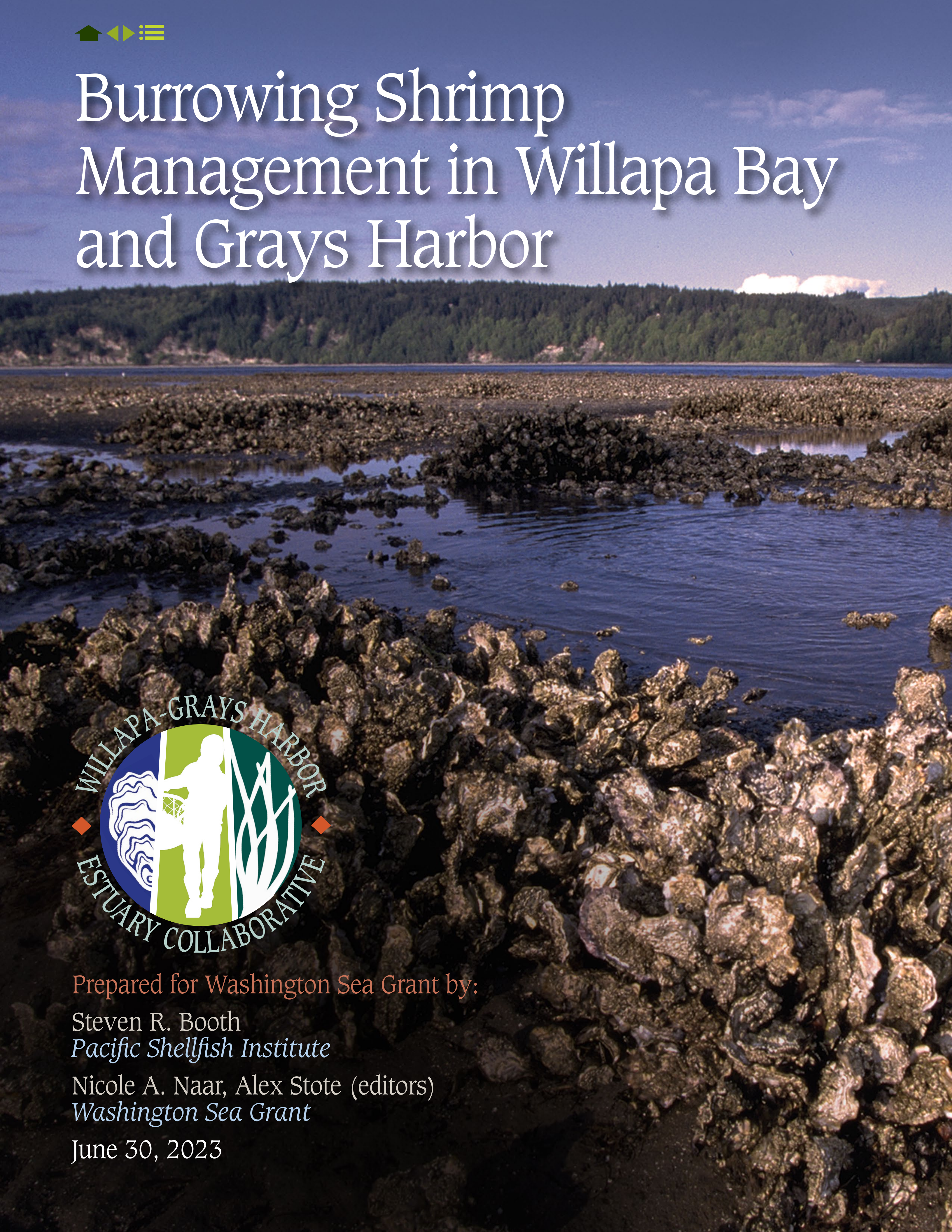

Burrowing Shrimp Management in Willapa Bay and Grays Harbor

WILLAPA-GRAYS HARBOR ESTUARY COLLABORATIVE

Prepared for Washington Sea Grant by:

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Pacific Shellfish Institute

Nicole A. Naar, Alex Stote (editors)
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AC	alternating current
AChE	acetylcholinesterase
a.i.	active ingredient
ATV	all-terrain vehicle
BA	Biological Addendum
BiOp	Biological Opinion
BMP	Best Management Practices
BSCC	Burrowing Shrimp Control Commission
DAT	days after treatment
DBT	days before treatment
DC	direct current
DNR	Washington State Department of Natural Resources
ECY	Washington State Department of Ecology
EFED	Environmental Fate and Effects Division
EIL	Economic Injury Level
EIS	Environmental Impact Statement
ESA	Endangered Species Act
ET	Economic Threshold
EUP	Experimental Use Permit
FEIS	Final Environmental Impact Statement
GABA	gamma-aminobutyric acid
GLP	Good Laboratory Practices
IR-4	Inter-regional Research Project #4
IPM	Integrated Pest Management
LC50	lethal concentration to 50%
LD50	lethal dose to 50%
MOA	Memorandum of Agreement
NHL	non-Hodgkin lymphoma
NIFA	National Institute of Food and Agriculture
NMFS	National Marine Fisheries Service
NPDES	National Pollution Discharge Elimination System
NWP	Nationwide Permit

PCHB	Pollution Control Hearings Board
PCSGA	Pacific Coast Shellfish Growers Association
PMRA	Pest Management Regulatory Agency
PMSP	Pest Management Strategic Plan
PRC	principal response curve
PSI	Pacific Shellfish Institute
RA	Risk Assessment
RED	Reregistration Eligibility Decision
RFP	Request For Proposals
RQ	Risk Quotient
SAP	Sampling and Action Plan
SEPA	State Environmental Policy Act
SEIS	Supplemental Environmental Impact Statement
SFEIS	Supplemental Final Environmental Impact Statement
SIZ	Sediment Impact Zone
SOP	Standard Operating Procedures
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USEPA	United States Environmental Protection Agency
WAC	Washington Authority Code
WCSAS	Washington Coast Shellfish Aquaculture Study
WDF	Washington State Department of Fisheries
WDFW	Washington State Department of Fish and Wildlife
WGHOGA	Willapa-Grays Harbor Oyster Growers Association
WSCPR	Washington State Commission on Pesticide Registration
WSDA	Washington State Department of Agriculture
WSG	Washington Sea Grant
WSU	Washington State University
YOY	young of the year

Preface

Willapa Bay and Grays Harbor are two of the largest bays on the West Coast and home to a 125-year-old industry that provides a substantial percentage of the nation's cultivated shellfish. The surrounding counties — Pacific and Grays Harbor — are among the most dependent on marine fisheries and shellfish production in Washington State. In 2018, two longstanding, but continuously evolving, challenges affecting the local shellfish industry reached a crisis point: perceived conflicts between shellfish farming practices and eelgrass habitat conservation, and the lack of effective burrowing shrimp pest management on farms. In response, the Washington Coast Shellfish Aquaculture Study (WCSAS) — a three-year program funded by the Washington State Legislature and other grants and coordinated by Washington Sea Grant — was launched in 2019.

Willapa Bay and Grays Harbor are two of the largest bays on the West Coast. These "Twin Harbors" in southwestern Washington are home to a 125-year-old industry that provides a substantial percentage of the nation's cultivated shellfish. The goal of WCSAS was to improve the long-term sustainability of shellfish aquaculture in the Twin Harbors under changing environmental conditions by establishing a collaborative ecosystem-based management framework. Joint fact-finding based on the best available science has been crucial for arriving at shared understandings among diverse stakeholders in past controversies surrounding shellfish aquaculture in Washington State. Therefore, our approach was an integrated program of outreach and research aimed at promoting dialogue and common understandings about interactions among shellfish farming, eelgrass and burrowing shrimp in Willapa Bay and Grays Harbor. The engagement component convened a diverse working group of shellfish farmers and resource managers, while the research component focused on reviewing the existing information and developing comparative habitat assessment protocols.

A key deliverable of the WCSAS is a systematic review of the existing scientific and management literature to help inform the multi-stakeholder WCSAS working group and the ecosystem-based management collaborative. This report — a review of the history and strategies informing burrowing shrimp management — has been many years in the making and is intended to provide information in support of ongoing collaborative problem-solving in the region. It joins another report, *Ecological Interactions Between Shellfish Aquaculture, Eelgrass, and Burrowing Shrimp in Willapa Bay and Grays Harbor*, as well as the *Aquaculture Timeline* and several other online resources, fact sheets, and infographics generated on behalf of the project. For links to these documents and more information about the WCSAS, please visit the project website (*https://wsg.washington.edu/community-outreach/aquaculture-outreach/coast-shellfish-study/*).

Executive Summary

Willapa Bay and Grays Harbor — two coastal estuaries in the southwest corner of Washington State — provide a substantial percentage of the nation's oysters, and the shellfish industry is central to the local economies of Pacific and Grays Harbor counties. In recent years, shellfish growers have contended with many ecological stressors that threaten the future viability of the industry, including ocean acidification, mortality events caused by harmful algal blooms and summer heat waves, and invasive species. The increased uncertainty generated by these large-scale environmental changes has also contributed to conflicts between shellfish growers and regulators about aquaculture practices and their impacts on protected species and habitats.

The Washington Coast Shellfish Aquaculture Study

To make progress on the most pressing of these regulatory conflicts in the bays, the Washington Coast Shellfish Aquaculture Study (WCSAS) — a three-year program of integrated engagement and research guided by stakeholders and scientists, coordinated by Washington Sea Grant (WSG), and funded by the Washington State Legislature and other grants — was initiated in 2019. ***The goal of WCSAS was to sustain shellfish aquaculture in the region under changing environmental conditions by establishing a collaborative, ecosystem-based management framework that addresses two key challenges: perceived conflicts between shellfish farming and eelgrass habitat conservation, and the lack of effective burrowing shrimp pest management on shellfish farms.*** Central to this endeavor is a shared foundation of information for developing and evaluating management and adaptation strategies. To that end, WSG commissioned a series of reports synthesizing the scientific and management literature related to system-scale environmental challenges in Willapa Bay and Grays Harbor.

Main Findings

This report focuses on burrowing shrimp management in the bays, highlighting the history of strategies employed and their impacts, as well as the long-standing and continuing effort to develop an effective integrated pest management (IPM) plan. Chapter 1 describes the history of burrowing shrimp management in Willapa Bay and Grays Harbor. The insecticide carbaryl was applied to shellfish beds in the area to control burrowing shrimp from 1963 until 2013, when its use was discontinued as part of a legal settlement and a formal IPM approach was adopted. Various tactics to manage burrowing shrimp and attempts to integrate them into an IPM program have been attempted since the 1990s, including a multi-year, multi-million dollar effort to permit the use of the pesticide imidacloprid on shellfish beds, which was ultimately denied. ***The development of an effective, economically feasible, and socially and environmentally acceptable IPM plan is an ongoing challenge. Alternative management tactics continue to be investigated*** as part of a settlement agreement between the Washington State Department of Ecology (ECY) and the Willapa-Grays Harbor Oyster Growers Association (WGHOGA). In the meantime, shellfish growers have been struggling to manage burrowing shrimp on shellfish beds for several years, which threaten the survival of the local shellfish industry.

Chapter 2 provides an overview of IPM and its application to shellfish aquaculture. The scientific and regulatory challenges of managing pests that are well-adapted native ecosystem engineers living in a subterranean estuarine environment, combined with the logistical constraints and variability of shellfish aquaculture, generates fundamental incompatibilities with traditional IPM management strategies. ***Dozens of studies of potential physical, biological, cultural, and chemical control strategies identified only a few tactics that could suppress shrimp densities for longer than a single growing season***, but considering economic and logistical factors, only the pesticide imidacloprid showed potential for full-scale implementation.

Chapters 3 and 4 review the risk assessments and impact analyses of two pesticides: carbaryl, which was applied for 50 years to control burrowing shrimp, and imidacloprid, which underwent several years of trials and testing but was ultimately not approved for use. Carbaryl is a broad-spectrum carbamate insecticide that blocks nerve transmission by inactivating the enzyme acetylcholinesterase. Imidacloprid is a more selective neonicotinoid insecticide that blocks the neurotransmitter acetylcholine by disrupting nicotine receptors. ***Risk assessments determined that neither carbaryl nor imidacloprid posed substantial risk to a wide variety of non-target organisms when applied to manage burrowing shrimp on commercial shellfish beds*** and according to the EPA's registered label. Four field trials conducted from 2010—2014 featuring 10 large plots (5—20 acres) included measures of imidacloprid concentrations on-plot and off-plot following application. Examinations of potential impacts to Dungeness crab, sturgeon and benthic invertebrates showed potential impacts to crustaceans at one of the sites. Based on that finding, only one of five risk assessments conducted in Willapa Bay showed potential localized and seasonal effects for a few genera of benthic invertebrates. The low frequency of negative effects on benthic invertebrates at the time of testing was likely due to brief and low-concentration exposures, natural resilience to disturbance and extreme environmental events, and — in the case of imidacloprid — low toxicological susceptibility.

Next Steps and Recommendations

IPM is ultimately a decision-making process that depends on the monitoring of pest populations to determine when a threshold of economic injury has been reached and when pest management interventions become necessary. Despite many years of research efforts, each of these steps is ***constrained by persistent data and information gaps that have hindered successful IPM plan development***. As such, several areas of research should be prioritized as burrowing shrimp IPM efforts continue. These include standardized methods for determining burrowing shrimp population density, dynamic models that can be used to hindcast and forecast burrowing shrimp populations and action thresholds linking burrowing shrimp distribution to ecological and economic impacts. Finally, ***research that expands the suite of effective management options is essential.***

The focus on pesticides in the media and by the broader public is easily misperceived as simply replacing one pesticide with another without looking at more sustainable management interventions. However, several years of research and millions of dollars in funding have been dedicated to finding a wider arsenal of effective management tactics to include in the burrowing shrimp IPM toolkit. Unfortunately, suggested management interventions have thus far been ecologically and/or economically infeasible. The importance of the local shellfish industry to the communities surrounding Willapa Bay and Grays Harbor, to Washington State, and to the entire nation compels persistence, and the search for additional management tactics continues under the coordination of the IPM Working Group co-led by ECY and WGHOGA.

Future Research Priorities for Burrowing Shrimp IPM

- Standardized methods for determining burrowing shrimp population density, distribution and range
- Dynamic models using past and present population trends, ocean and estuarine conditions, climate data, etc. to hindcast and forecast burrowing shrimp populations
- A monitoring framework linking burrowing shrimp distribution to negative impacts on shellfish beds and other tidelands
- Reliable methods for estimating economic injury to shellfish growers with different farm sizes, markets, culture methods, and site conditions
- A diverse toolkit of cost-effective management strategies that are environmentally safe and socially acceptable
- Rigorous science-based evaluation of the efficacy, feasibility and non-target impacts of proposed management methods

Introduction

Social license for marine aquaculture in the United States increasingly depends on public perceptions and concerns about potential environmental impacts (Froehlich et al. 2017, Knapp and Rubino 2016), and the messages informing public perception often include sincere environmental concerns (e.g., Ryan et al. 2017, Schlag 2010) alongside anti-aquaculture activism and misinformation (e.g., Cullen Knox et al. 2019, Osmundsen and Olsen 2017).

Along the West Coast, the perceptions of urban consumers exert considerable political and economic leverage even though aquaculture activities occur primarily in rural areas where they often sustain local livelihoods and communities (e.g., Harrington and Harrington 2021, Kliem 2013). The current situation facing Willapa Bay and Grays Harbor reflects these broader regional and national challenges to the diversification and expansion of aquaculture, as well as economic and ecological conditions specific to managing shellfish aquaculture in the southwest coastal estuaries (see I. Baker 2016).

Willapa Bay and Grays Harbor are two of the largest bays on the West Coast and are located a mere 25 km apart (Figure 1). Known for their superior water quality and productive intertidal habitats, these "Twin Harbors" in the southwest corner of Washington provide a substantial percentage of the nation's cultivated shellfish (Flores and Batker 2014). Cultivated species include Pacific oysters (*Crassostrea gigas*) and Manila clams (*Ruditapes philippinarum*) grown using both on- and off-bottom culture methods. In 2015, the total value of shellfish production was 5.95 million pounds and $15.6 million in revenue in Willapa Bay, and 1.2 million pounds and $3.96 in revenue in Grays Harbor (WSG 2015). Consequently, the counties surrounding the Twin Harbors — Grays Harbor and Pacific — are among the most seafood-dependent in the state (WSG 2015). In terms of direct economic impacts, the 2010 shellfish-related payroll in Pacific County was $45M, representing 1,580 jobs; in Grays Harbor County, shellfish-related payroll was $6M, with 210 jobs (Northern Economics Inc. 2013). In spatial terms, shellfish aquaculture occupies over 20% of the intertidal area of Willapa Bay (Dumbauld et al. 2009), and each acre under cultivation generates an annual average of $5,230 in economic output and $2,604 in labor income (Flores and Batker 2014). Many small businesses also specialize in processing, equipment sales and tourism related to the shellfish industry. Considering these indirect economic impacts, the shellfish industry accounts for 15—24% of total labor-earned income in Pacific County (Flores and Batker 2014). Maintaining this 125-year-old industry in southwest Washington, however, may now hinge on resolving consumer concerns about the safety of its products and its impacts on estuarine ecosystems. In addition to adapting to rapid environmental changes — including ocean acidification (Gruber et al. 2012), mortality events caused by harmful algal blooms (King et al. 2021) and summer heat waves (Raymond et al. 2022), invasive *Spartina* cordgrass (Aberle 1990), and invasive European green crab (McDonald et al. 2001), shellfish growers are simultaneously under intense scrutiny triggered by perceptions that their practices harm the environment and negatively impact protected and managed species.

Figure 1. A map of the Washington Coast, including Willapa Bay and Grays Harbor. Source: Razor Clam Society. https://razorclamsociety.org/

One of the most pressing issues currently affecting bivalve aquaculture production in the coastal estuaries is the lack of an effective, sustainable approach for managing burrowing shrimp — native species that, when present in large numbers on shellfish beds, alter the substrate and cause bivalves to sink and suffocate (Feldman et al. 2000) (Figure 2). Controlling burrowing shrimp on shellfish farms in Willapa Bay and Grays Harbor is a decades-long management issue fraught with logistical, environmental, social, and political challenges

(Feldman et al. 2000). Recently, the issue reached a new level of urgency when the Washington State Department of Ecology (ECY) denied a permit to use imidacloprid — a neonicotinoid pesticide commonly used in land-based agriculture — as part of an integrated pest management (IPM) approach for burrowing shrimp on shellfish beds (Doenges 2018). It is also important to note that pesticides can only be applied on the tidal flats at low tide, which occur 3—5 consecutive days a month with intervals of 4—6 hours total and only 6 months of the year during daylight hours, rather than on the water at any given time. Anti-aquaculture activists and concerned seafood consumers were very engaged in the permitting decision, but misinformation — such as the misperception that growers intended to spray imidacloprid directly on farmed shellfish — added fuel to a backlash against the permit among environmentalists, chef-restaurateurs and other seafood consumers (Westneat 2015).

Figure 2. John L. Wiegardt Jr. demonstrates the softness of an oyster bed infested with burrowing shrimp on the south side of Oysterville Flat in 1962. Source: WSG Aquaculture Timeline. https://bit.ly/AQtimeline

The pursuit of a permit for imidacloprid was part of a multi-year effort to develop an IPM program for burrowing shrimp, which officially began after a legal settlement phased out the use of carbaryl, a more broad-spectrum pesticide that had been in use since the 1960s. The National Roadmap to IPM, a document created by a coalition of all federal agencies with input from a stakeholder forum that included growers, environmentalists, state IPM coordinators, and industry representatives, describes IPM as “a sustainable, science-based, decision-making process that combines biological, cultural, physical, and chemical tools to identify, manage and reduce risk from pests and pest management tools and strategies in a way that minimizes overall economic, health and environmental risks” (USEPA 2018). As documented below, IPM operates at several levels of complexity and has proved to be especially difficult to apply to the commercial production of shellfish in estuarine intertidal zones that also support dense populations of burrowing shrimp. Detailed assessment, however, reveals the substantial past and ongoing investments of time, labor and funding devoted to those efforts.

Chapter 1 of the report presents a chronological overview of burrowing shrimp management approaches, from the use of carbaryl in the 1960s up to the ongoing pursuit of an effective IPM program. Chapter 2 provides an in-depth discussion of the specific challenges of developing an IPM program for burrowing shrimp and the many strategies and tactics that have already been explored. Chapters 3 and 4 describe the impact assessments conducted for carbaryl and imidacloprid, respectively, and detail the effects of each pesticide on multiple groups of organisms. Finally, future research priorities to advance ongoing efforts toward a successful IPM plan are provided in the conclusion.

1

History of Burrowing Shrimp Management

Burrowing shrimp management in Willapa Bay and Grays Harbor has a complicated regulatory history that can be divided into three phases: (1) carbaryl-based pest management, (2) development of an IPM program, and (3) attempts to implement the IPM program, in part by transitioning to the use of imidacloprid.

1.1. Carbaryl-based Management

Beginning in the 1960s, carbaryl was applied to commercial oyster ground with shrimp burrow densities greater than 10/m^2, most often by helicopter during low tides on the tidal flats, and with a maximum treated acreage allowance of 800 acres across the two estuaries. Applications were made to non-contiguous farms at 2-4-year intervals, so the total amount applied to a given area was different every year.

In 1963, the Washington Department of Fisheries (WDF), Washington State Department of Agriculture (WSDA), and USEPA "developed a review and approved policy for … [carbaryl's] use" that included a maximum treated acreage of 300 acres (121 ha) in Willapa Bay and 100 acres (162 ha) in Grays Harbor (WDF and ECY, 1985). Although the use of carbaryl (Sevin 80S; Union Carbide) was permitted in 1973 under special control permits issued by WDF that were exempt from the State Environmental Policy Act (SEPA), beginning in 1976, every application required environmental checklists. Subsequently, ECY required compliance with SEPA, and growers were required to obtain a short-term modification to the water quality standards.

In 1981, a Washington State Special Local Needs Permit (24(c)), issued by the USEPA through WSDA, was included as an additional requirement. The permit contained 12 restrictions, including: maximum treated acreage, a 200-ft (61-m) buffer around treated areas, an application rate of 10 lbs. of active ingredient (a.i.) per acre (11.2 kg/ha), maximum wind speeds during application, and a seasonal application window to minimize impacts to migrating salmon. WDF issued draft and final Environmental Impact Statements (EIS) in 1984 and 1985, respectively (WDF and ECY 1985), followed by a Supplemental EIS (SEIS) in 1989 and a Supplemental Final EIS (SFEIS) in 1992 (WDF and ECY 1992). The latter document reaffirmed the existing application criteria, but decreased the application rate to 8 lbs. a.i. per acre (8.97 kg/ha) and modified the allowable annual treatment area to 600 acres in Willapa Bay and 200 acres in Grays Harbor (243, 81 ha, respectively), due to an increased density and range of burrowing shrimp.

1.2 Formal Adoption of Integrated Pest Management (IPM)

In 1991, the Burrowing Shrimp Control Committee (BSCC) was formed through the Washington State Legislature to develop a plan for continued burrowing shrimp management and IPM development. The BSCC membership consisted of agencies, legislators, tribes, and commercial shellfish farmers. The EIS for the use of carbaryl against burrowing shrimp (WDF and ECY 1985), the SFEIS (WDF and ECY 1992), and a commissioned study conducted by Battelle Pacific Northwest National Laboratory (DeWitt et al. 1997) recommended developing an IPM Plan for burrowing shrimp.

In 2001, multiple organizations voluntarily entered into a Memorandum of Agreement (MOA) to complete the IPM process. Signatories and participants included: WGHOGA, WSDA, the Washington State Department of Fish and Wildlife (WDFW), ECY, Washington State University (WSU), the Washington State Commission on Pesticide Registration (WSCPR), the Pacific Coast Shellfish Growers Association (PCSGA), the Pacific Shellfish Institute (PSI), the Toxics Coalition, and the Ad-hoc Coalition for Willapa Bay. Per the MOA, an IPM Coordinator was hired and an IPM Committee was formed with members from the signatory associations and agencies. Developing an IPM plan that included biological and mechanical controls for burrowing shrimp was also included as a condition of WGHOGA's National Pollutant Discharge Elimination System (NPDES) permit for carbaryl applications (ECY Permit No. WA0040975), which ECY began requiring in 2002. The IPM Plan (Booth 2003) was submitted in 2003 and updated in 2007 in compliance with reissuance of the NPDES permit and in 2010 at the request of WSDA.

In 2003, WGHOGA settled a legal challenge to the NPDES permit by the Washington Toxics Coalition and the Ad-hoc Coalition for Willapa Bay by agreeing to successively reduce the amount of carbaryl applied annually by 10% for three years before terminating its use entirely by 2012. In 2011, all signatories agreed to a temporary extension of the NPDES permit through 2013, and the use of carbaryl to manage burrowing shrimp was discontinued after that season.

1.3 Implementation of Imidacloprid

Pesticides, especially those with a selective mode of action, can be an important component of an IPM program when used in a sustainable manner (e.g., applied at the appropriate time and rate) (Croft 1990; Kogan 1998), and a discussion of potential chemical controls, as well as potential mechanical and biological controls, was included in the IPM plan (Booth 2003). After a multi-year and comprehensive investigation of dozens of potential management tactics, both chemical and non-chemical, that yielded no viable alternative, the neonicotinoid class of pesticides was deemed an important potential management candidate as part of the overall IPM plan in 2007 (see Chapter 4). Although less effective against burrowing shrimp than carbaryl, several neonicotinoid pesticides significantly reduced burrow densities for several months (again, see Chapter 4). Neonicotinoids have a relatively narrow spectrum of activity, thereby reducing risks to non-target species. The producers of most neonicotinoid pesticides (i.e., Bayer, Inc. and Cerexagri, Inc.) would not support the registration of their products for use against burrowing shrimp, but imidacloprid came off patent in 2006, and other companies began to produce it. NuFarm Americas, Inc. agreed to produce a formulation of imidacloprid for potential use against burrowing shrimp in Willapa Bay and Grays Harbor, but was unable to assist financially with the regulatory process (e.g., costs of field trials, permitting, etc.).

The Inter-regional Research Project #4 (IR-4) was established in 1963 by the U.S. Department of Agriculture (USDA) to facilitate the registration of sustainable pesticides by helping registrants develop research data to support new USEPA tolerances and labeled product uses in minor crops. For the registration of imidacloprid for use on commercial shellfish beds, the IR-4 process included field applications to oysters using certified Good Laboratory Practices (GLP) personnel and protocols, treatment of one replicate at ten times the proposed field rate, and laboratory analysis of oyster meat for imidacloprid residues. Analysis of field-treated oysters at 30 days after treatment with Nuprid 2F applied at 0.5 lb. a.i. per acre (0.56 kg a.i./ha) showed no residues in the meat, and no residues were observed at ten times this rate (50 lb. a.i. per acre) (Dorschner 2011).

Large scale (>50 acre) field trials of both granular and liquid formulations of imidacloprid were subsequently conducted in 2008, 2009, 2011, 2012, and 2014 under federal (USEPA) and state (WSDA) Experimental Use Permits (EUPs), and an additional federal EUP was granted for ten acres in 2010. In addition to determining imidacloprid's efficacy against burrowing shrimp, the trials assessed its fate and transport and its impacts on sturgeon, crab and benthic invertebrates. The experimental activities associated with the 2012 and 2014 applications were detailed in a Sampling and Action Plan (SAP) developed in collaboration with investigators from WSU, the University of Washington, PSI, ECY, and participating consultants. The ultimate objective of the SAP was to define the sediment impact zone (SIZ) of the imidacloprid applications as defined under the Washington Authority Code (WAC) 173-204.

In October 2014, the USEPA registered imidacloprid (Protector 2F [liquid] and Protector 0.5G [granular]; Nufarm America, Inc.) to WGHOGA for use against burrowing shrimp in Willapa Bay and Grays Harbor. As with any federally registered pesticide, the accompanying label contained several restrictions. For the Protector labels, they included buffers between treated areas and shellfish beds with harvestable crop, a quarter mile buffer between treated areas and public use areas, signage in public areas indicating treatment locations, and a maximum wind speed of 10 mph during application. In April 2015, ECY issued an FEIS regarding the proposed use of imidacloprid that included responses to public comments received during a 45-day period in 2014 (ECY 2015). ECY also issued a NPDES Waste Discharge Permit in April 2015 (No. WA0039781) requiring, among other things, continued large-scale field investigations on the effects of imidacloprid on benthic invertebrates and its environmental persistence for the life of the permit (five years).

Following several negative media reports on the permit's issuance (e.g., Westneat 2015), including interviews with several Seattle area chefs (e.g., Clements 2015), and subsequent public resistance to imidacloprid's use on shellfish beds (*The Seattle Times* News Staff 2015), WGHOGA decided to cancel the permit on May 3, 2015 (Gallagher 2015). On January 8, 2016, WGHOGA reapplied for an NPDES permit for a specific subset of members on a reduced number of total acres and without aerial application (ECY 2017). Following a request from ECY, WGHOGA provided additional information in March 2016, and in May 2016, ECY issued a SEPA Determination of Significance and "adopted and incorporated by reference" (Pollution. Control Hearings Board [PCHB] 2018) the 2015 FEIS. ECY conducted an SEIS that included a public comment period and two public meetings, followed by an SFEIS released on January 5, 2018. In April 2018, ECY issued a tentative denial of the NPDES permit followed by a final denial in September 2018 (Doenges 2018). The denial cited new evidence from the SFEIS (see below) that imidacloprid application could have negative and more widespread impacts on benthic invertebrates, expressed uncertainty about long-term environmental impacts, and emphasized the need for additional research. In response, WGHOGA appealed to the PCHB in October 2018 to reverse the decision. A year later, WGHOGA reached a settlement agreement with ECY and all other parties, and the case was dismissed (PCHB 2018). In exchange for WGHOGA dropping the appeal, ECY agreed to provide regulatory guidance and, among other things, "engage with WGHOGA…to obtain funding through legislative appropriation request in the Supplemental Legislative Session beginning in January 2020." The legislature ultimately funded the appropriation of $650,000 towards the development of a new IPM plan (PCHB 2018).

1.4 Current Status

Burrowing shrimp on commercial shellfish grounds in southwest Washington estuaries have not been managed since 2013. As a result, burrowing shrimp densities have increased, and significant productive acreage has been abandoned (ECY 2017). By 2022, projected cumulative losses were estimated to reach 500 acres of seed ground, 575 acres of fattening beds, and 530 acres of clam beds (Patten 2016), corresponding to a loss of $50 million. The economies of the surrounding communities have been indirectly impacted by lost employment, recreation and tourism opportunities (Taylor et al. 2015).

Some growers have responded by turning to alternative methods and markets, shifting away from bottom-culture for the shucked meat market. As noted above, oysters grown in flip bags are very appealing to the fresh half-shell market. However, single-oyster production for the half-shell market is an entirely different and more specialized industry, requiring distinct farming, processing and marketing approaches. The transition from shucked meat to single oyster production is costly and not appropriate for all companies or growing areas within Willapa Bay and Grays Harbor (Dewey 2015).

A 2018 survey of commercial shellfish growers in WGHOGA indicated that burrowing shrimp, if left unchecked, would reduce their oyster and clam production by 80—90%, causing direct economic impacts totaling nearly $50 million over the next five years (K. Patten, pers. comm.). The lack of effective measures for managing burrowing shrimp recently motivated Pacific County to adopt Resolution No. 2018-042, declaring an economic state of emergency for the oyster industry. In the same year, the Washington Department of Natural Resources' (DNR) Rural Community Partnerships Initiative funded additional research on mechanical control methods.

Though shellfish companies have tried to adapt by shifting to new grounds or experimenting with new growing techniques, a subset of shellfish farmers reported in 2022 that over 1,400 acres of productive shellfish beds have been lost to burrowing shrimp infestation and four shellfish farms have either been sold or gone out of business (ECY 2017).

As previously noted, the Settlement Agreement between the State of Washington and WGHOGA regarding ECY's denial of the NPDES Permit for the use of imidacloprid on commercial shellfish beds in Willapa Bay and Grays Harbor included the further development of an IPM Program for Burrowing Shrimp (PCHB 2018). An IPM Working Group was formed, headed by the WSDA's Director of Strategic Initiatives with representatives from WGHOGA, ECY, WSDA, DNR, the Conservation Commission, and an environmental organization currently represented by the Surfrider Foundation; WSG also participates as an *ex officio* member. The WSDA issued a request for proposals (RFP) and funded five initial research projects with support of the IPM Working Group. These included: (1) a laboratory screening of 74 chemicals comprising mostly compounds on the USEPA's minimum risk 25b list (e.g., mostly botanicals and other organic materials), followed by preliminary field trials of the six candidate materials that showed the most potential in the laboratory; (2) a dye study to look at off-site movements of a potential compound applied according to conventional surface techniques, by subsurface injection or mixed with shell hash on the surface; (3) the development of a written "Framework for the Integrated Management of Burrowing Shrimp in Southwest Washington," plus an annotated bibliography of associated literature; (4) a study on the potential use of drones as a tool for mapping burrowing shrimp populations; and (5) a study on the effects of burrowing shrimp on eelgrass and improved techniques to monitor shrimp densities using core sampling. Subsequent projects funded by this grant include: (1) a field study to address causes and consequences of variability in burrowing shrimp populations and the impact on oyster performance; (2) a study to test the impacts of mechanical control for burrowing shrimp; (3) a review and analysis of the IPM Working Group's current resources and development of stakeholder communications and coordination strategy; (4) a facilitated update of industry led Best Management Practices that include IPM to address burrowing shrimp; and (5) assistance with the Willapa-Grays Harbor Estuary Collaborative as it relates to the IPM work. Additional projects will be supported through at least 2025.

2

Applying IPM to Shellfish Aquaculture

In keeping with the MOA and in compliance with the NPDES permit for carbaryl use, “A comprehensive plan towards an integrated pest management program for burrowing shrimp on commercial oyster beds” (Booth 2003)[2] was submitted to ECY in 2003 (hereafter referred to as the IPM Plan). Further dissemination of the IPM Plan was greatly advanced by the creation of two key documents: the “Crop Profile for Bivalve (Oysters, Manila Clams, Geoduck Clams and Mussels) Aquaculture in Washington, a comprehensive list of the pests of commercial bivalves” (Booth 2010b); and “The Pest Management Strategic Plan (PMSP) for Bivalves in Washington and Oregon”[2] (DeFrancesco and Murray 2010).

The IPM Plan adhered to the legal definition(s) of IPM as presented to Washington State agencies with pest control responsibilities: “a coordinated decision-making and action process that uses the most appropriate pest control methods and strategy in an environmentally and economically sound manner to meet agency programmatic pest management objectives...” (RCW 17.15.010, 1997). The inclusion of decision-making and action is representative of the more than 60 commonly accepted definitions of IPM (Bajwa 1996, Bajwa and Kogan 2002).

2.1 The IPM Paradigm

The conceptual foundation of the Plan is based on Kogan’s (1998) paradigm for modern agriculture, which consists of three levels of IPM integration that increase in complexity and scale in tandem with the associated ecological, human and agricultural communities (Figure 3). The scales are parallel and hierarchical among ecological systems and human social systems, and similarly hierarchical and parallel interactions between them define the agricultural system and thus the complexity of IPM. In other words, the scale and complexity of IPM integration depends on both the ecosystem and the social system that defines that agricultural setting.

At first glance, the agricultural setting for commercial oyster pest management in Willapa Bay and Grays Harbor appears to exist at a low level of complexity and scale. Although they comprise two separate species (ghost shrimp [*Neotrypaea californiensis*] and mud shrimp [*Upogebia pugettensis*]), burrowing shrimp are the sole pest of economic importance, and commercial shellfish farming in Willapa Bay is practiced by a relatively small number of individuals relying on similar tactics to grow oysters on relatively small acreages. According to Kogan’s paradigm, the suite of management tactics that target burrowing shrimp should be at a low level of complexity. Indeed, the conventional carbaryl-based management was basically a Level I IPM strategy: the chemical treatment of

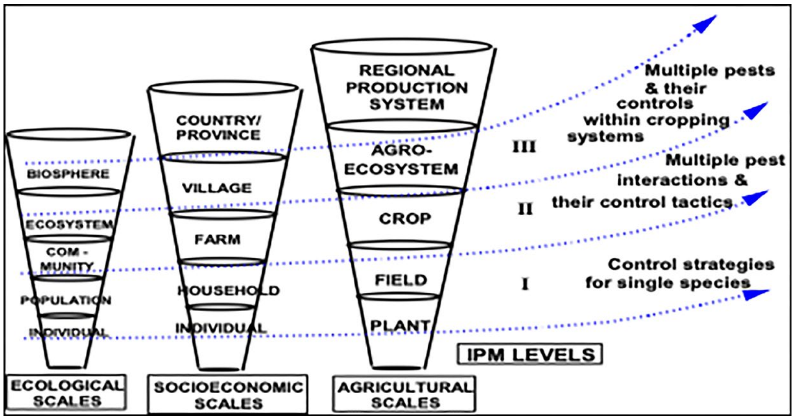

Figure 3. Graphical representation of the ecological and socioeconomic scales that define the scale of agricultural systems, and the corresponding levels of IPM integration. Source: Kogan 1998.

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1. Development of the IPM plan was partially funded by the Western Region Sustainable Aquaculture Research and Education program, which is part of the USDA National Institute for Food and Agriculture (NIFA). The IPM plan was included in the 2007 Final Report (Booth 2007a).
2. The PMSP was the primary outcome from a planning workshop held on March 11, 2010, and attended by primary stakeholders from all growing regions in Washington and Oregon and facilitated and funded by representatives from the Western IPM Center at Oregon State University.

later life stages of (essentially) a single pest on specific shellfish beds when densities were above an accepted economic threshold of 10 burrows/m^2.

However, the scales of ecological, social and agricultural interactions in Willapa Bay and Grays Harbor are, in fact, diverse, dynamic and complex. Burrowing shrimp population ecology is influenced by conditions in estuaries and ocean currents that extend far beyond the Washington coast (Johnson and Gonor 1982, Pimental 1983). Commercially important populations of salmonids and crab move seasonally through the bays. The demography and economy of southwest Washington have become increasingly diverse, with greater contributions from retirees, recreation and tourism (Huppert et al. 2003). Bivalve aquaculture in the region has also become more complex, with some oyster growers adopting off-bottom culture methods and expanding to single oysters for the half-shell market. The IPM program for burrowing shrimp could therefore be correspondingly complex.

The IPM plan for burrowing shrimp has remained at the lower levels of IPM integration for at least six reasons, three due to the unique biology and ecology of burrowing shrimp and three due to more practical considerations. First, burrowing shrimp in Willapa Bay and Grays Harbor are indigenous species that control their habitat. As ecosystem engineers, they "modulate the availability of resources (other than themselves) to other species by causing physical state changes in biotic and abiotic materials. In so doing, they modify, maintain and/or create habitats" (Jones et al. 1994). Second, burrowing shrimp are extremely well adapted to their fossorial habitats within the estuarine soft-bottom ecosystem. Conditions are harsh, especially at the depths to which burrowing shrimp can live (Atkinson and Taylor 2005, Taylor et al. 2000), where sediments are extremely low in oxygen but enriched in carbon dioxide and sulfides (Pillay and Branch 2011). Although burrowing shrimp ventilate their burrows via irrigation by beating their pleopods, the burrows can still become hypoxic, which the shrimp tolerate for long periods. Burrowing shrimp are also tolerant of high sulfide levels, which they can convert to less toxic thiosulfates. Third, burrowing shrimp can tolerate interventions that are lethal to many other organisms. Liou and Weaver (2006) found that ghost shrimp in the laboratory could construct burrows in substrates with levels of densification much higher than those found in the field. Shrimp could only be crushed at stress levels found at least 1.5 m below the ground surface in association with very high surface loads.

From a more practical standpoint, there are very few examples of pest management for aquaculture on which to model an IPM program, particularly for estuarine aquaculture. Unlike burrowing shrimp, almost all targets of aquatic IPM programs are invasive species that have escaped the biological and environmental population controls of their native habitats (Hubert et al. 2021). Most pesticides registered for aquatic use in the United States are herbicides to manage invasive plants (USEPA 2021). Pesticides to kill sea lice on finfish are usually administered as additives to food pellets rather than by broadcast application (Burridge et al. 2010). Burrowing shrimp that disrupt penaeid shrimp culture in Nicaragua are managed by draining the ponds and applying pesticides (Felder et al. 2003) that are not registered for aquatic use in the United States. In addition, conducting field research in the intertidal zone of estuaries is inherently difficult for multiple reasons. Accessing sites is confounded by daily high tides and soft, muddy substrates that are difficult to traverse. Many commercial oyster beds are accessible only by boat. Field research in the mudflat is limited to maximum low tidal intervals of 4—6 hours that occur for only 3—5 consecutive days within a two-week period and during daylight hours only six months of the year. The development of an IPM program for burrowing shrimp lacked investigative and financial support for many years. However, in 2018, $650,000 was allocated towards the development of an IPM program for burrowing shrimp management as a result of the settlement agreement between WGHOGA and ECY (PCHB 2018).

2.2 Management Strategies and Tactics

As implied in the definition of IPM, the IPM plan for burrowing shrimp distinguished pest management strategies from pest management tactics. A tactic is an activity created with specific and measurable objectives, whereas a strategy is a big picture approach to problem solving that incorporates and integrates a series of steps and tactics. At the most complex scale, management strategies could include the integration of multiple chemical, biological, mechanical, and/or cultural management tactics.

2.2.1 Monitoring techniques

Successful implementation of virtually any IPM strategy and its tactics depends on comprehensive knowledge of pest life history and ecology. This includes the answers to questions such as: What are the most vulnerable life stages? When do they occur? How fast do individuals and populations grow and reproduce? What controls those developmental rates? When and where do they reproduce? What are their natural enemies? Can they be studied in the laboratory or the field with suitable rigor? Knowing, or reliably predicting, pest abundance is also critical for understanding the threat to the crop.

The abundance of burrowing shrimp recruits at key locations in Willapa Bay has been tracked annually for dozens of years as part of an ongoing research program on the life history, population dynamics and recruitment ecology of burrowing shrimp (Bosley, Coleman and Dumbauld 2019, Bosley, Wainwright and Dumbauld 2019, Dumbauld and Bosley 2018, Dumbauld et al. 2021), as well as their interactions with shellfish aquaculture (Dumbauld 1994, Dumbauld et al. 1996, Dumbauld and Cheney 2002). Kim Patten, PhD, WSU Long Beach Extension (retired), also monitored the abundance and geographic distribution of burrowing shrimp recruits from 2014 to spring 2019 (K. Patten, pers. comm.). The distribution of adult burrowing shrimp in Willapa has also been mapped in comparison to eelgrass density and distribution (Dumbauld and McCoy 2015, Subbotin and Ruesink 2021, Wecker and Dumbauld 2007).

Adult burrowing shrimp primarily remain in their burrows, where they are difficult to study or even monitor, but they have occasionally been observed occupying burrow entrances and even moving across the mudflat (Posey 1986). Short-term experiments in the laboratory designed to assess movement across much smaller distances suggest that only males move across the surface and that females remain in their burrows and move horizontally below the sediment surface (B. Dumbauld pers. comm.). This is supported by mating behavior observations of a similar shrimp species, *Nihonotrypaea japonica* (Somiya and Tamaki 2017). Vertical movement of shrimp within the tidal cycle has also been observed to determine when they might be most vulnerable to control mechanisms (Patten and Stern 2005). The depth of shrimp was uniform regardless of the time of day or tidal height, with an average depth of 23 cm and a maximum depth of 60 cm during a high tide.

The most common method for estimating densities of burrowing shrimp is based on the abundance of their burrows, derived from a series of counts within a 0.25 m^2 quadrat (Dumbauld et al. 2021). However, the relationship is not linear and includes considerable variability, both within and among sites (Dumbauld and Bosley 2018). Counts of shrimp burrows often differ among census takers (Dumbauld et al. 2006), in part because shrimp burrows can resemble those of clams, polychaetes, and other burrowing estuarine invertebrates. Their appearance also depends on the tidal stage, the weather and the season. The number of counts needed for a reliable estimate has not been determined, but efforts to standardize burrow count methodology are ongoing (Booth and Hudson 2022, Dumbauld et al. 2021, Subbotin and Ruesink 2021).

Alternatives to burrow counts for monitoring burrowing shrimp and their effects have also been studied. Luring shrimp into traps was not particularly effective (Patten 2016). Tags used in attempts to assess population size via mark and recapture technique either fell off or killed the shrimp. Measures of substrate firmness, such as the width of craters formed by dropped balls or readings from penetrometers, were highly variable depending on substrate type, duration of bed exposure and presence of vegetation (Booth, unpublished data). Pelagic larval stages of ghost shrimp were sampled in the water column in the fall immediately after hatching, but abundances did not reliably predict how many shrimp settled into the substrate during the subsequent winter or early spring (Bollens 2006, Graham and Bollens 2010). Genomic sequencing techniques based on mitochondrial DNA have also been used to identify ghost shrimp pelagic larvae. Parr et al. (2007) successfully used the technique to track larval dispersal in coastal ocean currents and identified the source populations for Washington estuaries (see also Buncic 2010).

2.2.2 Thresholds for pest management actions

As noted by Kogan (1998) and others (Higley and Pedigo 1996, Norris et al. 2003, Radcliffe et al. 2009), the decision-based structure of IPM relies on thresholds to trigger management actions. In other words, one must know when to treat. The action threshold in IPM is the point at which a pest needs to be treated in order to manage its population before pest population size reaches the economic injury level, or the lowest density of pests that will cause economic injury unless pest densities are suppressed. The carbaryl-based management program for burrowing shrimp had always depended on a "rule-of-thumb" action threshold of 10 burrows/m^2, but the relationship between that density and actual crop injury had never been established. In 2001, a draft damage-density model based on a logistical relationship between burrow density and oyster yield was developed (Booth 2001a) and empirically tested in both small arenas and large field plot trials (Dumbauld and Booth 2007). Although a reliable and accurate relationship between burrow density and oyster yield could not be derived from the data, the results showed that larger oysters sank within three months and seed oysters sank within two months at burrow densities greater than 30/m^2. To link an economic component to trigger action, a compartmentalized equation of oyster net values was constructed (Booth 2001b). It included harvest price, harvest cost, transplant density, transplant cost, seed density, and seed cost. Growers were interviewed to determine these costs relative to the cost of managing (or not managing) burrowing shrimp. A traditional IPM action threshold could not be defined due to extreme market volatility and grower variation in culture tactics and marketing practices (Dumbauld and Booth 2007). Ultimately, a decision tree for shrimp management was developed based on the duration that oyster crop would remain on the bed, treatment history, recent shrimp recruitment patterns, and a revised and adjustable minimum threshold burrow count (Dumbauld et al. 2006).

2.2.3. Biological management methods

Although biological control is frequently presented as the suppression of a pest by predators (e.g., Huffaker 2012, Radcliffe et al. 2009, Van Den Bosch et al. 1982), predation is only one of several strategies of biological control. Other potential biological control agents include parasites, microbial pathogens (e.g., fungi, free-living bacteria, nematodes that carry bacteria, viruses and other diseases) (Van Den Bosch et al. 1982, Wraight et al. 2009), and competitor species (Debach and Rosen 1991). While not strictly considered under biocontrol, other biological methods of managing pests include deploying sterile males of the same species (Dyck et al. 2021), using mating disruption via pheromone confusion (Card´e 1990), and in the broadest sense, manipulating the tolerance of the pest's target organism(s) through breeding (Smith 2009) or genetic manipulation (Lemaux 2008). Despite the high level of interest in biologically based management tools for managing burrowing shrimp, many complex interactions and outcomes must be considered before implementing any type of biological control measure (Croft 1990, Follett and Duan 2012).

2.2.3.1 Natural and augmentative biological control by indigenous generalist predators

At least four categories of biological control by predation have been identified based on the original geographic distribution of the control agent, the geographic distribution of the intended target, and the level of human intervention required for implementation: (1) natural biological control, where both the control agent(s) and pest are native, and little manipulation of either is required; (2) augmentative biological control, where the abundance of indigenous natural enemies is increased either by augmentative release or manipulation of their natural habitats; (3) classical biological control, where a foreign natural enemy is introduced to control a foreign pest; and (4) neoclassical biological control, where a foreign natural enemy is introduced to suppress a native natural enemy (Ehler 2000, Lockwood 1996). Although introductions of foreign species into new geographical areas are now carefully assessed and studied to avoid unintended consequences (Huffaker 2012, Van Den Bosch 1971), neither classical nor neoclassical biological control strategies are feasible in this estuary system due to concerns about the potential for unknown trophic consequences. Biological management of burrowing shrimp in Willapa Bay has focused on indigenous natural enemies, primarily generalist predators.

Several species of estuarine and marine fish have been observed feeding on burrowing shrimp (Posey 1986, Russo 1975), but very few have a specific preference for burrowing shrimp, or a particular ability to suppress them. Posey (1986) identified large numbers of burrowing shrimp in the gut contents of staghorn sculpin (*Leptocottus armatus*). Dumbauld et al. (2012) confirmed that staghorn sculpin prey on ghost shrimp of all sizes, including small, recently recruited juveniles. Although densities of burrowing shrimp in lower intertidal zones increased after predatory fish were excluded (Posey 1986), the feasibility of manipulating the feeding habits of mobile generalist predators to achieve farmable levels of burrowing shrimp density on select commercial shellfish beds appears low. A quantitative molecular probe for ghost shrimp DNA was developed to better document specific predators (Vadopalas and Friedman 2007), but its implementation was limited by small sample sizes and poor data quality (Bollens and Sylvester 2007).

Sturgeon may be impacting shrimp populations to some degree in areas where they are currently abundant (Armstrong et al. 1995, Moser et al. 2017, Suhrbier et al. 2007). Burrowing shrimp represented a significant proportion of the stomach contents of commercially landed sturgeon, particularly green sturgeon (*Acipenser medirostris*) (Borin et al. 2017, Dumbauld et al. 2008). Mean shrimp density inside predator exclosures (102 shrimp/m^2) was statistically lower than the shrimp density found outside the exclosures (120 shrimp/m^2) (Dumbauld et al. 2008). In slightly larger areas where sturgeon were excluded for over a month, shrimp density increased by 18% inside the exclosures and declined by 15% outside of them. Unless these large fish could be penned or enclosed, direct burrowing shrimp control by sturgeon on aquaculture beds seems unlikely. Sturgeon are long-lived, slow growing, and only spawn intermittently in distant natal streams (Moser et al. 2017), raising further concerns about their effectiveness as a potential biological control.

Gray whales have been documented feeding on burrowing shrimp (Weitkamp et al. 1992). Their dependence on shrimp motivated DNR to ban the harvest of burrowing shrimp for fish bait on state-owned lands in north Puget Sound in April 2014, pending further study (Pruitt and Donoghue 2016). Results showed whale foraging was not limited by shrimp density, and the ban was lifted (Calambokidis 2017). Like green sturgeon, the potential of these large, mobile, transitory animals to biologically control shrimp seems limited.

While crab prey on burrowing shrimp, their consumption rates may not be high enough to make them effective as biological controls. Adult rock and Dungeness crab in fenced enclosures preyed on shrimp over 2—7 days, and burrow densities declined 5—25% (Patten 2005c). However, final burrow counts remained very high. Crab are also injurious to shellfish and higher populations would likely impact yield.

2.2.3.2 Biological control by parasites

Some species of nematode worms are known to parasitize crustaceans (Poinar and Kuris 1975), including burrowing shrimp (Poinar and Thomas 1976), and their potential as biological control agents against burrowing shrimp has been explored (Booth 2007c, Kuris et al. 2002). A field study (Booth 2007c) of indigenous nematodes infesting burrowing shrimp (primarily an undescribed species of *Ascarophis*) found the degree of parasitism varied by shrimp species, collection site and collection date. Though many ghost shrimp were infected at some locations, the nematode did not infect mud shrimp, and even high levels of parasitism did not appear to affect ghost shrimp behavior or survival. Commercially produced nematodes used to control insect pests were also tested in bay water (where they survived for 2—3 days), but highly exposed ghost shrimp kept in aquaria survived up to six weeks past exposure.

Dumbauld et al. (2012) also found an undescribed species of *Ascarophis* nematode infesting ghost shrimp populations at some sites in Willapa Bay at similar rates as Booth (2007c), but found much lower infestation rates at sites in Tillamook Bay and Yaquina Bay in Oregon. As in the Booth (2007c) study, no nematodes infested mud shrimp. The Dumbauld et al. (2012) study also measured rates of nematode infestation in the hypothetical secondary host, staghorn sculpin. The parasite was only found in one individual, which also had a shrimp in its stomach, suggesting that staghorn sculpin are not a potential secondary host of these nematodes. Preliminary laboratory studies suggested nematode infestation did not affect ghost shrimp burrowing and surfacing behaviors, but sample sizes were quite small. Additional studies are forthcoming.

Bopyrid isopods are highly host-specific parasites of crustaceans and could also have potential as a biological control for burrowing shrimp. *Orthione griffenis*, an invasive isopod likely introduced from Japan via ballast water (Dumbauld et al. 2011, Griffen 2009), has been identified as a parasite of mud shrimp in the coastal estuaries of both Oregon and Washington, including Willapa Bay and Grays Harbor (Chapman et al. 2012). *O. griffenis* has a complex life cycle that involves two alternating host species. A pheromone is released by the female isopod to attract a mate upon settlement on the shrimp; but shortly after settlement, the female isopod becomes a male and the pheromone is no longer released. *O. griffenis* currently parasitizes mud shrimp at levels of approximately 80% and has severely impacted populations coast wide (Dumbauld et al. 2011). Its potential as a biological control agent against ghost shrimp is being assessed by examining its relationship to the meiofaunal community that grows on shrimp burrow walls (J. Chapman, pers. comm.). The relationship appears symbiotic, so by manipulating that community, it may be possible to also manipulate the parasite, and ultimately the burrowing shrimp. A related native bopyrid, *Ione cornuta,* infests ghost shrimp at a rate of less than 3% (Dumbauld et al. 2011). Therefore, although its life cycle is better understood, its potential to biologically control burrowing shrimp pests on bivalve aquaculture beds is even lower.

2.2.3.3 Microbial biological control

In terrestrial pest management, microbial control agents (pathogens or vectors of pathogens), frequently exhibit a high degree of host-specificity and can be mass-produced as bio-pesticides and applied seasonally or as needed (Anwer 2017, Kogan 1998). However, commercial bio-pesticides are often short-lived and expensive. They require special storage and application measures, and currently none are approved for burrowing shrimp management.

In 1997, a unicellular spore-forming fungal pathogen (microsporidian) that infests mud shrimp was identified as a new species of either *Thelohania* or *Pleistophora*, both of which are often quite pathogenic and host selective (J. D. Shields, pers. comm.). However, it is highly unlikely their effects on burrowing shrimp could be localized to selected shellfish beds.

2.2.3.4 Biological control by competitive displacement

Biological control by competitive displacement features the propagation and release of other species that might compete directly with the target pest (Debach and Rosen 1991). For example, the strategy has been used to successfully displace deleterious fungal pathogens in wheat with benign strains of bacteria (e.g., Luongo et al. 2005).

After observations by a commercial oyster grower that the indigenous lugworm, *Abarenicola pacifica*, seemed to be displacing burrowing shrimp, that hypothesis was tested using three experimental approaches: observations of both species in aquaria, mapping lugworm distributions in the field, and transplanting lugworms into high density shrimp plots (Booth 2007d). Burrowing shrimp and lugworms survived nearly equally in experiments with adults of both species in large aquaria, and with juveniles of both species in small aquaria. Elevation, rather than presence of either lugworms or shrimp, likely determined their relative distributions, as overlap was minimal at three separate locations and times. Lugworms did not survive transplantation to nearby areas of high shrimp density. Accordingly, lugworms likely play a minimal role in shrimp distribution and survival and have minimal potential as biological control agents for burrowing shrimp (Booth 2007d).

2.2.3.5 Biological control by sterile male release

Sterile male release has been quite effective in the control of some insect pests (Klassen and Curtis 2005, Kogan 1998), but the strategy has little immediate potential to suppress burrowing shrimp on commercial shellfish grounds. Since burrowing shrimp release larvae into the nearshore water column that then recruit broadly, there would be no easy way to limit the impact of sterile males to specific areas. Furthermore, there is relatively little known about the mating behavior of burrowing shrimp, and the technology to rear sterile male ghost shrimp en masse does not exist.

2.2.4 Physical and mechanical control strategies

Attempts to manage burrowing shrimp using various physical or mechanical means have a long history in Willapa Bay and Grays Harbor. One grower in Willapa Bay began experimenting with compaction and harrowing in the late 1950s. From the 1970s until the late 1990s, shellfish farmers explored other tactics to crush and disrupt the shrimps' subsurface habitat with heavy vehicles, harrows and dredges, by dumping large amounts of gravel or oyster shell onto the bed, and even by injecting bentonite clay into burrows (Burrowing Shrimp Control Committee [BSCC] 1992). Plastic mesh and other materials were staked on the substrate in attempts to suffocate burrowing shrimp. Most of these tactics showed little promise for suppressing burrowing shrimp. Non-target effects were rarely measured or reported, but very likely included disrupting or killing epibenthic and benthic invertebrates, substantially altering the chemistry of benthic substrates, and altering the direction and speed of surface tidal flow. Oysters placed on plastic could not hold fast and were washed away. Shellfish growers, researchers and agencies have continued experimenting with very similar tactics ever since. As in the early studies, preliminary trials usually suppressed shrimp initially, but multi-year efficacy was rarely achieved without radically altering the environment. In addition, non-target biological and physical effects were often not assessed.

Figure 4. Weasel pulling a spring tooth harrow across an oyster bed. Photo courtesy of Dennis Tufts.

Figure 5. Snow Cat pulling a roller across an oyster bed. Photo courtesy of Dennis Tufts.

Figure 6. Weasel (in lead) and Snow Cat pulling rollers. Photo courtesy of Dennis Tufts.

Figure 7. John L. Wiegardt straddling rolled and unrolled segments of the Espy Oyster Bed in 1962. Photo courtesy of Dennis Tufts.

2.2.4.1 Habitat crushing and disruption

Initial trials to disrupt and crush burrowing shrimp habitat were conducted by Wiegardt and Sons from 1959—1962 under the direction of John L. Wiegardt Jr. The "Weasel,"[3] a U.S. army tracked vehicle, was used to pull spring tooth harrows across oyster beds heavily infested with burrowing shrimp (Figure 4), which brought shrimp to the surface. The land was rolled after harrowing using a similar tracked "Snow Cat"[4] (Figures 5 and 6) to pull weights of differing composition and weight. These practices were moderately effective over the short-term (two to three seasons) (Figure 7) but were also quite expensive.

In keeping with the WGHOGA/interagency MOA signed in 2001, the search for alternatives to carbaryl for managing burrowing shrimp, including tactics to disrupt burrowing shrimp habitat, expanded greatly in the early and mid-2000s. A large-wheeled semi-amphibious vehicle, the Rolligon™ (Figure 8), was tested in 2001 (Milne et al. 2002) and then again in 2003 (Patten 2007a, Patten 2016), but there were operational problems in both trials, especially in very soft substrates. A smaller, more maneuverable tracked vehicle pulling a heavy roller was less effective and the machine was damaged (Milne et al. 2002). Trials continued in 2004 using the WSDA's Marsh Master II (Figure 9), which had previously been used to crush the invasive cordgrass *Spartina alterniflora*. Burrow densities were temporarily reduced in some areas after multiple passes. In areas with high or medium initial burrow density, however, burrow density never declined below 10 burrows/m^2 (Booth 2007a) — the currently accepted threshold for oyster production — and burrow densities returned to high levels within six months.

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[3] Developed by the U.S. army in World War II as a light air-transportable amphibious armored weapons carrier, primarily for use in the heavy snow of Norway (www.tanks-encyclopedia.com).

[4] Specialized over-snow vehicle, from the original 1946 trademark by Tucker Sno-Cat Corporation (https://en.wikipedia.org/wiki/Snowcat).

Figure 8. The Rolligon. Photo courtesy of Steve Booth.

Figure 9. The Marsh Master II. Photo courtesy of Kim Patten.

Observations in 2002 during trials against the invasive cordgrass, *Spartina alterniflora,* suggested that shallow rototilling may have some potential to suppress burrowing shrimp. The Kansas Machine, a modified airboat (Master's Dredging, Inc., Lawrence, Kansas) with an exceptionally large engine and a front-mounted rototiller that could be hydraulically raised and lowered to a maximum depth of 4 inches (Figure 10), was involved in the *Spartina* trials throughout the summer of 2003. The machine was not available for testing against burrowing shrimp until October, when cooler temperatures make shrimp retreat to lower tidal elevations and become less active. Trials with the Kansas machine were finally conducted in shrimp infested ground on a 2+ tide, higher than most commercial oyster beds. One week later, shrimp burrow density was significantly higher on adjacent untreated ground than in the tilled transects (Booth and Penny 2007).

Beginning in 2003, Taylor Shellfish contributed substantially toward the development of tactics to remove burrowing shrimp from the substrate with high-powered water jets (Johnson 2005a). A centrifugal pump driven by a ~200 hp diesel engine (Figure 11) able to produce up to 150 PSI was coupled to a steel sled carrying a water manifold fitted with a row of nozzles. Water was delivered through rubber hoses from the pump and engine that were mounted on a 65' oyster boat. This model proved difficult to guide and maneuver while maintaining a constant speed, and shrimp burrow densities were not reduced, prompting the construction of a smaller, more maneuverable jet sled in 2004 (Figure 12). The new sled moved slowly enough to provide adequate water jet penetration, but was still difficult to steer during towing. Treated areas had significantly fewer burrows than untreated areas at two weeks after treatment, but the scoured bed was substantially lower in elevation and non-target impacts to benthic infauna were severe.

In 2005—2006, McGregor Company (Pasco, WA) and Jim Durfey (WSU Department of Crop and Soil Sciences) developed a large iron harrow with skids that could be adjusted to different lengths, but the unit was too heavy to easily pull and steer. The unit was modified in 2006 by removing the skids, but it was still too difficult to pull (Durfey and Booth 2007).

The potential of sub-surface (benthic) explosions to both disrupt shrimp habitat or kill shrimp was also investigated (Patten 2005a). The Rodex 4000™ featured electronic circuitry to ignite a 97/03% oxygen/propane mix at the end of a 6-ft wand. However, the sediment was too dense and moist to allow gas to fully permeate the burrow and the resulting explosions were too small to kill burrowing shrimp.

More recent "Proof of Concept" trials of a large "roller-chopper" harrow towed by the Marsh Master (dry harrow technique) indicated shrimp densities in 1-m deep core samples were reduced by 79—89% (DNR 2018). The use of a wet harrow technique, either like the subsurface technology described above or by using somewhat shorter tines towed by a skiff, were less effective, as were attempts to liquefy a large (0.5 acre) plot by flooding. Further trials of the dry harrow technique are ongoing (DNR 2018).

2.2.4.2 Surface barriers to burrowing shrimp

Smothering burrowing shrimp by covering the surface of oyster beds is another potential pest management tactic with a long and continuing history. Early materials included wooden boards, and plastic sheets (BSCC 1992) have also been tried. Neither tactic was particularly effective long term, as the wooden boards sank and deteriorated, and the plastic sheets were torn and fragmented. Although non-target impacts to the epibenthic and benthic communities were not specifically detailed, they were generally reported as severe. A 2005 study tested a cement layer thin enough to allow some aeration of the benthic substrate, but shrimp were able to dig through it and reduce it to fragments (Liou and Weaver 2006).

Figure 10. The Kansas Machine

Figure 11. Pump with diesel engine

Figure 12. Water jet sled

More recently, a pilot project tested the efficacy of materials that would hypothetically suppress shrimp activity but allow better surface aeration and biodegrade in time (Hudson and Beugli 2020). These included: terrafibre hemp (sponge-like) blankets, C32BD (more loosely constructed coir), coir matting 900 (coir rope weaves with wide mesh), and coir 1000 (dense coir/burlap). Materials were held in place by foot-long wooden stakes, most of which came loose within a single tide, or 18-inch hooked rebar, which held effectively but was heavy and difficult to install. The terrafibre tore during installation and decomposed very quickly. The C32BD did not affect shrimp activity. The coir 900 did not affect shrimp and quickly became buried in sediment. The thin mesh burlap of the C1000 decomposed rapidly, leaving only the coarser coir rope intact. The C1000 performed the best, but burrowing shrimp activity was nevertheless barely affected. Given the cost of materials and installation, none of the options tested offer much as a potential tactic for shrimp pest management.

2.2.4.3 Electroshock and hydrosound

The potential of electroshock to either kill shrimp, drive them to the surface, or otherwise deter them from burrowing was investigated in a series of trials using shrimp in aquaria (Dumbauld and Harlan 2009, Gross 2018, Harlan 2006). In aquaria filled with salt-water only, shrimp would jerk in synchrony with an alternating current (AC) electrical pulse, but greater proximity to the electrical field did not result in immobility and was not sufficient to prevent shrimp from burrowing (Harlan 2006). Direct current (DC) applied for two minutes could eventually lead to death, but pulsed DC was ineffective at the low frequencies of 2—4 Hz. Tests of shrimp in aquaria that included some substrate required higher power, and the effects on shrimp could not be as easily observed directly. Shrimp that appeared dead at 12 hours frequently recovered and were recorded alive at 24 hours. In more recent studies (Gross 2018), ghost shrimp survival was reduced by over 50% with 4, 10-minute exposures to continuous DC once a day. Tests using ultrasonic technology (hydrosound) to kill, injure, or force burrowing shrimp to relocate yielded similar results. High frequencies and long exposure times were needed to kill shrimp in aquaria filled with salt water; and they could not be killed within the sediment (Patten 2005b). Accordingly, field tests of both electricity and hydrosound have not been executed.

2.2.5 Cultural control strategies

2.2.5.1 Harvesting burrowing shrimp

Burrowing shrimp are commercially harvested for a fish bait market under license by WDFW on a few select, heavily infested tidelands in Willapa Bay. The most common harvest method is pumping large volumes of water at a high velocity into the substrate at the leading edge of a neap or flood tide, thereby eroding the substrate and accompanying shrimp burrows (J. Collins, pers. comm.). The shrimp are washed into channels created by the waterspouts and captured in small baskets with long handles. The method essentially washes the face of the exposed tideflat, including all the benthic organisms, into the tides. The magnitude of impact is limited by the permitted size of the water jet hose. Furthermore, the commercial harvesters in Willapa Bay have not been able to compete with a much larger commercial operation in North Puget Sound (Booth et al. 2007).

Alternative harvest methods have been tested, but were ineffective (Patten and Durfey 2007). Attempts to suck shrimp from their burrows without removing sediment were able to pull large volumes of sediments, but few shrimp were harvested. Another idea was to force air into the substrate during high tide to blow shrimp into the water column where they could be harvested by net (Patten and Durfey 2007). Two systems were tested: a system operated from a small barge, and a much larger shank system mounted from a boat. Based on data from underwater cameras, there was no evidence that any shrimp were raised from the substrate. Burrow counts post-treatment were temporarily reduced by 39% with the high-volume air bubble method (60 vs. 98 burrows/m^2).

2.2.5.2 Alternative tactics to culture oysters

Initial trials to grow mussels on vertical long lines in Willapa Bay were not very successful (Johnson 2005b). It took several years to develop hanging basket and flip bag technologies that could withstand the severe weather and tidal conditions of Willapa Bay (E. Hall, pers. comm.). The major alternative to on-bottom culture of oyster clusters has become the culture of single oysters in bags hung from horizontal lines. The bags rise and fall with the tides, and the constant jostling from wave action produces a deep-cupped oyster that is more suited to a fresh on-the-half-shell market (E. Hall, pers. comm.). Although the suspended flip bags are less susceptible to the bioturbating effects of burrowing shrimp, they are most often established in areas with lower shrimp densities and firmer substrates.

2.2.6 Chemical control strategies

To date, only carbaryl and imidacloprid have been registered to manage burrowing shrimp on shellfish beds in Willapa Bay and Grays Harbor, and only carbaryl was fully implemented as a chemical control strategy (see Chapter 3). As part of the development of an IPM plan, in 1996, four compounds were compared for efficacy against burrowing shrimp (Schreiber 1997): fenoxycarb, diflubenzuron, abamectin, and imidacloprid. Fenoxycarb and diflubenzuron demonstrated little to no efficacy. Average shrimp burrow densities were significantly lower in areas treated with abamectin and imidacloprid compared to untreated areas. Imidacloprid was the most effective; but at the time it was prohibitively expensive for shellfish producers in Willapa Bay and Grays Harbor.

A wide range of chemicals were subsequently tested for efficacy and non-target effects to explore their potential for federal and state registration. These preliminary trials featured traditional topical application methods (backpack sprayer or from an all-terrain vehicle [ATV]) to small plots (<30 m^2) with a total combined acreage of less than one acre. Therefore, only a state experimental use permit was required but not an additional federal permit. Chemicals with low potential efficacy were minimally replicated, but later trials of stronger candidates were replicated in blocks and compared to untreated control plots. Efficacy was assessed by comparing pre-treatment burrow densities to those at one or more months after treatment (Patten 2007b). Overall, only a few chemistries suppressed shrimp to levels below or near the accepted action threshold of 10 burrows/m^2. Most of the substances on the USEPA's 25b list of "minimum risk" compounds that are exempt from federal registration suppressed burrowing shrimp minimally or not at all. Most organically registered materials, which would have been easier to register than synthetic chemistries, did not provide sufficient management either. Azadiractin was ineffective even at very high application rates. Others, like the sulfur compounds, showed moderate but inconsistent efficacy. Pyrethrums (organic) and pyrethroids (not organic) were more effective (Patten 2007b), but both the USEPA and WSDA indicated the likelihood of registering either substance for use in Washington State estuarine waters would be extremely small. Despite their low mammalian toxicity, pyrethroids have a relatively low lethal concentration to 50% (LC50)[5] against fish and have broad-spectrum toxicity against arthropods, especially non-target crustaceans.

The neonicotinoids, including imidacloprid, were generally the most effective of the chemicals tested (Patten 2007b). The producers of the neonicotinoids tested (i.e., Bayer, Inc. and Cerexagri, Inc.) would not support the registration of their products for use against burrowing shrimp. However, when imidacloprid came off patent in 2006, NuFarm Americas, Inc. agreed to produce a formulation for use against burrowing shrimp in Willapa Bay and Grays Harbor. A pesticide manufacturer will typically help pay the costs of federal registration and state permitting, but NuFarm was largely unable to financially assist in the process. Registration would require WGHOGA and individual growers to assume large portions of the expense with limited financial support from federal and state grants. WGHOGA determined imidacloprid had sufficient efficacy, environmental compatibility and potential for registration to continue pursuing it as a chemical control option within the developing IPM program. A multi-year effort costing millions of dollars was initiated (see Chapter 4).

Results from recent laboratory trials of "softer" chemistries have been mixed. Emamectin benzoate, derived from the organic compound avermectin, has demonstrated some toxicity towards both adult and juvenile burrowing shrimp (C. E. Grue, pers. comm.). Emamectin benzoate binds to the gamma-aminobutyric acid (GABA) receptors to disrupt nerve transmission, which manifests as broad-spectrum toxicity towards a wide variety of arthropods (Arena et al. 1995), including crustaceans. It has a marine registration as an in-feed additive (SLICE®, Merck Animal Health) to prevent sea lice (Copepoda: Caligidae) from infesting farmed salmon (Lees et al. 2008). However, the LC50 for juvenile salmonids (174 µg/L) is close to the LC50 of adult ghost shrimp (C. E. Grue, pers. comm.). Other laboratory trials have shown both adult and juvenile shrimp are sensitive to high concentrations of table salt (NaCl) (C. E. Grue, pers. comm). All juvenile ghost shrimp exposed to seawater salinity concentrations 2—3 times greater than ambient salinity died within two hours. Field trials and impacts to non-target species, including juvenile Dungeness crab, have yet to be conducted.

In addition to testing chemistries for the potential to directly impact burrowing shrimp, several common commercial adjuvants, such as stickers and sinkers, were also tested for their ability to improve pesticide efficacy (Patten 2007b). Lignosulfate, which reportedly enhances the ability of some compounds to stick to sediment particles, was also tested. None of the materials substantially improved pesticide efficacy against burrowing shrimp.

Several different tactics were also tested or developed for delivering potential pesticidal materials sub-surface to improve efficacy and reduce non-target effects, but the methods were technologically challenging and only somewhat effective. The Rolligon, used in the crushing trials, was modified to apply pesticides sub-surface (Figure 13), improving efficacy somewhat, but its use was limited to moderately firm substrates, and it was expensive and difficult to maintain (Patten et al. 2007a). Subsurface applications were also made using SpokeWheel™ technology, which featured eight spike-wheels

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[5] Lethal concentration 50 (LC50) and lethal dose 50 (LD50) refer to the amount of a substance required to kill 50% of test animals during a predetermined observation period. These values are frequently used as a general indicator of a substance's acute toxicity.

pulled behind an ATV with GPS guidance to precisely regulate pesticide delivery. The ATV-mounted spike-wheel was able to efficiently deliver pesticides, but its use was also limited to firm substrates. The SpokeWheel™ technology was also applied to a pontoon raft that was propelled by a 16-foot aluminum boat (Patten et al. 2007b). The spike-wheels were mounted on a bracket that could be raised or lowered using a hand-powered winch. A non-spiked drive wheel placed in front of the spike-wheels rotated at the same speed and regulated injection timing. Jim Durfey (WSU) and McGregor Co. designed and constructed a flexi-coil spring harrow with injection through the leading row of tines (Patten et al. 2007b), but the unit was difficult to operate, and the rate of chemical delivery was difficult to regulate.

Figure 13. A Rolligon modified to inject chemical controls. Photo courtesy of Steve Booth.

3

Impact Analyses of Carbaryl

The insecticide carbaryl (1-naphthyl N-methylcarbamate) belongs to the carbamate class of insecticides, which blocks nerve transmission by inactivating the enzyme acetylcholinesterase (AChE) (Fukuto 1990). Although carbamates are somewhat selective towards insect AChE and have a relatively low toxicity for vertebrates, they are still considered broad spectrum insecticides (EXTOXNET 1993). In the late 1950s, carbaryl was used to manage oyster drills on the East Coast (WDF and ECY 1992), because it has a short residual time and low environmental persistence. Carbaryl was therefore selected in the early 1960s as the primary tactic for burrowing shrimp management in the coastal estuaries of both Washington and Oregon.

3.1 Impact Assessments

Several comprehensive assessments and reviews of carbaryl's use to manage burrowing shrimp have been conducted over the past 60 years. Results from a series of field trials conducted during the early 1960s were published in reports to WDFW. The reports featured contributions from agency personnel and researchers from the University of Washington and addressed the efficacy of carbaryl at various experimental rates (Tufts 1989, Tufts 1990). They also assessed the impact of carbaryl on non-target organisms, primarily Dungeness and Rock crab and associated measurements of carbaryl concentrations in water at various distances from treated sites over time (Tufts 1989, Tufts 1990). An EIS (WDF and ECY 1985) and an SEIS (WDF and ECY 1992) reported results from investigations in Willapa Bay on carbaryl's fate and transport (Creekman and Hurlburt 1987, Tufts 1989), persistence (Creekman and Hurlburt 1987, Tufts 1989, Tufts 1990), and effects on other invertebrates (Hueckel et al. 1989, Simenstad and Cordell 1989, Tufts 1990). In 2003, the USEPA Environmental Effects Division conducted a comprehensive risk assessment of carbaryl use worldwide in support of the Reregistration Eligibility Decision (RED), which included a similarly comprehensive assessment of the special use of carbaryl for managing burrowing shrimp in Willapa Bay (Jones et al. 2003).

To aid in the permitting process, ECY gathered data regarding carbaryl's persistence in sediment (Stonick 1999) and fate and transport of carbaryl in the water column (Johnson 2001) following treatment for burrowing shrimp. Another study of the persistence of carbaryl in sediment and its effect on benthic infauna was conducted by WGHOGA in compliance with Washington State Sediment Management Standards (WAC 173-204-200) to describe the SIZ related to the carbaryl applications in compliance with the NPDES permit (Booth 2007b). WGHOGA also monitored carbaryl concentrations in the water following carbaryl applications from 2002 until 2015, when its use was terminated.

In May 2008, a Biological Addendum (BA) was prepared for Endangered Species Act (ESA) compliance with the USACE's Nationwide Permit (NWP) 48, which provides regulatory coverage for bivalve shellfish commercial aquaculture, with explicit and specific consideration of carbaryl use in Willapa Bay and Grays Harbor to manage burrowing shrimp (Environ International Corporation 2008). This BA is the most thorough and comprehensive assessment on the effects of the carbaryl burrowing shrimp management program to date. It summarizes data on key threatened, endangered, and other relevant species in consideration of potential indirect effects. Plants, terrestrial mammals, avian species (marbled murrelet, Western snowy plover, brown pelican, heron, eagle, osprey, ducks), reptiles and amphibians, fish (green sturgeon, bull trout, chum salmon, Coho salmon, steelhead, Chinook salmon, English sole), and invertebrates (Dungeness and Rock crab) were included. The fate and transport of carbaryl was tangentially addressed, as well.

A 2009 Biological Opinion (BiOp) issued by the National Marine Fisheries Service (NMFS) under the ESA Related to Pesticides and Pacific Salmon and Steelhead Species Act addressed the environmental effects of carbaryl use in Washington State, including for burrowing shrimp management, on Pacific Salmon and Steelhead species (USEPAHQ-OPP-2008-0654). Other recent studies have addressed the impact of carbaryl on salmonids (Major III et al. 2005), sturgeon (Troiano 2014) and shiner perch (Major III et al. 2005, Troiano et al. 2013).

3.2 Fate and Transport

The ability of a pesticide to persist in water and sediment depends on its solubility, potential to stick to soil or particulate organic carbon, and the rate at which it degrades to its breakdown products. Rate of breakdown, in turn, depends on factors like temperature, pH, oxygen levels, and the type and abundance of bacteria in the soil or sediment. Carbaryl does not bind as tightly to sediment and breaks down relatively quickly compared to most insecticides. Reported half-lives of carbaryl (technical grade) in soil range from 4 days in aerobic conditions to 72 days in anaerobic conditions (Bayer 2006).

Within Willapa Bay, results from four separate studies showed that carbaryl dissipated to lower than detectable levels in sediments within six months after application (Booth 2006, Dumbauld 1994, Felsot and Ruppert 2002, Stonick 1999). Each study had different detection limits and sampling occurred on different types of substrate, but carbaryl decayed by at least a factor of ten within the first month and to non-detectable levels within four months after application. Booth (2006) sampled in sediments from an area of commercial aerial application and found carbaryl substantially lower than those of the other three studies. High eelgrass densities at that site may have prevented some carbaryl from entering the sediments.

In all studies, concentrations of carbaryl in waters on or near oyster beds treated for burrowing shrimp dissipated rapidly and exponentially with rising tides. A model of carbaryl dissipation due to tidal inundation was developed based on the 8 lb. a.i. per acre (8.96 kg/ha) application rate and an assumed sigmoidal model of inundation. Carbaryl concentrations were projected to decline from initial levels near 12,000 µg/L to a concentration near 3,000 µ/L (or ppb) at a depth of one foot (0.30 m) and to 500 ppb at a depth of six feet (1.8 m) at 3.4 hours after the initial inundation[6] (Grue et al. 2011). The model was compared to field conditions by measuring carbaryl concentrations in water sampled on and near an oyster bed following application. Carbaryl concentrations actually declined to 500 ppb within two hours after treatment, and the water was about six inches (15 cm) deep. Models that factored in the possibility of carbaryl becoming absorbed or otherwise trapped in the sediment or carried off site estimated the concentration in six inches of water at two hours after treatment to be 395 ppb (Grue et al. 2011).

The NPDES permit to apply carbaryl to selected commercial oyster beds in Willapa Bay and Grays Harbor (ECY Permit No. WA0040975) specified that concentrations of carbaryl in the water would be monitored for exceedance of acute (3 ppb at 2 days after treatment, DAT) and chronic (0.07 ppb at 30 DAT) criteria. The criteria were derived by ECY based on average concentrations in both the top layer and bottom layer of Willapa Bay waters at 2 and 30 DAT with a 103 conservation factor (Johnson 2001). Sampling occurred from 2002—2013 and was conducted in accordance with U.S. Geological Survey (USGS) "clean hands/dirty hands" Standard Operating Procedures (SOP). Field quality control procedures included submission of equipment blanks and duplicate samples, within the USEPA recommended holding time for carbaryl of 7 days for each year. Concentrations of carbaryl in water sampled at 2 DAT exceeded the acute criteria of 3 ppb twice in 2006 and not at all in any of the other 58 samples taken between 2006 and 2010. Forty-nine of the 58 samples (85%) had concentrations <1.2 ppb. Concentrations of carbaryl in 15 samples taken at 21—31 DAT never exceeded the criteria for chronic toxicity of 0.07 ppb at 30 DAT, and carbaryl was not detected at all in eight of the 15 samples at a quantitation level of <0.01 ppb. Results from all years showed that the fate and transport of carbaryl following commercial applications depended largely on the amount and frequency of treatment, as well as site-specific characteristics such as direction and velocity of estuarine channels and mudflat drainage sloughs. The areas where carbaryl levels would not exceed criteria and where exceedances were more likely could be predicted with a high degree of accuracy when given the proposed treatment acreage.

3.3 Effects on Benthic Invertebrates

Carbaryl is generally considered a broad-spectrum insecticide; however, its effect on intertidal benthic organisms appears more selective. Dumbauld et al. (2001) found that some polychaetes were not very susceptible to carbaryl. At one study site, for example, a dominant polychaete (*Mediomastus californiensis*) was significantly more abundant in treated than in untreated plots at two weeks after treatment, slightly more abundant at one month, significantly lower at three months, and approximately the same in both types of plots at one year after treatment. Dumbauld counted 12 species and 28,400 individuals of polychaetes at two experimental sites over five sample dates and concluded, "no response to carbaryl could be detected" (Dumbauld et al. 2001). Crustaceans were generally most affected, but some very abundant species, such as *Leptochelia dubia, Cumella* spp. and *Corophium* spp. were not significantly impacted.

Simenstad and Cordell (1989) observed low impacts to epibenthic crustaceans, since significantly more epibenthic crustaceans were sampled in a sprayed area immediately after a commercial application of carbaryl compared to an unsprayed area. The authors attributed this somewhat unexpected result to an over-representation of killed animals in surface waters compared to deeper in the water column, wind and current conditions, sublethal rather than lethal effects, and/or possible behavioral changes affecting the likelihood of sampling. Two weeks after treatment, the abundance of most taxa in the treated areas had returned to levels comparable to those in the untreated areas. Two of the more abundant species (*Cumella vulgaris* and a *Corophium* species), however, remained significantly suppressed in the treated area after two weeks. The authors suggested that the increased availability of the two species shortly after the carbaryl application might have triggered greater predation by fish. Alternatively, carbaryl might have caused a delayed mortality.

Booth (2006) assessed the SIZ associated with a commercial aerial application of carbaryl by comparing sprayed and unsprayed areas and found that benthic infauna, as represented by total abundance, species richness and two diversity indices, was impacted more by seasonal effects than spray effects. In seven out of 28 observations, the abundance of nine classes of benthic invertebrates was less than 50% in the sprayed compared to the unsprayed area 74 DAT, but these effects did not persist to the next sample date at 134 DAT. The Simpson's Diversity Index of polychaetes, mollusks and crustaceans did not differ significantly between treatments, nor did the relative abundance of the 21 most abundant benthic invertebrates. In an ancillary analysis (Booth 2008a), the SIZ study sites were compared to other intertidal sites sampled in Willapa Bay for other research and monitoring projects (Ferraro and Cole 2007, Partridge 2007). Benthic infauna in the SIZ study sites was representative of the benthic infauna of Willapa Bay more broadly, especially in areas with high densities of eelgrass cover and burrowing shrimp.

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[6] A sigmoidal model of tidal inundation assumes the first few centimeters of incoming water arrive relatively slowly, increase as the tide rises, then slow and level off as maximum tide is reached.

3.4 Effects on Dungeness Crab

Given the local importance of the Dungeness crab fishery, the effects of carbaryl on Dungeness crab (*Metacarcinus magister*) were of great concern in the draft EIS, and considerable resources were directed toward determining non-target impacts (WDF and ECY 1992). The effects of field applications on large juvenile and adult crab were examined by caging them at various distances and locations from the treatment site (Tufts 1989, Tufts 1990). Results were mixed, with low mortality at shallow depths just outside treated areas, but higher mortality (40 and 45%) in a shallow slough directly on site. Mortality to very early-stage juvenile (young of the year, YOY) crab on treated ground was estimated as 4—5% during 1986—1988 (Doty et al. 1990). Doty et al. (1990) also determined that densities of YOY Dungeness crab were higher in vegetated habitat and tidelands with high densities of shellfish, which provide refuge from predators, compared to unvegetated or bare substrate. A comprehensive analysis of these and other measurements of crab mortality and abundance in different habitats led Doty to conclude that the indirect benefits of enhanced refugia likely outweighed the direct mortality caused by carbaryl, regardless of affected life stage (Doty et al. 1990). Several investigations have since confirmed that cultured oysters function as refugia for Dungeness crab, especially for megalopae and early-stage juveniles (Dumbauld et al. 1993, Eggleston and Armstrong 1995, Fernandez et al. 1993; McMillan et al. 1995).

3.5 Effects on Fish, Particularly Salmonids

Effects on Chinook salmon were mitigated by the requirement that carbaryl applications occur in July and August (SFEIS) or July—September (NPDES permit), outside the window of juvenile migration through the estuaries. The FEIS concluded that the magnitude of loss to finfish depended on the amount of habitat on and near the treated area for five species, specifically: saddleback gunnel, staghorn sculpin, bay goby, threespine stickleback, and starry flounder (WDF and ECY 1992). At the time, the variety of habitat types and the lack of carbaryl concentrations in waters following treatment hindered further assessments. Since then, effects on cutthroat trout (*Oncorhynhcus clarki clarki*) (Grue et al. 2011, Labenia et al. 2007, Majo r III et al. 2005) and green sturgeon (Troiano 2014) have been measured, primarily via the inhibition of AChE in the brain.

In laboratory studies, Labenia et al. (2007) found behavioral impairment in cutthroat trout exposed to carbaryl concentrations above 500 ppb for six hours. Olfaction was affected such that the trout failed to avoid seawater containing carbaryl, and subsequent exposure to higher rates diminished swimming performance and increased vulnerability to predators. The authors also hypothesized that the removal of burrowing shrimp as prey for cutthroat trout would lead to trophic cascade effects.

It is important to note, however, that both empirical and hypothetical carbaryl concentrations in water over treated beds fell below the critical concentration for cutthroat trout (500 ppb) within two hours after treatment. In addition, the water depth over treated beds two hours after treatment is only six inches — too shallow for cutthroat trout to forage. No cutthroat trout were sampled in trawls and gillnets above oyster beds treated with carbaryl in 2003 (Major III et al. 2005). Furthermore, levels of AChE inhibition in fish captured on-bed (Chinook salmon) and in channels adjacent to treated beds (cutthroat trout) were lower than levels observed in the laboratory. Brain AChE inhibition in field-captured trout and Chinook (Major III et al. 2005) was significantly lower than the enzyme inhibition (>70%) associated with the reductions in swimming endurance and predator avoidance that Labenia et al. (2007) observed.

The 2008 USACE's NWP 48 BA included an Addendum (Environ International Corporation 2008) concluding carbaryl applications for burrowing shrimp management were not likely to adversely affect any fish listed under the Endangered Species Act as threatened or endangered fish in Willapa Bay or Grays Harbor, except for bull trout (listed as threatened) in Grays Harbor. Bull trout are not believed to reside in or move through Willapa Bay (WDFW 2004).

No other listed distinct salmon populations pass through or forage in Willapa Bay and Grays Harbor. As evidence of ESA-Listed Pacific salmonid occurrence in Willapa Bay and Grays Harbor, the BiOp (USEPAHQ-OPP-2008-0654) cited personal communications and a single unpublished article stating that juvenile salmonids "bounce" up the Washington coast as they leave the lower Columbia River and have been identified using DNA analysis in three Pacific Coast bays; however, Willapa Bay and Grays Harbor are not listed among those bays. Only a single adult Chinook salmon has been captured during 568 hours of sampling (using sinking and floating gill nets) for salmonids above oyster beds and within channels adjacent to beds in Willapa Bay following carbaryl treatments for burrowing shrimp (Grue, unpublished data). As Deborah Edwards, USEPA Director of the Office of Pesticide Programs, noted, the BiOp's conclusion was based on several misconceptions about the burrowing shrimp program, including analysis of outdated results and erroneous assumptions about the presence of lower Columbia River Chinook salmon in Willapa Bay (Edwards 2009).

3.6 Effects on Birds

Carbaryl is considered largely non-toxic to birds, with the possible exception of smaller passerine species if ingested (Jones et al. 2003). Most of the birds on the Threatened and Endangered Species list rarely, if ever, visit exposed oyster beds. None of the bird species that were either studied or on the list were designated adversely affected by the carbaryl treatments (Environ International Corporation 2008).

3.7 Effects on Humans

In 2001, a study was conducted by Zheng et al. that found that the use of carbamate insecticide can lead to an increased risk in non-Hodgkin lymphoma (NHL) through epidemiological studies. There were 985 white male subjects, and 2,895 control subjects surveyed. This study showed a 30%—50% increased risk in NHL in farmers that use carbamate pesticides rather than the 0% increased risk in NHL of farmers who did not use carbamate pesticides. Specifically, the use of the carbaryl product, Sevin, was shown to cause an increased risk of NHL when people: (1) personally handled the product; (2) used the product for ≥20 years prior to being diagnosed with NHL; and (3) used Sevin for longer time durations in one sitting (Zheng et al. 2001). However, it is important to note that further research conducted has been inconclusive about the specific cancer and disease effects carbaryl can cause in human health (Jorsaraei et al. 2014, Lerro et al. 2021, Mahajan et al. 2007, Weichanthal et al. 2010).

Both the pesticide label and the listed use directions for the use of Sevin against burrowing shrimp specify measures to minimize any potential hazards to human health both during and after treatment. These include a re-entry interval to treated areas of 12 hours, requirements for personal protective equipment, requirements for adequate storage and disposal, and appropriate responses to spilling. The NPDES permit listed additional requirements for signage and warnings during application and for responses to spills. Furthermore, the limited yearly treated acreage to isolated tidelands located hundreds of yards from human populations, plus the limited frequency of treatment, further limited the risk of exposure.

In that late 1980s and early 1990s, a series of failed pregnancies among Tribal members at the Shoalwater Bay Tribe's Reservation near Tokeland was reportedly linked to the application of carbaryl to suppress burrowing shrimp (Shukovsky 1999). In response, the USEPA assessed four possible causes: (1) drainage from a nearby abandoned dump; (2) agricultural runoff from cranberry farms, forestry and other sources; (3) tideflat sediments on or near Tribal lands; and (4) drinking water at Tribal household taps. Of these, the assessment found pesticides in runoff from the cranberry farms to be the most "troubling" (USEPA 1997). Neither carbaryl nor its breakdown products were found in intertidal sediment samples, but the report recommended further study of the long-term ecological impacts of both carbaryl and glyphosate. In addition to potential exposure to pesticides via runoff from cranberry bogs, a later study by the Centers for Disease Control and Prevention identified poverty, poor diet, drug use, and alcoholism as possible (though not statistically significant) contributing factors to pregnancy loss (original report no longer available) (Verhovek 2000).

Grayland cranberry growers began to research and implement a number of best management practices (BMPs) to eliminate pesticides in the ditches that drain the cranberry growing region in 1994 (Pacific Conservation District and Pacific Coast Cranberry Research Foundation 1999), but water samples in 2012—2015 indicated the BMPs were not completely effective, despite a 95% implementation rate (R. Baker 2016). The Shoalwater Bay Tribe continues to measure pesticide levels in waters at the terminus of both major ditches that drain the Grayland cranberry growing region and from tidelands on and near the reservation (L. Pfleeger-Ritzman, Natural Resources Director, Shoalwater Bay Indian Tribe, pers. comm.). Results indicate waters in the ditches were sometimes contaminated in 2018, ostensibly because of cranberry farming.

4

Impact Analyses of Imidacloprid

Imidacloprid ((2E)-1-[(6-Chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinimine) belongs to the neonicotinoid class of insecticides. Neonicotinoids are agonists of the primary neurotransmitter of the cholinergic nervous system, acetylcholine, and block its transmission at the site of the receptor (Tomizawa and Casida 2003, Van Der Sluijs et al. 2015). The molecular structure of the nicotinic receptor site in insects makes them more susceptible to neonicotinoids than other animals, particularly vertebrates. Neonicotinoids are most effective against pests that feed directly on plant tissues, as the insecticide is absorbed by, and moves within, the treated plant (Simon-Delso et al. 2015).

Neonicotinoids are "reduced risk" insecticides (Ehler and Bottrell 2000) and are compatible with the IPM programs of many cropping systems. The selective nature of neonicotinoid insecticides towards targeted insect pests has helped make them the most widely used class of insecticides in the world (Simon-Delso et al. 2015). Imidacloprid has limited use in freshwater systems, and the financial costs of registering imidacloprid for use in an estuary were expected to be especially high.

4.1 Efficacy

Initial small-scale trials of imidacloprid showed it to be less effective at suppressing shrimp burrow densities then carbaryl, but substantially more effective than most other candidate compounds (Patten 2007b, see Chapter 3) and the most effective of the candidate compounds with a strong potential for registration. Shrimp burrow densities were reduced by 47—97% at 14 DAT compared to one day before treatment (DBT) among 18 applications to commercial shellfish beds with the liquid or the granular formulation at 0.5 lb. a.i. per acre (29.5 acres and 21.8 acres, respectively) (Patten 2011). In the 2012 large-scale experimental trials, burrow densities were reduced by 65—84% at 14 DAT compared to 1 DBT among two sites and the two formulations (Barrett and Stutes 2014). In the 2014 large-scale trials, efficacy ranged from 27—97%, with most sites rated at > 60% (reduction in burrow density at 14 DAT compared to one DBT) (Barrett and Stutes 2015). In almost all trials, burrow densities were usually suppressed below the threshold for management of 10/m^2.

Field observations following the experimental applications of imidacloprid, including the relatively slow rate of shrimp burrow decline compared to carbaryl application (K. Patten, pers. comm.) and the observation of adult Dungeness crab in a state of tetany (Booth et al. 2019), suggested imidacloprid was not directly killing burrowing shrimp. It was hypothesized that imidacloprid-induced tetany in field-treated burrowing shrimp caused them to cease tending their burrows, which collapsed after several days and led to the shrimps' suffocation (Grue et al. 2011). That hypothesis has since been verified in the laboratory (Grue and Grassley 2013).

4.2 Impact Assessments

Five risk/impact assessments focusing directly on the use of imidacloprid to manage burrowing shrimp in Willapa Bay and Grays Harbor were conducted over the decade-long process to register and permit imidacloprid for that use. The assessments increased in scope and length in tandem with the number and complexity of associated field and laboratory studies.

In association with WGHOGA's application for a Federal EUP, the USEPA's Environmental Fate and Effects Division (EFED) conducted a review of the proposed use in 2009 (USEPA 2009). Imidacloprid is mobile and dissipates from the environment through photolysis and anaerobic aquatic metabolism. The primary degradate, imidacloprid guanidine, was flagged as concerning in the review because it persists under aerobic soil conditions, but it is less mobile than the parent imidacloprid. Imidacloprid was not expected to bioaccumulate. The review concluded that "no risks to terrestrial organisms are expected because the proposed uses are all in aquatic areas," but that acute and chronic risks to invertebrates in the pore water could result. Regarding estuarine fish, the review found no evidence to expect direct acute and chronic toxic effects. "Secondary adverse effects (fish life stage development) and adverse effects at the ecosystem level — both to the organisms themselves as well as producing food chain and population disruptions — are also unlikely due to the limited extent of the applications within the bays" (USEPA 2009).

In 2013, a risk assessment (RA) for the use of imidacloprid on shellfish beds to manage burrowing shrimp was prepared (Compliance Services International [CSI] 2013). In addition to several elements covered in the EFED review and reiterated in later reviews, the authors noted that substantial daily tidal flushing in the estuaries would speed imidacloprid's dilution, dissipation and metabolic breakdown. "The overriding weight of evidence indicates that imidacloprid treatment will not significantly impact endemic species or the ecology of Willapa Bay and Grays Harbor," they concluded.

In April 2015, prior to issuing the NPDES permit, ECY also issued an FEIS on imidacloprid (ECY 2015). The FEIS compared three scenarios — no action, continued carbaryl application with IPM, and imidacloprid application with IPM — in terms of potential impacts to nine environmental elements in Willapa Bay and Grays

Harbor[7] and mitigation measures to minimize those impacts. The FEIS determined that the imidacloprid with IPM alternative would have no significant unavoidable adverse impacts to the environmental elements considered given the mitigation measures required by the permit. Regarding animals, the FEIS noted that, aside for some salmonid life stages, many animals would not be present during imidacloprid treatment. Effects on Dungeness crab would be "temporary, and only from direct contact." Citing the large-scale trials of imidacloprid that had already been conducted in 2011 and 2012 (Barrett and Stutes 2014, Booth and Rassmussen 2011), the FEIS determined there would be limited effects on benthic invertebrates.

A Preliminary Aquatic RA to Support the Registration Review of Imidacloprid was released by the USEPA in December 2016 (USEPA 2017). The USEPA uses a risk quotient (RQ) to assess ecological risk to individual organisms (usually species) subject to a given exposure route and exposed to a measured or estimated exposure concentration (Jones et al. 2004). The assessment also incorporates toxicity values such as the LD50 and LC50, which are derived using standardized laboratory protocols (usually static conditions for a 48-hr or 96-hr exposure interval). The USEPA's RA noted that the available data on acute (six species) and chronic toxicity (three species) for saltwater invertebrate species was more limited than the data available for freshwater invertebrates. They derived the estimated acute toxicity endpoint for saltwater invertebrates (16.6 µg/L) by using the lowest LC50 among the six species (the mystid shrimp, *Americamysis bahia*) divided by two. Although the RA classified applications of imidacloprid to manage burrowing shrimp in Willapa Bay as a non-agriculture use pattern, it also distinguished it from other non-agricultural uses. The RQs for saltwater invertebrates exposed via a non-agricultural use were calculated for scenarios based on poplar and Christmas tree farms, nurseries and perimeter treatments of turf. No RQs were calculated specifically for the use against burrowing shrimp in Willapa Bay.

In 2016, Health Canada's Pest Management Regulatory Agency (PMRA) reevaluated imidacloprid's use in Canada (PRVD2016-20) (PMRA 2018). The published report reached two major conclusions: (1) measured concentrations of imidacloprid were at "harmful" levels for aquatic insects, and (2) "continued high volume use of imidacloprid in agricultural areas was not sustainable." Accordingly, PMRA proposed phasing out the use of imidacloprid in agriculture and most other outdoor uses in three to five years. Notably, the vast majority of the PMRA review focused on freshwater organisms. Only two paragraphs in the decision address monitoring data from estuarine or ocean water, and no risk assessment was made for marine invertebrates because of these data limitations. PMRA relied on the same species as the USEPA RA (2017) to derive acute and chronic endpoints for marine and estuarine invertebrates.

An SFEIS was conducted and released by ECY in January 2018 (ECY 2018). The SFEIS considered three alternative management plans: no action, continued carbaryl with IPM, and imidacloprid with IPM using two different application methods and treatment thresholds (2,000 acres with helicopter application vs. 500 acres without helicopter application). The SFEIS incorporated findings from the large-scale experimental trials conducted in 2014 (Barrett and Stutes 2015) that were not present in the FEIS and referenced the literature reviews of the effects of imidacloprid included in the USEPA (2017) and PMRA (2018) risk assessments described above.

4.3 Fate and Transport

All risk assessments and impact statements associated with experimental applications of imidacloprid to manage burrowing shrimp in Willapa Bay emphasized the following points: imidacloprid dissipates from the environment through photolysis and anaerobic aquatic metabolism; it is mobile, and its primary degradate, imidacloprid guanidine, persists under aerobic soil conditions; and imidacloprid guanidine is less mobile than imidacloprid.

Studies of the fate and transport of imidacloprid following the large-scale field applications (2011, 2012, 2014) were conducted according to standardized practices detailed in the SAPs. Imidacloprid concentrations were sampled over plots on the first and subsequent flood tides after treatment until they were no longer detected (Grue and Grassley 2013). In 2012, the average concentrations of imidacloprid in the field plot surface waters at a depth of 10 cm on the first flood tide were 108 ± 127µg/L (SE, N = 20) and ranged from 7—2,400 µg/L (Barrett and Stutes 2014, Barrett and Stutes 2015). However, all positive concentrations were at stations near the downslope border of the treated area, which were the first to receive incoming waters. All concentrations at the remaining 16 stations in the central region of the plot were zero. Average imidacloprid concentrations from additional samples from the wetting front of the flood tide and in shallow pools within and immediately adjacent to the treated plots following other experimental applications were 170 ± 34 (SE) µg/L (N = 28) (Patten and Norelius 2017). Concentrations were rapidly diluted by the incoming tide, which increases in depth at a rate of approximately 2.8 cm/min. At that rate, on-bed concentrations of imidacloprid would be diluted by 50% at a depth of 10 cm within 3.5 minutes, then subsequently diluted by half at intervals of 7, 14, 28, 56, and 112 minutes to a final theoretical concentration of 5 µg/L after ~ 3.5 hours (Figure 14). Imidacloprid concentrations in both sediment porewaters and sediments were sampled concurrently with the surface water samples and in waters at increasing distances from treated plots. Average on-bed imidacloprid concentrations in porewater declined precipitously after treatment according to a power function (Figure 15). The average imidacloprid concentration in samples from the water column on the high tide in channels and swales immediately adjacent to the 2011 and 2012 experimental large-scale trials in Willapa Bay was 2.2 ± 1.6 µg/L (N = 28) at about six hours after treatment (Grue and Grassley 2013).

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[7] Existing conditions and possible impacts to the following nine environmental elements were considered: sediments, air quality, surface water, plants, animals, human health, land use, recreation, and navigation.

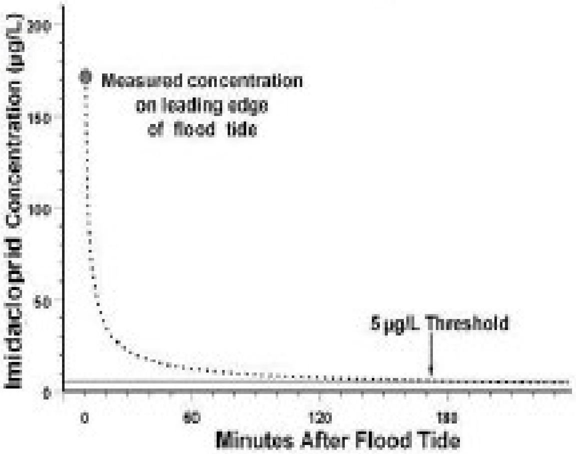

Figure 14. Dilution of on-plot concentration of imidacloprid concentrations in surface waters on the first flood tide after treatment (based on data from Patten and Norelius 2017).

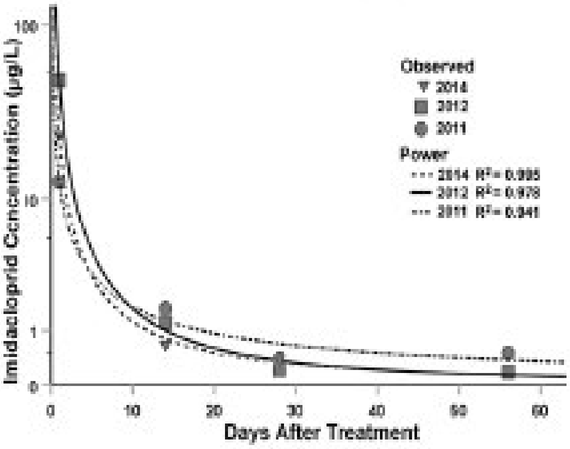

Figure 15. Persistence of imidacloprid in porewater after application at all large-scale plots in 2011, 2012, and 2014 and associated best-fit (power) curves (based on data from Grue and Grassely 2013, Barrett and Stutes 2014, Barrett and Stutes 2015).

A recent study used Rhodamine WT dye (FWT Red 200 Liquid; Kingstoke Chemicals) to better understand how imidacloprid (and the herbicide imazamox) is transported from application sites in Willapa Bay (Barrett and Patten 2019). The authors demonstrated the dye was a good proxy for imidacloprid given its similar water solubility, application methods and application concentrations. Results confirmed observations of imidacloprid concentrations in the field. The exposure interval of concentrations near the application rate was 5—20 min, and concentrations were significantly reduced with increasing distance from the application site, according to an exponential decay curve. Concentrations in the incoming tides more than 200 m upslope from treated sites were <10% of peak concentrations when those waters crossed over the treated plot. Patterns of movement varied depending on local conditions (i.e., bed topography and the amount of standing water) as well as nearby off-site conditions (i.e., presence of tidal channels and major geographic features such as peninsulas and islands).

4.4 Effects on Benthic Invertebrates

Reported effects of imidacloprid on aquatic invertebrates are much less common compared to effects on insects. Recent comprehensive reviews of neonicotinoid impacts on non-target invertebrates reported, “[t]here are no published works regarding the marine environmental contamination of neonicotinoids” (Pisa et al. 2015), and “[t]he impact on marine and coastal ecosystems is still largely uncharted” (Pisa et al. 2017).

Although effects to benthic invertebrates in Willapa Bay from field applications of imidacloprid were examined in earlier trials (Booth 2008b, Booth 2010a), the 2011, 2012 and 2014 commercial-scale field trials collected a large dataset using standardized methods (Barrett and Stutes 2014, Barrett and Stutes 2015). Invertebrates were sampled at each of 20—30 stations in an untreated and treated plot on the day before and at 14 and 28 DAT. In keeping with the Sediment Management Standards Puget Sound marine criteria for benthic abundance (WAC 173-204-320 (3)C), determination of effects was based on the numerical abundance and taxonomic richness of each of three primary taxonomic assemblages (polychaetes, mollusks and crustaceans) with additional information provided by the taxonomic diversity of each assemblage, for a total of nine metrics. An effect was considered to have occurred if a metric value from a treated plot was 50% less and significantly different (p=0.05) than its value from data in an untreated plot (e.g., the “50% test”), and whether an effect reversed over time. Because treated and untreated plots were over 300 m apart, and because local conditions in Willapa Bay are highly variable (metrics from treated and untreated plots were often significantly different before treatment), additional site-specific considerations were also considered when appropriate.

Over three years, eight trials were conducted among five study areas. This should have provided 72 different metrics, but no mollusks were found in either the test or control plot before treatment in four tests. Of the 68 metrics tested, only 8 had values that were equivalent between the test and control plots before treatment. None had values that were less than 50% on the test plot compared to the control plot at either 14 or 28 DAT, which strongly indicated imidacloprid did not negatively impact those metrics. The remaining 62 metrics had pretreatment values that were either significantly lower on the test plot relative to the control plot (n = 27) or significantly larger on the test plot relative to the control plot (n = 35). Of these 62, 43 passed the test for no effect at 14 DAT and 37 passed the test at 28 DAT. The remaining determinations were made by examining the change in the ratio of the metric from the test plot over the control plot from before to after treatment in the context of site-specific characteristics that might account for that change.

ECY's interpretations of the results of the metric test results differed between the FEIS and the SFEIS. The FEIS determined that imidacloprid applications on commercial shellfish beds to manage burrowing shrimp would be "unlikely to adversely affect polychaete worms or mollusks (bivalves, snails), including oysters and clams," with a potential exception for sediments high in organic matter (ECY 2015). In contrast, the SFEIS (ECY 2018) specified the results of two metric tests — crustacean abundance and polychaete abundance — at one site in northern Willapa Bay (Cedar River in 2011) as evidence of more than a minor adverse effect. The results from these two metric tests were also cited in ECY's ultimate denial of the NPDES permit for imidacloprid applied to shellfish beds in Willapa Bay and Grays Harbor (Doenges 2018).

In addition to the determination of adverse effects on benthic invertebrates via the "50% metric test," ECY estimated an area of potential contamination that was five times the size of the treated area. ECY used an area-weighted averaging technique (Inverse Distance Weighting, IDW) to interpolate the measured concentrations of imidacloprid in surface waters at sites not directly sampled. The estimated concentrations were then compared against the USEPA's (2017) endpoint for acute toxicity of imidacloprid to saltwater invertebrates (16.5 µg/L), which was a conservative estimate derived from limited data on marine invertebrate species based on a 96-hr exposure interval. However, as mentioned, imidacloprid concentrations in on-plot surface waters were measured on the leading edge of the incoming tide after treatment during field trials, and ECY did not consider the effect of tidal dilution of concentrations.

Booth et al. (2019) re-examined the results of the 2011, 2012 and 2014 field trials of imidacloprid. Sixty principal response curve (PRC)[8] analyses were conducted to examine the response of six taxonomic assemblages from the eight studies conducted over three years at the five sites. Both the response and treatment effects were significant ($p < 0.05$) in 49 of the analyses; but, as with the "50% tests," pre-treatment differences in assemblage abundance and composition at test and control plots often confounded the interpretation of results. In most analyses, the response of the treated assemblage relative to the control assemblage did not change much over time, indicating a neutral treatment effect. Only six PRCs out of 60 (five mollusk assemblages and one crustacean assemblage) indicated a negative effect from imidacloprid application. None of the analyses showed negative effects on polychaetes. The low frequency of a negative effect was likely due to the low concentration and short period of imidacloprid exposure, the low toxicological susceptibility of many taxa to imidacloprid, and natural resilience to disturbance and extreme environmental events.

4.5 Effects on Dungeness Crab and Mysid Shrimp

Based on a previous study (CSI 2013), ECY's FEIS (2015) determined that imidacloprid applied according to the USEPA's registered label instructions (bed exposed during low tide, application rate of 0.5 lb. a.i. per acre, etc.) "would not cause direct mortality in Dungeness crab….[,]" but could cause impacts by inducing a temporary state of paralysis, or tetany, after exposure. This state is manifested in adult crabs when all appendages, including mandibles, tremble but are otherwise motionless (CSI 2013). Megalopae larvae and early instar juveniles in tetany are completely motionless and unresponsive to gentle prodding with a toothpick but recover full activity after transfer to estuarine water without imidacloprid. Both adult and juvenile crabs in tetany are likely more vulnerable to predation. The FEIS described these effects on Dungeness crab as "temporary."

The SFEIS (ECY 2018), citing scientific literature not available for the FEIS (e.g., Osterberg et al. 2012, Patten and Norelius 2017), determined that imidacloprid applications would "result in death of planktonic and juvenile Dungeness crab on-plot. Dungeness crab in off-plot areas may also experience mortality, particularly in those areas closest to the sprayed plots." The SFEIS noted most offsite impacts would be limited to older juveniles rather than early-stage juvenile crab. No cumulative effects to the Dungeness crab population were expected because: (1) the number of crab killed on the plots is a very small proportion of the entire population; (2) the majority of Willapa Bay and Grays Harbor tidelands would not be directly treated with imidacloprid, and would therefore remain as nursery and foraging habitat for the species; and (3) for planktonic forms, any impact would be offset by the very high fecundity of females of this species (approximately two million eggs/individual). There is also uncertainty regarding the overall impacts to crabs. For example, the outer extent of off-plot impacts has not been identified, and sublethal impacts have not been quantified.

Osterberg et al. (2012) focused on laboratory assays for acute toxicity of several common agricultural pesticides on blue crab. The "simplified dilution study" cited by the SFEIS in its determination of potential effects on adult Dungeness crab in Willapa Bay was a small ancillary analysis by Osterberg et al. (2012). Overspray of Trimax Pro (40.80% imidacloprid; Bayer CropScience) in ditches near treated cotton fields resulted in concentrations of imidacloprid greater than the LC50 for juvenile blue crab (816.7 µg/L) when water depth was < 4.1 cm (Osterberg et al. 2012). Concentrations were estimated based on a "cuboid" model of ditch dimensions (vertical sides) and did not include factors such as tidal flow, substrate porosity or temperature effects. Willapa Bay estuarine channels are irregularly shaped, and both water depth and current velocity are constantly changing. Most later-stage juvenile and adult Dungeness crab move to deeper waters during daylight hours and as the tide recedes from intertidal ground (Holsman et al. 2006).

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[8] PRC analysis is a multivariate ordination technique that was developed to simplify assessment of pesticide treatments on abundances of aquatic invertebrates in mesocosms (Van den Brink and Ter Braak 1999). In PRC, the effect of time is removed (Borcard et al. 1992), allowing treated and untreated species assemblages to be compared along a horizontal time axis, simplifying the interpretation of results. PRC analysis also estimates the taxonomic weight of each species as its correlation with the response pattern of the entire taxonomic assemblage (Van den Brink and Ter Braak 1999).

Patten and Norelius (2017) conducted a series of laboratory tests of the effects of imidacloprid on Dungeness megalopae larvae and early instar juveniles at exposure intervals and concentrations similar to those in the field. They found low direct mortality in megalopae larvae and no direct mortality in early-stage juvenile crabs. Exposure to much higher concentrations for longer time periods often induced tetany or partial tetany, but this was reversible after transfer to estuarine water without imidacloprid. All juveniles and all megalopae recovered from tetany 13 hours after removal from a two-hour imidacloprid treatment of 500 µg/L. More than 80% of the megalopae larvae exposed to ≤12,500 µg/L imidacloprid for two hours recovered after 21 hours in pure sea water. All first instar juveniles exposed to high concentrations (625,000 or 125,000 µg/L) of imidacloprid were in tetany after two hours. Although none of the juveniles exposed to 625,000 µg/L had recovered after 21 hours in pure seawater, all of those exposed to 125,000 µg/L had recovered after 13 hours. The SFEIS also discussed large juvenile and adult crab in tetany that were killed by seagulls or crushed by ATV during treatment application (Barrett and Stutes 2014, Patten and Norelius 2017). Out of 141 crabs observed during surveys of treated plot perimeters or near on-plot transects, 137 were in tetany or killed. The SFEIS cited these numbers as a violation of Sediment Management Standards because the corresponding proportion was >50%. However, the local population of adult crabs on treated plots prior to treatment was not determined during either study.

Though not available at the time the SFEIS was released, a recent paper more fully described the effects of imidacloprid on juvenile Dungeness crab and discussed additional factors influencing the relationship among shrimp, crab and imidacloprid treatments (Patten and Norelius 2017). Building on Doty et al.'s (1990) research showing that habitat benefits provided by shellfish cultivation outweighed mortality caused by carbaryl treatments, Patten and colleagues suggest this tradeoff should be even more favorable with the use of imidacloprid to manage burrowing shrimp because imidacloprid results in lower direct crab mortality.

Recent laboratory tests have also studied the effects of imidacloprid on another crustacean. Mysid shrimp (*Americamysis bahia*) were exposed to imidacloprid and three other chemicals, using a 25-min exposure scenario mimicking a field application (Barrett and Patten 2019). For imidacloprid, each of three initial exposure concentrations (500, 250 and 125 µg/L) were spiked to double the concentration, and then serially diluted to 75%, 20%, 10%, and finally to 0% of the maximum concentration. For example, 500 µg/L was spiked to 1000 µg/L at five minutes after initial exposure and then serially diluted to 750, 200, 100, and 0 µg/L seawater at 10, 15, 20, and 25 minutes after initial exposure. All 40 of the shrimp were in tetany one hour after initial exposure to the 500 µg/L initial exposure concentration scenario; but after 23.5 hr in pure seawater, 38 shrimp were swimming normally, one was dead, and one was missing.

4.6 Effects on Fish

A comprehensive review and assessment on the effects of imidacloprid on human health and environmental risk (Anatra-Cordone and Durkin 2005) concluded: "[u]sing the standard classification scheme proposed by USEPA-EFED (2001), imidacloprid would be classified as practically nontoxic to fish." Results from a series of controlled laboratory tests (static 96-hr) on juvenile rainbow trout, juvenile Chinook and juvenile white sturgeon[9] are presented below in Table 1 (Grue 2009). In all cases, LC50 values were substantially lower than the theoretical maximum imidacloprid concentration in 10 cm of water at an application rate of 0.5 lb. a.i. per acre (5.6 x 103 ppb). Another laboratory study looked at the survival of saddleback gunnel (*Pholis ornata*) after exposure to imidacloprid. Survival was 100% after five days in estuarine water at an imidacloprid concentration of 10,000 ppb and 93.3% at 100,000 ppb (Patten, unpublished data).

Additional studies examined imidacloprid exposure levels in juvenile Chinook salmon and white sturgeon captured on or near treated beds after test applications in Willapa Bay, as measured using an enzyme-linked immunosorbent assay technology adapted for use in biological tissues (Frew and Grue 2012, Frew and Grue 2015). Only one out of 20 juvenile Chinook salmon captured and analyzed had imidacloprid residue levels greater than the limit of quantification of the assay (261 ppb compared to detection limit of 21 ppb) (Frew and Grue 2012). The 261-ppb level was ~10 times lower than levels measured in laboratory-controlled exposure experiments to a range of field-simulated concentrations. No overt effects were observed in white juvenile sturgeon exposed to imidacloprid in simulated field exposures (Frew et al. 2015).

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[9] White sturgeon was used a surrogate for green sturgeon.

Table 1. Median lethal concentrations (LC50) and lowest-observed-adverse-effect levels (LOAEL) for four species of fish common to Willapa Bay and Grays Harbor. Source: Grue 2009.

Species	LC50 (ppb)	Range (ppb)	LOAEL (ppb)
Juvenile Rainbow Trout (3 g)	17.0×10^4	$(15.9\text{-}18.1) \times 10^4$	3.2×10^4
Juvenile Rainbow Trout (20 g)	16.3×10^4	$(14.8\text{-}17.7) \times 10^4$	3.2×10^4
Juvenile Chinook	10.8×10^4	$(10.2\text{-}11.8) \times 10^4$	9.6×10^4
Juvenile White Sturgeon	12.4×10^4	$(9.3\text{-}17.0) \times 10^4$	4.6×10^4

Actual porewater concentrations of imidacloprid were significantly lower than concentrations for either acute or chronic effects. Corresponding RQs were considerably lower than the level of concern for direct effects from either acute or chronic exposure to an endangered species. Measurements of imidacloprid concentrations in porewater and in ghost shrimp following experimental applications were used to extrapolate potential exposure routes to green sturgeon (Frew and Grue 2012). Comparisons between treated and untreated control beds indicated green sturgeon fed opportunistically on imidacloprid-impaired shrimp. Comparisons of models based on branchial vs. dietary uptake indicated that the primary exposure route was porewater. Concentrations and durations of exposure were below thresholds for direct acute or chronic toxic effects.

The SFEIS (ECY 2018) concluded that imidacloprid would be unlikely to affect salmonids (including bull trout) either through direct exposure or indirectly by feeding on crustacean prey, including burrowing shrimp. However, the SFEIS speculated that significant declines in abundance of other important invertebrate prey at specific times and locations could possibly affect fish indirectly.

4.7 Effects on Birds

All relevant risk assessments of the proposed use of imidacloprid to manage burrowing shrimp have indicated minimal to no direct effects on birds (CSI 2013, USEPA 2009, USEPA 2017, ECY 2015, ECY 2018). The risk assessments also note that most migratory species passing through Willapa Bay and Grays Harbor are not present during the summer spray window for the applications.

Imidacloprid has inherently low toxicity to all vertebrates due to its mode of action. Routes of exposure are limited following field applications to manage burrowing shrimp. The pellet of the granular formulation is extremely small (~1 mm diameter) and does not resemble the natural prey of waterfowl that typically forage on intertidal mudflat (e.g., gulls, brant). Furthermore, the granule changes to a soft slurry within minutes after exposure to a moist surface, then continues to dissolve so that it is nearly invisible to the human eye 24 hours after treatment (Booth unpublished data).

Of particular concern is black brant, one of the most common birds that forage on the mudflats, which could potentially feed on eelgrass treated with granular imidacloprid. At the application rate of 0.5 lb. a.i. per acre (i.e., 1.102 mg/m^2), 2,357 granules are distributed over one square meter and each granule contains 0.467 µg imidacloprid. A brant would have to consume 10.7 million granules to acquire 5,000 mg imidacloprid, the LC50 for mallard duck (Toll 1991). This is equivalent to foraging over 4,500 m^2 of mudflat or, in areas of dense eelgrass coverage, consuming 454 kg of eelgrass. This is also assuming all the imidacloprid remains on the eelgrass, which is highly unlikely.

Conclusion

Shellfish harvesting and/or cultivation have been central to the history and identity of the coastal communities along Willapa Bay and Grays Harbor for as long as people have called the region home, and the shellfish industry is currently “the backbone of…[the local] economy” (Flores and Batker 2014). However, the future of shellfish aquaculture in the coastal estuaries is threatened by the lack of an effective IPM plan to manage burrowing shrimp. The scientific and regulatory challenges of managing pests that are hearty native ecosystem engineers living in a subterranean estuarine environment, combined with the logistical constraints and variability of shellfish aquaculture, generates fundamental incompatibilities with traditional IPM management strategies. Though several iterations of an IPM program to manage burrowing shrimp on shellfish aquaculture beds have been attempted since the 1990s, the development of effective, economically feasible, and socially and environmentally acceptable strategies and tactics remains elusive.

The insecticide carbaryl was applied to shellfish beds in Willapa Bay and Grays Harbor to manage burrowing shrimp from 1963 until 2013, when its use was discontinued as part of a legal settlement and a broader IPM approach was adopted. Dozens of studies of potential physical, biological and chemical control strategies were subsequently undertaken, but they identified only a few tactics that could suppress shrimp densities for longer than a single growing season. Only the neonicotinoid insecticide imidacloprid was determined to have potential for full implementation, and the shellfish industry invested seven years and millions of dollars in research to evaluate imidacloprid’s effectiveness and environmental impact. Although the USEAP federally registered an imidacloprid product for regulated use on selected acreage, the ECY denied an NPDES permit for that use in 2018, leaving burrowing shrimp largely unmanaged on shellfish beds and threatening the survival of the local shellfish industry. Alternative management tactics continue to be investigated by the IPM Working Group as part of the settlement agreement between ECY and WGHOGA. To date, shellfish growers in Willapa Bay and Grays Harbor still do not have an effective and permitted strategy for managing burrowing shrimp populations on their farms. A 2022 internal polling of WGHOGA membership reported that currently, 589 acres of seed/nursery ground, 487 acres of fattening/harvest beds and 352 acres of clam ground are no longer in production due to increases in burrowing shrimp in Willapa Bay. The response rate covered about three quarters of the farmed land in Willapa Bay, but no responses were received from Grays Harbor farmers.

IPM allows for the judicious, but ideally not exclusive, use of pesticides. However, when the only environmentally and economically feasible management tactics encountered to date are pesticides, determining whether and when their use is “judicious” is less easily resolved by the best available science and more easily influenced by concerns about scientific uncertainty and public perceptions about potential health risks and environmental harms. Both chemical controls — the registered and permitted use of carbaryl and the registered experimental use of imidacloprid — were subject to numerous scientific assessments of their efficacy and non-target impacts. These studies demonstrated that neither pesticide, as used on commercial shellfish beds to manage burrowing shrimp, posed substantial risk to a wide variety of non-target organisms, including most benthic invertebrates, fish (including ESA-listed salmonids and green sturgeon), birds, and humans. Only a single risk assessment of imidacloprid and two accompanying analyses of the large-scale trials conducted in Willapa Bay showed potential localized and seasonal effects to a few genera of benthic invertebrates. The low frequency of negative effects on benthic invertebrates for both chemical controls were likely due to exposures that were limited to low concentrations and short time periods, natural resilience to disturbance and extreme environmental events, and — in the case of imidacloprid — low toxicological susceptibility.

As the pursuit of an effective IPM Plan for burrowing shrimp continues, several areas of research should be prioritized. IPM requires (1) monitoring of pest populations to determine when (2) a threshold of economic injury has been reached and (3) pest control actions become necessary. Each of these steps is constrained by key data and information gaps. Standardized methods to determine the distribution and range of burrowing shrimp populations and dynamic models that can use historical and current data on population trends, ocean and estuarine conditions, climate, etc. to hindcast and forecast burrowing shrimp populations in Willapa Bay and Grays Harbor would fill critical data gaps on the monitoring front. Determining action thresholds would benefit from a monitoring framework that links burrowing shrimp distribution to negative impacts on shellfish beds and other tidelands, as well as economic injury to shellfish growers with different farm sizes, markets, culture methods, and site conditions. Finally, diversifying the toolkit of management tactics that are effective, environmentally safe and socially acceptable is essential.

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