only possible method for knotweed control in a riverine CMZ. Glyphosate in the formulation of the products Aquamaster® or Aquaneat® were chosen for this project because they are approved for aquatic use and are considered to have minimal on the aquatic environment. All products used throughout this project are approved for aquatic use, even though none of them were applied directly to the aquatic environment (129). The first herbicide application was made in late summer of 2003. The primary method for herbicide application for 2003 and 2004 was stem injection. Five milliliters per stem was injected into canes greater than 0.75” in 2003 and the dose was lowered to three milliliters per stem in 2004. The injection method in 2003 applied Aquamaster® product by veterinary syringes and hypodermic needles, while the 2004 method used straight Aquamaster® product injected with an injection gun specifically designed for injections (the JK Injection Tool) into knotweed (124). Smaller plants were sprayed with 5% Aquamaster® and the surfactant Li-34®. Some knotweed clumps had some canes that were large enough for stem injection and canes that were too small for stem injection. In those circumstances, the large canes were injected and the small canes were sprayed. The applicators in this project were careful not to exceed the maximum application rate per unit area as described on the herbicide label, even in areas with dense knotweed canes where stem injections can sometimes easily surpass the label rate (129). The number of injections made in 2004 was greatly reduced compared to 2003 because many of the surviving plants in 2004 were too small for cane injection, representing good control of mature plants as a result of the 2003 applications (124).

In 2005, herbicide was applied in August, when plants were fully grown or even flowering (129). Glyphosate treatments in 2005 were again made either by stem injection or foliar spray. Injections into canes 0.5" or larger were made using three milliliters of Aquamaster® injected into the lower node of each cane using the JK Injection Tool. The three milliliter injection method was reported to have reduced efficacy compared to the five milliliter injection. The JK Injection Tool was redesigned with a shorter needle to address problems where the long needles poked through canes was tried that year. Again, foliar applications were made on canes that were too small for injection. Foliar applications were made either by a *Solo* backpack sprayer or a hand-held one liter spray bottle. Foliar spray solutions were 8% Glypro® or Aquamaster® (a.i. glyphosate) with 0.3% surfactant (Agri-Dex®, Li-34® or R-11) and a 0.3% aquatically approved marker dye. Although an 8% solution is a relatively high concentration for river applications, the project wanted to try a higher application rate to see if it would increase efficacy (123). Their goal is to control knotweed with a single application, therefore reducing the overall amount of herbicide used over time (129). Due to the prevalence of short and smaller knotweed plants, the main method of application was foliar spray, which uses less herbicide per area (123).

Herbicide was applied from August to October during 2007. The application methods were the same as in 2005, and again foliar spray was the predominate method. They initially used an herbicide solution of 8% Aquamaster® , 1.5% Agri-Dex® and a marker dye, but after discovery that the 8% solution was killing the foliage too fast without time to migrate to the rhizomes resulting in ineffective control of the plant, the spray was switched to a 6% Aquamaster® and 1.5% Agri-Dex® solution. The 6% Aquamaster® solution was over 99% effective. Overall, only 1.23 gallons of herbicide was used (125).

In 2008, a maximum of 274 stems were treated across 0.11 acres totaling in 0.64 gallons of herbicide used. The majority of applications were made by foliar spray with methods the same as years before. The herbicide solution contained 4% Aquamaster®, 1% Polaris™ or Habitat® and 1.5% Agri-Dex® surfactant were used along with BlazeonBlue® marker dye. Since 2005, they have been noting knotweed resprouting from underground rhizomes some distance away from the original stand of knotweed. This year, with input from the OKWG and WSU, the knotweed project added imazapyr to the herbicide solution in the form of 1% Polaris™ or Habitat® to help increase the transfer of herbicide from leaves to rhizomes. Both Habitat® and Polaris™ are approved for aquatic sites. Imazapyr travels through the plant at a lower rate, acts longer than glyphosate and persists in the soil, so it may have better efficacy at controlling rhizomes. Imazapyr was considered because of these factors, as well as having reportedly no impacts on salmon. Again, stems 0.5" or larger were treated by 5 mL stem injection (126).

Herbicide application in 2009 took place later in the season (mid-August to mid-October) to achieve maximum knotweed growth for better identification and control. A total of 1,000 acres were surveyed in 2009 and of that only 0.025 acres needed treatment. Application of herbicides were made in methods similar to the years before, with the product Aquaneat® (a.i. glyphosate) being injected into stems 0.5” or greater and a foliar spray method of a hand-held one-liter bottle. Again, foliar application was the primary method. The spray solution was 3% Aquaneat®, 1% Habitat® or Polaris™, 1.5% Competitor® surfactant and 1% marker dye. A total of 1.4 pints of herbicide concentrate (in 34.67 pints of water) was applied by foliar application and 1.5 pints of Aquaneat® was applied by injection (127).

During the 2010 season, just 108 plant sites were found in total, and only 304 ft^2 were treated with herbicide. Herbicide solution was applied in the same concentrations and methods as 2009, except a backpack sprayer was needed at three sites for large stands. Five milliliters of Aquaneat® was injected into each cane, totaling in 0.6 pints of Aquaneat® used for injection. The project used a total of 2.8 pints of herbicide in 8.6 gallons of water for 2010 (128).

Up until 2009, herbicides were stored in the Olympic Region Washington Department of Natural Resources in Forks, WA herbicide shed. Currently, herbicides are stored in the Pacific Coast Salmon Coalition’s equipment storage facility and a local private property in a locked protected shed that has some heat in the winter (129).

Efficacy and challenges

Efficacy of each treatment was evaluated each fall the year after treatment. Some sites were able to be monitored a within 20 days after herbicide application and the following spring. Surveys in 2004 of the 2003 herbicide application showed that over 98% of knotweed biomass was reduced (124). The surveys noted that some of the injected plants were able to survive or regenerate and that this may have been due to missed plants. In stands of knotweed with over 100 stems, tracking of which stem had been treated was difficult. Also, plants with large rhizomes that had occasional resprouts survived injection treatment, although this was rare (124). Foliar applications made in 2003 to plants with stems that were too small to be injected resulted in 100% control in areas where plants were dry and remained dry for a period of time after application. Glyphosate that was applied by spray to damp leaves or applications shortly followed by a mist or rain had reduced effectiveness (124).

Effectiveness monitoring in the Hoh River for the summer/fall 2004 applications suggested that knotweed plants were relatively well controlled. New plants were discovered in 2005 due to new areas being surveyed and new deposits made by floods and river migration. Most areas with previous glyphosate applications had fewer knotweed plants. In addition, average heights of knotweed plants decreased from previous years, except at one site, where knotweed detection was difficult and some plants were likely not treated during 2004. Also, the search for new plants that may have propagated by seed became a priority (123).

In 2007, sampling and control treatment were conducted from August to October. Many areas had reduced stem counts, with some areas having as much as a 91% decrease from the original infestation sampled in 2002. One rarely flooded site had no reduction in stem count, but a reduction in biomass. Additionally, due to winter floods, knotweed was deposited further upland than in previous years representing a new area of infestation that was previously knotweed free. New plants were also discovered at some sites which could be due to missed plants in previous years, gravel bar formation and new survey areas (125).

A total of 1063 acres were able to be surveyed in 2008. Results of the 2007 treatment were similar to the previous year, with areas having reduced stem counts and reduced biomass. As in other years, the river showed a significant change in channels and bank erosion from the winter floods, making some areas more difficult to access. Spruce Creek, as in the year before, had new plants deposited further inland from the river due to flood deposits. The stem count at this site was not reduced but plants were shorter and stems were smaller than in previous years. All of the plants except for a patch at the mouth have been previously identified as Bohemian knotweed, but this year two sites of Giant knotweed were discovered. Similar to previous years some sites had an increase in knotweed numbers and this may be due to missed plants either by survey or difficulty of access, gravel bar formation and expanded survey areas (126).

Surveys conducted in from mid-August to mid-October 2009 showed a continuing decrease in knotweed stem count, size and biomass. The survey was conducted later in the season for better knotweed identification and control; 1,000 acres were able to be surveyed. Only one plant was found in the original infestation site, where there had been over 4,000 canes found in 2002. Two large root crowns were relocated with sprouts developing. The crowns were difficult to access and attempted herbicide applications have failed. These crowns are a risk to the project and are to be monitored. Giant knotweed had been identified at new sites in addition to the two new sites noted in 2008. The plants may have migrated from upriver on private property and efforts to gain access were underway (127).

As in 2009, survey and control treatments started in mid-August and went through mid-October in 2010. A total of 1,900 acres were surveyed. Some new priority sites were established from a new connection with a local landowner who provided information on new infestation sites. The variety of knotweed plant height, size, leaf color and leaf shape made detection difficult. Just 108 plant sites were found in total (128).

This project has been highly effective at removing knotweed from the Hoh River. Even though knotweed still persists in small single stem plants that can be found in old and new sites, the occurrence of large, dense patches is rare. Because rhizomes can survive underground for an unknown period of years and the movement and flooding of the river and its tributaries can spread rhizomes, this project aims to continue survey and control methods for several years, and perhaps a decade. The large rhizome clumps that do not produce sufficient leaf area and are not able to be fully controlled by current herbicide applications are capable of producing new sprouts and migrating downriver and pose continuing challenges. The Institute is hopeful that the addition of imazapyr to the herbicide spray mix will help control these large rhizome clumps. They are evaluating the best tools for controlling these large rhizome groups and are considering the potential impact to water due to the location of these large rhizomes. The Institute is aware that glyphosate may leak out of rhizomes, especially with stem injections, and therefore may be less effective at controlling large patches and also may pose risk to native plants. There has been very limited impact on native plants due to the Hoh River Knotweed Project control efforts. The impacts on the native plants were restricted to sites with fine-grained soils and they believe that the benefits of eliminating knotweed far out way the limited impact on the native plants and the Hoh River aquatic ecosystem (20,128).

2.2 Example of Pesticide: Glyphosate

Glyphosate (N-(phosphonomethyl) glycine) is one of the most widely used herbicides with applications in agriculture, forestry, industrial weed control, lawn, garden, and aquatic environments. Glyphosate can be applied as an acid, monoammonium salt, diammonium salt, isopropylamine salt, potassium salt, sodium salt, and trimethylsulfonium or trimesium salt (40). Glyphosate inhibits an enzyme found in plants that is essential for specific amino acid formation (112).

2.2.1 Application rate

Application rates vary by crop, pest and formulation. For example, the maximum application rate for Roundup Pro® is 10.6 quarts of product per acre per year. Roundup Pro® contains 4 pounds per U.S. gallon of glyphosate in the form of isopropylamine salt. This equals 3 pounds per U.S. gallon of the glyphosate acid (112), which yields a maximum of approximately 2.9 ppm of glyphosate A.E. per acre per year. The maximum application rate for Rodeo®, which is approved for aquatic use, is approx 2.97 ppm A.E. per acre per year (8 quarts product per acre, which would be about 6.1 ppm product/acre foot), with single applications not to exceed approx 1.38 ppm A.E. (7.5 pints product/A, which would be about 2.9 ppm product/acre foot) (111).

2.2.2 Degradation rate

The half-life of glyphosate in soil ranges between two and 197 days depending on soil and climate conditions, with a typical field half-life of 47 days. Glyphosate is stable to chemical and photo decomposition. Microbial action is responsible for the majority of the degradation in the soil. Glyphosate adsorbs tightly to soil and is expected to be immobile. The half-life of glyphosate in water ranges from a few days to 91 days and is relatively stable to hydrolysis and photodegradation in water. There is potential for surface water contamination due to aquatic uses and soil erosion. Glyphosate is not expected to volatize due to low vapor pressures ranging from

1.84E-7 to 6.75E-8 mmHg at 25ºC making it stable in air. Very little of glyphosate is metabolized by plants (40).

2.2.3 Known toxicity to NOAA Trust Species

2.2.3a Acute LC_{50}

Acute 96 hour LC_{50s} for juvenile chinook, chum and coho salmon ranged from 10 to 211 mg/L for technical glyphosate (slightly to practically nontoxic) (149). Herbicide formulations containing glyphosate may have different toxicity levels than technical glyphosate due to inert ingredient including surfactants. The formulation Roundup®, which includes a surfactant in the formulation, was slightly toxic to salmonids with 96 hour LC_{50s} for juvenile chinook at 17 to 33 mg/L (149,116), juvenile chum at 11 to 20 mg/L (149), juvenile coho at 13 to 30 mg/L (81,116,122,148,149) and juvenile sockeye salmon at 26.7 to 28.8 mg/L (122). The formulation MON 842 was also slightly toxic to juvenile chinook, coho and chum salmon with LC_{50s} ranging from 23 to 67 mg/L (149). The glyphosate formulation Rodeo® with X-77® surfactant was practically nontoxic to juvenile chinook and coho salmon (acute 96 hour LC_{50} 600-1440 mg/L) (81) and the formulation Vision™ was slightly toxic to juvenile chinook and coho salmon (acute 96 hour LC_{50} 20 and 22.4 mg/L, respectively) (97). Coho salmon smolts were shown to be able to survive and adapt to seawater after a ten day exposure up to 3.2 mg/L of Vision™ (97).

In addition to practically nontoxic and slightly toxic acute effects of technical glyphosate to juvenile rainbow trout, there were some data that showed moderately toxic lethal effects of technical glyphosate (96 hour LC_{50s} of 1.3 to 9.0 mg/L) to juvenile rainbow trout (37,139). The Roundup® toxicity data for rainbow trout generally was consistent with the data for salmon, exhibiting slight toxicity (116,122,148,149) although there was data to suggest moderate toxicity with 96 hour LC_{50s} of 1.3 to 8.3 mg/L (37) as well as practically no toxicity with a 96 hour LC_{50s} of 106 mg/L (122). These within formulation variations are likely due to environmental factors such as water hardness, temperature and pH (37). Other glyphosate formulations that were tested on juvenile rainbow trout but could not be found for endangered/threatened salmonids include MON 77360 which was found to have a 96 hour LC_{50} of 5.4 mg/L (moderate toxicity) (138), 80WDG formulation with a 96 hour LC_{50} of 67.9 mg/L (slight toxicity) and SL Formulation with a 96 hour LC_{50} of 824 mg/L (practically nontoxic) (138). As evident from the available data, the acute lethal toxicity of glyphosate formulations can vary. These differences are likely due to effects of inert ingredients such as surfactants in the formulations as well as varying test conditions.

Roundup® surfactant (MON 0818) was moderately toxic to juvenile chinook, chum, coho and sockeye salmon with 96 hour LC_{50s} ranging from 1.4 to 4.6 mg/L (122,149). Juvenile rainbow trout also exhibited moderate as well as high toxicity to Roundup® surfactant (MON 0818) (37,122). Other surfactants used with glyphosate have varied acute toxicities. Surfactants

Li- 34® and Agri-Dex® are practically nontoxic to juvenile rainbow trout with 96 hour LC_{50s} of 130 mg/L and >1,000 mg/L, respectively. The surfactant R-11 is moderately toxic to juvenile rainbow trout with a 96 hour LC_{50} of 3.8 mg/L (28).

It is unlikely that technical glyphosate will enter the environment as a result of direct application at concentrations high enough to produce an acute lethal effect in salmonids if applied at or below the maximum allowed label rates. However, because the surfactants included in glyphosate formulations such as Roundup® are more toxic to fish than glyphosate itself, strictly going by the maximum application rate of glyphosate may underestimate the risk of these formulation applications to non-target species. Understanding the maximum application rates of the product itself and comparing the toxicity of the entire formulation to non-target species is important when considering exposure and risk. According to Diamond and Durkin 1997, if Roundup Pro® consists of 15% surfactant, which would be 150 g/L, then the maximum application rate would be about 1.21 ppm per acre per year of surfactant (28). This concentration is very near the range of reported 96 hour LC_{50s} for juvenile chinook, chum, coho and sockeye salmon (122,149), therefore surfactants could cause acute mortality at maximum application rates.

There were no acute data found for endangered or threatened steelhead trout, sturgeon, sawfish, Pacific eulachon and rockfish. There were also no acute data found on endangered or threatened cetaceans, pinnipeds, marine turtles, coral, abalone or Johnson's seagrass.

2.2.3b Sublethal and Chronic Toxicity

Glyphosate may have sublethal effects on salmonids' olfactory ability. Exposure to 1, 10, and 100 mg/L technical glyphosate reduced electro-olfactogram response in juvenile coho salmon in a concentration dependent manner and significant decreases occurred more rapidly with increasing concentration. Exposure to 0.1 mg/L had no electro-olfactogram response. Exposure to 10.9 mg/L for two minutes inhibited electro-olfactogram responds by 50% and exposure to 8.17 mg/L for five minutes and longer inhibited electro olfactogram response by 50% (135). Tierney et al. (2007) demonstrated that juvenile rainbow trout were able to detect Roundup® at 0.01 and 0.1 mg/L (concentrations expressed as A.I. of Roundup®, isopropylamine salt of glyphosate), but showed no avoidance at these concentrations. Juvenile rainbow trout had significantly reduced electro-olfactogram after two minute exposure to both 0.1 and 1 mg/L A.I. but had no significant effect at 0.01 mg/L A.I.. In that same study, juvenile rainbow trout did avoid Roundup® at concentrations 10 mg/L A.I. and 100 mg/L, but these concentrations were lethal within 30 minutes of exposure. In addition, exposure to 0.01 mg/L A.I. did not alter preference for L-histidine, but preference was absent at 0.1 and 1 mg/L A.I.. This may be in part due to a reduction in juvenile rainbow trout activity level following 30 minutes exposure to 1 mg/L A.I. (136). Other studies have shown that juvenile rainbow trout did not avoid concentrations of 0.1, 1.0 and 10 mg/L isopropylamine salt of glyphosate (37,38). Threshold avoidance reaction concentrations for juvenile rainbow trout were observed at 54 ppm (Vision™ and 15% surfactant) and 150 ppm (Vision™ and 10% surfactant) (82). These results suggest that salmonids may be able to detect glyphosate at sublethal levels, but do not avoid it. This may interfere with olfactory ability and therefore behavior in juvenile salmonids (136).

Behavior and other sublethal effects may occur during high acute exposures to glyphosate formulations. Juvenile trout displayed erratic swimming and rapid respiration beginning at 13.5 ppm after a 24 hour exposure to Vision™ with 15% surfactant and an erratic swimming and labored respiration was observed starting at 37.5 ppm after a 24 hour exposure to Vision™ with 10% surfactant (82). However, a study testing relatively high concentrations of Vision™ with surfactant (up to 60 ppm) for four hours on juvenile coho salmon showed inconsistent results indicating that there was no major plasma lactate, plasma glucose, hematocrit or leucocrit response to Vision™ with surfactant at levels up to and including 60 ppm (58). Also, an exposure of equal to or less than 2.78 ppm Roundup® for ten days did not significantly alter sodium or hematocrit levels in seawater challenge for coho smolts and did not alter feeding behavior or weight gain (80,116). While there were no significant differences in juvenile coho salmon plasma lactate or plasma glucose levels when exposed to 3.75, 7.50, 37.5 and 60 ppm of Vision™ with 10% surfactant for four hours, there were significant increases in hematocrit concentrations at 3.75 and 30 ppm for four hours as well as a significant increase in leucocrit concentrations at 37.5 ppm for four hours. However, exposures to concentrations both above and below those that exhibited hematocrit and leucocrit concentrations showed no effect. Also, exposures to 1.35, 2.70, 13.5 and 21.5 ppm of Vision™ with 15% surfactant for four hours had no significant effect on plasma lactate, plasma glucose, hematocrit and leucocrit concentrations (58).

No evidence was found for chronic sublethal effects of glyphosate formulations at relatively low doses to endangered salmonids. Juvenile rainbow trout exposed to Vision™ for one and two months of 4.5 and 45.75 µg/L showed no significant differences in ingestion, growth, captures per attack or behaviors such as wig wags and lateral displays (83).

Pesticides are commonly tested for the ability to alter estrogenic activity. Seven days of exposure to 0.11 mg/L technical glyphosate had no estrogenic effect on juvenile rainbow trout. The R-11 surfactant, however, significantly increased vitellogenin (a measure of estrogenic activity) in juvenile rainbow trout after seven days of exposure to 0.73 mg/L and 1.46 mg/L. No observed effect was noted at 0.146 mg/L (152). According the application rates suggest by the R-11 label and Rodeo® label, R-11 can be applied as a 0.5% solution. When applying the maximum rate of Rodeo® (7.5 pints/A) in a solution with 1 or 2% herbicide with 0.5% R-11, the surfactant will be applied at approximately 0.7 ppm. This suggests that while glyphosate may not affect estrogenic activity, the glyphosate formulations that include the surfactants R-11 may have potential estrogenic effects at label rates.

A few studies were found that monitored salmonid populations and responses to direct aquatic over-sprays of glyphosate formulations. A study that intentionally over-sprayed a tributary with Roundup® achieving 1.88 kg/ha (0.62 ppm) application rate of glyphosate resulted in no indication of changes in juvenile coho growth. Any changes in preference for coho fingerlings to use these streams as a winter refuge were inconclusive and there was some suggestion of limited short term stress after application. However, there appeared to be no effect after three years on juvenile coho salmon (47,110). An application of 2.2, 22, and 220 kg/hectare A.I. of Vision™ (0.72, 7.2 and 72 ppm) direct over-sprays showed no observable mortality and no symptoms of stress or physical discomfort in fingerling rainbow trout (97).

2.2.3c *Indirect effects*

Vegetation along riverbanks and lakes provides habitat for juvenile salmon food sources. Removal of this vegetation may reduce prey availability.

2.2.4 Persistence of pesticide in ambient water

Glyphosate is moderately persistence with a half-life of a few days to 91 days and it is relatively stable to hydrolysis and photodegradation. It also has high water solubility (40). There is a potential for continued low level concentrations in surface waters due to soil erosion (40) and low concentrations may have sublethal effects on olfactory ability (135, 136).

2.2.5 Bioaccumulation potential in non-target species

Glyphosate is not stored in the body and rapid excretion from tissues suggests that glyphosate will not bioaccumulate (86). The Log K_{ow} is less than -3.2, and so it has very low affinity to lipophilic compounds (40). Bioaccumulation, therefore, is not expected in non-target species.

Chapter 3

Herbicide Use in a Marine/Estuarine Restoration Context

Estuaries are susceptible points of invasion due to the high introduction rates from ships, ship ballast, currents, aquaculture and estuarine land use. San Francisco Bay has over 230 non-native species which now dominate the ecosystem and Chesapeake Bay now has over 160 non-native species (57). Invasive plants in the estuarine environment have the potential to decrease plant and animal biodiversity, pose risks to the survival of endangered species, shore birds, and alter wetlands, tides and flood control (52, 34). Herbicides may be used in restoration projects involving invasive plant species. Programs that aim to eradicate and control plants species that have invaded marine systems, such as bays and estuaries pose a unique challenge, because herbicides will inevitably end up in the marine surface waters due to proximity and tidal inundation. The BMPs and pesticides implemented in estuarine restorations projects have the potential to influence estuarine habitats and their valuable resources such as endangered and threatened species. This case study on herbicide use in an estuarine restoration context includes the following sections:

1. A case study of the San Francisco Estuary Invasive Spartina Project that highlights their pesticide best management practices for eradicating Spartina complemented with BMPs from Spartina programs in Washington State.
2. A description of imazapyr, a commonly used aquatic-registered herbicide which includes available toxicity information on endangered/threatened anadromous fish.

3.1 San Francisco Bay, California Case Study: *Spartina* Management with Pesticides Applied to a Marine Environment

3.1.1 Background

San Francisco Bay Estuary is a highly diverse, important estuary. It is the largest and most ecologically important site of tidal mudflats and salt marshes in the contiguous western United States (62). The Bay houses important shorebird, mammal, marsh, invertebrate and fish habitat (41). In 1970, *Spartina alterniflora*, a cordgrass native to the east coast of the United States, was introduced by the Army Corps of Engineers to stabilize levees in the Bay. *S. alterniflora* quickly spread to other parts of the Bay and by the 1990's had hybridized with the native Pacific cordgrass, *S. foliosa*, and created a highly invasive hybrid which is now the dominate species of non-native cordgrass in the estuary. *S. densiflora*, a cordgrass native to Chile, was introduced to the San Francisco Estuary in the 1970s as a part of a revegetation effort. It was mistaken for a *S. foliosa* variant and transported from Humboldt Bay**.** *S. densiflora* has spread and remains a challenge to eradicate because it is very persistent, even with herbicide use.

S. anglica, which is a hybrid of *S. alterniflora* and *S. maritime* (a European native cordgrass) is present at one site in the Bay, but it is carefully monitored due to its worldwide highly invasive reputation. *S. patens* is also a native to the eastern United States and is present at one marsh site in the Bay (41). The invasion and spread of non-native Spartina in the Bay has several potential impacts, including: genetic extinction of the only native Spartina on the west coast, *Spartina foliosa*, loss and conversion of tidal flats into meadows, elimination of critical shorebird habitat, inhibition of native marsh restoration, loss of tidal sloughs and channels, increased need for dredging, alteration of beach forming processes, habitat reduction of the endangered salt marsh harvest mouse, elimination of endangered and native plants, creation of mosquito-breeding areas, and acting as a Spartina source to other Pacific Northwest Estuaries (41).

The Invasive Spartina Project (ISP) was initiated in 2000 by the California State Coastal Conservancy to record, monitor and eradicate San Francisco Bay non-native Spartina (62). The ISP coordinates with partners (Conservancy Grant Entities) around San Francisco Bay. The grant entities are: Alameda County Department of Public Works-Flood Control and Water Conservation District, United States Fish and Wildlife Service, California Wildlife Foundation, Friends of Corte Madera Creek Watershed, California State Parks, East Bay Regional Parks District, City of Palo Alto, City of Alameda, San Mateo County Mosquito and Vector Control District, and the City of San Leandro (41). The ISP and its partners implement Spartina monitoring, manual and chemical treatments, site evaluations, and water quality surveys. The goal of the ISP and its partners is to effectively reverse non-native Spartina invasion to the point of eradication in order to protect native cordgrass and other important flora and fauna of the Bay. Due to the highly invasive nature of Spartina, the control costs and the potential threats to native habitats and species, there is no acceptable level of Spartina infestation (62). The ISP has been effective in reducing the number of Bay acres infested by Spartina. Initial survey efforts in 2000 to 2001 estimated that Spartina had invaded about 483 solid acres in the estuary extending over 5,300 acres (118). The solid acres of Spartina infestation was estimated at a maximum in the year 2005 with 809 solid acres. As of 2009, the number of solid acres of Spartina has been reduced to 158 acres. The ISP uses integrated vegetation management and adaptive strategies as part of their plan to eradicate Spartina. This adaptive management approach allows the ISP to respond to changes in Spartina behavior and improvements in survey and treatment methods (41). In addition to their own experience, the ISP uses information and strategies learned from Spartina work in Washington State, particularly the research performed in Willapa Bay.

3.1.2 Introduction to the Invasive Species: *Spartina* spp.

3.1.2a History

Spartina, commonly known as cordgrass, has been invading the pacific coast of the United States since at least the 1800's. As mentioned above, San Francisco Bay now harbors four non-native species of cordgrass (Atlantic smooth cordgrass - *S. alterniflora*, English cordgrass - *S. anglica*, Chilean cordgrass - *S. densiflora*, and salt-meadow cordgrass - *S. patens*) (62). Other bays along the West Coast have established populations of cordgrass. Willapa Bay, for example, was thought to have multiple introduction events of *S. alterniflora* between 1894 and 1920 from packing material or transport containers of eastern oysters. Since the initial introduction, Spartina has spread throughout Willapa Bay (20). Spartina has invaded several other Washington State bays including Grey's Harbor and Puget Sound (101). Some species, like *S. alterniflora*, spread by seed while others spread by spontaneous establishment. A highly invasive hybridization of Atlantic smooth cordgrass with native Pacific cordgrass (*S. alterniflora x foliosa*) was formed through cross pollination and is now a prominent marsh species in the San Francisco Bay area and spreading through wave action (62). Programs in Washington State and California have spent years of vigorous effort to try to stop the spread and eradicate non-native cordgrass (62, 101).

3.1.2b Biology

Standing at a range of one to six feet tall with hollow and hairless stems, Spartina is a rhizomatous, deciduous, perennial grass that grows in salt-water areas (102,132). The size range of all Spartina species is highly dependable on local genetics and environmental factors. The four Spartina species that have invaded the west coast have very similar biologies. The Atlantic smooth cordgrass has distinctive "disk" shaped colonies, but this is not typical when plants are mature (62). The leaf blades of *S. alterniflora* are usually 1/4 to 3/5 inches wide and lack auricles but have ligules that consist of fringed hairs. The flowers are not clearly visible because they grow within spikes at two to three inches long (102). The stems grow from the dense rhizome system in the spring and reproduce by either rhizomes or seed and flower from June to September, although some plants do not flower every year (132). English cordgrass is shorter than Atlantic cordgrass and has a more grayish color. Because Chilean cordgrass is adapted to low marsh environments, they lack the advanced tissues to transport air from the leaves to roots. Salt-Meadow cordgrass has slender stems, rolled leaves, and favors well drained marshes. Spartina are also capable of hybridizing and these hybrids can be highly invasive. The hybrids produce 21 times more pollen than other species, thus allowing for higher fertility rates (62).

3.1.2c Problems

Nonnative Spartina species can be highly invasive and through its mass, height and rhizomes alter both the physical and biological compositions of tidal marshes, mudflats, and creeks (52). Cordgrass reduces biodiversity by out-competing the native plants such as eelgrass (*Zostera marina*) and decreasing ecological functions. Spartina also eliminates habitats for native species by converting mudflats to vegetated marshes and reduces flood control (52). The dense monotypic stands of Spartina turn originally unvegetated mudflats into habitat no longer suitable for use for waterfowl, shorebirds, and some species of crustaceans, mollusks and juvenile fish

(34).

3.1.2d Pathways of introduction

Broken fragments of rhizomes and floating seeds can disperse long distances (95). Wave action is responsible dispersal (62).

3.1.2e Overview of Chemical Control

A mixture of mechanical and chemical control methods have been used, including mowing, covering, and spraying with herbicides with backpack, helicopter, truck, or airboat application (52). The two most commonly used herbicides for Spartina control that are to be included in the soon-to-be-issued EPA General Permit are glyphosate and imazapyr. These herbicides are used with a surfactant and can be sprayed, wiped, or painted on leaves or applied as a paste on cut stems. Glyphosate and imazapyr can also be used in combination. The best time to apply these herbicides is mid-summer through early fall (23).

3.1.3 Summary of BMPs

The San Francisco Estuary Invasive Spartina Project is a good example of direct pesticide application to marine systems where the application of herbicides for the eradication of the invasive species is considered less of a threat that the invasive species itself to the ecosystem and populations of endangered/threatened species. However, due to the area of the San Francisco Bay and the amount of herbicides needed over years of treatment, the herbicides may potentially impact non-target species and their habitat. The ISP uses current research and adaptive management to inform and implement BMPs in order to effectively control non-native cordgrass while protecting and limiting impacts to native species in this important estuary. Below are some Spartina BMPs synthesized from the ISP action plans, treatment, monitoring and water quality reports and general Spartina research and practices. Included are highlights of how these practices reduce risk and maximize efficacy along with hazards of herbicide application, followed by a more detailed description of survey and monitoring methods, treatment history and efficacy and water quality results.

3.1.3a Alternative Methods

Non-chemical methods are used as a part of the ISP BMP. Alternative control methods are used in areas where Spartina infestations are new and small, or after chemical control efforts have reduced Spartina to small patches. Every known method of non-chemical control was evaluated for each site in the ISP and the criteria for determining which control effort would be used included efficacy of Spartina control, human health and safety, environmental damage, water quality impact, feasibility, and cost. The methods that are used in site specific plans include hand-pulling and manual excavation, covering/blanketing, and mechanical excavation or dredging. Manual excavation is achieved by pulling cordgrass plants by hand, spade or other similar tools. This method can remove above ground plant parts, but is ineffective at removing the rhizomes. Manual excavation must be repeated for several seasons to exhaust the rhizomes of resprouting capability. Often, Spartina will sprout back more vigorously once cut or pulled. Disposal of plant fragments is problematic because material that becomes contacted with moist soil will regenerate. The manual method is most effective on isolated seedlings, or young discrete clones. Also, this method is commonly employed on *S. densiflora,* which has discrete shallow roots. It is ineffective on *S. alterniflora* and its hybrid due to the extensive and dense rhizome mats (62). Washington State IPMs recommend pulling out 100% of the plant in cases where the plant is small and isolated (101).

Mechanical excavation and dredging methods use amphibious dredges or excavators working from mats. Another method is maceration of soil and plant remains on site. This method pulverizes the plant material into particles too small to regenerate. Mechanical removal includes removal of rhizomes, so therefore may be more effective than manual removal. A problem with mechanical removal is the ability of the equipment to access the Spartina. Often the equipment is too heavy or can get stuck. There is also the concern of physical disturbance to the marshland (62).

Covering and blanketing of Spartina is done by lying opaque geotextile fabric completely over the cordgrass in an attempt to exhaust the energy and nutrition reserves of the roots. Due to the difficulty of securing the fabric and tidal activity, the use of the blanketing technique is limited. Artificial wrack can be used to cover Spartina, but securing the wrack is difficult. Other methods such as mowing, burning, crushing, flooding and draining were considered but were determined to have significant limitations and are not planned to be used. Herbicides are used at sites where non-chemical methods have been determined to be ineffective, non-feasible or destructive to the environment (62).

Public outreach is also a key component of ISP. The California Coastal Conservancy maintains a website on the project where project documents, information on species identification, the problem, impacts, results, informational brochures, prevention BMPs and newsletters are available to the public (119).

How does this practice maximize benefits and reduce risk?

- The use of non-chemical alternatives inherently reduces the risk that is posed by pesticides.
- Evaluating the potential non-chemical control methods for each site increases the likelihood that appropriate, effective methods will be used.

- Public education and outreach will help prevent Spartina spread and increase public support for the ISP.

Hazards

- Many non-chemical methods for Spartina control can be labor and cost intensive, and may not produce efficacy of similar scale to herbicide use, therefore increasing the number of years that require treatment.
- Many alternative methods can be destructive to marsh and tidal flat habitat, such as the traffic of heavy machinery and widespread dredging and mulching, thereby increasing risk to non-target species
- Improper disposal of Spartina plant fragment during excavation and manual removal may lead to increased spread of Spartina due to its regenerative ability.

3.1.3b Pesticide(s) and Product(s)

Currently, the ISP uses aquatically approved imazapyr in the formulations of Habitat® or Polaris® as the primary method of chemical control, with glyphosate formulations applied at limited sites. Imazapyr is the herbicide of choice because it remains active in the soil longer than glyphosate, rates of application are lower and there is no need to “spray-to-wet” as in glyphosate applications. Also, imazapyr can be applied at low volume applications making sprays by helicopter easier and more effective (62). Imazapyr has been the chemical of choice since it was registered for aquatic use in 2005 because glyphosate is ineffective on Spartina, especially the hybrid *S. alterniflora x foliosa* which represents the majority of the infestation in San Francisco Bay (49,62). Since the ISP began using imazapyr, there have been significant declines in non-native cordgrass throughout the Bay (48). Native marsh grass species such as pickleweed (*Salicornia pacifica*) have been observed to colonize areas treated by imazapyr in Washington State and San Francisco Bay, suggesting that pickleweed is tolerant to imazapyr and/or imazapyr does not persist in estuarine environments (62). Imazapyr has been observed to have reduced mortality efficacy on *S. densiflora* seedlings due to the small leave area, although it will generally stop seed production (41). This is a common problem when applying systematic herbicides to plants with small leaf areas, as not enough herbicide will translocate to the root to produce mortality (101).

The aquatically approved glyphosate formulations used by the ISP are Rodeo® and Aquamaster® (62). Glyphosate has been determined to be ineffective for Spartina eradication in Washington State and San Francisco Bay, but has limited use in areas with particularly sensitive native plants species or in conjunction with imazapyr or used a “brown down” agent to indicate treatment (66, 101). The sediment and salt deposited on Spartina vegetation by the tides inactivates glyphosate, which decreases its efficacy (41). Currently for the ISP, glyphosate is only used at Southampton Marsh and in persistent *S. densiflora* stands. Southampton Marsh has an endangered annual plant, *Cordylanthus mollis mollis*, and there is a concern that imazapyr may suppress seed production, therefore glyphosate is the product used. Persistent *S. densiflora* stands are treated with an imazapyr/glyphosate mixture in the hopes that the combination will increase efficacy (66). Occasionally, glyphosate is used in a mixture with imazapyr as a "brown-down indicator" because the effects of glyphosate can be seen earlier than imazapyr, allowing applicators to monitor if any patches had missed treatment and retreatments could be made that same season. The effects of glyphosate can be seen within 7 to 21 days while effects of imazapyr are noticeable about 2 to 4 weeks after treatment and sometimes is not noticeable until the following spring. In this way, glyphosate is valuable as a season long marker dye for where imazapyr has been applied. It reduces the amount of guesswork involved therefore decreasing the probability of over-treatment or under-treatment of plants (62, 101).

As described in the imazapyr and glyphosate toxicity sections of this report (sections 3.2.3 and 2.2.3, respectively), both chemicals are practically non-toxic to fish. The ISP commissioned an environmental assessment report for the use of imazapyr for the treatment and eradication of Spartina in the Estuary in 2005. The report concluded that there was no significant risk to the estuarine environment from the proposed use of imazapyr (71). Water quality monitoring reports over the years have resulted in concentrations of imazapyr and glyphosate to be well below the acute toxicity thresholds for anadromous fish (64). Due to flushing and dilution by the tides, chronic exposures of glyphosate and imazapyr are not expected (71).

How does this practice maximize benefits and reduce risk?

- Imazapyr is the most effective herbicide for control and is applied at lower rates than glyphosate, which reduces the amount of pesticide entering the environment.
- The use of imazapyr also seems to promote the recolonization of pickleweed, an important native marsh grass.
- The use of glyphosate at sites with endangered native plants decreases the risk of reducing the native plant's seed production.
- The use of glyphosate in the herbicide mixture as a "brown down" indicator maximizes the ability to track where herbicides were treated and what areas may need retreatments later in the season.
- Both imazapyr and glyphosate are approved for aquatic environments and are practically non-toxic to fish, reducing impacts to wildlife and endangered/threatened anadromous fish.
- The production of an environmental assessment reduces risk by outlining potential risks of applying herbicide and can result in necessary mitigation strategies.

Hazards

- Imazapyr is toxic to many grass species, so care must be taken not to apply to native marsh grasses.

- Glyphosate also has the potential to harm native plants, so care needs to be taken not to overspray on desired vegetation.

3.1.3c Adjuvant(s)

Surfactants are often needed to increase the efficacy of herbicides, but can also be highly toxic to fish (28,37,51,122,149). Therefore, care is needed when choosing a surfactant for use in and near aquatic and marine systems. The surfactant Competitor®, which is a methylated seed oil, is used by the ISP. It has been determined by Washington State to be an effective surfactant, especially when the "dry time" of the leaves is less than six hours. From the ISP's experience, the surfactant lecithin product, Liberate® has also shown to be highly effective. In addition, Liberate® is a drift retardant, therefore making it an attractive option. Both of these products are approved for use with imazapyr and glyphosate and are the only products currently used by the ISP. The ISP did however consider the surfactants LI-34®, Agri-Dex®, Dyne-Amic® and Kinetic®. Based on research and experience, Liberate® and Competitor® are deemed to be the preferred choices, however, the ISP does state that it may use LI-34® in formulations of glyphosate to properly balance the pH when necessary. The ISP also uses the colorant Blazon® as a spray pattern indicator which is considered to be nontoxic (62). In Washington State Spartina eradication programs, Competitor® is the surfactant of choice although Agri-Dex® surfactant is preferred some programs (101).

How does this practice maximize benefits and reduce risk?

- Using non-toxic, effective surfactants increases efficacy of the herbicides while reducing risk to non-target organisms.
- Surfactants that are also drift retardants increase the efficacy of the herbicide application.
- The evaluation of several available surfactants results in informed decisions of efficacy and risk.

Hazards

- Surfactants may still increase the toxicity of herbicide formulations, so monitoring their use is important for evaluating any potential risks and impacts. Be sure to use the least toxic surfactants.

3.1.3d Licensing and Certification of Applicators, Professional and Trade Associations

The state of California requires all pesticide applicators to be licensed, and certifications are needed for restricted use pesticide applications and supervisions. Air craft pilots for pesticide applications must also be licensed. Licensing and certification is through the California Department of Pesticide Regulation. Requirements for licensing and registration include exams in appropriate categories and continuing education classes and workshops for recertification. Renewal of licenses and certifications is required every two years (17).

The ISP partners are very diverse and represent various agencies and vegetation management contractors through the nine counties in the Bay area. These partners have a variety of affiliations with several professional associations in noxious weed science, wetland ecology, vegetation management, mosquito abatement as well as regional groups such as the San Francisco Bay Joint Venture (62).

How does this practice maximize benefits and reduce risk?

- Licensing and certification requirements for applicators allow for an enforceable standard that all applicators have the knowledge for safe and effective pesticide applications.
- Affiliations with professional associations provide managers with up to date BMPs and environmental issues from other professionals.
- Continuing education courses and required renewal help applicators to minimize human error, increase application efficacy and decrease potential environmental risks.

3.1.3e Application Methods

Herbicides are applied by backpack sprayers, trucks, amphibious tracked vehicles, boats, airboats and helicopters. The major considerations for which application methods are used in what areas are: accessibility, effectiveness, cost and reduction in non-target and water exposure. The application method(s) used are site-specific. Manual spray methods such as backpack sprayer and sprayers from trucks allow for direct herbicide application to invasive plants while minimizing exposure to plants and water surfaces. However, many of the cordgrass mash and tidal flats are unable to support the weight of a person, therefore methods requiring applicators to walk on the marsh or tidal flats are not an option. Applications by amphibious tracked vehicles and boats allows for spot treatments in areas inaccessible by foot or truck, while still limiting the amount of herbicide directly applied to non-target vegetation and water (62). Applications by boat are considered in areas that are deemed to be particularly sensitive to physical disturbance by heavy machinery on the marsh or mudflat (120). Airboats are also useful for transporting applicators across marshes and mudflats where crossing by foot can become difficult or dangerous, leading to increased access to Spartina sites (41). Aerial applications are of the greatest concern for herbicide drift and overspray and are made in areas with dense cordgrass infestations where there is little native vegetation present (62). Aerial applications are made according to the product label and supplemental label for Aerial Application in California Only. Aerial spray drift reduction advisory information and recommendations are followed (120). Aerial applications were used extensively during the beginning of the ISP because they allowed for relatively quick and effective herbicide application to the majority of Spartina sites which consisted of large monoculture patches. Aerial applications are now limited due to the successful control of large Spartina patches earlier on by aerial application; most patches are now too small for aerial application. Therefore, aerial applications are being phased out and replaced by spot ground applications (41). This is also preferable because ground treatments have been shown to be positively correlated with increases in plant diversity over treatment years, while aerial applications have no such correlation (48). Each partner (grant entity) is responsible for applying herbicides or contracting for herbicide application. Herbicides will be applied by California Department of Pesticide Regulators-certified applicators or persons under their direct supervision (120).

How does this practice maximize benefits and reduce risk?

- Site-specific tailored application methods increase efficacy of control at each site, as well as reduce non-target exposure.
- Ground applications allow for enhanced precision of herbicide treatment which reduces non-target and environmental exposure.
- Amphibious vehicles and boats allow for access to tidal flats that are inaccessible by foot.
- Applications by boat reduces the physical impact applicator traffic has on the tidal flat and marsh.
- The switch from aerial to ground applications now that Spartina is more sparsely scattered across Bay sites reduces risk of non-target exposure due to drift that is inherent from aerial sprays. This is a good example of adaptive management.

Hazards

- Ground applications may reduce potential drift compared to aerial applications and provide for more precise control, however, physical disturbance by foot traffic or machinery may be damaging to the tidal flat. Also, even with amphibious vehicles and boats, full access may not be achievable at some sites, therefore reducing efficacy.

3.1.3f Equipment and Calibration

The amphibious tracked vehicles include the Argo, Hydrotraxx and MarshMog. Amphibious tracked vehicles are valuable because they allow for ground access in areas that cannot be reached by foot or truck. Also, they are able to carry 25 to 50 gallons of herbicide solution depending on the model, which reduces the need for applicators to walk back and forth to refill. This decreases the amount of foot traffic on the marsh, increases safety and increases efficiency. The Argo and Hydrotraxx are small one-to-two person vehicles. The MarshMog is a larger vehicle which is a Bombardier snowcat with an enclosed cab, GPS-automated controls, an extendable boom and hose applications. It has a ground pressure of 0.6 lbs/inch^2. Trucks are used by parking them on nearby levees or upland sites and applying herbicides from an attached hose (63). The equipment for aerial applications is either a boom sprayer or a spray ball attached to a helicopter. The boom may be shortened for areas of small cordgrass patches to limit the amount of overspray (62). All applicators are licensed and are educated on how to appropriately calibrate equipment in order to achieve desired application rates. Aerial and spray equipment nozzles are calibrated to produce low pressure large droplets in order to reduce drift. Each applicator will take into consideration droplet size, nozzle pressure, number of nozzles, nozzle orientation, nozzle type, boom orientation and application distance (120). Spray pattern, deposition and the amount of active ingredient that reaches the target leaf surface are among the most important considerations when calibrating and applying herbicides (101).

How does this practice maximize benefits and reduce risk?

- Amphibious vehicles can carry larger volumes of herbicide solution, which reduces the physical impact of back-and-forth refill traffic on the marsh and also increases efficiency.
- Amphibious vehicles increase marsh accessibility.
- Appropriate calibration of nozzles, droplet size and distance increases herbicide application efficacy and reduces drift.

Hazards

- Amphibious vehicles and foot traffic may still pose some disturbance to the tidal flats.
- Improper calibration of equipment will reduce efficacy of application and increase risk of drift.

3.1.3g Application Rates

The ISP applies imazapyr and glyphosate products in accordance with the product labels. For aerial applications, imazapyr is applied in a solution of 5% or 7.5% Habitat®, which is 96 oz (six pints) of product/A in 15 or 10 gallon solution/A (66). This results in a maximum application rate of 1.5 lb a.e./A or 0.55 ppm of imazapyr. Most hand-held high-volume sprayer applications of imazapyr were made by using solutions of 0.52 to 0.75% Habitat® applied at about 100 gal/A which results in application rates of 1 to 1.5 lb a.e./A. Now that Spartina no longer occurs in dense stands in the Bay due to the success of the program, high-volume sprays are no longer used (66). Low-volume directed sprays of imazapyr are applied at solutions of 0.7 to 3% Habitat® at 20 gal/A resulting in application rates of 0.3 to 0.6 lb a.e./A (0.11 to 0.22 ppm) (62). Most ground applicators now apply imazapyr product solutions at about 3% (41,66). High-volume sprays are most appropriate over medium Spartina stands, while low volume sprays are should be applied over smaller Spartina stands (101). Most Washington State eradication programs recommend applying imazapyr products at four to six pints per acre, which is the maximum label rate. The application rate depends on what level of control is desired. For complete eradication, the best way to use imazapyr effectively and use the least amount of herbicide possible is to apply at four to six pints per acre so retreatment is less likely to be needed the next year. In programs with vast amounts of Spartina acreage and limited funding, applying three to four pints of imazapyr per acre over the entirety of the Spartina meadow will be more effective then applying six pints per acre over a portion of the meadow. Leading edges and outlier populations of Spartina should be targeted for eradication at six pints as to stop spread. As the amount of Spartina has dramatically decreased in Washington State programs, they now use six pints to be sure that when Spartina is found, the treatment will be effective with just one season of control. It is important to note, however, that imazapyr rates may be different depending on site specific efficacy. Some areas in Washington State have had good control Spartina control with four pints per acre, and therefore did not feel the need to increase to six pints. This is highly dependent on site and stage of eradication. For control programs not aiming for eradication, a reduced application rate may be used (101). However, repeated herbicide applications will most likely be needed in the future to maintain desired control levels.

Presently in the ISP, glyphosate is applied in herbicide solutions of 2% Aquamaster. Very little glyphosate has been used over the past six years and therefore has not exceeded maximum application rates. Glyphosate as 2% Aquamaster solution is either used alone or in combination with an imazapyr solution at limited sites (66). Washington Sate Spartina eradication programs have used 2 to 8% glyphosate. Higher rates of herbicide, particularly glyphosate, were used earlier on in the program when many acres were being treated because estuarine water was being used for the mix solution. The salt in the water deactivates much of the glyphosate, so higher rates were needed to achieve brown down. Mixing with freshwater or distilled water greatly increases efficacy of glyphosate and is more common practice now that less acres are needed to be treated. Glyphosate is in not as effective as imazapyr, so it is encouraged that if glyphosate is to be used in conjunction with imazapyr it should be applied at 2% mixed in freshwater/distilled water or preferably no glyphosate at all (101). The surfactants used by the ISP are usually applied at 1% (62) and the marker dye is applied at a 1% solution or less depending on the preference of the applicator (66).

The imazapyr application rates recommended for Spartina eradication are well below the 96 LC50s for juvenile rainbow trout and chronic LC_{50s} for rainbow trout eggs (138) and glyphosate application rates are well below the 96 hour LC_{50s} for salmonids (149). Results from the ISP Water Quality Monitoring Program reports suggest that the application rates of imazapyr and glyphosate and the resulting aquatic doses do not exceed the toxicity thresholds for mammal, birds, fish or invertebrates (64).

See the Glyphosate Known Toxicity to NOAA Trust Species and Imazapyr Known Toxicity to NOAA Trust Species sections of this report (sections 2.2.3 and 3.2.3, respectively) for a more detailed discussion of glyphosate and imazapyr formulation and surfactant toxicity to salmonids and relevance to application rates.

How does this practice maximize benefits and reduce risk?

- The application of imazapyr at the maximum application rate is generally most effective, and can reduce the need for retreatment in following seasons.

- Adaptation of rates between sites and throughout the evolution of the program allows for the development of the lowest rate with the greatest efficacy.
- When herbicide volume is limited, treatments of entire Spartina meadows at lower rates are more effective when compared to partial meadow treatments at higher rates.
- Applying maximum imazapyr rates to colonizing, leading edges and outlier Spartina populations reduces the risk of spread in following season, thereby reducing the amount of herbicide needed in the future.
- Both rates of imazapyr and glyphosate that are used do not lead to surface water concentrations that are acutely lethal to anadromous fish.

Hazards

- The efficacy of particular rates may be site and species specific.
- Mixing herbicide solutions with estuarine water decreases herbicide efficiency, particularly glyphosate, which then requires greater application rates.
- High herbicide solution concentrations of glyphosate in freshwater or distilled water may lead to leaf burn-off and decrease effectiveness of the herbicides (101).

3.1.3h Application Timing

The ISP applies herbicide in the summer and early fall, when Spartina is large and actively growing. This allows for increased efficacy of herbicide. Also, in San Francisco, there is little rainfall in the summer, therefore reducing the chance of postponement of treatment and runoff into surface water. Herbicides are applied during a falling tide, preferably as soon as plants are exposed, which maximizes herbicide contact with the plant before tide inundation and decreases the amount of herbicide entering the water (41,101). The most suitable tides for herbicide application in the Estuary occur from June, July and August, with September and October having limited opportunities (41). Prior to 2008, due to the presence of the endangered California clapper rail (*Rallus longirostris obsoletus)*, the majority of treatments were unable to proceed prior to September 1st, when the breeding season ended. Based on a biological opinion produced in 2008, the treatment timing was extended up to three months, allowing for treatment to commence during summer, which is when herbicide treatment is most effective (41). If treatments are applied too late in the season, Spartina are able to drop viable seeds which then contribute to forming new populations (48). Experience in Washington State reveals that surveys earlier in the season beginning in June allow for evaluation of plants, followed by treatments a few weeks later applied to plants with larger leaves increases control effort efficacy. Also, new plants may reveal themselves later in the season. However, vast acres of land and limited manpower may not always be available for a pretreatment survey (101). The ISP has been improving survey methods to be able to provide the control programs with more same season survey data (41).

How does this practice maximize benefits and reduce risk?

- Applications in seasons when growth is dense and vigorous increases herbicide efficacy.
- Timing applications with the start of the receding tide and applying as soon as Spartina is no longer inundated increases herbicide contact time and reduces the amount of herbicide entering surface water.
- Spartina surveys prior to treatments increase treatment efficacy.
- Allowing the treatment season to begin in June during the clapper rail breeding season allows for much increased efficacy.

Hazards

- Applying herbicide too late in the season may result in Spartina plants producing and dropping viable seeds, which contribute to new populations.
- Applying herbicides too early in the season may reduce treatment efficacy and miss any plants that sprout later in the season.

3.1.3i Application Conditions

When rain is forecasted, herbicide applications are postponed. Herbicides are sprayed during low wind conditions (less than 10 mph) to minimize drift (62, 120). During the summer in the Estuary, there are light morning breezes followed by gusts of wind starting as early as 10 am, therefore, most herbicide activities are stopped by noon or 1 pm (41). Also, aerial applications will be avoided in conditions of temperature inversion and low relative humidity, which can increase droplet evaporation (120). Herbicides are also most effective when applied to healthy, vigorously growing plants, so applications to damaged, unhealthy plants may reduce efficacy. Treatments of small plants with large root mass results in reduce efficacy. Plants that have begun to senesce also have reduced uptake. It should be left up to the applicators' experience and professional judgment to determine whether or not treatment of unhealthy Spartina will commence, since the decision will often depend on Spartina species and other site-specific conditions. The decision not to treat should be followed by a type of manual control such as plant removal or seed clipping (101).

How does this practice maximize benefits and reduce risk?

- Postponing herbicide applications when rain is forecasted reduces the risk of runoff as well as increases the herbicides efficacy.
- Planning herbicide activities around known wind pattern conditions increases efficacy and reduces the risk of drift.
- Halting spray activities during a temperature inversion and low humidity reduces risk of non-target and environmental exposure through droplet evaporation and drift.
- Treatment of appropriately sized, healthy plants increases treatment efficacy.

Hazards

- The treatment of wet, senescing or unhealthy plants reduces herbicide efficacy and if unavoidable, treatment should be left to the applicators' judgment with considerations of Spartina species, site-specific conditions and manual treatments.

3.1.3j Mitigation

The ISP has identified mitigation strategies to address potential impacts in water quality of the San Francisco Bay area. Because herbicides will inevitably enter surface water due to tidal inundation, the ISP will apply herbicides during a receding tide and avoiding precipitation events. Applicators have the proper licensing and training for herbicide applications. In addition, the ISP is covered under the Statewide NPDES Permit for the Use of Aquatic Herbicides and conducts studies to determine the potential impacts of the herbicide solutions being used. Also, adaptive management will be used to determine and adjust herbicide solutions to ensure maximum Spartina control efficacy while reducing impacts. To mitigate the impacts of herbicide spills, the ISP requires herbicides and adjuvants to be stored on-site only if an approved spill prevention and containment plan is in place. Only areas that are protected for the minimization of chemical spread may be used for mixing and filling operations. Herbicide containers larger than 2.5 gallons must remain in the staging area(s) at a suitable upland site. Spill response plans must be in place to ensure herbicide does not enter the marsh or surface waters. The ISP employs equipment that uses gasoline and other fuels, which if spilt, can cause water quality impacts. As part of their mitigation, the ISP requires that all fuel be stored off-site and that transport equipment may not be fueled on-site. Hand-held gasoline powered equipment may be fueled on-site with precautions. Spill preventions and management plans must be in place (62).

Site specific plans (SSPs) are written to include consideration of endangered species. Each site plan is required to identify any endangered species that is present within the site and specify measures that will be taken to avoid and minimize potential impacts (41). For each SSP there is an attached mitigation checklist, which are required to be incorporated into the work plans and to be submitted upon completion of each treatment to the ISP and signed by a supervisor. This ensures that mitigation techniques will be appropriately applied in the field. Any failure to comply with the mitigation measure is reported the ISP and California Coastal Conservancy who will then consult with the relevant agency to determine a course of action (42). The mitigation and conservation measures on the checklist include more mitigation measures that are mention above and include geomorphology and hydrology, water quality, biological resources, air quality, noise, human health and safety, visual resources, land use, cultural resources, and cumulative impacts (120).

How does this practice maximize benefits and reduce risk?

- Proper mitigation strategies for minimizing herbicide entry into surface water reduce risk to aquatic organisms.
- Adaptive management strategies for herbicide methods and rates will increase treatment efficacy and reduce environmental impact.
- Mitigations and plans for spill prevention and control reduce environmental exposure risk.
- Storing fuel and restricting areas for fuelling reduces the risk of a fuel spill.
- Site-specific mitigation checklist and measures allow for tailored strategies for each site, which will reduce risk of impacts.
- Accountability for mitigation measure and appropriate disciplinary action increases the likelihood that mitigation measures will be followed.

3.1.3k Monitoring

Estuary-wide Spartina monitoring began in 2000, with yearly monitoring efforts starting in 2005. The purpose of the monitoring program is to track the Spartina infestation over time for analysis and also to map sites to inform treatment efforts. From 2004 to 2008, permanent plots were maintained to evaluate the effectiveness of control treatments, particularly imazapyr treatments. Imazapyr was found to be more effective than manual methods and glyphosate applications. Results from these plots showed a decrease in Spartina stem density with increasing imazapyr treatment years. Ground applications of imazapyr also were positively correlated with plant diversity. However, aerial treatments had no correlation, and this was thought to be due to the higher precision of ground treatments to non-native plants (48). The current efficacy monitoring program involves photographing 146 locations which are representative of marsh types and treatment methods. Photos are taken starting in late May to provide information on the previous year's treatment efficacy as well as inform treatment methods that may be appropriate for the upcoming treatment season. Photos are repeated later in the season to record immediate effects of treatments. Photographers find the photo points using GPS and take photos at consistent angles. In addition to photos, maps are created using GPS to collect point, line and polygon data containing Spartina species and percent cover using ArcPad software. Sites are accessed by walking, boating, kayaking and helicopter and are done in ways that are most efficient, thorough, cost-effective and least destructive (48). The monitoring program surveys over 69,000 acres in San Francisco Bay. Due to the amount of man hours required to map all sites, it is often not feasible for the control program to get same year data from the monitoring program. To help with this problem, helicopters are flown 15-25 feet above the marsh and pause at spots over non-native Spartina for GPS recordings. This is an improvement of accuracy from the previously used aerial infrared surveys which became less reliant when Spartina stands became smaller, and freed up time so more sites could be evaluated and reported before treatment began that same year. In 2009 the ISP began treatment surveys at pilot sites, which are aimed at recording treatments, navigating applicators to previously known Spartina sites and assisting with hybrid identification (41). This effort was expanded in 2010 and 2011 and monitors use ArcPad in GPS units to access current year's inventory data, historical inventory data and genetic results. As many site detections approach zero, the treatment monitors are a crucial part to achieving eradication (66). Samples of Spartina are taken for genetic analysis to help with correct identification and monitoring of the Spartina species and hybrids. Sites with successful Spartina eradication will be assessed for revegetation and restoration (41).

Also a part of the ISP is a water quality program, which involves taking samples at 10% of the total treatment sites. Site types are categorized into four representative site types: Type I: tidal marsh, microtidal marsh, former diked byland, backbarrier marsh; Type II: fringing tidal marsh, mudflats, and estuarine beaches; Type III: major tidal slough, creek or flood control channel; and Type IV: urbanized rock, rip-rap, docks, ramps, etc. The water quality program sampling is mandated by the Statewide NPDES Permit. Samples are taken 24 hours prior to treatment, during treatment (about two to six hours immediately after treatment, depending on when the tide comes in) and 7 days post-treatment. These samples are evaluated for imazapyr, glyphosate, the glyphosate metabolite AMPA, and water quality parameters such as dissolved oxygen, turbidity, salinity, temperature, pH and conductivity. Based on the results of the past six years of water quality data, the field water concentrations of imazapyr and glyphosate do not pose a significant threat to wildlife in the Bay. In addition, the concentrations of imazapyr are commonly reduced by over 95% one week after treatment and glyphosate concentrations are often below the detection limit. There also appears to be no effect on water quality (62, 64). Details including methods and yearly water quality monitoring results can be found in the Case Study Details section (section 3.1.4) of this case study as well as in the Water Quality Monitoring Reports available on the ISP website.

How does this practice maximize benefits and reduce risk?

- Evaluating the effectiveness of treatments in permanent field plots for four years allows for quantitative data for adjusting herbicide formulations, rates and treatment methods, which increases the efficacy of the program.
- Annual monitoring allows for long-term invasion and treatment history, and efficacy data as well as informs same season treatment methods.
- The use of GPS and GIS equipment provides reliable maps which increases treatment efficacy.
- Adaptive strategies for monitoring increases monitoring efficacy and decreases the amount of hours and manpower needed. It also provides for more same season pretreatment data to be utilized.
- Sampling of Spartina for hybridity allows for evaluation of treatment efforts, population changes and field identification errors.

- Water quality data inform the program of the actual field concentrations of herbicide entering surface water. This evaluation will decrease risk to aquatic organisms as it allows for adaptations if concentrations surpass aquatic organism thresholds.

3.1.3l Storage of Chemical

Herbicides and adjuvants are stored according to specific label instructions and general rules listed in the ISP Action Plan appendix. These rules include storing the chemicals in a locked, dry, cool, well-ventilated shelter. Chemicals are not exposed to extreme heat or cold. Absorbent material and plastic containers are available in case of a spill. The storage facility and containers are inspected regularly for leaks and spills (62).

How does this practice maximize benefits and reduce risk?

- The use of proper pesticide storage reduces the risk of spills and environmental contamination, thereby reducing potential exposure to non-target organisms.

Hazards

- The improper storage of pesticides can lead to human and environmental health risks.

3.1.3m Disposal of Chemical and Equipment

Chemical containers are disposed of according to the guidelines provided by the ISP Action Plan rules for container disposal. They require that containers be disposed of according to government regulations or be returned to the manufacturer. Containers may be triple-rinsed with water and the rinsate emptied into an appropriate receptacle and rinsed containers may be disposed of in a landfill approved for pesticide disposal if allowed by the government (62).

How does this practice maximize benefits and reduce risk?

- Proper disposal of herbicide and rinsate reduces the risk of environmental contamination.

Hazards

- Rinsing equipment in or near surface water can result in environmental contamination.

Acknowledgements: This case study was supplemented with information provided by personal interviews with Drew Kerr, San Francisco Estuary Invasive Spartina Project Treatment Program Co-Manager, and Chad Phillips, Washington State Department of Agriculture Spartina Program Coordinator.

3.1.4 San Francisco Estuary Invasive Spartina Project Case Study Details

The following are ISP details synthesized from treatment, monitoring and water quality reports, action plans, programmatic and environmental assessment reports and personal communications.

Partners, Permits and Regulations

The ISP coordinates with partners (Conservancy Grant Entities) around San Francisco Bay that receive grants from the State Coastal Conservancy for Spartina control and they assist with planning, coordinating and implementing treatment efforts. Each partner is responsible for particular sites. The grant entities are: Alameda County Department of Public Works-Flood Control and Water Conservation District, United States Fish and Wildlife Service, California Wildlife Foundation, Friends of Corte Madera Creek Watershed, California State Parks, East Bay Regional Parks District, City of Palo Alto, City of Alameda, San Mateo County Mosquito and Vector Control District, and the City of San Leandro. The ISP assists the grant entities in acquiring necessary permits by preparing documents such as the Programmatic Environmental Impact Statement and Report, Programmatic Biological Opinion and the National Pollutant Discharge Elimination System (NPDES) Permit. The ISP also assists to be sure that Federal, State and local permitting requirements are met (41).

Surveys, Maps and Monitoring

An Estuary-wide monitoring program began in 2000, with yearly monitoring starting in 2005. The purpose of the monitoring program is to track the Spartina infestation over time for analysis and also to map patches to inform treatment efforts. Maps are created using GPS to collect point, line and polygon data containing Spartina species and percent cover using ArcPad software. Sites are accessed by walking, boating, kayaking and helicopter and are done in ways that are most efficient, thorough, cost-effective and least destructive (48). Coordinating the Spartina monitoring program with the treatment program has been difficult in past years, due to the sheer size of the Bay, the amount of time it takes to survey, and the amount of time it takes to put together a report. Estimating the amount of Spartina in the Bay has always and continues to be a challenge. Earlier in the program when there were large vast stands of Spartina, aerial photographs using infrared to estimate the amount of Spartina coverage were taken to supplement ground crews which couldn’t survey the entire Bay. Prior to June 2008, monitoring could not begin in clapper rail sites before September 1st which meant that sites couldn’t be monitored before treatments. Monitoring season coincides with treatment season and due to the man hours required for monitoring and compiling data, same year monitoring data for treatment protocols was only partially available. In 2008, the Monitoring Program began using small helicopters that fly about 15-25 feet over the marsh and take GPS site recordings above Spartina stands. This reduced the amount of time spent monitoring and helped to catalog data before treatment commenced. The biggest factor contributing to improved data collection and analysis of Spartina monitoring was the allowance of ground surveys to commence earlier in the season, allowing for more survey time (41). Currently, monitoring takes place from May to December with the majority done between mid-June and mid-October (48). Crew continue to refine monitoring methods and low staff turnover has meant a high percentage of crew with the knowledge to identify and map cryptic Spartina hybrids. Information from surveys is put into GIS for acreage estimation. Data is logged an analyzed using ArcPad, which allows users to download GPS files in the field to find past Spartina sites (48). Survey methods will continue to be modified as the non-native Spartina population continues to decrease and becomes harder to find (41). The ISP monitoring program has also collected samples starting in 2000 for testing to determine the hybridity of Spartina in the Bay. The RAPD-based and microsatellite genetic testing is used to confirm taxonomic field identification, due to the difficulty of identifying Spartina species and hybrids (48).

In order to assess efficacy of treatment methods for each season and over the years, photographs are taken at 146 locations which are representative of marsh types and treatment methods. Photos are taken starting in late May and are used to inform the ISP Control Program about Spartina locations and possible treatment methods. Photo locations are found using GPS and are taken at the same direction and angle every year. Another set of photos are taken later in the season in the same manner to assess the same season's treatment methods efficacy and impact (48).

In 2009, the ISP began treatment surveys at about ten sites. The ISP monitors walk along with treatment crew and help navigate them to previously known locations Spartina stands as well as record where treatments were applied. This will help treatment crews to get as near as 100% treatment of non-native Spartina in a marsh, as well as correctly identify hybrids (41). The treatment monitoring effort was expanded in 2010 and 2011. Monitors run ArcPad on GPS units and display the current year's inventory data, historical inventory data and genetic results (66). Sites with successful Spartina eradication will be assessed for revegetation and restoration (41).

Site Evaluations

The ISP coordinates with US Fish and Wildlife Service, local landowner and managers, and other grant entities to develop site-specific plans (SSPs) which are updated about every two to three years taking in account what was learned from previous years' treatment efforts. Currently, there are about 26 SSPs, with many having several sub-areas with individualized plans. This is because each site and sub-site may differ in what is appropriate for treatment methods depending on environmental conditions, non-target species present, and stage of eradication. Each site is evaluated for management need, feasibility, endangered species, threats posed by non-native Spartina, impacts Spartina may pose on cultural and visual resources and impacts to adjacent land uses (41).

Treatment History and Efficacy

The site-specific plans that are developed for each site describe the treatment method, equipment, access and materials needed for preferred Spartina control, which are then followed by treatment and monitoring reports (41). There are 26 sites each with several subsites, so summarizing the history of infestation and treatment of each site and subsite will not be presented here, but rather an overall summary on treatment history and efficacy in the San Francisco Bay based on treatment and monitoring reports. Details including treatment applications and difficulties, maps and manual treatment methods for each site and subsite are described in treatment and monitoring reports found on the ISP's website: www.spartina.org.

Prior to 2005, the herbicides Rodeo® and Aquamaster® (a.i. glyphosate) were used for Spartina control as it was the only herbicide registered for use in California. Glyphosate was not effective because it binds to sediment and salt deposited on cordgrass during the tide, becomes inactivated and reduces the amount of herbicide translocated to the roots and rhizomes. In 2005, imazapyr was approved for use in the form of Habitat® and Polaris™ in California. Imazapyr remains active in sediment and salt and is highly effective in producing Spartina mortality. The use of glyphosate was quickly phased out and is now only used in areas with the endangered annual, *Cordylanthus mollis*, and in persistent *S. densiflora* stands. Before 2008, most herbicide treatments were not able to be made prior to September 1st, as to avoid the endangered clapper rail breeding season. Only helicopter applications were permitted in select areas (41). For example, in 2005 herbicide applications that were monitored for water quality were made from September 9th to October 22nd (117). Delayed herbicide application was less effective and allowed for viable non-native Spartina seeds to form and drop therefore providing sources for new infestations (48). Imazapyr has and continues to be applied at 5 to 7.5% solution in aerial applications (66). Most hand-held high volume sprayer applications of imazapyr were made by using solutions of 0.52 to 0.75% Habitat® applied at about 100 gal/A. Low-volume ground applications have varied from solutions of 0.7 to 3% Habitat® at 20 gal/A (41,62). The preferred concentrations have changed over time. For example, 1.25 to1.5% solutions were the most common concentrations in 2006 (63), but currently the majority of applications are made at 3% (41). Aquamaster® has been used in the past at a 5% herbicide solution when glyphosate was commonly applied (117), but now it is only used at 2%, both when applied alone and in mixture with imazapyr (66).

As of 2009, *Spartina alterniflora x foliosa* hybrids are now found in all nine counties throughout the Bay project area. The primary areas for the hybrids are San Mateo and Alameda counties. *S. densiflora* is mostly found in Marin County where it was originally planted. *S. densiflora x foliosa* hybrids are also now found at these sites. *S. anglica* is restricted to Creekside Park in Marin County and *S. patens* is only found in Benicia State Recreation Area in Solano County (48).

The first monitoring efforts which began in 2000 to 2001 estimated that Spartina had invaded about 483 solid acres in the estuary extending over 5,300 acres. Monitoring efforts in 2003 suggested that there was an average increase in net acres of non-native Spartina of about 244%. Based on that rate of spread, the 2003 net acreage was estimated to be 900-1,200 acres. Net acreage in 2004 was estimated at 120 to 758 acres (41, 118). In 2005, there was an estimated 809 solid (net) acres of the Bay infested with invasive Spartina (41). This number dropped about 25% in 2006. The 2007 monitoring methods used digitized aerial imagery, which was determined that it underestimated the amount of Spartina due to small patches that were difficult to spot. Approximately 275 net acres of Spartina was mapped in 2008. There were about 158 net acres of non-native Spartina in 2009. This is a 42% decline from 2008 and an 80% decline from 2005, when complete treatment began. The estimated amount of acres to require treatment in 2009 was 322, which is reduced from the 431 acres in 2008. Some areas of the Bay have shown slight increases in Spartina, but that is mostly due to the discovery of new populations and problems with accurately identifying plants. Some areas of the Bay, such as Southern South Bay, have experienced less treatment efficacy than other areas of the Bay. There is high variability between subsites, with some having Spartina decreases of about 90% while others have increased populations of invasive Spartina (48). Currently, the cover of Spartina has been reduced by the ISP by over 90% in the past five to six years (62).

Another method of efficacy monitoring that has been used in the past was permanent plots. The plots were established in 2004 and were monitored until 2008. The plots covered a range of marsh types. Percent cover of all vegetation and density of invasive cordgrass was recorded. Shannon-Weaver index for biodiversity and Spartina stem count was calculated (48). In 2006, imazapyr was determined to be the most effective at reducing stem densities of Spartina compared to glyphosate applications or manual methods (49). Comparing cumulative years of imazapyr treatment from 2005 to 2008, results showed that *S. alterniflora x foliosa* stem count was significantly negatively correlated with years of treatment. Also, Shannon-Weaver diversity index significantly increased with the number of treatment years. Efficacy monitoring of *S. densiflora* yielded similar results. Both aerial and ground treatments significantly decreased *S. alterniflora x foliosa* stem count over the years (negative correlation). Ground based imazapyr treatments had a positive correlation with Shannon-Weaver diversity, but cumulative aerial treatments had no significant correlation. The increase in diversity is assumed to be due to the release of native plants from competition. It is not confirmed why aerial treatments have no effect on plant diversity in the Bay while ground treatments have been positively correlated with plant diversity, but it is hypothesized that ground treatments have greater accuracy therefore reducing native plant exposure to treatments. The permanent plot monitoring began before the efficacy of imazapyr treatment was not known. Due to the high efficacy of imazapyr and the consistent annual monitoring of infestations and treatments throughout the Bay, the permanent plot method was discontinued in 2008 (48).

Water Quality Monitoring

The ISP conducts water quality monitoring as a part of its action plan according to Statewide NPDES permit requirements. Every year at least 10% of the sites treated around the Bay are sampled for herbicide residue and other water quality measurements 24 hours prior to treatment, just after treatment, and one week post-treatment. Samples taken prior to treatment are recorded with a GPS and flagged with PVC pipe. “During treatment” samples are taken adjacent to the treatment site about two to five hours post-treatment after the tide has re-flooded the site. Samples taken seven days after treatment are made at a time when there is enough water present for sampling. Samples are taken by using a rod attached with a one-liter amber glass jar lowered into about half the depth of the water. Jars are capped once brought to the water surface. Measurements such as depth, water temperature, pH, dissolved oxygen, conductivity and salinity are also taken with each sample. Samples are labeled and sent off to an analysis lab where the samples are analyzed within 21 days for imazapyr and 14 days for glyphosate. Each year, the lab provides a quality assurance plan that meets USEPA standards. There are four site types that are chosen to be representative of treatment sites. These are Type I: tidal marsh, microtidal marsh, former diked byland, backbarrier marsh; Type II: fringing tidal marsh, mudflats, and estuarine beaches; Type III: major tidal slough, creek or flood control channel; and Type IV: urbanized rock, rip-rap, docks, ramps, etc. Each year’s sampling effort usually includes all four site types, and site types I and II are more heavily sampled since they are predicted to result in detectable residue concentrations (64).

At the site monitored for imazapyr in 2004, pretreatment samples detected no imazapyr, while samples taken immediately after a 7.5% Habitat® solution with the surfactant Agri-Dex® application were measured at a mean of 7.7 ppb imazapyr. Imazapyr concentrations one week post-treatment were measured to be about 0.45 ppb. At the sites monitored for glyphosate, pretreatment, immediate and one week post-treatment samples from applications of a 5% Aquamaster® herbicide solution with Li-34® surfactant and Blazon® spray indicator were under the detection limits for glyphosate (26).

The variety of herbicide application methods performed at sites included in the 2005 water quality study were helicopter, Argo (amphibious vehicle) and truck. Imazapyr was applied at 5% Habitat® herbicide solution for helicopter applications at 15 gallons solution/A. For truck, Argo and helicopter applications, Habitat® was applied at 6 pints/A. At the site in which glyphosate was applied, they used a 5% Aquamaster® herbicide solution. All herbicide solutions had a surfactant of either Competitor® or Liberate® added as well as Blazon® marker dye. The drift reduction agent StayPut® was also used for truck applications. One pre-treatment site had detectable traces of imazapyr. All sampled sites had detectable traces of imazapyr one to six hours after treatment, with the highest concentration being 40 ppb. Two of the three samples with detectable traces of imazapyr one week post-treatment were in-fact retreated one day before the final sampling, due to a miscommunication, so they represent concentrations seen after one day of retreatment. None of the detected concentrations were lethal to fish or invertebrates. Glyphosate and AMPA (the primary metabolite of glyphosate) were not detected in pretreatment and one week post-treatment samples. Samples taken immediately after treatment, however, had relatively high concentrations of glyphosate at 30,000 ppb and AMPA 765 ppb. The LC_{50} levels were exceeded for some invertebrates. It is thought that these initially high concentrations may have been due to poor tank mixing of the herbicide (117).

Sample sites in 2006 represented the following herbicide application methods: helicopter, Argo and MarshMog amphibious vehicles, truck, and backpack. Of the samples taken before treatment, 89% had no imazapyr detection. Mean concentrations of imazapyr detected during treatments were about 282 ppb with a maximum of 500 ppb. One sample showed no imazapyr detection. Imazapyr was not detected at 25% of the sites one week post-treatment and the mean amount of imazapyr detected at this time was 0.67 ppb, with a maximum of 2.2 ppb. Sites showed a 98 to 100% reduction in imazapyr one week after treatment. Samples for glyphosate were taken at one site, and neither glyphosate nor its metabolite AMPA were detected before, during or after treatment (63).

Results from the 2007 water quality monitoring program found an average concentration of 49.51 ppb imazapyr two to five hours post-treatment, with a maximum detection at 200 ppb. One week post-treatment samples of imazapyr were measured to be at an average 0.82 ppb for sites where imazapyr was detected, with a maximum detection of 2.45 ppb resulting in an average drop of 89%. Sites represent a variety of treatment methods including backpack, truck, helicopter, boat, and Argo and MarshMog. There were some positive detections of imazapyr in the pre-treatment samples, but these were attributed to laboratory error. Glyphosate was only applied to one site in 2007 therefore only one site for glyphosate was sampled. There was no detection of glyphosate in pre-treatment and one week post-treatment. The concentration of glyphosate in the sample taken just after application was 19.3 ppb. The primary metabolite of glyphosate, aminomethyl phosphonic acid (AMPA) was not detected (64).

Sample sites in 2008 included the following application methods: backpack, truck, airboat, helicopter, and MarshMog. Pretreatment samples had 86% negative imazapyr detections, with a 0.17 ppb average for all sites. The average amount of imazapyr detected during treatment (sampled two to five hours post-treatment) was 71.17 ppb with a maximum of 260 ppb. Samples taken one week post-treatment had an average imazapyr concentration of 1.19 ppb with a maximum of 4.18 ppb. Imazapyr was non-detectable post-treatment at five of the fourteen sites. The mean reduction of imazapyr was 97% one week after treatment. Glyphosate was applied and sampled at one site in 2008, and was not detected in pre-, during and post-treatments. AMPA was also not detected in any of the samples (64).

In 2009, sample sites represented the following imazapyr treatment methods: backpack, airboat, Hydrotraxx and MarshMog amphibious vehicles, helicopter and truck. Methods employing the EPA 8151A resulted in the detection of imazapyr prior to treatment. The mean amount of imazapyr detected in 2009 during treatment was 222.21 ppb, with a maximum of 1,310 ppb, which is the highest concentration reported throughout the years. However, 2009 also had the most samples of non-detection samples taken during treatment. The mean concentration of imazapyr one week post-treatment was 1.59 ppb with a maximum of 3.14 ppb and nine of the 14 sites had no imazapyr detection. This results in a 99% reduction in imazapyr one week post-treatment. No samples for glyphosate were taken in 2009 (64).

In 2010, sites with herbicide application methods using backpacks, airboats, Argo, Hydrotraxx, and trucks were sampled. Helicopter sites were not sampled because aerial applications are no longer frequently used due to the efficacy of the control program. Imazapyr was detected in 40% of the pre-treatment sites. Samples with low imazapyr detection (<0.10 ppb) were suggested to have laboratory contamination while the others (>0.18 ppb) were thought to result from treatments that occurred in nearby sites before samples were taken at the sample sites. Samples taken during treatment had average imazapyr concentrations of 55.08 ppb with a maximum detection of 180 ppb. There were no sites where imazapyr was not detected. Samples taken on week post-treatment had mean imazapyr concentrations of 1.05 ppb with a maximum of 6.5 ppb. This results in an imazapyr concentration reduction of 99%. Only one site was below the detection limit. Two sights had increases in imazapyr concentration one week post-treatment. This occurred at sites with *S. densiflora*, which grows higher on the marsh plan. Therefore, it may take longer for tides to flush imazapyr through the marsh plain and into sampled water. One site was sampled for glyphosate and AMPA, and neither compound was detected in the three sample times (64).

Due to the rapid decline in imazapyr consistently for all years of sampling, there is a high probability that all sites with detectable amounts of imazapyr one week post-treatment will fall below detection limits with a few days (64). Based on toxicity data for fish, invertebrates, birds and mammals the concentrations of imazapyr found in water quality samples in the Bay are not expected to affect wildlife due to the high margins of safety between detected concentrations and toxicity concentrations. There are no State or EPA-based water quality standards for imazapyr. Based on the toxicity of glyphosate to wildlife, low application rates and the rapid deactivation and degradation of glyphosate in the field, no impacts from glyphosate are expected. The water quality parameters including temperature, dissolved oxygen, salinity, turbidity and conductivity were not significantly affected by the herbicide treatments from 2004-2010. Any impacts on water quality are not expected due to the twice daily tidal exchange in the Bay (64).

Future Challenges

Although the ISP has been highly successful, Spartina still remains in the San Francisco Estuary and vigilant monitoring and treatment is still needed to ensure eradication. There are several challenges that are posed to the ISP. *S. densiflora* is a tough persistent plant. Herbicide applications on *S. densiflora* are not as effective as on other Spartina species. Small *S. densiflora* plants with large rhizomes do not translocated enough herbicide to produce significant mortality. This phenomenon has been called the “living dead”, where established *S. densiflora* stands exhibit half dead looking plants one year after herbicide treatments. These plants are not healthy enough to translocate herbicide. Mowing has been added to help produce green growth to increase efficacy of herbicide treatments. Herbicide treatment will provide a couple of years of seed control however (65). An herbicide solution of imazapyr and glyphosate is being tried for controlling *S. densiflora* (66). Due to the efficacy of the ISP, Spartina are now widely spread apart and finding isolated plants is difficult and time intensive. Ground monitoring efforts continue to be valuable yet time consuming and are necessary to prevent new populations of Spartina from emerging. Identifying between *S. alterniflora x foliosa* hybrids and native *S. foliosa* in the field is difficult due to varying morphologies and in some cases can only be confirmed with genetic testing. This ambiguity can lead to hybrid being left untreated for a season (48). The ISP continuously addresses these challenges and uses adaptive management strategies to increase efficacy and success of eradication efforts.

3.2 Example of Pesticide: Imazapyr

Imazapyr is a systemic non-selective herbicide that inhibits plant growth by preventing amino acid synthesis. Imazapyr (2-(4-isopropyl-4-methyl-5-oxo-2-imidazolin-2-yl)-nicotinic acid) belongs to the chemical class imidazolinone. It is used for pre- and post-emergent control of grasses, broad-leaved plants, woody plants and riparian and aquatic plants.

3.2.1 Application rate

The maximum allowed application rate of imazapyr is 1.5 lbs a.e./A for aquatic sites (0.55 ppm) (107). The maximum application rate for the imazapyr formulation Habitat®, which is register for aquatic use, is 6 pints/A (2.3 ppm of product). Many Spartina restoration projects recommend application rates from four to six pints Habitat® product/A, which is 1 to 1.5 lb a.e./A (0.34 to 0.55 ppm) (101).

3.2.2 Degradation rate

Imazapyr is generally persistent in the environment. Imazapyr is both persistent and mobile in soils (107) with half-lives in soil reaching several months and may persist in dry soils for over a year (55). Half-lives of imazapyr on plants are about 12 to 40 days (54). Imazapyr is does not readily volatilize, but volatilization may increase with temperature and moisture content in soil (55). A photolysis study in water showed a half-life of 3 to 5 days (107).

3.2.3 Known toxicity to NOAA Trust Species

3.2.3a Acute LC_{50}

Studies suggest that imazapyr is practically nontoxic to rainbow trout in acute exposures. A 96 hour LC_{50} study of an imazapyr formulation (a.i. 21.5%) had a NOEL of 110 ppm and an LC_{50} of >110 ppm. A 93% a.i. imazapyr formulation had a NOEL of 100 ppm with an LC_{50} of >100 ppm. Imazapyr in its isopropylamine salt form resulted in a 96 hour NOEL of 56 ppm and an LC_{50} of 112 ppm (138). No acute lethal studies were available for endangered/threatened anadromous fish, cetaceans, pinnipeds, marine turtles, marine invertebrates or marine plants.

3.2.3b Sublethal and Chronic Toxicity

A 28 day chronic early life stage test on rainbow trout eggs exposed to imazapyr resulted in a 92 ppm LOEC in which 92% egg hatch occurred and a NOEL of 43.1 ppm (138). An acute 96 hour sublethal test on the survival of seawater entry by chinook salmon smolts showed that smolts were able to maintain osmoregulatory capability with exposures from 0 to 1.6 mg/L of imazapyr (94). This suggests that chinook smolts will experience no significant smolting effects at imazapyr concentrations recommended by the label (maximum rate 0.55 ppm). Other than the chinook smolt test, no sublethal or chronic lethal studies were available for endangered/threatened anadromous fish, cetaceans, pinnipeds, marine turtles, marine invertebrates or marine plants.

3.2.3c Indirect effects

Unintended removal of native plant species in lakes, rivers, streams and bays may have adverse effects on salmon habitat and prey availability. Care is needed to ensure that habitat quality is maintained when using any herbicide.

3.2.4 Persistence of pesticide in ambient water

Imazapyr is water soluble (54) and has a surface water half-life of 3 to 5 days (107). Because imazapyr is water soluble and doesn’t readily bind to organic matter, imazapyr is highly mobile in soil and water and can travel by surface runoff to contaminate surface waters and well as leach into ground water. The persistence of imazapyr in soil and its high mobility may lead to acute and chronic exposures of imazapyr to aquatic non-target organisms (54). Incidents with terrestrial herbicide applications of imazapyr may have resulted in fish kills in adjacent ponds due to agricultural runoff. Other incidences of fish, bird and aquatic plant mortalities as a result of an herbicide mix containing imazapyr have been reported (107). More field studies may be needed to determine if field concentrations of imazapyr in surface water negatively effects fish and other non-target mortality, behavior or reproduction.

3.2.5 Bioaccumulation potential in non-target species

Imazapyr is an anion at most environmental pHs and therefore is not expected to bioaccumulate. The metabolites of imazapyr: hydroxy-dicarboxylic acid and pyridine dicarboxylic acid are thought to behave similarly to the parent compound (107). Imazapyr has a K_{ow} of 0.22 and a calculated BCF of three (71). Therefore, bioaccumulation in non-target species is of little concern.

Chapter 4

Piscicide Use in a Lentic Restoration Context

Piscicides are often used to eradicate non-native fish species in order to restore desired fisheries and overall water body ecosystem health. Invasive fish produce a wide range of problems including disrupting the ecosystem, introducing diseases, and outcompeting other native fish species, sometimes driving them to extinction. Fish eradication projects involve direct pesticide applications to the water bodies when using chemical control. Piscicides may be applied to lotic and lentic systems, each with their own challenges. The BMPs and pesticides implemented in these projects have the potential to significantly impact aquatic habitats and their valuable resources such as endangered and threatened species. Below is:

1. A case study of the Cheney Lake Restoration Project that highlights their pesticide best management practices for eradicating Northern Pike;
2. A description of rotenone, a commonly used aquatic-registered piscicide which includes available toxicity information on endangered/threatened anadromous fish

4.1 Cheney Lake, Alaska Restoration Project: Removal of an Invasive Northern Pike Population through Piscicide Application

4.1.1 Case Study Background

Cheney Lake, located east of Anchorage, Alaska, is a man-made lake that Alaska Department of Fish and Game (ADF&G) has been stocking with rainbow trout since 1982. Northern pike (*Esox lucius*) was illegally introduced to the 24.2 acre lake in 2000. Although northern pike is native to most of Alaska, they are an invasive species to South-central Alaska and can cause substantial economic and ecological damage. The pike were highly predatory on the juvenile rainbow trout, sticklebacks, aquatic invertebrates, and juvenile waterfowl and quickly depleted the population. The Cheney Lake fishery was reduced from 5000 angler days spent fishing to 1000 days. The pike presence forced ADF&G to stop stocking the lake with rainbow trout in 2001.The pike population became under stress after large pike had been harvested by anglers, leaving the pike to begin maturing and spawning at smaller sizes and not sought by anglers. Cheney Lake is near Chester Creek which is home to natural salmon runs, so there was an increased chance of northern pike invading the creek and threatening the native fish population. With the eradication of pike in Cheney Lake using the piscicide CFT Legumine™ (5% liquid rotenone), ADF&G was able to restore the rainbow trout fishery and regain recreational opportunities (18).

4.1.2 Introduction to Northern Pike

4.1.2a History

Northern pike have a native range from western Alaska to eastern Canada and south to Nebraska, Missouri, and Pennsylvania, but pike are not native to all watersheds in these regions. In many cases, pike were intentionally stocked to provide sport fish opportunities and in many western states, pike have been illegally introduced, causing management concerns because they prey heavily on juvenile salmonids. In the early 1950's, a pilot illegally transported pike from the Yukon drainage to Yentna River drainage in south Alaska in which the pike population began to accelerate (74).

4.1.2b Biology

Northern pike are moderately compressed fish with forked caudal fins, flattened snouts, and large teeth. They live in cold waters and spawn in shallow waters after the ice melts in spring. Their rapid growth rate is dependent on several factors, including temperature, food availability, and access to suitable habitat. Northern pike are primarily opportunistic piscivorous, but will also prey on other organisms like amphibians, invertebrates, and vertebrates. Pike can survive in very low dissolved oxygen levels due to their broad physio-chemical tolerances. Pike can survive in both freshwater and salt water environments (74).

4.1.2c Problems

Pike are highly predatory and can reduce native species of fish, mammals, and waterfowl, leading to a decrease in species diversity. Economically, illegally introduced pike creates problems in fish hatchery investments and benefits, along with the cost of controlling the invasion (74).

4.1.2d Pathways of Introduction

Humans illegally stocked pike (18).

4.1.2e Overview of Chemical Control

Due to high costs of other chemical treatments, rotenone has been used in Alaska, prior to statehood, to prepare lakes for fisheries enhancement (18). Rotenone is a naturally occurring substance from tropical plants that has been a control agent for fish. Effective at low concentrations, when rotenone is applied to the water, it enters the - blood stream through the gills, and inhibits a biological process that facilitates oxygen intake at the cellular level. Rotenone breaks down when exposed to light, heat, oxygen, and alkaline water. Most lakes with rotenone treatment will completely detoxify within five weeks. Another chemical treatment piscicide (fish-killing agent) that is included in the soon-to-be-issued EPA General Permit used for pike eradication is antimycin. Antimycin is an antibiotic produced by mold that is lethal to fish (74).

4.1.3 Summary of BMPs

The objective of the Cheney Lake Restoration Project was to eradicate northern pike from Cheney Lake by using rotenone in order to enable restocking the lake with hatchery-produced rainbow trout for recreational fishing. The Cheney Lake Restoration Project BMPs for northern pike eradication with rotenone provided a case study highlighting how these practices reduce risk, and maximize efficacy of rotenone application (18).

4.1.3a Alternative Non-chemical Methods

Consideration of non-chemical control methods are a crucial part to any BMP. The Cheney Lake Restoration Project attempted alternative methods to pike removal, including public service announcements, publications, classroom education and material, and a webpage as educational outreach strategies. Management actions utilized public outreach coordination by encouraging anglers to harvest more pike by putting no limit on the number of pike that can be harvested; however, this was insufficient because there was a reduced angling effort due to the small sized pike (18).

ADF&G (Sport Fish Division) biologists attempted to remove pike from the lake with gill nets and Fyke nets. Even though many pike had been captured and removed, netting by itself did not result in eradication due to pike that were generally inactive pike, unless they were looking for food. Gillnetting is also not an efficient way to eradicate pike because it is labor intensive and catching other species is inevitable (18).

ADF&G considered plans to lower the water level in Cheney Lake by the storm drain pipe that connects to Chester Creek. By lowering the level during late fall to 18 inches, the remaining water would freeze solid in winter and kill the pike. However, the mechanism to control the flow of water through the storm drain could not be manually operated. Also, the public and residents near the lake preferred the idea of using chemical means to eradicate the pike (18).

How does this practice maximize benefits and reduce risk?

- The use of effective non-chemical methods before the use of pesticides inherently decreases the risk of non-target organism exposure to the pesticides. The decision to use pesticides in this case was deemed as the most effective method of eradicating pike, as previous methods were not sufficient.

- Early detection and recreationist education, along with angler harvesting, can prevent or reduce the need of pesticides.

Hazards

- Be sure to know the animal biology and consequences when attempting an alternative control method, as in some cases, the methods can create problems for non-target species.

4.1.3b Pesticide(s) and Product(s) Choice

The ADF&G used the piscicide (a fish-killing agent) CFT Legumine™ (5% liquid rotenone) to eradicate northern pike in Cheney Lake. The CFT Legumine™ rotenone formulation was designed as an improvement over the more hazardous powder form that had been widely used by fisheries managers before. This formulation also is designed to spread evenly throughout the treated water body. Rotenone is highly toxic to fish, but is effective at low concentrations because it is readily absorbed through the thin layer of the gills. Non-target organisms that do not have gills are not negatively affected at pesticide label concentrations. Rotenone naturally degrades with light and temperature. Rotenone is not expected to contaminate groundwater because Rotenone binds readily to sediments and is broken down in soil and water through hydrolysis, photolysis, and biodegradation. Rotenone also does not negatively affect plants at the concentrations necessary to kill fish, and monitoring results of the plant communities suggested they were not impacted by the treatment (16). A concern with using Rotenone was the potential exposure of native fish in the stream that is downstream of the lake connected by a storm drain. On-site assays using caged rainbow trout as sentinel fish confirmed the concentration used was not sufficient enough to cause fish mortality in the storm drain that leads to Chester Creek. ADF&G also created environmental review tables on the effects and impacts on the natural environment and human environment (18).

<u>How does this practice maximize benefits and reduce risk</u>?

- The new formulation is less hazardous than the power form that had been used in previous fish eradication projects.
- Groundwater is not contaminated due to rotenone’s degradation rates.
- Rotenone does not harm plants, which are important for native fish life.
- On-site assays were used with sentinel fish to monitor the concentration levels in the storm drain leading to the nearby Chester Creek.

Hazards

- Rotenone is highly toxic to fish and other organisms with gills, so care is needed to not expose non-target organisms during pesticide applications.

4.1.3c Adjuvant(s)

The CFT Legumine™ is formulated so it will disperse evenly throughout the treated water body; therefore, no adjuvants were needed to be added to this treatment (16).

4.1.3d Licensing and Certification of Applicators, Professional and Trade Associations

All applicators are certified through the US Fish and Wildlife National Rotenone Certification Program as well as licensed by the state of Alaska for pesticide applications (16). The U.S. Fish & Wildlife Service has a training program for rotenone in fish management which allows trainees to practice hands-on application and explores strategies for safe application (87).

How does this practice maximize benefits and reduce risk?

- Certification requirements for applicators and technicians allow for an enforceable standard that all applicators have the knowledge for safe and effective pesticide applications.
- Affiliations with professional associations provide managers with up to date BMPs and environmental issues from other professionals.
- Yearly training and refresher courses help applicators to minimize human error, increase application efficacy and decrease potential environmental risks.

4.1.3e Application Methods

The rotenone was dispersed into the lake with a small motorboat via submerged venture pumps. Backpack sprayers also treated wetlands directly adjacent to the lake to eliminate the chance of pike escaping the rotenone-treated waters (18). Cheney Lake is shallow (30 feet) so no deep water applications were needed. The motorboat was driven around the lake during and after application to assist with rotenone mixing.

How does this practice maximize benefits and reduce risk?

- The use of a submerged pump allows for direct application into the water body and therefore eliminates potential for drift.
- The prop wash from the outboard motor will help in mixing rotenone through the water column.
- Applying rotenone by backpack along shorelines where there is significant vegetation increases herbicide application efficacy.

4.1.3f Equipment and Calibration

The application equipment used in the Cheney Lake Restoration Project included a small motorboat with submerged venture pumps and a backpack sprayer (18). The submerged venture pumps and backpack sprayer were calibrated to apply at the correct pesticide rate to achieve targeted rotenone concentrations. The backpack sprayer used a straight shot spray hose for direct application on shoreline instead of a mist sprayer to reduce drift. Assays were used in calibration of equipment for quality control (16).

How does this practice maximize benefits and reduce risk?

- The backpack straight shot hose provides for direct spray, limiting the potential for drift.
- The motorboat pump application allows for direct application, limiting the potential for drift.
- Calibration assays of pumps ensured correct application rates.

Hazards

- Improper calibration and positioning of hose for application may lead to increased drift, which increases non-target exposure.

4.1.3g Application Rates

The ADF&G followed the pesticide label and never exceeded the label maximum application rates. Following the label recommendation for “normal pond use”, the concentration of the rotenone formulation in Cheney Lake treatment was applied at 1 ppm (0.05 ppm of active rotenone) or about 1 mg of CTF Legumine™ per liter of water. The volume of the lake was used to determine the needed amount of CTF Legumine™ to achieve a 1 ppm application rate. In order to determine if the rate used in the Lake Cheney treatment was effective at pike eradication, sentinel rainbow trout were used. For invasive fish eradication projects, the target species is never used as the sentinel fish, so this ensures that the invasive fish is not accidentally re-introduced in the project area (18). CFT Legumine™ is very highly toxic to fish, with an LC50 of 7.4 µg/L at 4 hours for juvenile rainbow trout (35).

How does this practice maximize benefits and reduce risk?

- Never exceeding the legal maximum herbicide application rates reduces risk of exposure to non-target organisms, as determined by the EPA.
- Using sentinel fish in the lake to determine if rotenone rates are lethal allows for increase efficacy of pike control.

Hazards

- Do not apply pesticides at such a high rate that negative effects on non-target animals occur.
- Do not apply pesticides at rates lower than what is effective.

4.1.3h Application Timing

Rotenone was applied to Lake Cheney in early October 2008 (16). Since rotenone naturally degrades with light and temperature, cold water application of rotenone enhanced the effectiveness of the chemical and ensured a longer exposure time during a period of naturally decreasing dissolved oxygen levels. In addition, the freezing of the lake surface limited non-target species from being in the treatment area (18). The lake was frozen when rotenone was applied, so applicators had to break the ice on the lake. Applying rotenone during October also ensures a slower degradation rate, which prolongs the exposure of the pike in the lake to the rotenone therefore increasing efficacy. Rotenone levels were continued to be detected in Cheney Lake until early March (16).

The timing of the important native salmon runs was also considered in the timing of applications. In Chester Creek, all coho salmon have completed spawning by October and salmon eggs are less sensitive and would not be expected to be affected by the application rates of Rotenone (18).

How does this practice maximize benefits and reduce risk?

- The late October treatment decreases the degradation rate of rotenone due to temperature, therefore increasing the efficacy of pike eradication in the lake.

Hazards

- To ensure efficacy of rotenone, be sure to apply when there is low light and temperature. Follow label directions.

4.1.3i Application Conditions

The colder the water, the more effective rotenone is and the longer the exposure due to low dissolved oxygen level (18). As described above, the lake was frozen when rotenone was applied; therefore the lake was cold enough to prolong rotenone exposure (16). Also, non-target organisms such as mammals, birds and amphibians will be less likely to migrate to and utilize the lake once frozen (18).

<u>How does this practice maximize benefits and reduce risk</u>?

- The freezing of the lake surface limited non-target species from being in the treatment area.

4.1.3j Mitigation

The Cheney Lake Restoration Project had mitigation measures in place for if rotenone was entering Chester Creek at lethal levels. Caged sentinel fish were placed at the outflow storm drain pipe that flows into the creek as a monitoring precaution. If the sentinel fish responded to the rotenone, an air bladder would have been used to temporarily block entrance of lake water to the storm drain and a drip station of potassium permanganate would have been used to neutralize the rotenone before entering the creek. Up to 70% of the pike killed during rotenone treatment immediately sank to the bottom of the lake, while dead pike that surfaced was collected daily by ADF&G and disposed of properly (18). The sentinel fish were not affected by the treatment and the use of potassium permanganate or the air bladder was not needed (16).

Due to the high toxicity of rotenone, the possibility of rotenone entering a nearby stream, Chester Creek, home to a coho salmon run was considered. There are three ways in which rotenone can be detoxified: basic fresh water dilution, application of potassium permanganate, and natural detoxification. Discharge rates from Cheney Lake to Chester Creek are weather-dependent; however, rotenone was already diluted when it was applied to the lake, so with more rain/storm water flushing into Chester Creek, the rotenone-treated water was even further diluted and was determined to be no longer at a dangerous concentration level for native fish (18).

<u>How does this practice maximize benefits and reduce risk</u>?

- The sentinel fish served as a monitoring aspect to ensure the water entering Chester Creek was safe for the native fish.
- Mitigation measures such as the air bladder and neutralizing agent provide for a quick and effective action if needed.
- The pike that sank to the bottom of the lake stimulated plankton growth and aided in the recovery of zooplankton and aquatic insect populations.

4.1.3k Monitoring

During the summer before the rotenone treatment, baseline data on the water chemistry and dominant macro-invertebrate taxa was collected. This same data was collected the summer after treatment to confirm the lake has re-established to pre-treatment conditions (18). Macro-invertebrate samples indicated that there were still live invertebrates present after rotenone treatment (16). Water samples for Cheney Lake were collected monthly during the rotenone treatment early March, when Rotenone was no longer detected in the lake (16). On-site assays of caged sentinel fish in Cheney Lake and Chester Creek monitored water quality entering Chester Creek, as well as monitored the effectiveness of the rotenone treatment within the lake. Sentinel fish located in Cheney Lake continued to display lethality for a few months after treatment (16). Cheney Lake was monitored throughout winter and spring to ensure pike had been eradicated (18). The eradication effort was successful and stickleback and rainbow trout were re-stocked in the lake by June 2009. Unfortunately, in spring 2011, two illegally, re-introduced pike were caught by ADF&G and it is thought that they are the result of recent pike introduction (16).

How does this practice maximize benefits and reduce risk?

- Monitoring effectiveness of pesticide application allows for adjustment of product, concentration and application methods that are most effective, enhancing the control effort benefit.
- Surveying after treatment allows for re-treatments when necessary and documents long-term efficacy efforts.
- Quantitative methods allow for accurate evaluation.
- A vigilant education program will help to prevent re-introduction of the invasive species.

4.1.3l Storage of Chemical

The rotenone was stored in a locked facility in Kenai, Alaska and was stored according to the label (16).

How does this practice maximize benefits and reduce risk?

- The use of proper pesticide storage reduces the risk of spills and environmental contamination, thereby reducing potential exposure to non-target organisms.

Hazards

- The improper storage of pesticides can lead to human and environmental health risks.

4.1.3m Disposal of Chemical and Equipment

The equipment was hosed off back into the treated lake and disposed of at the site. The MSDS protocols were followed for disposal of rotenone (16).

How does this practice maximize benefits and reduce risk?

- Rinsing equipment and supplies back into the treatment area reduces risk of contamination of untreated, native areas.
- Following the MSDS protocols reduces the risk of environmental contamination.

Hazards

- Be sure that the rinsing of equipment does not lead to significant increased concentrations of product in the treated area

Acknowledgements: This case study was supplemented with information provided by personal interviews with Dan Bosch, Alaska Department of Fish and Game.

4.1.4 Cheney Lake, Alaska Restoration Project Case Study Details

Case study details can be found in "Cheney Lake Restoration Project: Removal of an Invasive Northern Pike Population through the Application of Rotenone" at http://www.adfg.alaska.gov/static/species/nonnative/invasive/rotenone/pdfs/cheney_lake_ea.pdf

4.2 Example of Pesticide: Rotenone

Rotenone, (6R, 6aS, 12aS)-1,2,6,6a,12,12a-hexahydro-2-isopropenyl-8,9-dimethoxychromenyl [3,4- bfuro[2,3-h]chromen-6-one, is a plant-based, selective pesticide that is used to control insects and eradicate fish. Rotenone inhibits cellular respiration and is available in liquid, powder, and wettable powder forms (33,108,109).

4.2.1 Application rate

The maximum application rate of Rotenone is 50 ppm in streams and rivers and up to 250 ppm in lakes, reservoirs, and ponds (108).

4.2.2 Degradation rate

Rotenone is rapidly broken down in soil, water, and sunlight, and is not able to leach through soil and thus is not considered a groundwater pollutant (32). The half-life of rotenone in soil ranges from one to three days and it loses nearly all toxicity between two to six days of sunlight (32).

4.2.3 Known toxicity to NOAA Trust Species

4.2.3a Acute LC_{50}

Rotenone is highly toxic to salmonids. In juvenile rainbow trout, rotenone is very highly toxic (1.9 (98% A.I.) to 2.82 ppb (96.5% A.I. 96 hour LC_{50s})) (138). In addition, the formulation Nusyn-Noxfish® Toxicant synergized rotenone LC_{20} toxicities for rainbow trout ranged from 6.2 (8 hour) to 11.5 ppb (48 hour, 5/10% A.I.), formulation Derris (6.5% rotenone) ranged from 0.025 ppm (24 hour, 1.6 ppb A.I.) to 3.1 ppm (24 hour), formulation CFT Legumine® rotenone ranged from 7.4 (4 hour) to 5.3 ppb (8 hour), Pro-Noxfish® Synergized Emulsifiable Concentrate (2.5% rotenone) ranged at a very high level of toxicity from 1.02 ppb (96 hour) to 13.0 ppb (1 hour), and formulation Dactinol® (5% rotenone) ranged from 0.47 to 5.8 ppm (48 hour) (35,76,114,138, 139). A non-reported formulation of rotenone was highly toxic to rainbow trout and toxicities ranged from 57.0 ppb (48 hours) to 46.5 ppb (5% A.I., 24 ppb NOEL, 96 hours) and in juvenile rainbow trout, 48.9 ppb (2.5% A.I., 40 ppb NOEL, 96 hours) to 16.5 ppb (1 hour, 33% A.I.) (50,76,138).

The formulation Noxfish® (5% rotenone) is very highly toxic to juvenile chinook salmon with ranges from 212 ppb (3 hour) to 71 ppb (96 hour) and to coho salmon, 62 ppb (96 hour) to 358 ppb (3 hour); however, it is moderately toxic to chinook salmon eggs, at >3.00 ppm (96 hour) (76, 91). Noxfish® is also moderately toxic to rainbow trout eggs at 2.50 to 5.60 ppm (96 hour) and very highly toxic to juvenile rainbow fish at about 28.3 to 40.0 mg/L (75).

There were no acute data found for chum, sockeye, steelhead salmon, as well as Bocaccio, sturgeon, sawfish, Pacific eulachon, and rockfish. There were also no data found on endangered or threatened cetaceans, pinnipeds, marine turtles, coral, abalone or Johnson's seagrass.

4.2.3b Sublethal and Chronic Toxicity

A study that exposed juvenile rainbow trout to 96.5% rotenone formulation for 32 days resulted in a 1.01 ppb NOEL and a 2.21 ppb LOEC (138). A study testing sublethal swimming behavior in juvenile rainbow trout showed that Ucrit, which is defined as the speed that a fish can no longer propel itself forward and becomes exhausted, was significantly decreased at exposures of 3, 4 and 5 µg/L and exposure times of 2, 4, 6, 12, 16, 24 and 48 hours. The same study showed that peak active metabolic rate decreased tremendously at rotenone exposures of 1.5 ppb or more (19). Juvenile rainbow trout exposed to 0.034 ppm Barbasco® (6.8% rotenone) displayed a loss of equilibrium at 20-100 minutes (113). Rainbow trout have been observed to display avoidance behaviors to rotenone. Juvenile rainbow trout spent decreased in time in cells with concentration exposures at 0.045, 0.075, and 0.15 ppm at 18 minute increments to pure rotenone, Nusyn-Noxfish® Toxicant synergized rotenone, and a powdered formulation containing cube root brittle extract of rotenone (46). Adult rainbow trout are able to metabolize rotenone, with only 2% of a 120 µg/kg dose remaining in the body after 20 minutes, resulting in an half life from the whole body of 68.5 hours (39). Population effects can be see through an Australia stream section study, where after 1 ppm concentration of rotenone was applied, after 2 days, all of the rainbow trout were eradicated (73).

No chronic or sublethal data for rotenone were found for endangered/threatened anadromous fish, cetaceans, pinnipeds, marine turtles, marine invertebrates, or marine plants listed on Table 2.

4.2.3c Indirect effects

Rotenone is used mainly as a piscicide although it has toxicity to aquatic invertebrates. This may influence prey availability, however most fish would likely die with rotenone concentrations high enough to result in significant invertebrate mortality (35). Because rotenone may result in salmon mortality if applied inappropriately or as a result of a spill or other incident, prey availability may be reduced for killer whales, beluga whales and pinnipeds in this type of situation.

4.2.4 Persistence of pesticide in ambient water

Persistence in water is estimated to be short due to its half life of 1 to 3 days in soil and rapid degradation of toxicity due to exposure to sunlight (5 to 6 days in spring sunlight and 2-3 days in summer sunlight) (32). However, field applications of rotenone made in the winter under ice cover in lakes have resulted in rotenone detections for up to five months (16).

4.2.5 Bioaccumulation potential in non-target species

Rotenone has a low bioaccumulation potential and has a low propensity to bioaccumulate in fish (108).

Chapter 5

Pesticide Use for Vector Control in a Public Health Context

Mosquitoes are vectors for several serious diseases worldwide, such as West Nile virus, and pose a public health hazard. Each year, over one million people die from mosquito-borne diseases. Mosquito-borne diseases also affect dogs, horses and birds and other livestock. Larvicides and adulticides are often needed to control mosquito populations in areas with mosquito-borne pathogen outbreaks (3). Vector control programs can involve direct pesticide applications to water bodies when using chemical control and some of these areas may house or be connected to habitat for fish and other non-target organisms. The BMPs and pesticides implemented in these projects have the potential to significantly impact aquatic habitats and their valuable resources such as endangered and threatened species. This case study on pesticide use for vector control in a public health context includes the following sections:

1. A case study of the New York City Comprehensive Mosquito Surveillance and Control Plan that highlights their pesticide best management practices for vector control.
2. Descriptions of *Bacillus thuringiensis* variation *israelensis* (Bti) and *Bacillus sphaericus*, which are commonly used aquatic-registered larvicides, and include available toxicity information on endangered/threatened anadromous fish.

5.1 New York City, New York Case Study: Mosquito Vector Control

5.1.1 Background

New York City saw its first introduction of West Nile (WN) virus causing encephalitis and other neuroinvasive diseases in 1999 and since then, the virus has persisted in the City. In 2010, there were 34 confirmed cases of WN neuroinvasive disease, with likely many more undiagnosed cases. The WN virus is thought to persist by either overwintering in the hibernating adult *Culex pipiens*, infected resident birds, or the reintroduction of the virus each year from infected migratory birds. Infected birds and mosquitoes are present in the spring and over time the virus is transmitted back and forth between mosquitoes and birds. The virus then amplifies to a point where mosquito species that feed on both human and other mammals become infected, therefore transmitting the virus to humans. The goal of the Department of Mental Health and Hygiene's (DOHMH) vector surveillance program is to detect the virus in local mosquito populations before it reaches the point of spillover to human by bridge vector species such as *Cx salinarius* and *Cx pipiens*. Mosquitoes of the species *Cx pipiens* shift feeding habit from birds to humans in the mid –late summer when their preferred host the American robin (*Turdus migratorius)* start migrating from the NYC. The DOHMH monitors mosquito populations at 52 permanent trapping sites throughout WN virus season (June – October). Each season, 40 – 120

Supplemental trapping sites are added to determine extent and intensity of viral activity. Mosquitoes from these sites are tested for WN virus infection on weekly basis by using real-time polymerase chain reaction (PCR). Mosquito surveillance data and the test results are used to estimate risk of disease transmission to humans. DOHMH also monitors bird and mammal populations as early detection and monitors human infections. They map mosquito breeding habitats, determine areas for regular inspection, collect larval habitat information and conduct mosquito trapping. When need arises, the DOHMH conducts larviciding efforts and in cases where data indicate a significant risk to human health, adulticiding is performed (11).

5.1.2 Introduction to the Problem: Mosquitoes as Viral Vectors

Mosquitoes are found worldwide and can be a nuisance to humans and animals. Mosquitoes can transmit diseases to both humans and animals, including malaria, yellow fever, dengue, filariasis, and encephalitis such as WN virus. Mosquitoes lay their eggs on the surface of water or in moist soil. Common habitats include standing water in cans, pools, tires, ponds, puddles, creeks ditches, tree holes, irrigated pasture, salt and freshwater marshes, and catch basins. Eggs hatch into larvae after about four to 14 days. Larvae live in water and feed on microorganisms, organic matter, or other mosquito larvae. Larvae must come to the surface to breathe air through a siphon. A larva will molt four times at which point it becomes a pupa. Pupae float at the water's surface and breathe through tubes called "trumpets". Metamorphosis into an adult mosquito occurs within the pupal case. When metamorphosis is complete the adult emerges, rests on the surface of the water for while, and then takes flight. Only adult female mosquitoes bite and feed on blood meal which is used for egg development; males and females both feed on the nectar of flowers for nutrition. Humans are often a secondary choice for mosquitoes compared to mammals and birds. There are many species of mosquitoes and they differ in activity period time of day, their preference for mammals or other animals, and whether or not they are capable of transmitting diseases (3).

Because mosquitoes are a nuisance and can pose a risk to human and animal health, vector control methods near human populations are often needed during the mosquito breeding season. The primary method of control is source reduction: the removal of standing water to reduce mosquito breeding and larvae habitat. In permanent areas of standing water such as ponds and lakes, the use of mosquito eating fish or other predators for biological control may be an option. In cases where standing water removal is not possible and the use for biological control is not an option or is ineffective, pesticides including larvicides and adulticides are used. (3, 14)

5.1.2a Overview of Chemical Control

There are two main types of pesticides used for mosquito control: larvicides and adulticides. Larvicides are pesticides that control mosquitoes during their larval stage, when they are in the water. Larvicides that are registered for mosquito control and are included in the upcoming EPA General Permit are: *Bacillus thuringiensis israelensis*, *Bacillus sphaericus*, methoprene, temephos and monomolecular film. Larvicides are generally applied as liquids or granules, depending on the formulation. They are applied to aquatic areas where mosquito larvae occur to prevent the emergence of adults. Adulticides are pesticides that control mosquitoes during their adult flying stage. Adulticides that are registered for mosquito control and are included in the upcoming EPA General Permit are: naled, permethrin, resmethrin, sumithrin, pyrethrin and malathion. Adulticides are often applied as an Ultra Low Volume (ULV) spray in areas where adult mosquitoes are of concern. Larvicides are generally applied first and adulticides are only used as a last resort if adult mosquito populations become a problem (14). The toxicity of vector control pesticides to humans and non-target species is of concern. Because pesticides for vector control are applied either near or directly to water, exposure to aquatic organisms and the resulting risks must be considered. Some of these chemicals are highly toxic to fish (138, 139), so care must be taken to choose chemicals that are effective yet protective of the environment.

5.1.3 Summary of BMPs

The New York City Comprehensive Mosquito Surveillance and Control Plan is an example of a vector control BMP. This case study is extremely relevant because vector control programs occur throughout the United States on an annual basis. Due to the wide occurrence of vector control programs and the amount and frequency of pesticide applications, programs with adaptive management strategies such as the NYC vector control program are extremely valuable for increasing program efficacy and reducing the need for pesticides as well as environmental pesticide exposure. The NYC vector control program uses adaptive management by continuously evaluating pesticide products, application rates and application method strategies for efficacy and environmental impact. Below are NYC's vector control BMPs synthesized from the New York City Comprehensive Mosquito Surveillance and Control Plan and personal communications with the program's executive director, Dr. Waheed Bajwa. Included are highlights of how these practices reduce risk and maximize efficacy along with hazards of larvicide and adulticide applications.

5.1.3a Alternative non-Chemical Methods

NYC's Department of Health and Mental Hygiene (DOHMH) implements an integrated pest management approach. The primary method of mosquito control in New York City is the encouragement and implementation of source reduction. Source reduction and public outreach should be the main components of any vector control BMP. Reducing mosquito larval habitat and breeding sites such as standing water in play pools, bird baths and tires is an effective first step. Through public outreach and education, the DOHMH emphases the need to reduce/eliminate and report standing water. NYC has a standing water reporting program and the

DOHMH conducts inspections following complaints (11). Other important public outreach for mosquito control and disease prevention components that the DOHMH provides are media press releases, public service announcements, WNV activity maps and fliers, on-site presentations at senior centers, community board meetings, etc., regular correspondence with community boards and elected officials, presentations in multiple languages, distribution of mosquito repellent to at risk populations, and multilingual WNV posters, pamphlets and factsheets (12). Proactive larval mosquito surveillance and control is also a major part of the program. Other non-chemical methods include biological control such as stocking of mosquito fish which can help with reducing larval populations have been considered and the NYC Department of Environmental Protection (DEP) (under the direct supervision of DOHMH) stocks mosquito eating fish at wastewater treatment plants. Adulticide spraying is only applied when non-chemical methods and larviciding are no longer sufficient at controlling mosquito populations (11).

How does this practice maximize benefits and reduce risk?

- Utilizing non-chemical methods first, such as source reduction, increases the efficacy of mosquito control and reduces the amount of pesticide needed for control.
- Biological control can reduce the need for pesticide use.
- Mosquito larvae surveillance and standing water reports will determine if source reduction methods are effective.
- Public outreach helps with the success of source reduction efforts and also helps to protect public health.

Hazards

- Stocking of mosquito eating fish in some habitats may lead to inadvertent introduction of non-native species to aquatic habitats.

5.1.3b Pesticide(s) and Product(s)

The NYC vector control program uses bacterial larvicides as a first choice when larvicide applications are needed. Larviciding is performed in areas where standing water cannot be removed such as storm drains, wastewater treatment plants, freshwater ponds, wetlands, salt marshes and parks. The following products are used: VectoLex® CG and VectoLex® WSP (a.i. *Bacillus sphaericus*), VectoBac® CG, (a.i. *Bacillus thuringiensis* var. *israelensis*), and VectoMax® CG larvicides (mixture of *B. sphaericus* and Bti). Bti and *B. sphaericus* products are occasionally mixed (11, 12). Both *B. sphaericus* and Bti are considered to be practically nontoxic to freshwater, marine and estuarine organisms (9), including steelhead trout (151). Wildlife is not expected to be negatively impacted by the label use of these products (70). The use of the larvicide methoprene in the formulation of Altosid® has been used in the past and may be considered in the event of resistance development to *B. sphaericus* and/or Bti. The formulation Altosid® has been tested to be practically nontoxic to rainbow trout and slightly toxic to coho salmon in acute toxicity tests (78). Other registered products that may increase efficacy will continue to be evaluated (11).

The use of adulticides is a last resort tool and they are applied only when there is persistent mosquito-borne pathogen detection or a detection in bridge vector mosquitoes in or near NYC. The program uses a decision tree to determine if adulticide applications are needed (12). Factors that contribute to the determination of adult mosquito control are mosquito density and distribution, mosquito species, persistence of WN virus activity, weather, time of year and proximity to human populations. The DOHMH evaluates products containing the active ingredients sumithrin, permethrin, or naled (11). Sumithrin and permethrin are synthetic pyrethroids that kill adult mosquitoes on contact by disrupting the nervous system (105,137). Synthetic pyrethroids are very highly toxic to fish, and 96 hour LC_{50s} are in the µg/L range for juvenile coho salmon and rainbow trout (138, 139). The DOHMH uses sumithrin because it has a good record of mosquito control, degrades rapidly in sunlight, does not persist in the environment and has little toxicity to mammals. The sumithrin product that is used for adult mosquito control is Anvil® 10+10 ULV. Anvil® 10+10 ULV has a high efficacy at low application rates and does not persist in the environment. Anvil® 10+10 ULV is the adulticide product of choice and is used almost exclusively (12). Naled is an organophosphate and kills adult insects by inhibiting acetylcholinesterase, an enzyme involved in the transmission of nerve impulses from one nerve cell to another (96). Naled is highly toxic fish such as rainbow trout (138, 139). It is the intention of the NYC vector control plan to control mosquitoes by source reduction and larviciding so as to reduce or eliminate the need for adulticiding (11).

How does this practice maximize benefits and reduce risk?

- The use of larvicides controls the larval population and therefore the adult population which reduces the need for adulticides.
- Using the larvicides Bti and *B. sphaericus*, which are effective yet have low toxicity to non-target organisms, reduces the risk of potential harm to aquatic species due to larviciding.
- Considering alternative larvicides and adulticides in the case of resistance development allows for a knowledgeable, effective reaction time.

Hazards

- Never use adulticides as a main vector control strategy. They are highly toxic to aquatic organisms.

5.1.3c Adjuvant(s)

The OSVC doesn't add additional adjuvants to their pesticides, but the adulticide formulation they use, Anvil® 10+10 ULV, is 10% piperonyl butoxide (4). The synergist piperonyl butoxide (PBO) is an adjuvant which is commonly used with pyrethroids to increase effectiveness. The PBO synergist can increase acute toxicity of permethrin and sumithrin by a factor of 3 to 4 in brook trout. Both permethrin and sumithrin with PBO also had a greater intoxicating effect than permethrin or sumithrin alone, showing intoxication at 4.5 µg/L permethrin with PBO and 3.2 µg/L sumithrin with PBO after 6 hours of exposure to brook trout (96). The OSVC addresses the concern of adulticide formulation toxicity by monitoring for fish kills and other non-target organism die-offs to determine if the adulticide formulation applications are causing non-target organism mortalities (12).

How does this practice maximize benefits and reduce risk?

- The use of pyrethroid formulations with POB enhances efficacy.

Hazards

- While using pyrethroid formulations that have POBs increase efficacy, only apply when public health has been determined to be threatened; POBs with pyrethroids are highly toxic to fish.

5.1.3d Licensing and Certification of Applicators, Professional and Trade Associations

Larviciding and adulticiding will be performed according to permits issued by the New York State Department of Environmental Conservation (DEC) (11). The DEC is the state agency that regulates pesticides and is responsible for compliance assistance, public outreach activities and enforcement of State pesticide laws. The DEC requires all pesticide applicators and technicians to be certified through the department. There are several categories of certification, and the applicators for mosquito vector control must be certified under the Aquatic Insect and Misc Aquatic Organisms Control and Public Health Pest Control categories. In order to become certified applicators, applicants must have achieved one or more qualifications within the past five years: one year of verifiable experience as a technician with an additional 12 hours of category-specific recertification training; or two years of verifiable experience as a technician; or three years of verifiable full-time experience as an apprentice working in the category or categories in which the individual is seeking certification; or three years of verifiable experience as a certified private applicator in a corresponding private category; or certification in another state that New York State has reciprocity. Technicians must have appropriate apprenticeship and/or experience in addition to core and appropriate category examinations. Once certified, technicians cannot apply restricted pesticides without the supervision of a certified applicator. Technicians and applicators must be recertified every three years. Each applicator/technician is given a pesticide photo identification card that they have with them at all pesticide application events (99).

In addition to the DEC certifications, all managers and supervisors in the program are associated with the American Mosquito Control Association and the Northeastern Mosquito Control Association. Also, all pesticide applicators are provided with training programs at the beginning of each mosquito treatment season. Every year the program conducts three to six training programs for the applicators as a refresher course. The courses are approved by New York State Department of Environmental Conservation for recertification and certification hours. The courses conducted for 2011 were: Integrated Pest Management (IPM) Training for Mosquito Control in NYC, Mosquito Larviciding and Equipment Calibration, and Mosquito Adulticiding and Equipment Calibration. In 2009, a week-long certification course was offered in medical entomology and urban IPM. These yearly courses and association affiliations provide for continuous learning and improvement of applicator methods and skills (12).

How does this practice maximize benefits and reduce risk?

- Certification requirements for applicators and technicians allow for an enforceable standard that all applicators have the knowledge for safe and effective pesticide applications.
- Affiliations with professional associations provide managers with up to date BMPs and environmental issues from other professionals.
- Yearly training and refresher courses help applicators to minimize human error, increase application efficacy and decrease potential environmental risks.

5.1.3e Application Methods

Larvicides are applied to catch basins, sewage treatment plants and areas of permanent standing water. The Office of Vector Surveillance and Control (OVSC) applies larvicides by hand or backpack. In cases where ground application is not possible, aerial applications may be performed. Approximately 145,000 catch basins are inspected and/or treated throughout the season (11). If catch basins are not clogged, are wet and are free of debris, they are treated by dropping VectoLex® CG or VectoMax® CG into the basin. If debris is found within one foot of the surface, the basin will not be treated. Catch basins are marked with spray paint if treated. Larvicide products are rotated (Bti, B. sphaericus and Bti/B. sphaericus mixtures) and used in various combinations. A mosaic of spatially separated applications is used. This may help increase efficacy and reduce the risk of resistance development. Aerial applications of larvicides are made in areas inaccessible by foot or truck such as big marsh and wetlands areas within Staten Island, Queens and Bronx. Aerial applications are made close to the water to minimize drift (12).

Ground applications of adulticides are made in areas of immediate concern of mosquito vector transmission and pathogens. Anvil® 10+10 ULV is only applied by ground (12), although aerial sprays of adulticides will be considered in cases of an epidemic (11). Adulticides may also be applied in response to community mosquito nuisance concerns in Rockaway Peninsula. Adulticides are applied using an ultra-low volume spray (ULV), which maximizes pesticide application efficiency while reducing non-target exposure. All adulticide applications are monitored by city, state and federal officials to ensure compliance with laws and regulations (126). Adulticide application events are recorded with details such as weather conditions, license presence, MSDS sheet presence, fuel supply, pesticide supply, condition of equipment, spray equipment checks, etc. The DOHMH staff also provides monitors to assist applicators if necessary to ensure appropriate pesticide practices are followed (12).

How does this practice maximize benefits and reduce risk?

- Ground application methods allow for greater accuracy, efficiency and less non-target exposure due to drift.
- Aerial applications may be needed for effective control in areas not accessible by ground, while this may increase risk of drift into non-target aquatic areas, it will increase the efficacy of the program.
- ULV spray of adulticides for mosquito control maximizes efficacy and reduces environmental exposure.
- Cataloging of adulticide application events and presence of monitors allows for the evaluation of adherence to pesticide application rules and regulations.

Hazards

- Ground ULV sprays still pose a risk of drift.

5.1.3f Equipment and Calibration

Dry granular larvicide material is applied by hand using a measuring spoon or cup in small areas such as ditches, culverts, and potholes. Backpack blowers are used in larger areas such ponds, lakes and wetlands. In 2005, the NYC control program purchased a helicopter for aerial applications. The helicopter is equipped with an Isolair Dry Broadcast System that distributes granular VectoBac® CG and/or VectoLex® CG. Calibrations of larviciding equipment are done at least twice a season to prevent misapplication of pesticides. Deposit characterization is conducted during each aerial application event, and recalibration of equipment is performed if needed (12).

Anvil® 10+10 ULV is only applied by ground (12), although aerial sprays of adulticides will be considered in cases of an epidemic (11). Ground applications of Anvil® 10+10 ULV are made either by Grizzly ULV or Cougar Foggers from trucks. Grizzly foggers are powered by an 18 horse-powered gasoline engine that drives a rotary positive displacement blower. The air blast from the displacement blower is what creates pesticide droplet size spectrum through a laminar air-flow nozzle. In accordance with the label, the foggers are adjusted so the volume median diameter is 8 to 30 microns. Droplet size is influenced by product, pest, host and spray volume. ULV applications require a fine droplet size in order to ensure proper coverage and efficacy, but as spray volume decreases, finer droplets are needed for adequate coverage which increases risk of drift. Therefore, fogger equipment is calibrated so that the droplet sizes are between 8 to 30 microns, which is the suggested range on the label. Calibrations of foggers are made using the Army Insecticide Measuring System (AIMS) which measures droplet size. The AIMS probe uses hot-wire instrumentation and is positioned directly in front of the fogger's nozzle at fixed distances and measures 1,000 droplets during each adulticide release. AIMS is used to calibrate equipment twice a year, once before the season starts and once mid-season (12).

How does this practice maximize benefits and reduce risk?

- The use of proper equipment increases efficacy and reduces the likelihood for leaks, spills and inadvertent applications.
- Frequent calibration testing will ensure that insecticides will be applied at the proper rate, increasing efficacy and decreasing the risk for non-target exposure due to excess application and drift.

Hazards

- As the volume of the pesticide decreases, droplet size will decrease and result in increased risk of drift. Applicators must take this into account and make correct adjustments.

5.1.3g Application Rates

Larvicides and adulticides are applied at label application rates. The rates will vary depending on habitat type. Application rates are monitored for efficacy in the field to continuously determine which rates are most effective (12). The recommended application rate for VectoLex CG (7.5% A.I.) is 5 to 20 lbs product/A (1.8 to 7.4 ppm) for wastewater, stormwater, water bodies, and marine/coastal areas (145). The range of application rates for VectoBac® CG is 2.5 to 10 lbs product/A (0.9 to 3.7 ppm) (143). Application rates for VectoMax® CG (a mixture of Bti and *B. sphaericus*) vary from 5 to 20 lbs product/A (1.8 to 7.4 ppm) in wastewater, storm waters, marine/coastal areas and other water bodies (147). These larvicide application rates are well below the concentrations required to produce sublethal effects and mortality in fish (151).

Anvil® 10+10 ULV (a.i. sumithrin) is applied at 0.21 to 0.62 fluid ounces/A, which results in concentrations of 0.0012 to 0.0036 lbs/A of sumithrin (0.44 to 1.3 ppb) (4). While these concentrations are within the range that is known to cause mortality in fish (138, 139), the NYC vector control program uses buffer zones and drift minimization practices to reduce exposure to aquatic organisms (12).

How does this practice maximize benefits and reduce risk?

- Effective application rates ensure that non-target organisms aren't exposed to needless amounts of pesticides.
- Tailoring application rates to each site will increase efficacy.

Hazards

- Direct application of Anvil® 10+10 ULV rates over water bodies with fish may cause fish mortality.

5.1.3h Application Timing

Larvicides are applied to wastewater treatment plants, parks and other surface waters starting as early as April if larval breeding is present. Applications are made throughout the season as needed determined by larval presence (11, 12). Storm drain (water catchment basins) larviciding begins in June and is dependent on the presence of larvae. Three rounds of catch basin larviciding are completed per season; and application is made on a monthly basis from June to August. One round of treatments takes 30 days to larvicide all catch basins in the City (12). Adulticides will be applied only to at risk areas for WN virus transmission to humans. DOHMH's criteria for adulticiding are based on estimation of "WN virus transmission risk" in an area considering the following factors:

- Evidence of persistent virus activity, which refers to the ongoing presence of West Nile virus in the trapped mosquitos from an area.
- Successive weeks of increasing mosquito populations testing positive for West Nile virus in the area, or with mosquito counts exceeding 100 per trap per night.
- The mosquito species with West Nile virus must be known to be those that bite humans, feed on birds, or are opportunist and feed on anything. Only mosquitos that feed on both birds and humans are vectors for disease.
- The weather conditions must be favorable for mosquito activities and viral transmission. (11).

How does this practice maximize benefits and reduce risk?

- Beginning larviciding applications toward the beginning of the mosquito breeding season and when larvae are present ensures maximum efficiency and control of mosquitoes.
- Applications made throughout the season as needed assists with continuous control.

- Applying larvicides during larval stages when the larvae are actively feeding is critical to pesticide efficacy.
- Adulticiding only when human health is at risk decreases non-target exposure to highly toxic adulticides.

5.1.3i Application Conditions

Larviciding will take place when larval monitoring determines the need (11). Larvicides will be applied by instructions according to the label, and are made during low tide and during winds speeds of less than ten miles per hour. Larviciding of catch basins will proceed if either no rain or light drizzle is forecasted. Larviciding will cease in conditions of hard rain (12). Applications of adulticides will be made when adult mosquitoes are most active (typically during dawn and dusk) and during permitting weather conditions. The DOHMH will follow label instructions and appropriate Federal and State regulations (11). Weather, such as forecasted rain, temperature and wind speed is considered when approving adulticiding events. Pre-approved adulticiding events are typically cancelled and rescheduled if winds are above 10 mile per hour and/or there is predication of over 50% chance of rain during or within four hours after the spray event. Conditions of every application event are recorded in a spray report (12).

How does this practice maximize benefits and reduce risk?

- Following the label instructions is required by law and is intended to increases effectiveness of application as well as reduce environmental exposure.
- Spraying of adulticides when mosquitoes are most active increases application efficacy.
- Spraying only during permitting weather conditions will increase efficacy of pesticide application and also reduce exposure to non-target organisms.

Hazards

- Excess winds and precipitation may lead to non-target exposure of adulticides.

5.1.3j Mitigation

The OSVC cooperates with the DEC to evaluate water bodies and pre-determine which bodies of water and wetlands within each spray zone may be impacted by adulticide application. Buffer zones of 300 to 400 feet are implemented around all water bodies (12). According to the Environmental Impact Statement published in 2001, there would be no expected adverse impacts due to vector control activities to shortnose sturgeon and sea turtles (NOAA trust species) that are occasionally found in NYC waters (1).

In order to prevent spills, pesticides are handled carefully and transported and stored in small amounts. Loading of pesticides into ULV fogging equipment is always monitored by the

DEC and sometimes by the USEPA. If a spill occurs, instructions on each pesticide label will be followed as well as emergency response information that accompanies all shipments classified as hazardous by the Department of Transportation. All spills are required to be immediately reported to the New York State DEC Spill Hotline, as well as to the New York City Department of Environmental Protection (NYCDEP) and the New York City Department of Health (NYCDOH). In the case of a spill, the area will be isolated with barriers, ignition sources will be removed and the area thoroughly ventilated if in an enclosed space. Cleanup personnel will wear proper safety equipment. The general protocol for small spills is to absorb with material such as sawdust or clay, sweep into chemical waste container, wash the site with soap and water, absorb rinse with inert material and dispose of in chemical waste container and finally wash area to remove and trace material. For large spills, the leak is to be stopped, barriers provided so the spill doesn't spread into waterways, the material is to be pumped, siphoned or drained into suitable containers, then small spill procedures will be employed for the remaining cleanup. Spills that occur on soil require affected areas to be dug up and placed in containers for proper disposal (1,12). The NYC vector control program and its contractors have not experienced any minor or major pesticide spills at the pesticide storage facility or in the field (12).

How does this practice maximize benefits and reduce risk?

- Buffer zones decrease the risk of pesticide drift into water bodies.
- Spill prevention and mitigation plans reduce the risk of environmental contamination from pesticide spills.

5.1.3k Monitoring

In order to evaluate the effectiveness of control by larvicides applications, larval surveillance will take place before and after pesticide applications to catch basins (storm drains) and natural mosquito-breeding sites. The efficacy, accuracy and quality of adulticiding efforts are also monitored. Mosquitoes are surveyed by using light traps, gravid traps, directional Fay Prince traps and mosquito magnet traps (11). Application rates are continuously evaluated in the field for efficacy (12). Local mosquitoes are monitored for resistance development to the *B. sphaericus* and Bti products and the adulticide products. If resistance is discovered, the DOHMH will evaluate and use other products with different larvicides and/or adulticide active ingredients (11). See Pesticides and Products section of this case study (section 5.1.3b) for possible alternatives.

The DOHMH implements year round mosquito pathogen surveillance with the goal of detecting populations of viruses before amplification can occur and so efforts in source reduction and larviciding will reduce risk of transmission to humans as well as reduce the risk of needing to use highly toxic adulticides. The rigorous and extensive testing for mosquito-borne pathogens, amplification and vector bridges is key to forecasting and preventing disease epidemics. Adults are trapped at 50 permanent sites among the five city boroughs and mosquitoes are collected every week. The DOHMH also works with other NYC agencies in creating maps of potential mosquito larvae habitat and updates this information continuously throughout the season. Areas that have been determined to be prime larvae habitat are regularly inspected (11).

The DOHMH also evaluates and researches the potential environmental impacts that may occur as a result from adulticide applications by conducting pre- and post-spray environmental sampling (11). In order to evaluate the efficacy of the 300 to 400 foot buffer zones, the USEPA and Public Health Engineering collect pre- and post-spray water samples from all water bodies within a spray zone. Water samples for pesticides are collected in one-liter amber bottles approved by the USEPA method of analysis performed in accordance with DEC pesticide laboratory procedures. Two one-liter amber jars are filled from each location are collected, although four bottles are collected for every fifteenth sample due to quality assurance performed by the lab. The samples are immediately stored at 4ºC for transportation to the contracted laboratory. The samples are sent to the State's Water Testing Laboratory located in Westchester County for analysis to determine the presence of adulticides or their metabolites (12).

In order to evaluate if adulticide applications are impacting non-target organisms, all water bodies specified by the DEC that are in areas within or adjacent to spray zones are monitored for fish and wildlife mortality by the NYC Parks Department. The visual inspections are conducted within 24 hours of an application event to check for fish kills and other impacts to non-target organisms. If any dead fish or other dead, non-target organisms are observed, samples will be collected, about 12 to 20 fish or non-target organisms when possible. If specimens are collected, additional water samples will also be collected for analysis. Samples are labeled with location of kill, species name or type, and field observations. Cause of death will be determined. Environmental sampling procedures are evaluated every year to improve effectiveness of non-target organism impact surveillance. The NYC Vector Control program has been successful at minimizing non-target organism impacts; from 2003 to 2011 there have been no observed fish kills or other non-target organism die-offs (12).

How does this practice maximize benefits and reduce risk?

- Surveillance of mosquito larvae determines when larviciding will be most appropriate and effective.
- Monitoring the effectiveness of larviciding allows for adjustment of treatments and rates if needed.
- Surveillance of adult mosquitoes allows for the assessment of adulticiding need. Adulticides will not be applied until absolutely necessary to protect humans and other organisms.

- Monitoring the development of resistance to larvicides and adulticides allows for adjustments in pesticide chemical choice increasing the effectiveness of the program while reducing non-target organism pesticide exposure to pesticides that are no longer effective.
- Year round surveillance of mosquito populations and the pathogens will result in appropriate management actions (such as source reduction and larviciding) that reduce human risk and reduce the need for the use of adulticides.
- Environmental sampling of adulticide residues in water bodies adjacent to adulticide applications allows for evaluation of buffer zone efficacy.
- Monitoring of fish kills and other non-target organism die-offs will evaluate if adulticides applications are causing non-target organism mortality.

5.1.3l Storage of Chemical

The OVSC stores pesticides, vehicles for application and all other materials for mosquito control in a pesticide distribution and storage center located in Brooklyn. All pesticides are stored according to the labels. Materials are kept in closed original containers and are stored in a locked, well-ventilated, dry storage area. They are also protected from ignition sources and extreme heat or cold. Secondary containment is provided in case of leaks or spills (1,12).

How does this practice maximize benefits and reduce risk?

- Proper storage of pesticide materials will reduce the risk of spills and environmental contamination, thereby reducing potential exposure to non-target organisms.

Hazards

- The improper storage of pesticides can lead to human and environmental health risks.

5.1.3m Disposal of Chemical and Equipment

The OSVC follows FIFRA regulations for the disposal of pesticides, pesticide containers and pesticide waste containing products. Outdated pesticide products are returned to the manufacturer for disposal or with the help of NYC DEC. Incineration is preferred. Materials that are non-combustible such as steel drums are triple-rinsed and returned to manufacturer for disposal (1,12).

How does this practice maximize benefits and reduce risk?

- Proper disposal of herbicide and rinsate reduces the risk of environmental contamination.

Hazards

- Rinsing equipment in or near surface water can result in environmental contamination.

Acknowledgements: This case study was supplemented with information provided by personal interviews with Dr. Waheed Bajwa, Executive Director New York City Department of Health and Mental Hygiene.

5.1.4 New York City's Comprehensive Mosquito Surveillance and Control Plan Case Study Details

Use the following website to access New York City's Comprehensive Mosquito Surveillance and Control Plan.
http://www.nyc.gov/html/doh/downloads/pdf/wnv/wnvplan2011.pdf

5.2 Example of Pesticides: Bacillus thuringiensis variation israelensis and B. sphaericus

Bacillus thuringiensis variation *israelensis* (Bti) and *Bacillus sphaericus* are microbial/bacterial pesticides that are approved for larval mosquito control in areas such as ditches, standing ponds, pastures, storm water retention areas, tidal waters and salt marshes. Both Bti and *B. sphaericus* work as larvicides by exhibiting a toxic action in the gut of insects once ingested (70).

5.2.1 Application rate

The recommended application rates for the Bti products VectoBac® G (2.8% A.I.) and AquaBac® 200G (2.86% A.I.) are 2.5 to 20 lbs product/A (0.9 to 7.4 ppm) (5,144). Application rates of *B. sphaericus* vary by product. The recommended application rate for VectoLex® CG (7.5% A.I.) is 5 to 20 lbs product/A (1.8 to 7.4 ppm) for wastewater, stormwater, water bodies, marine/coastal areas and dormant rice fields and the application rates for waste tires are 20 to 80 lbs product/A (7.4 to 29.4 ppm) (145). The recommended application rates for VectoLex® WDG (51.2%) are 0.5 to 1.5 lbs product/A (0.2 to 0.6 ppm) (146).

5.2.2 Degradation rate

Bti is effective in water for up to 48 hours. *Bacillus thuringiensis* products have a half-life of approximately four months in soil (10). Due to the rapid breakdown of *B. thuringiensis* with exposure to ultraviolet light, the half-life in normal sunlight is 3.8 hours (10) and the half-life on foliage is one to four days (140). *B. sphaericus* has low water solubility at 10 mg/L and is persistent in soil (8). These microbial pesticides do not leach into ground water (10).

5.2.3 Known toxicity to NOAA Trust Species

5.2.3a Acute LC50

An acute toxicity study on steelhead trout showed that Bti has low toxicity to juvenile steelhead trout. Steelhead trout experienced no mortality after a 24 hour exposure to 1,000 ppm of Teknar® HP-D, a Bti product. Exposure to 5,000 ppm for 24 hours resulted in 10 to 30% mortality and exposure to 10,000 mg/L for 24 hour resulted in 100% mortality of steelhead trout. Juvenile steelhead trout that were longer in fork length had no mortality with exposure to Teknar® HP-D for 2 and 24 hours at concentrations up to 150 ppm (151). These mortality concentrations far exceed the application rates recommended by the label (5,144,145,146). No 96 hour LC_{50} tests for Bti or *B. sphaericus* were available for endangered or threatened anadromous fish, cetaceans, pinnipeds, marine turtles, marine invertebrates, or marine plants listed in Table 2. Both Bti and *B. sphaericus* are considered to be relatively nontoxic to fish, mammals and other wildlife (70).

5.2.3b Sublethal and Chronic Toxicity

A study testing acute sublethal effects of the Bti product Teknar HP-D found that steelhead trout were immobilized after 48 hours of exposures greater than 1,000 ppm, but survived after transfer to fresh water. Some particulates and mucus were found in fish exposed to 2,000 ppm for four hours, but this result was highly variable (151). The sublethal concentrations tested in this study were well above the application rates of Bti products (5,144,145,146). There were no chronic studies found for Bti or *B. sphaericus* for endangered or threatened anadromous fish, cetaceans, pinnipeds, marine turtles, marine invertebrates, or marine plants listed in Table 2. Again, both Bti and *B. sphaericus* are considered to be relatively nontoxic to fish, mammals and other wildlife and are not expected to pose risks to non-target organisms when applied at labeled recommended application rates (70).

5.2.3c Indirect effects

Populations of Lepidoptera, Coleoptera, and Diptera may be temporarily reduced during Bti applications therefore predators such as fish may be slightly impacted due to reduced prey availability, but this risk is low at the labeled application rates (140).

5.2.4 Persistence of pesticide in ambient water

Bti is active for 48 hours in water, then it will adhere to organic matter and settle out (10), therefore chronic exposure through water is not expected. *B. sphaericus* likely behaves in a similar manner, due to its low water solubility (8). Both Bti and *B. sphaericus*, however, are persistent in soil (8,10).

5.2.5 Bioaccumulation potential in non-target species

Although Bti and *B. sphaericus* persist and can accumulate in the soil, there was no information available on bioaccumulation potential (8,140).

III. References

1. “Adult Mosquito Control Programs Final Environmental Impact Statement.” New York City Department of Health, July 2001. Web. 5 Sep. 2001. <http://home2.nyc.gov/html/doh/html/wnv/feis.shtml>.
2. Aguilar, A., A. Borrell, and T. Pastor. 1999. Biological factors affecting variability of persistent pollutant levels in cetaceans. *Journal of Cetacean Research and Management*, Special Issue 1:83-116.
3. “American Mosquito Control Association." *AMCA*. Web. 25 Jul. 2011. <https://amca.memberclicks.net/>.
4. “Anvil 10+10 ULV Label.” Clarke Mosquito Control Products, Inc. Web. 6 Sep. 2011. <http://www.mda.state.md.us/pdf/msdlabel/Anvill.pdf>.
5. “AquaBac 200G Label.” Becker Microbial Products, Inc. Web. 27 Jul. 2011. <http://www.hudsonregional.org/mosquito/Files/Labels/Aquabac200G_label.pdf>.
6. “Aquamaster Label.” Monsanto Company, 2009. Web. 12 Aug. 2011. <http://www.cdms.net/LDat/ld4BL017.pdf>.
7. “Aquathol K Aquatic Herbicide Label.” Cerexagri, Inc. Web. 21 Jul. 2011. Alabama Cooperative Extension System. <http://www.aces.edu/dept/fisheries/rec_fishing/documents/aquatholk_label.pdf>.
8. “Bacillus sphaericus.” Agriculture and Environment Research Unit, Pesticide Properties Database. 19 Apr 2011. Web. 12 Aug 2011. <http://sitem.herts.ac.uk/aeru/footprint/en/Reports/55.htm>.
9. *“Bacillus thuringiensis* subspecies *israelensis* strain EG2215 (006476) Fact Sheet." *Pesticides: Regulating Pesticides*. U.S. Environmental Protection Agency, 12/2010. Web. 12 Jan 2011. <http://www.epa.gov/oppbppd1/biopesticides/ingredients/factsheets/factsheet_006476.htm>.
10. “Bacillus thuringiensis." *E X T O X N E T - Extension Toxicology Network: Pesticide Information Profiles.* Oregon State University, 06/1996. Web. 12 Jan 2011. <http://extoxnet.orst.edu/pips/bacillus.htm>.
11. Bajwa W, M. O’Connor, S. Slavinski, M. Campbell and Z. Shah. “Comprehensive Mosquito Surveillance and Control Plan 2011.” New York City Department of Health and Mental Hygiene, New York, NY. (2011) Print. 9 Aug 2011.
12. Bajwa, Waheed. Personal Communication. 2 Sep. 2011.
13. Barnes, C., L. Bozzi and K. McFadden 2009. Exploring an Ecosystem Approach to Management: Review of the Pertinent Literature. NOAA Ecosystem Goal Team. http://www.nmfs.noaa.gov/pr/sars/improvement/pdfs/eam_lit_review.pdf [accessed 16 June, 2010].
14. “Best Management Practices for Mosquito Control in California." *California Department of Public Health*. Mosquito and Vector Control Association of California. Web. 13 Jan. 2011. <http://www.cdph.ca.gov/HealthInfo/discond/Documents/BMPforMosquitoControl08-10.pdf>.
15. “Biology and Control of Aquatic Plants: A Best Management Practices Handbook.” Ed. Lyn A. Gettys, William T. Haller and Marc Bellaud. Marietta, GA: Aquatic Ecosystem Restoration Foundation, 2009. Web. 21 Jul. 2011.

<http://www.aquatics.org/aerf_handbook.pdf>.

16. Bosch, Daniel. Personal Interview. 23 Aug 2011.
17. “California Department of Pesticide Regulation.” State of California, 2010. Web. 7 Sep. 2011. <http://www.cdpr.ca.gov/index.htm>.
18. “Cheney Lake Restoration Project: Removal of an Invasive Northern Pike Population through the Application of Rotenone." *Division of Sport Fish*. Alaska Department of Fish and Game. Web. 22 Aug. 2011. <http://www.adfg.alaska.gov/static/species/nonnative/invasive/rotenone/pdfs/cheney_lake_ea.pdf>.
19. Cheng, W., and A. Farrell. "Acute and Sublethal Toxicities of Rotenone in Juvenile Rainbow Trout (Oncorhynchus mykiss): Swimming Performance and Oxygen Consumption." *Archives of Environmental Contamination and Toxicology* 52.3 (2007): 388-96. Web. 25 Feb. 2011.
20. Civille, J.C., K. Sayce, S.D. Smith, and D.R. Strong. “Reconstructing a century of *Spartina alterniflora* invasion with historical records and contemporary remote sensing.” *Ecoscience* 12.3 (2005): 330-338.
21. Code of Federal Regulations (2011). 40 CFR 122.2, as amended March, 2007. Available at: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?type=simple&c=ecfr&cc=ecfr&rgn=Section+Number&idno=40&q1=122.2
22. “Consumer Factsheet On: Endothall." Factsheets. US EPA. Web. 1 Nov. 2010. <http://www.epa.gov/safewater/pdfs/factsheets/soc/endothal.pdf>.
23. “Control Program." *SF Invasive Spartina Project*. San Francisco Estuary Invasive Spartina Project. Web. 01 Aug. 2011. <http://www.spartina.org/control/control-desc-treatment.htm>.
24. Cullon, D., M. Yunker, C. Alleyne, N. Dangerfield, S. O'Neill, M. Whiticar, P. Ross 2009. Persistent organic pollutants in Chinook salmon (*Oncorhynchus tshawytscha*): Implications for resident killer whales of British Columbia and adjacent waters. *Environmental Toxicology and Chemistry* 28:1, pp. 148-161.
25. Curran, C.A. "Olfactory-Mediated Behavior in Juvenile Salmonids Exposed to Aquatic Herbicides." University of Washington, 2007. Web. 5 Nov. 2010.
26. Davis, Nicole. “San Francisco Estuary Invasive Spartina Project 2004 Water Quality Monitoring Report.” San Francisco Estuary Institute, 16 Dec. 2004. Web. 30 Aug. 2011. <http://www.spartina.org/project_documents/2004_WQ_Monitoring_Rept.pdf>.
27. “Department of Forestry Division 620 Chemical and Other Petroleum Product Rules.” *Oregon Forests Practices Act.* Oregon Department of Forestry, Jun 2011. Web. 5 Aug 2011. <http://arcweb.sos.state.or.us/rules/OARS_600/OAR_629/629_620.html>.
28. Diamond, G.L., and P.R. Durkin. "Effects of Surfactants on the Toxicity of Glyphosate, with Specific Reference to Rodeo." Ed. Agriculture, United State Department of. Riverdale: SERA, 1997. <http://www.fs.fed.us/foresthealth/pesticide/pdfs/Surfactants.pdf>.
29. Emanuel, R., A. Hulting, and R. Koepke-Hill. “Biology and Management of Knotweeds in Oregon: A Guide for Gardeners and Small-Acreage Landowners.” *Oregon State University Extension Service.* Oregon State University, Jun 2011. <http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/21809/em9031.pdf>.
30. “Endothall." PMEP Home. Web. 1 Nov. 2010. <http://pmep.cce.cornell.edu/profiles/extoxnet/dienochlor-glyphosate/endothall-

ext.html>.

31. “Executive Summary: Oregon Department of Forestry Aerial Pesticide Application Project Final Report.” *Oregon Department of Forestry*. Oregon Department of Forestry, Mar 2000. Web. 5 Aug 2011. <http://www.oregon.gov/ODF/privateforests/docs/ChemAppExecSum.pdf?ga=t>.
32. “EXTOXNET PIP - ROTENONE." EXTOXNET - The Extension Toxicology Network. Web. 12 Jan. 2011. <http://extoxnet.orst.edu/pips/rotenone.htm>.
33. “Factsheet - Rotenone." Pesticide Action Network UK. Web. 12 Jan. 2011. <http://www.pan-uk.org/pestnews/Actives/rotenone.htm>.
34. Feist, B.E., and C.A. Simenstad. “Expansion rates and recruitment frequency of exotic smooth cordgrass, *Spartina alterniflora* (Loisel), colonizing unvegetated littoral flats in Willapa Bay, Washington.” *Estuaries* 23.2 (2000): 267-274.
35. Finlayson, Brian, William L. Somer, and Mark R. Vinson. "Rotenone Toxicity to Rainbow Trout and Several Mountain Stream Insects." *North American Journal of Fisheries Management [N. Am. J. Fish. Manage.]*. 30.1 (2010): 102-11. *Environmental Science and Pollution Management.* Web. 25 Feb. 2011.
36. “Fluridone (Sonar, Brake, Pride) Herbicide Profile 3/86." PMEP Home. Web. 02 Mar. 2011. <http://pmep.cce.cornell.edu/profiles/herb-growthreg/fatty-alcohol-monuron/fluridone/herb-prof-fluridone.html>
37. Folmar, L. C., H. O. Sanders, and A. M. Julin. "Toxicity of the Herbicide Glyphosate and Several of Its Formulations to Fish and Aquatic Invertebrates." *Archives of Environmental Contamination and Toxicology* 8.3 (1979): 269-78. Print.
38. Folmar, Leroy C. "Overt Avoidance Reaction of Rainbow Trout Fry to Nine Herbicides." *Bulletin of Environmental Contamination and Toxicology* 15.5 (1976): 509-14. Print.
39. Gingerich, W. H. "Tissue Distribution and Elimination of Rotenone in Rainbow Trout." *Aquatic Toxicology* 8.1 (1986): 27-40. Web. 25 Feb. 2011.
40. “Glyphosate Technical Fact Sheet." NPIC- National Pesticide Information Center. OSU. Web. 1 Nov. 2010. <http://npic.orst.edu/factsheets/glyphotech.pdf>.
41. Grijalva, Erik and Drew Kerr. “San Francisco Estuary Invasive Spartina Project Treatment Report for 2008-2009.” California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, Feb. 2011. Web. 23 Aug. 2011. <http://www.spartina.org/project_documents/2008-09_TrRpt.htm>.
42. Grijalva, Erik, Drew Kerr, and Peggy Olofson. “Invasive Spartina Control Plans for the San Francisco Estuary 2008-2010 Control Seasons.” California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, June 2008. Web. 30 Aug 2011. <http://www.spartina.org/project_documents/2008-2010_site_plans_doc_list.htm>.
43. Hagen Erin N., and Peter W. Dunwiddie. “Does Stem Injection of Glyphosate Control Invasive Knotweeds (*Polygonum* spp.)? A Comparison of Four Methods.” *Invasive Plant Science and Management* Weed Science Society of America 1.1 (2008):31-35. Web. 8 Aug 2011. <http://www.bioone.org/doi/full/10.1614/IPSM-07-013R.1>.
44. Hamelink, J.L., et al. "Toxicity of Fluridone to Aquatic Invertebrates and Fish." *Environmental Toxicology and Chemistry* 5.1 (1986): 87-94. Web. 25 Feb. 2011.
45. Hatzell, Hilda and Eleanor Foerste. “Quarterly Progress Report: Fourth Quarter FY 07.” Hydrilla/ Hygrophila Demonstration Projects Osceola County, FL. 2007. Web. 13 Jul.

2001. <http://plants.ifas.ufl.edu/osceola/qr/qr_4th_07.html>.

46. Hogue, Cheryl C. "Avoidance Responses of Rainbow Trout and Utah Chub to Rotenone." *North American Journal of Fisheries Management* 19.1 (1999): 171-79. Web. 25 Feb. 2011.

47. Holtby, L. B., and S. J. Baillie. "Effect of the Herbicide Roundup on Coho Salmon Fingerlings in an over-Sprayed Tributary of Carnation Creek, British Columbia." 1987. Print.

48. Hoogle, Ingrid. “San Francisco Estuary Invasive Spartina Project 2008-2009 Monitoring Report.” California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, 25 Apr. 2011. Web. 23 Aug. 2011. <http://www.spartina.org/project_documents/2008-09_MonReport.htm>.

49. Hoogle, Ingrid. “San Francisco Estuary Invasive Spartina Project Monitoring Report for 2006.” California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, 15 Jan 2008. Web. 23 Aug. 2011. <http://www.spartina.org/project_documents/2006_MonReport_Web.pdf>.

50. Howland, R.M. "Interaction of Antimycin a and Rotenone in Fish Bioassays." *The Progressive Fish-Culturist* 31.1 (1969): 33-34. Web. 25 Feb. 2011.

51. Hulting, Andrew. Personal Interview. 1 Aug 2011.

52. Humboldt Bay NWRC: Invasive Spartina." *U.S. Fish and Wildlife Service Home*. Humboldt Bay National Wildlife Refuge Complex. Web. 01 Aug. 2011. <http://www.fws.gov/humboldtbay/spartina.html>.

53. “Hydrothal 191 Aquatic Algicide and Herbicide Label.” United Phosphorus Inc. Web. 21 Jul. 2011. www.CDMS.net. <http://www.cdms.net/LDat/ld225006.pdf>.

54. “Imazapyr." Agricultural Chemistry Research and Extension. Oregon State University. Web. 1 Nov. 2010. <http://www.oregon.gov/ODF/privateforests/docs/imazapyr.pdf>.

55. “Imazapyr." Weed Control Methods Handbook. The Nature Conservancy. Web. 1 Nov. 2010. <http://www.invasive.org/gist/products/handbook/17.Imazapyr.pdf>.

56. “Invasive Species.” Arid Lands Information Center, University of Arizona. 5 Dec. 2006. Web. 13 Sep. 2011. <http://alic.arid.arizona.edu/invasive/index.shtml>.

57. “Invasive Species.” NOAA Ocean Service Education. *National Oceanic and Atmospheric Administration*, 25 Mar. 2008. Web. 13 Sep. 2011. <http://oceanservice.noaa.gov/education/kits/estuaries/media/supp_estuar09d_invasives.html>.

58. Janz, D. M., et al. "Acute Physiological Stress Responses of Juvenile Coho Salmon (Oncorhynchus Kisutch) to Sublethal Concentrations of Garlon 4), Garlon 3a) and Vision) Herbicides." *Environmental Toxicology and Chemistry [Environ. Toxicol. Chem.]*. 10.1 (1991): 81-90. *Environmental Science and Pollution Management* Web. 9 Nov. 2010.

59. Jepson, Paul. “Pesticide Drift Management.” *Oregon State University Extension Service.* Oregon State University, 2007. Print. 9 Aug 2011.

60. Jones, Dean, Jeremy Slade and Michael Netherland. “Large Scale Hydrilla Projects” Presentation for 2010 Aquatic Weed Short Course. May 3-6, 2010. Web. 2 Sep. 2011. <http://conference.ifas.ufl.edu/aw10/presentations/Thurs/Session%20A/1050%20Jones.pdf>.

61. Ken Langeland and Frederick M. Fishel. “Licensing of Aquatic Herbicide Applicators in Florida.” University of Florida IFAS Extension. Web. 2 Sep. 2011.

<http://edis.ifas.ufl.edu/pi011>.

62. Kerr, Drew. "Aquatic Pesticide Application Plan for the San Francisco Estuary Invasive Spartina Project." *San Francisco Estuary Invasive Spartina Project.* Aug. 2010 Web. 19 Aug 2011. <http://www.spartina.org/project_documents/2010_APAP_FINAL_ALL.pdf>.

63. Kerr, Drew. "San Francisco Estuary Invasive Spartina Project Water Quality Monitoring Report for 2006." California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, 27 May 2007. Web. 23 Aug. 2011. <http://www.spartina.org/project_documents/2006_WQ_MonRpt_web.pdf>.

64. Kerr, Drew. "San Francisco Estuary Invasive Spartina Project Water Quality Monitoring Report for 2007-2010." California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, May 2011. Web. 23 Aug. 2011. <http://www.spartina.org/project_documents/2007-10_WQ_MonRpt.pdf>.

65. Kerr, Drew. "*Spartina densiflora* Eradication in the San Francisco Estuary." Humboldt Bay *Spartina densiflora* Symposium, Wharfinger Building, Eureka, CA. June 30, 2010.

66. Kerr, Drew. Personal Communication. 22 Aug. 2011.

67. Kiely T., D. Donaldson, and A. Grube 2004. Pesticides Industry Sales and Usage: 2000 and 2001 Market Estimates. EPA 733-R-04-001. Washington, DC: U.S. Environmental Protection Agency. http://www.epa.gov/oppbead1/pestsales/01pestsales/market_estimates2001.pdf [accessed 16 June, 2010].

68. Kogan, M. 1998. Integrated Pest Management: Historical perspectives and Contemporary Development. *Annual Review of Entomology*. 43:243-70.

69. Laetz, C., D. Baldwin, T. Collier, V. Hebert, J. Stark, and N. Scholz 2009. The Synergistic Toxicity of Pesticide Mixtures: Implications for Risk Assessment and the Conservation of Endangered Pacific Salmon. *Environmental Health Perspectives*. 117:3, pp. 348-353.

70. "Larvicides for Mosquito Control." *Pesticides: Mosquito Control*. U.S. Environmental Protection Agency, 12/2010. Web. 12 Jan 2011. <http://www.epa.gov/opp00001/health/mosquitoes/larvicides4mosquitoes.htm#microbial>.

71. Leson and Associates, Pless, P. "Use of Imazapyr Herbicide to Control Invasive Cordgrass (*Spartina* spp.) in the San Francisco Estuary: Water Quality, Biological Resources, and Human Health and Safety." Prepared for the San Francisco Estuary Invasive *Spartina* Project, May 4, 2005. Web. 20 Aug. 2011. <http://www.spartina.org/referencemtrl/SF-Imazapyr-EA.pdf>.

72. Liguori, V. M., et al. "Toxicity of the Herbicide Endothall to Juvenile Chinook Salmon (Oncorhynchus Tshawytscha)." *Aquatic Toxicology and Hazard Assessment: Sixth Symposium. American Society for Testing and Materials Philadelphia. PA.* 1983 (1983): 530-44. *Environmental Science and Pollution Management* 18 Jul. 2011.

73. Lintermans, M. "Recolonization by the Mountain Galaxias Olidus of a Montane Stream after the Eradication of Rainbow Trout Oncorhynchus Mykiss." *Marine & Freshwater Research [Mar. Freshwat. Res.]*. 51.8 (2000): 799-804. *Environmental Science and Pollution Management.* Web. 25 Feb. 2011.

74. "Management Plan for Invasive Northern Pike in Alaska." *University of Alaska-Fairbanks*. Southcentral Alaska Northern Pike Control Committee. Web. 22 Aug. 2011.

<http://www.uaf.edu/ces/aiswg/resources/ADFGpike_management_plan.pdf>.

75. Marking, L. L., T. D. Bills, and J. R. Crowther. "Effects of Five Diets on Sensitivity of Rainbow Trout to Eleven Chemicals." *Progressive Fish-Culturist* 46.1 (1984): 1-5. *Aquatic Sciences and Fisheries Abstracts* Web. 4 Nov. 2010.
76. Marking, LL, and TD Bills. "Toxicity of Rotenone to Fish in Standardized Laboratory Tests." *Investigations in Fish Control, United States Department of the Interior, Washington D. C.*72 (1976). Web. 8 Mar. 2011.
77. Martin, D. Strayer., R. D. Caldwell, and P. A. Vogue. Final Report, Evaluation of Potential Human and Aquatic Ecological Health Risks Associated with the Use of the Aquatic Herbicides 2, 4-D, Endothall and Fluridone. Seattle, WA: Municipality of Metropolitan Seattle, 1986.<http://www.fs.fed.us/foresthealth/pesticide/pdfs/0521002a_Fluridone.pdf>
78. McKague, AB, and RB Pridmore. "Toxicity of Altosid and Dimilin to Juvenile Rainbow Trout and Coho Salmon." *Bulletin of Environmental Contamination and Toxicology* 20.1 (1978): 167-69. *ECOTOX*. Print.
79. McMillan, John. R., and James C. Starr. “Identification and Prioritization of Salmon Tributaries for Conservation in the Hoh River Basin, Washington State.” *Wild Salmon Center*. Wild Salmon Center, Jun 2008. Web. 2 Aug 2011. <http://www.wildsalmoncenter.org/pdf/WSC_Hoh_Tributary_Report.pdf>.
80. Mitchell, D. G., P. M. Chapman, and T. J. Long. "Seawater Challenge Testing of Coho Salmon Smolts Following Exposure to Roundup) Herbicide." *Environmental Toxicology and Chemistry* 6.11 (1987): 875-78. Print.
81. Mitchell, DG, PM Chapman, and TJ Long. "Acute Toxicity of Roundup® and Rodeo® Herbicides to Rainbow Trout, Chinook, and Coho Salmon." *Bulletin of Environmental Contamination and Toxicology* 39.6 (1987): 1028-35. Print.
82. Morgan, J. D., et al. "Acute Avoidance Reactions and Behavioral Responses of Juvenile Rainbow Trout (Oncorhynchus Mykiss) to Garlon 4), Garlon 3a) and Vision) Herbicides." *Environmental Toxicology and Chemistry [Environ. Toxicol. Chem.]*. 10.1 (1991): 73-79. *Environmental Science and Pollution Management* Web. 9 Nov. 2010.
83. Morgan, M. J., and J. W. Kiceniuk. "Response of Rainbow Trout to a Two Month Exposure to Vision, a Glyphosate Herbicide." *Bulletin of Environmental Contamination and Toxicology [Bull. Environ. Contam. Toxicol.]*. 48.5 (1992): 772-80. Print.
84. Mudge, J.E., T.E. Northstrom, and T.B. Stables. "Acute Toxicity of Hydrothol 191 to Phytoplankton and Rainbow Trout." *Bulletin of Environmental Contamination and Toxicology* 37.1 (1986): 350-54. Print.
85. Muir, DCG, et al. "Comparison of the Uptake and Bioconcentration of Fluridone and Terbutryn by Rainbow Trout and *Chironomus tentans* in Sediment and Water Systems." *Archives of Environmental Contamination and Toxicology* 11.5 (1982): 595-602. Web. 24 Feb. 2011.
86. Munro, Ian C. “Backgrounder Summary of Human Risk Assessment and Safety Evaluation on Glyphosate and Roundup Herbicide.” Rep. Monsanto Imagine. 2005. <http://www.monsanto.com/products/Documents/glyphosate-background-materials/gly_human_risk.pdf>
87. “NCTC Course - CSP2132 - Rotenone and Antimycin Use in Fish Management." *National Conservation Training Center*. U.S. Fish & Wildlife Service. Web. 26 Aug. 2011.

<http://training.fws.gov/nctcweb/catalog/CourseDetail.aspx?CourseCodeLong=FWS-CSP2132>.

88. Netherland, Mike. Personal Communication. 29 Aug. 2011.
89. Newman, Michael. *Fundamentals of Ecotoxicology*. 3rd. Boca Raton, FL: Taylor and Francis Group, 2010. Print
90. NRCS (cited 2011): Definitions of terms. Available at: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043540.pdf
91. Olson, L. E., and L. L. Marking. "Toxicity of Four Toxicants to Green Eggs of Salmonids." *The Progressive Fish Culturist* 37.3 (1975): 143-47. Web. 25 Feb. 2011.
92. "Osceola County Hydrilla and Hygrophila Demonstration Project." University of Florida, 30 Aug. 2011. Web. 7 Sep. 2011. <http://plants.ifas.ufl.edu/osceola/index.html>.
93. Parkinson, Hilary, and Jane Mangold. "Biology, Ecology and Management of the Knotweed Complex." Montana State University Extension. Web. 29 July 2011. <http://msuextension.org/publications/AgandNaturalResources/EB0196.pdf>.
94. Patten, K. "Persistence and Non-Target Impact of Imazapyr Associated with Smooth Cordgrass Control in an Estuary." *Journal of Aquatic Plant Management* 41.1 (2003): 1-6. Web. 23 Feb. 2011.
95. Patten, Kim. "Evaluating Imazapyr in Aquatic Environments." *Agrichemical and Environmental News*. Washington State University. Web. 1 Aug. 2011. <http://aenews.wsu.edu/May03AENews/Patten/Patten.pdf>.
96. Paul, E. A., H. A. Simonin, and T. M. Tomajer. "A Comparison of the Toxicity of Synergized and Technical Formulations of Permethrin, Sumithrin, and Resmethrin to Trout." *Archives of Environmental Contamination and Toxicology* 48 (2005): 251-9. 10 Aug 2011.
97. Payne, N. J., J. C. Feng, and P. E. Reynolds. "Off-Target Deposits and Buffer Zones Required around Water for Aerial Glyphosate Applications." *Pesticide Science PSSCBG* 30.2 (1990): 183-98. Print.
98. "Pesticide Applicator Licenses." Florida Department of Agriculture and Consumer Services, 2011. Web. 7 Sep. 2011. <http://www.freshfromflorida.com/onestop/aes/pestapp.html>.
99. "Pesticide Certification and Business Registration - NYS Dept. of Environmental Conservation." *New York State Department of Environmental Conservation*. Web. 11 Aug. 2011. <http://www.dec.ny.gov/permits/209.html>.
100. "Pesticide/Pest Inspector Licensing Fact Sheet." Washington State Department of Agriculture. Web. 6 Sep. 2011. <http://agr.wa.gov/PestFert/docs/Form4375.pdf>.
101. Phillips, Chad. Phone Interview. 23 Aug. 2011.
102. "Pierce County Noxious Weed Control Board - Featured Weed - Smooth Cordgrass." *Pierce County Noxious Weed Control Board - Front Page*. Web. 01 Aug. 2011. <http://piercecountyweedboard.wsu.edu/smoothcord.html>.
103. Radcliffe, E.B. 2011. Integrated Pest Management Defined. *In:* E. B. Radcliffe,W. D. Hutchison & R. E. Cancelado [eds.], Radcliffe's IPM World Textbook, URL: http://ipmworld.umn.edu, University of Minnesota, St. Paul, MN.
104. Rawson, J.M. (1995) Congressional Research Service Report to Congress: Sustainable Agriculture: Available At National Library for the Environment: http://digital.library.unt.edu/ark:/67531/metacrs173/m1/1/high_res_d/95-

1062_1995Oct25.html
105. “Reregistration Eligibility Decision for d-Phenothrin." *Prevention, Pesticides and Toxic Substances*. U.S. Environmental Protection Agency, 09/2008. Web. 12 Jan 2011. <http://www.epa.gov/oppsrrd1/REDs/sumithrin_%28d-phenothrin%29_red.pdf>.
106. “Reregistration Eligibility Decision for Endothall." Prevention, Pesticides and Toxic Substances. US EPA. Web. 1 Nov. 2010. <http://www.epa.gov/oppsrrd1/REDs/endothall_red.pdf>.
107. “Reregistration Eligibility Decision for Imazapyr. Washington, D.C.: U.S. Environmental Protection Agency, Prevention, Pesticides and Toxic Substances, 2006.<http://www.epa.gov/oppsrrd1/REDs/imazapyr_red.pdf>
108. “Reregistration Eligibility Decision for Rotenone. Washington, DC: U.S. Environmental Protection Agency, Prevention, Pesticides and Toxic Substances, 2007. <http://www.epa.gov/oppsrrd1/REDs/rotenone_red.pdf>.
109. “Resource Guide for Organic Insect and Disease Management." Cornell University's New York State Agricultural Experiment Station. Web. 12 Jan. 2011.
110. Reynolds, P. E., et al. "A Summary of Carnation Creek Herbicide Study Results." (1989). Print.
111. “Rodeo Specimen Label”. Dow AgroSciences. Web. 24 June. 2011. <http://www.cdms.net/ldat/ld4TN001.pdf>.
112. “Round up Pro Herbicide Label.” Monsanto. Web. 16 Jun. 2011. <http://www.afpmb.org/sites/default/files/pubs/standardlists/labels/6840-01-108-9578_label_roundup_pro.pdf>
113. Rowe-Rowe, D. T. "Reaction Times of Certain Freshwater Fishes to a Rotenone-Containing Piscicide." *J South Afr Wildl Manage Assoc* 3.1 (1973): 16-18. Web. 25 Feb. 2011.
114. Rowe-Rowe, DT. "Rotenone Tolerances of Some Freshwater Fishes of Natal." *The Progressive Fish-Culturist* 33.4 (1971): 206-09. Web. 25 Feb. 2011.
115. Rudenko, Melody. "Integrating Restoration and Ecologically Based Weed Management Practices for Invasive Knotweed Control." Thesis. Oregon State University, 2009.
116. *Salmonid Toxicity Studies with Roundup*. Proceedings of the Carnation Creek Herbicide Workshop. 1989. *Aquatic Sciences and Fisheries Abstracts.* Web. 9 Nov. 2011
117. “San Francisco Estuary Invasive Spartina Project 2005 Water Quality Monitoring Report.” San Francisco Estuary Institute, 14 Feb. 2006. Web. 29 Aug. 2011. <http://www.spartina.org/project_documents/2005_WQ_Mon_Rpt.pdf>.
118. “San Francisco Estuary Invasive Spartina Project Monitoring Report for 2004-2005.” *San Francisco Estuary Invasive Spartina Project*. California State Coastal Conservancy, 11 May 2007. Web. 23 Aug. 2011. <http://www.spartina.org/project_documents/Complete_MonRept2004-05_Web.pdf>.
119. “San Francisco Estuary Invasive Spartina Project.” California Coastal Conservancy. Web. 13 Sep. 2011. <http://www.spartina.org/>.
120. “San Francisco Estuary Invasive Spartina Project: Spartina Control Program. Volume 1: Final Programmatic Environmental Impact Statement/Report.” California State Coastal Conservancy and U.S. Fish and Wildlife Service, Sept 2003. Web. 24 Aug. 2011. <http://www.spartina.org/Spartina_Final_EIR/Spartina_Final_EIR.pdf>.
121. Serdar, David M., and Arthur E. Johnson. "Seawater Challenge of Coho Salmon Smolts Following Exposure to the Herbicide Endothall." *Progressive Fish Culturist [Prog. Fish*

Cult.]. 58.2 (1996): 131-34. *Oceanic Abstracts*. Web. 4 Nov. 2010.

122. Servizi, J. A., R. W. Gordon, and D. W. Martens. "Acute Toxicity of Garlon 4 and Roundup Herbicides to Salmon, Daphnia, and Trout." *Bulletin of Environmental Contamination and Toxicology BECTA6* 39.1 (1987): 15-22. Print.
123. Silver, Jill and Martin Hutten. "Knotweed Control on the Hoh River: 2005 Summary Report." *10,000 Years Institute.* 10,000 Years Institute, 2005. Web. 2 Aug 2011. <http://www.10000yearsinstitute.org/10k_asp/knotweed.asp>.
124. Silver, Jill and Martin Hutten. "Knotweed Control on the Hoh River: Summary Report-2002 to 2004." *10,000 Years Institute.* 10,000 Years Institute, 2004. Web. 2 Aug 2011. <http://www.10000yearsinstitute.org/10k_asp/knotweed.asp>.
125. Silver, Jill. "Knotweed Control on the Hoh River: 2007 Summary Report." *10,000 Years Institute.* 10,000 Years Institute, 2007. Web. 2 Aug 2011. <http://www.10000yearsinstitute.org/10k_asp/knotweed.asp>.
126. Silver, Jill. "Knotweed Control on the Hoh River: 2008 Summary Report." *10,000 Years Institute.* 10,000 Years Institute, 2008. Web. 2 Aug 2011. <http://www.10000yearsinstitute.org/10k_asp/knotweed.asp>.
127. Silver, Jill. "Knotweed Control on the Hoh River: 2009 Summary Report." *10,000 Years Institute.* 10,000 Years Institute, 2009. Web. 2 Aug 2011. <http://www.10000yearsinstitute.org/10k_asp/knotweed.asp>.
128. Silver, Jill. "Knotweed Control on the Hoh River: 2010 Summary Report." *10,000 Years Institute.* 10,000 Years Institute, 2010. Web. 2 Aug 2011. <http://www.10000yearsinstitute.org/10k_asp/knotweed.asp>.
129. Silver, Jill. Phone interview. 3 Aug 2011.
130. Soll, Johnathan. "Controlling Knotweed in the Pacific Northwest." *The Nature Conservancy.* The Nature Conservancy, 16 Jan. 2011. Web. 9 Aug. 2011. <http://www.invasive.org/gist/moredocs/polspp01.pdf>.
131. "Sonar AS Aquatic Pesticide Label". SePRO Corporation. Web. 22 Jun. 2011. <http://www.sepro.com/documents/SonarAS_Label.pdf >.
132. "Spartina." *Whatcom Weeds*. Whatcom County Noxious Weed Control Board. Web. 1 Aug. 2011. <http://www.co.whatcom.wa.us/publicworks/pdf/weeds/aquatic/spartina.pdf>.
133. "Technical Fact Sheet On: Endothal."Environmental Protection Agency. Web. 1 Nov. 2010. <http://www.epa.gov/safewater/pdfs/factsheets/soc/tech/endothal.pdf>.
134. Thurston County Health Department. Fluridone. 2009. <http://www.co.thurston.wa.us/health/ehipm/pdf_aqua/aquatic%20actives/Fluridone.pdf >
135. Tierney, K. B., et al. "Changes in Juvenile Coho Salmon Electro-Olfactogram During and after Short-Term Exposure to Current-Use Pesticides." *Environmental Toxicology and Chemistry [Environ. Toxicol. Chem.]*. 25.10 (2006): 2809-17. *ProQuest.* Web. 4 Nov. 2010.
136. Tierney, Keith B., Christopher R. Singh, Peter S. Ross, and Christopher J. Kennedy. "Relating Olfactory Neurotoxicity to Altered Olfactory-mediated Behaviors in Rainbow Trout Exposed to Three Currently-used Pesticides." *Aquatic Toxicology* 81.1 (2007): 55-64. Web. 19 Nov. 2010.
137. Toynton, K., Luukinen, B., Buhl, K., Stone, D. *Permethrin Technical Fact Sheet*; National Pesticide Information Center, Oregon State University Extension Services,

2009. Web. 12 Jan 2011. <http://npic.orst.edu/factsheets/Permtech.pdf>.

138. United States. Environmental Fate and Effects Division. Office of Pesticide Programs. Washington D.C.: U.S.EPA. *Pesticide Ecotoxicity Database*. Web. 9 Mar. 2011. <http://www.ipmcenters.org/Ecotox/index.cfm>.
139. United States. Environmental Protection Agency. *ECOTOX*. Web. 11 Feb. 2011.
140. United States. Environmental Protection Agency. Prevention, Pesticides, and Toxic Substances. “Reregistration Eligibility Decision: Bacillus Thuringiensis.” Washington, D.C.: Environmental Protection Agency, Office of Prevention Pesticides and Toxic Substances, 1998. <http://www.epa.gov/oppsrrd1/REDs/0247.pdf>
141. United States. U.S. Department of Agriculture, Agricultural Research Service, Pacific West Area, Western Regional Research Center. *Biological Opinion: Water Hyacinth Control Program: 2003 to 2005*. Southwest Region, National Marine Fisheries Service. Web. 4 Nov. 2010.
142. Urgenson, Lauren S., Sarah H. Reichard, and Charles B. Halpern. "Community and Ecosystem Consequences of Giant Knotweed (Polygonum Sachalinense) Invasion into Riparian Forests of Western Washington, USA." *Biological Conservation*. University of Washington. Web. 29 July 2011. <http://faculty.washington.edu/reichard/Urgensonetal.pdf>.
143. “VectoBac CG Label.” Valent BioSciences Corporation, Jan. 2005. Web. 6 Sep. 2001. <http://www.nj.gov/counties/mercer/departments/pdfs/mcmc_vectobac_cg_label.pdf>.
144. “VectoBac G Label.” Valent BioSciences. Web. 27 Jul. 2011. <http://www.nj.gov/counties/mercer/departments/pdfs/mcmc_vectobac_g_label.pdf>.
145. “VectoLex CG Label.” Valent BioSciences. Web. 27 Jul. 2011. <http://www.nj.gov/counties/mercer/departments/pdfs/mcmc_vectolex_cg_label.pdf>.
146. “VectoLex WDG Label.” Valent BioSciences. Web. 27 Jul. 2011. <http://www.myadapco.com/res/pdf/labels/VectoLex%20WDG%20Label.pdf>.
147. “VectoMax CG Biological Larvicide Label.” Valent BioSciences Corporation, Sep. 2010. Web. 6 Sep. 2011. <http://www.msmosquito.com/pdf/VectomaxCG_label.pdf>.
148. Wan, M. T., R. G. Watts, and D. J. Moul. "Acute Toxicity to Juvenile Pacific Northwest Salmonids of Basacid Blue Nb755 and Its Mixture with Formulated Products of 2 ,4-D, Glyphosate, and Triclopyr." *Bulletin of Environmental Contamination and Toxicology BECTA6* 47.3 (1991): 471-78. *Environmental Science and Pollution Management* Web. 4 Nov. 2010.
149. Wan, M. T., R. G. Watts, and D. J. Moul. "Effects of Different Dilution Water Types on the Acute Toxicity to Juvenile Pacific Salmonids and Rainbow Trout of Glyphosate and Its Formulated Products." *Bulletin of Environmental Contamination and Toxicology [Bull. Environ. Contam. Toxicol.]*. 43.3 (1989). Print.
150. West, Sheldon D., et al. "Bioconcentration and Field Dissipation of the Aquatic Herbicide Fluridone and Its Degradation Products in Aquatic Environments." *Journal of Agricultural and Food Chemistry* 31.3 (1983): 579-85. Web. 23 Feb. 2011.
151. Wipfli, M. S., R. W. Merritt, and W. W. Taylor. "Low Toxicity of the Black Fly Larvicide Bacillus Thuringiensis Var. Israelensis to Early Stages of Brook Trout (*Salvelinus Fontinalis*), Brown Trout (*Salmo Trutta*), and Steelhead Trout (*Oncorhynchus Mykiss*) Following Direct and Indirect Exposure." *Canadian Journal of Fisheries and Aquatic Sciences.* 51.6 (1994): 1451-58. *Environmental Sciences and Pollution Mgmt*. Web. 2 Nov. 2010.

152. Xie, Lingtian, et al. "Evaluation of Estrogenic Activities of Aquatic Herbicides and Surfactants Using and Rainbow Trout Vitellogenin Assay." *Toxicological Sciences* 87.2 (2005): 391-98. *Environmental Sciences and Pollution Management* Web. 5 Nov. 2010.

Part IV: A Best Management Practice Framework for Aquatic Pesticide Management to Limit Impacts to Salmon

Abstract

Invasive species are a direct threat to endangered salmon. Control and eradication of invasive species can be challenging and expensive, and may require the use of pesticides. Pesticides may be toxic to salmon, so their use is of concern when applied to salmon habitat. There are tradeoff decisions that must be made between pesticide use for salmon habitat restoration and pesticide threat to salmon. Pesticide best management practices (BMPs) can be used in aquatic invasive species control programs to maximize control while limiting threats to salmon and other aquatic organisms. A BMP framework is provided to guide the process of developing and implementing BMPs for pesticide use in aquatic habitats for invasive species control and habitat restoration. This framework is supported by examples from two relatively successful invasive species control/habitat restoration projects: The Hoh River Knotweed Project and the Invasive *Spartina* Project. A pesticide BMP framework could be used as a tool by managers to clearly present BMPs and the tradeoff decisions that go into each invasive species control program. The framework also has the potential to be adapted to catalog and evaluate the efficacy of pesticide BMPs for invasive species control and impacts to non-target organisms.

Key Words: endangered species, herbicides, invasive species, restoration, salmonids

A. Introduction

Oncorhynchus spp. (salmon) are important economically, recreationally, and culturally and provide a link between marine and terrestrial nutrient cycles. Due to overfishing, loss of habitat, and dams many salmon populations have experienced significant declines (Bottom et al. 2009). Of the remaining Pacific salmon and steelhead Evolutionary Significant Units (ESUs), 28 are listed as either endangered or threatened under the U.S. Endangered Species Act (NOAA 2011). Another negative impact to salmon populations is the reduction of habitat quality by invasive species. Aquatic invasive species can alter riparian, freshwater, and estuarine plant communities, hydrological flows, nutrient cycling within streams, alter prey abundance and composition, and directly compete with salmon for food or space. There is also evidence to suggest that non-native species impacts on salmon could rival the impacts of the four H's: hydropower, habitat, hatcheries, and harvest which are attributed to salmon decline (Sanderson et al. 2009).

Invasive species eradication/control can be highly challenging and expensive. The most effective methods of reducing damages caused by non-native species and the cost to eradicate them are prevention, early detection and rapid response (Leung et al. 2002; Rejmánek & Pitcairn 2002). Early detection and rapid response to non-native species invasions can prevent widespread establishment and increases the likelihood of achieving eradication (Rejmánek & Pitcairn 2002). Integrated pest management (IPM) uses multiple strategies to control pests, including prevention, early detection, and physical, mechanical, cultural, biological, and chemical control. IPM was developed due to concerns of human health and environmental health impacts from pesticide use. IPM aims to use ecologically sound and effective strategies in order to reduce pesticide use (Kogan 1998). Best management practices (BMP) are similar to IPM, in that they aim to reduce water pollution in the waters of the United States (Protection of Environment 2007). One could argue that IPM is a BMP. BMPs also deal with uncertainty. The application of pesticides and other related invasive species control actions may have unknown consequences. BMPs utilize the best available knowledge to reduce the risks and threats caused by pest control actions thereby addressing and mitigating some of the uncertainty associated with these actions.

In cases where invasive species are well established and persistent, the use of pesticides may be the most effective (Patten 2002; Silver & Hutten 2004; Kerr 2010). The use of pesticides should include a set of pesticide BMPs in order to reduce the risk of water pollution from pesticides. This is especially pertinent because some pesticides are toxic to endangered species, such as salmon (Wan et al. 1989; USEPA 2011a). This concern is further amplified by pesticides used in aquatic, marine, or riparian settings. Salmon habitat restoration projects that necessitate the use of pesticides for the management of invasive species infestations represent projects where clear, effective pesticide BMPs are highly valuable.

In this article I present a pesticide BMP framework that is meant to guide the process of developing pesticide BMPs in salmon habitat restoration. This project is unique because there is a lack of literature on pesticide BMP frameworks with regard to aquatic habitat restoration, although there are some BMP frameworks that deal with land-use BMPs such as nutrient control and pesticides applied to agriculture (Qi & Altinakar 2011; Rousseau et al. 2012). The framework presented here is supported by examples from two case studies: The San Francisco *Spartina* Project and the Hoh River Knotweed Project, as well as from published literature in order to provide examples of the thought process that goes behind developing pesticide BMPs.

B. Formation of BMP Framework

Case studies of aquatic pest control programs utilizing aquatic pesticides and aquatic pesticide BMPs were synthesized by analyzing program technical reports and supplemented by personal communications with program managers. The aquatic pesticide BMP framework was formed by identifying common components in the aquatic pesticide program BMP case studies. Fourteen components were identified because they represent significant BMP steps or main decisions that must be made before, during, and after pesticide use. These components were grouped into six categories and coupled with main questions that managers and decision makers should ask when developing and implementing pesticide BMPs (Table 1). This framework is designed to be adaptive, with each component influencing the others as more information becomes available.

Table 1: Aquatic pesticide BMP Framework for Salmon

Group	Element	Main Questions
I: IPM	Alternative Non-Chemical Methods	Do alternative methods exist? Are they effective? What is the uncertainty of the efficacy and risk behind these methods? What are the tradeoffs and benefits?
II: Products	Pesticide and Product Choice Adjuvants	What products are most effective? Will they pose unnecessary risk to endangered salmon species? What is the uncertainty behind the use of these products with regards to efficacy and risk?
III: Applicator Knowledge	Licensing and Certification of Applicators	What licenses are required?
	Professional and Trade Associations	Do trade associations exist that provide information on pest control?
IV: Field Practices	Application Method Equipment and Calibration Application Rates Application Timing Application Conditions Mitigation	What practices enhance efficacy and reduce salmon exposure risk? What is the uncertainty of efficacy and risk behind these practices? Are these practices feasible for the logistics and funding of the project?
V: Monitoring	Monitoring	Was the treatment effective? Were salmon impacted?
VI: Off-site Practices	Storage of Chemical Disposal of Chemical and Equipment	Does the program have sufficient means to properly store and dispose of chemicals and contaminated equipment?

C. Case Study Descriptions

The Hoh River Knotweed Project and Invasive *Spartina* Project were chosen as case studies to provide examples to the BMP framework presented here because they represent highly successful projects that have used pesticide BMPs throughout their treatment programs for the eradication of invasive species that threaten salmon habitat. Both programs use current research and adaptive management to inform and implement pesticide BMPs in order to effectively treat non-native species while limiting disturbances to native species (Silver & Hutten 2004; Silver 2010; Grijalva and Kerr 2011). These programs have publicly available reports that describe their BMPs and the challenges that come with invasive species eradication and responsible pesticide use.

1. Hoh River Knotweed Project

The Hoh River Basin on the west coast of Washington State's Olympic Peninsula is home to a few of the last remaining relatively healthy, wild salmon runs in the lower 48 states. In 1998, a patch of *Polygonum x bohemicum* (Bohemian knotweed) was discovered at river mile 29.5. The knotweed quickly spread downstream along the riparian zone to the river's mouth, threatening riparian and river habitat quality. The threat of potential impacts to salmon habitat prompted a survey and control effort to begin in 2002 which is ongoing today and includes a partnership with the 10,000 Years Institute, the Hoh Tribe, Hoh River Trust, private landowners, the Department of Natural Resources, Olympic National Park, and the U.S. Forest Service. The Hoh River Knotweed Project (Hoh Project) has been highly successful and knotweed is now sparse along the river, although challenges for complete eradication are still present (Silver 2010).

2. San Francisco *Spartina* Project

San Francisco Bay Estuary is the largest and most ecologically important site of tidal mudflats and salt marshes in the contiguous western United States. The Bay houses important habitat for shorebirds, mammals, invertebrates, and fishes (Kerr 2010). Marshes and tidal flats are important nursery and feeding habitats for juvenile salmon, providing food and shelter from predators (California State Coastal Conservancy 2003). Tidal flats and native marsh are threatened by non-native *Spartina* spp. (cordgrass) invasions: *Spartina alterniflora*, *S. alterniflora* hybrid, *S. densiflora*, *S. patens*, and *S. anglica* (Grijalva and Kerr 2011). The Invasive *Spartina* Project (ISP) was initiated in 2000 by the California State Coastal Conservancy to record, monitor, and eradicate San Francisco Bay non-native *Spartina* (Kerr 2010). The ISP coordinates with grant entity partners from around the Bay. The ISP has been largely successful, with a *Spartina* infestation of 158 net acres in 2009 down from a maximum of 809 net acres in 2005 (Grijalva and Kerr 2011).

D. Pesticide BMP Framework

1. Alternative Non-Chemical Methods

The first, and arguably the most important step in any pesticide BMP is the consideration of alternative, non-chemical methods for pest control or eradication during a restoration effort. Alternative, non-chemical methods may include physical, mechanical, and biological control methods as well as cultural methods such as public outreach. Restoration projects that use effective alternative methods may decrease the amount of total pesticide needed (Kogan 1998). The efficacy and feasibility of some non-chemical methods for invasive species control in salmon habitat is dependent on the stage of infestation. For example, due to the extensive knotweed rhizome establishment along the Hoh River and the mechanism of knotweed spread, the Hoh Project determined that pesticide use was the only effective method of knotweed control for the Hoh River riparian ecosystem (Silver & Hutten 2004). The ISP uses a combination of non-chemical methods with the use of pesticides for *Spartina* control. The methods are evaluated through site-specific plans for feasibility and environmental impact (Kerr 2010). It is important to recognize, however, that non-chemical methods also pose environmental threats, such as is the case with knotweed and *Spartina* where physical and mechanical methods may stimulate plant growth and facilitate spread through plant fragments (Kerr 2010; Emanuel et al. 2011).

2. Pesticide and Product Choice

Pesticides and formulations will influence the efficacy and environmental impact of restoration programs. There are differences among pesticide active ingredients and formulations in pest control efficacy and toxicity to salmonids (Folmar et al. 1979; Liguori et al. 1983; Hamelink et al. 1986; Mudge et al. 1986; Wan et al. 1989; Patten 2002; Rudenko & Hulting 2010; USEPA 2011a; USEPA 2011b). Other aspects to consider are environmental persistence, human toxicity, and other non-target organism effects. The Hoh Project has worked with multiple groups such as Washington State University, the Olympic Knotweed Working Group, and federal, community, state, and local agencies to screen which products are least toxic to aquatic organisms and will still be effective at controlling knotweed. In addition, the Hoh Project uses only aquatically approved formulations, even when it is not required, in order to reduce risks to aquatic organisms (J. Silver. 2011, 10,000 Years Institute, Port Townsend, WA, personal communication). The ISP uses the most effective aquatically approved herbicides which have gone through environmental assessments (Kerr 2010). Both of the Hoh Project and the ISP have evolved their preferences in herbicides as their projects have matured (Silver & Hutten 2004; Kerr 2010; Silver 2010). Particularly with expansive, multi-year projects, adaptive management is a key component to success and should be employed in every step of a BMP.

There may be a tradeoff between efficacy of the pesticide and toxicity to salmon or other non-target organisms. In these cases, managers must consider the possibility of using a more toxic compound in order to achieve fast, effective control with limited future application, versus using a less toxic compound that may require repeated use of the pesticide over several years. In the case of the Hoh Project and the ISP, they both use the aquatically approved formulations of glyphosate and imazapyr (Kerr 2010; Silver 2010). The ISP uses almost exclusively imazapyr, due to the higher efficacy over glyphosate (Patten 2002; Kerr 2010). The Hoh Project, however, due to a closer efficacy for controlling knotweed between the two herbicides and a concern of imazapyr environmental persistence and toxicity to fish, chooses whether or not to use glyphosate, imazapyr, or a mixture dependent on local conditions, keeping in mind that imazapyr does have distinct advantages in some cases, such as with plants with large persistent rhizomes (Silver 2010; Rudenko & Hulting 2010). Other logistic considerations that will influence pesticide product choice such as the types of application methods and equipment needed for application will ultimately influence pesticide and product choices.

3. Adjuvants

Adjuvants often need to be added to pesticide mixtures in order to increase efficacy. Adjuvants include, but are not limited to: surfactants, dispersants, drift reduction, and marker dyes. Adjuvants, although often not required to undergo the same testing and registration as pesticide active ingredients, may increase the toxicity of the pesticide mixture to fish (Folmar et al. 1979; Wan et al. 1989; SERA 1997) and therefore must have equal consideration to their use with a pesticide. The possibility of a required adjuvant use may result in a different pesticide active ingredient or formulation choice, depending on the adjuvant or pesticide/adjuvant mixture toxicity. The Hoh Project and ISP take into account the efficacy and toxicity of the surfactants and marker dyes used as adjuvants in their treatment programs and only use non-toxic adjuvants (Kerr 2010; Silver 2010).

4. Licensing and Certification of Applicators

States will often have their own regulations regarding licensing and/or certification regarding the use of pesticides. Licensing and certification programs increase the likelihood that pesticides are applied by knowledgeable and capable applicators to reduce the likelihood of spills, misapplication, and poor application judgment. It also allows for accountability and disciplinary action when needed. States may also have regulations regarding pesticides for aquatic use, and therefore applicators must have specific endorsements to use pesticides in aquatic areas. For example, the Hoh Project has an Aquatic Plant and Algae Management National Pollutant Discharge Elimination System (NPDES) permit which is required for pesticide applications into natural areas. The Hoh Project field crew leader is pesticide certified with an aquatic endorsement from the Washington State Department of Agriculture (J. Silver. 2011, 10,000 Years Institute, Port Townsend, WA, personal communication). The ISP adheres to the state of California requirements for pesticide application. In California, all pesticide applicators must be licensed and certifications are needed for restricted use pesticide applications and supervisions. Air craft pilots for pesticide applications must also be licensed in the ISP since they use air craft equipment. Licensing and certification is through the California Department of Pesticide Regulation (California Department of Pesticide Regulation 2010). In addition, the ISP is covered under the Statewide NPDES Permit for the Use of Aquatic Herbicides (Kerr 2010). Both of these states require training and exams to achieve certification, as well as continuing education and workshops for frequent recertification (California Department of Pesticide Regulation 2010; WSDA)

5. Professional and Trade Associations

Professional and trade associations, such as state non-crop vegetation associations, vector control associations, or aquatic nuisance associations, facilitate professionals to obtain continuing education on the latest developments and BMPs, as well as collaborate, learn and discuss with experts and other professionals. Associations may provide courses and/or conferences where BMPs are discussed and evaluated. The Hoh Project works with the Olympic Knotweed Working Group which provides training workshops for knotweed eradication projects and the project leader is a board member on the Jefferson County Noxious Weed Board (J. Silver. 2011, 10,000 Years Institute, Port Townsend, WA, personal communication). The ISP partners are very diverse and represent various agencies and vegetation management contractors through the nine counties in the Bay area. These partners have a variety of affiliations with several professional associations in noxious weed science, wetland ecology, vegetation management, and mosquito abatement as well as regional groups such as the San Francisco Bay Joint Venture (D. Kerr. 2011, San Francisco Estuary Invasive *Spartina* Project, Berkeley, CA, personal communication). Applicators and managers that are affiliated with pest control professional associations will have more tools to employ informed and effective BMPs.

6. Application Method

The method of how pesticides will be applied may influence the extent and risk of non-target impact (aerial spray vs. wiping vs. injection). The methods of how a pesticide may be applied will be dictated by product formulation and method feasibility. There may be tradeoffs among application methods between efficacy, non-target exposure risk, water contamination risk and total quantity of pesticide used. For example, the Hoh Project uses mainly ground foliar spray methods for applying glyphosate and imazapyr formulations, due to the cane size and density of knotweed stands. Glyphosate is occasionally applied as a stem injection on plants with appropriate cane sizes; this practice was more common toward the beginning of the project, when plants were larger (Silver 2010 technical report). Although stem injections practically eliminate the risk of aerial drift, the quantity of pesticide used per plant is greater with stem injections and there is no observed difference between the efficacies of the two methods in the Hoh Project (J. Silver. 2011, 10,000 Years Institute, Port Townsend, WA, personal communication). The ISP uses a wide variety of herbicide application methods including backpack sprayers, boats, helicopters, amphibious tracked vehicles, etc. These application methods are site-specific and the criteria for determining what methods are used are: accessibility, efficacy, cost, and reduction in non-target and water exposure. For example, herbicides are applied by helicopter over large, dense stands of *Spartina* with little native vegetation present while applications by amphibious tracked vehicles and boats allows for spot treatments in areas inaccessible by foot or truck. Example tradeoffs associated with the ISP project are risks in aerial drift resulting in non-target and water exposure compared to the risk of damaging physical disturbance in mudflats and marshes from ground machines (Kerr 2010). These types of tradeoff decisions are not unique to the ISP and every restoration project, particularly in areas with endangered species habitat, should consider the most effective and environmentally benign application methods.

7. Equipment and Calibration

The use of appropriate equipment is important to ensure safe and effective distribution of pesticide. For example, the ISP uses amphibious tracked vehicles to allow access to areas of marsh that are unable to be accessed by foot or truck. They also reduce the overall traffic across the marsh because they are able to hold larger quantities of herbicide on the vehicle allowing for fewer refill trips (Kerr 2007). As mentioned earlier, the equipment used is site specific and depends on a number of variables such as cost, efficacy and environmental impact (Kerr 2010).

Proper calibration of equipment is crucial to ensure correct pesticide application rates. Calibration influences droplet size and drift of pesticide spray (Jepson 2007). In the ISP, each applicator is educated on equipment calibration in order to achieve desired application rates as well as reduce drift. Each applicator takes into consideration droplet size, nozzle pressure, number of nozzles, nozzle orientation, nozzle type, boom orientation, and application distance (California State Coastal Conservancy 2003). Because calibration influences pesticide application rates, which ultimately influence control effort efficacy and environmental exposure, calibration of equipment is essential.

8. Application Rates

Application rates will affect how much pesticide and adjuvant are entering the environment. Pesticide labels dictate the range of allowable amount of pesticide to be applied per area per single treatment and/or treatment season. Managers, in addition to adhering to the label, should consider recent research and experience as to what rate is most effective at pest control. If the application rate needed for desired pest control overlaps with the toxicity thresholds for salmon or other protected species that are present, then a different product may need to be considered. The Hoh Project (Silver 2010) and the ISP (Kerr 2010) use glyphosate at rates well below the 96 hour LC50s for salmonids (Wan et al. 1989) and imazapyr at rates well below 96 LC50s for juvenile rainbow trout and chronic LC50s for rainbow trout eggs (USEPA 2011b). And ISP water quality monitoring reports suggest that aquatic doses from herbicide application rates will not exceed toxicity thresholds for fish (Kerr 2011). The ISP also provides a good example of using varying application rates that are dependent upon *Spartina* densities, with high volume sprays most effective in high to medium density stands and low volume sprays most effective in low density stands (D. Kerr. 2011, San Francisco Estuary Invasive *Spartina* Project, Berkeley, CA, personal communication). It is important to keep in mind that cost may be a limiting factor and so there may be a balancing act between effective application rates and feasibility.

9. Application Timing

The timing of pesticide application is very important, both for pest control efficacy and for minimizing non-target exposure. Timing of pesticide application will influence pesticide residence time, active ingredient contact time with target pest(s) and if and at what life and development stages non-target species are present. In cases when the timing of peak pesticide efficacy overlaps with timing of salmon presence, a tradeoff decision will follow. Managers must consider the toxicity of the pesticide to the salmon as well as the efficacy decline if treatment time was to be altered. The Hoh Project and the ISP apply herbicides during high efficacy months due to the low toxicity concerns to salmon and other organisms (Silver 2010; Kerr 2011). However, because of the presence of the endangered California clapper rail (*Rallus longirostris obsoletus*), the ISP, prior to 2008, did not treat many areas of the San Francisco Bay before the clapper rail breeding season ended September 1st. Due to the results of a biological opinion in 2008, treatment was extended up to three months prior to September 1st, which has greatly enhanced efficacy (Grijalva & Kerr 2011). This represents a tradeoff decision that was made between the efficacy of an invasive species control program and the potential disturbance risk to an endangered species.

10. Application Conditions

Weather conditions and condition of invasive species will also affect pesticide efficacy and risk of non-target exposure (Silver & Hutten 2004; Jepson 2007; A. Hulting. 2011, Oregon State University, Corvallis, OR, personal communication). Conditions can influence which application methods, such as spray vs. injection, can be used and may result in the postponement/halting of applications. For example, in order to reduce the risk of drift, runoff, and reduced pesticide efficacy the Hoh Project will not apply herbicide to damp leaves (Silver & Hutten 2004) and the ISP will postpone aerial applications during rain and unfavorable wind conditions (Kerr 2010). Also, stressed plants, such as from drought, will also reduce herbicide efficacy (A. Hulting. 2011, Oregon State University, Corvallis, OR, personal communication). In some cases, restoration projects may need to determine if pesticides should be applied during unfavorable conditions or not at all that year.

11. Mitigation

Mitigation is an important component of minimizing non-target exposure. Mitigation strategies can include preventative or corrective action measures. The ISP has site-specific mitigation strategies that include the consideration of endangered/threatened species, such as salmon, and specifies measures to avoid and minimize negative impacts. Each site has a mitigation checklist that comprises a wide variety of mitigation measures such water quality and spill mitigation measures. This checklist must be signed by supervisors upon completion of each treatment (Kerr 2010; Grijalva & Kerr 2011). The ISP mitigation BMPs provide a good example of how mitigation strategies should be considered and used throughout the BMP development and implementation process yet should be made clear in a distinct section in order to clearly provide users with precautions and appropriate actions.

12. Monitoring

Monitoring of the pest population is also an important step for informing site specific control choices. Efficacy monitoring of pesticide applications serves as an evaluation for the success (or lack of success) of a restoration project and may also be used to serve adaptive management as a project progresses. Both the Hoh Project and the ISP perform multiple systematic surveys annually and create and update maps using GIS. Data collected include density, area cover, herbicide treatment, habitat type, native plant response, etc. Both of these programs use this data to inform herbicide efficacy, treatment methods for upcoming seasons, and responses from native vegetation (Silver 2010; Grijalva & Kerr 2011; Hoogle 2011).

Another important type of monitoring is environmental impact monitoring. A program that is able to incorporate this type of monitoring will better be able to determine whether or not the practices pose a risk to salmon or other wildlife. An example of environmental impact monitoring is the ISP water quality monitoring program. This program samples for herbicides and their metabolites in the water at representative sites 24 hours before treatment, most recent tidal inundation after treatment and 7 days after treatment. Other water quality parameters (temperature, dissolved oxygen, etc.) are also measured. The most recent available water quality data (2004-2010) indicate that field concentrations of the two herbicides used by the ISP do not pose a significant threat to salmon and other wildlife in San Francisco Bay (Kerr 2010; Kerr 2011).

13. Storage of Chemical

Although proper methods for the storage of a chemical is included on a pesticide label, and certified pesticide applications should be award of proper storage techniques, it is valuable for every BMP to explicitly state how and where the pesticides will be stored. Improper storage of a pesticide can lead to spills and environmental and human contamination risks, thus emphasizing the importance of clearly stating this BMP. The ISP states its general chemical storage rules in an ISP Action Plan appendix (Kerr, 2010).

14. Disposal of Chemical and Equipment

Proper disposal of pesticides is essential for minimizing potential environmental contamination. Each state and jurisdiction may have its own regulations on how to dispose of pesticides and pesticide containers, and the procedures should be made clear in every pesticide BMP. Improper disposal of pesticides and their containers especially when disposed in or near water bodies may lead to environmental contamination thereby posing risks to salmon, other wildlife and human health. Equally important is thorough cleaning of pesticide application equipment which is necessary to ensure equipment will work properly in the future (reduces occurrence of clogged nozzles, etc). BMPs should be included for rinsing equipment and disposing of the rinsate in an environmentally safe manner. For example, the Hoh Project reports BMPs in which they triple-rinse their equipment at the end of each day at a location far removed from water bodies, capture their rinsate and give herbicide containers to the DNR for disposal (Silver & Hutten 2004).

E. Conclusion

BMPs go far beyond the information provided on the pesticide label. Pesticide BMPs should also include recent research, site specific conditions, adaptive management, and professional association recommendations. A pesticide BMP framework could be used as a tool to clearly present BMPs and the tradeoff decisions that go into each invasive species control program. BMPs that clearly describe tradeoffs between invasive species management, endangered species, and ecosystem services may promote integration across management, science, and public sectors, as is a goal in ecosystem-based management (Rosenberg & Sandifer 2009). It should also be noted that this framework has applications to invasive species eradications and restoration projects beyond those concerning salmon and aquatic habitats. The framework also has the potential to be adapted to catalog and evaluate the efficacy of pesticide BMPs for invasive species control and non-target impacts.

F. Implications for Practice

1. A published BMP framework will provide managers with a tool for decision making in restoration projects using pesticides.
2. When used appropriately, this framework will lead to practices that reduce salmon exposure to pesticides while still maintaining effective control of invasive species.
3. The BMPs from this framework will need to be tailored to each pest and habitat situation, since many variables may influence local circumstances.
4. A common BMP framework may increase communication and engagement between restoration project managers.
5. The use of a transparent, common BMP framework may result in increased public support and funding of invasive species control and habitat restoration programs.

G. Acknowledgements

This project was funded through NOAA Grant No. NFFKPR00-11-05375. I thank S. Chan, P. Jepson and R. Emanuel for framework development ideas and review comments. I also thank Jill Silver and Drew Kerr for information provided for the case studies.

H. Literature Cited

Bottom, D., Jones, K., Simenstad, C., & Smith, C. 2009. Reconnecting social and ecological resilience in salmon ecosystems. Ecology and Society **14**: 5.

California Department of Pesticide Regulation. State of California, 2010. URL http://www.cdpr.ca.gov. [accessed 7 September 2011]

California State Coastal Conservancy and U.S. Fish and Wildlife Service. 2003. San Francisco estuary invasive *Spartina* project: *Spartina* control program. Volume 1: final programmatic environmental impact statement/report. California State Coastal Conservancy and U.S. Fish and Wildlife Service, Oakland, CA. URL http://www.spartina.org/Spartina_Final_EIR/Spartina_Final_EIR.pdf

Emanuel, R., A. Hulting, and R. Koepke-Hill. 2011. Biology and management of knotweeds in Oregon: a guide for gardeners and small-acreage landowners. Oregon State University Extension Service, Oregon State University, Corvallis, OR.

Folmar, L. C., H. O. Sanders, and A. M. Julin. 1979. Toxicity of the herbicide glyphosate and several of its formulations to fish and aquatic invertebrates. Archives of Environmental Contamination and Toxicology **8**:269-278.

Grijalva, E., and D. Kerr. 2011. San Francisco estuary invasive *Spartina* project treatment report for 2008-2009. California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, Berkeley, CA. URL http://www.spartina.org/project_documents/2008-09_TrRpt.htm

Hamelink, J. L., D. R. Buckler, F. L. Mayer, D. U. Palawski, and H. O. Sanders. 1986. Toxicity of fluridone to aquatic invertebrates and fish. Environmental Toxicology and Chemistry **5**:87-94.

Hoogle, I. 2011. San Francisco estuary invasive *Spartina* project 2008-2009 monitoring report. California State Coastal Conservancy and San Francisco Estuary Invasive Spartina Project, Berkeley, CA. URL http://www.spartina.org/project_documents/2008-09_MonReport.htm

Jepson, P. 2007. Pesticide drift management. Oregon State University Extension Service, Oregon State University, Corvallis, OR.

Kerr, D. 2007. San Francisco estuary invasive *Spartina* project water quality monitoring report for 2006. California State Coastal Conservancy and San Francisco Estuary Invasive *Spartina* Project, Berkeley, CA. URL http://www.spartina.org/project_documents/2006_WQ_MonRpt_web.pdf

Kerr, D. 2010. Aquatic pesticide application plan for the San Francisco estuary invasive *Spartina* project. San Francisco Estuary Invasive *Spartina* Project, Berkeley, CA. URL http://www.spartina.org/project_documents/2010_APAP_FINAL_ALL.pdf

Kerr, D. 2011. San Francisco estuary invasive *Spartina* project water quality monitoring report for 2007-2010. California State Coastal Conservancy and San Francisco Estuary Invasive *Spartina* Project, Berkeley, CA. URL http://www.spartina.org/project_documents/2007-10_WQ_MonRpt.pdf

Kogan, M. 1998. Integrated pest management: historical perspectives and contemporary developments. Annual Review of Entomology **43**: 243-270.

Leung, B., D. M. Lodge, D. Finnoff, J. F. Shogren, M. A. Lewis, and G. Lamberti. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. Proceedings of the Royal Society B: Biological Sciences **269**: 2407-2413.

Liguori, V. M., H. R. Zakour, M. S. Landolt, and S. P. Felton. 1983. Toxicity of the herbicide endothall to juvenile chinook salmon (*Oncorhynchus tshawytscha*). Aquatic Toxicology and Hazard Assessment: Sixth Symposium. American Society for Testing and Materials Philadelphia. PA.

Mudge, J. E., T. E. Northstrom, and T. B. Stables. 1986. Acute toxicity of hydrothol 191 to phytoplankton and rainbow trout. Bulletin of Environmental Contamination and Toxicology **37**: 350-354.

National Oceanic and Atmospheric Administration, Office of Protected Resources, 2011. URL http://www.nmfs.noaa.gov/pr/species/esa/fish.htm [accessed on 17 January 2011]

Patten, K. 2002. Smooth cordgrass (*Spartina alterniflora*) control with imazapyr. Weed Technology **16**: 826-832.

Qi, H., and M. S. Altinakar. 2011. A conceptual framework of agricultural land use planning with BMP for integrated watershed management. Journal of Environmental Management **92**: 149-155.

Rejmánek, M., and M. J. Pitcairn. 2002: When is eradication of exotic pest plants a realistic goal? Pages 249-253 in C. R. Veitch and M. N. Clout, editors. Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group, IUCN, Gland, Switzerland and Cambridge, U.K.

Rosenberg, A. A., and P. A. Sandifer. 2009. What do managers need? Pages 13-32 in K. L. McLeod & H. M. Leslie, editors. *Ecosystem-based management for the oceans*. Island Press, Washington, D.C.

Rousseau, A. N., P. Lafrance, M. P. Lavigne, S. Savary, B. Konan, R. Quiblé, P. Jiapizian, and M. Amrani. 2012. A hydrological modeling framework for defining achievable performance standards for pesticides. Journal of Environmental Quality **41**:52-63.

Rudenko, M., and H. A. Hulting. 2010. Integration of chemical control with restoration techniques for management of *Fallopia japonica* populations. Management of Biological Invasions **1**:37-49.

Sanderson, B. L., K. A. Barnas, and A. M. Wargo Rub. 2009. Nonindigenous species of the Pacific Northwest: An overlooked risk to endangered salmon? BioScience **59**: 245-256.

SERA (Syracuse Environmental Research Associates, Inc.). 1997. Effects of surfactants on the toxicity of glyphosate, with specific reference to Rodeo. SERA TR 97-206-1b Fayetteville, N.Y.

Silver, J., and M. Hutten. 2004. Knotweed control on the Hoh River: Summary report-2002 to 2004. 10,000 Years Institute, Port Townsend, WA. http://www.10000yearsinstitute.org/10k_asp/knotweed.asp.

Silver, J. 2010. Knotweed Control on the Hoh River: 2010 summary report. 10,000 Years Institute, Port Townsend, WA. http://www.10000yearsinstitute.org/10k_asp/knotweed.asp.

U.S. Environmental Protection Agency. 2011a. ECOTOXicology database system. Version 4.0. URL http:/www.epa.gov/ecotox/ [accessed on 15 February 2011]

U.S. Environmental Protection Agency, Ecological Fate and Effects Division. Office of Pesticide Programs, National Information System of the Regional Integrated Pest Management Centers. 2011b. OPP pesticide ecotoxicity database. URL http://www.ipmcenters.org/Ecotox/index.cfm [accessed 15 June 2011]

Protection of Environment, 40 C.F.R. pt. 122.2. 2007. [accessed on 30 August 2011]

Wan, M. T., R. G. Watts, and D. J. Moul. 1989. Effects of different dilution water types on the acute toxicity to juvenile pacific salmonids and rainbow trout of glyphosate and its formulated products. Bulletin of Environmental Contamination and Toxicology. **43**:378-385.

Washington State Department of Agriculture. n.d. Pesticide/pest inspector licensing fact sheet. AGR PUB 640-4375. Washington State Department of Agriculture, Olympia, WA. URL http://agr.wa.gov/PestFert/docs/Form4375.pdf