The Ecology and Management of the Kuroshio Shot Hole Borer in the Tijuana River Valley
2019-20 (Year 5)

Final Report

by

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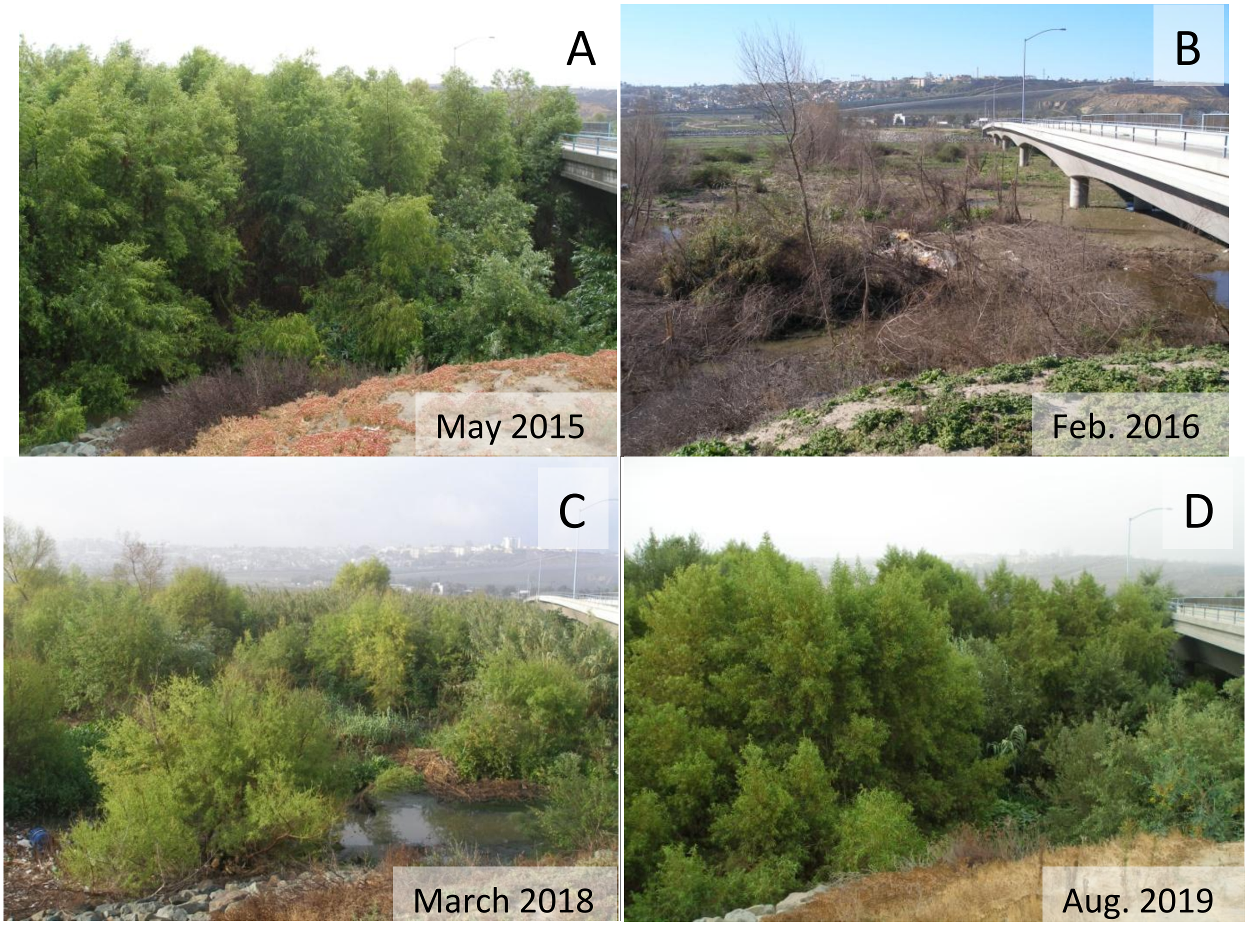


*Frontispiece. This sequence of photographs of the Wet Forest at Dairy Mart bridge illustrates three of the main storylines in this report – the initial impact of the KSHB (**A** to **B**), the speedy recovery of the willow forests (**B** to **D**) and the surprising finding that KSHB has not substantially reinvaded the recovering forests (**D**).*

TABLE OF CONTENTS

1. ABSTRACT

This report presents the current status of the Kuroshio Shot Hole Borer (KSHB, *Euwallacea kuroshio*, Coleoptera: Scolytidae) in the Tijuana River Valley. It provides current rates of KSHB infestation; documents the current state of post-KSHB recovery in the most impacted forests in the valley; compares the current data with data collected over the past five years; and uses GIS technology for the first time to accurately map the spread of the KSHB in the valley.

This report is the fifth in a series of annual reports about the KSHB in the valley. It adds to and further develops **four main storylines** about the KSHB in the valley:

1. **The KSHB in the valley went through a rapid boom-and-bust cycle**. Annual surveys of infestation rates in the field and annual calculations of canopy damage from satellite images show that the KSHB population went through a rapid outbreak and a rapid decline over a five-year period. The infestation rates peaked in Fall 2016 and the canopy damage was greatest between 2016 and 2017. The early increase in population was characterized by the KSHB's presence in the Wet Forests and the swift damage to these forests (see frontispiece). The later decrease in population was characterized by the KSHB's presence in the Dry Forests and the slower damage to those forests. The KSHB population decline appears to be due to the KSHB depleting their preferred host trees and not reinvading the recovering host trees in the Wet Forests. This boom-and-bust cycle occurred naturally, with no management interventions to control the spread or severity of the outbreak.

2. **The willow forests that were extensively damaged by the KSHB are responding with vigorous regrowth.** Since the KSHB heavily damaged the Wet Forests in 2015-17, there has been extensive willow forest recovery in three ways: by the survival of a few, scattered mature infested trees ('Big Trees'); by the resprouting of mature KSHB-damaged trees ('resprouts'); and by the seeding of new trees ('seedlings'). The frontispiece shows the striking recovery of one of the Wet Forests. Some of the forests have recovered so much in just four years that they are now similar to their pre-KSHB stature.

3. **The KSHB has not substantially reinfested the recovering willow forests.** Even though others predicted that all of the trees in the recovering Wet Forests would be quickly reinfested, only 3% of the Big Trees, 2% of the resprouting trees, 1% of the young trees, and 0% of the seedlings were infested with KSHB in 2019. This unexpected result begs the question: *Why are the recovering willows not being attacked by the KSHB?* In this report we suggest three possible reasons.

4. **The invasive plant, *Arundo donax*, is now a major problem.** Willow trees are arundo's only competitors in the valley, and when the KSHB attacked and heavily damaged the willows it allowed arundo to flourish more than ever before. Our

main recommendation for the park managers in the valley is to control the arundo on their property. To assist them we provide a map of the current distribution of arundo using satellite images and object-based imagery analysis (OBIA) software.

The research reported here is unique among KSHB studies. It involves detailed and long-term field surveys of the KSHB invasion in one valley, documents an entire boom-and-bust outbreak of the KSHB and describes the damage to and recovery of the forests. This report also discusses the six most important ecological findings and suggests that incorporating these findings into the existing predictive numerical model would make the model more accurate. Finally the report presents several recommendations for needed future research and for immediate management actions.

2. INTRODUCTION

The Kuroshio Shot Hole Borer (KSHB, *Euwallacea kuroshio*; Coleoptera: Scolytidae, Gomez et al. 2018) is an ambrosia beetle native to Asia that has recently invaded southern California. Until 2015 it had been seen in avocado groves and landscape trees only (Eskalen *et al.* 2013, Umeda et al. 2016). But in 2015, it was abundant in the native riparian forests in the Tijuana River Valley and has since caused extensive damage to those forests (Boland 2016, 2017b, 2018, 2019). In 2019 I estimated that the KSHB had infested more than 350,000 willows and killed more than 120,000 willows in the valley (Boland 2019). As the KSHB is now also being found in many other sites in southern California (Eskalen 2019), the authorities are extremely concerned that other sites are going to be impacted as badly as the Tijuana River Valley (Greer et al. 2018).

Since 2015 I have written four annual reports on the status of the KSHB in the Tijuana River Valley (Boland 2016, 2017b, 2018, 2019). This fifth report presents the current status of the KSHB in the valley in two main sections:

- KSHB IMPACTS IN THE TIJUANA RIVER VALLEY – The progression of the KSHB infestation during the past five years, focusing on the impact that the KSHB has had on the riparian habitats in the valley; and

- RESPONSE OF VEGETATION IN THE KSHB-DAMAGED RIPARIAN HABITATS – The response of the vegetation in the heavily-damaged riparian habitats.

This report draws on data from previous years and builds upon the earlier work through the addition of this year's data and new GIS mapping by Dr. Kellie Uyeda. It therefore contains the most accurate description of the impact and progression of the KSHB infestation in the valley, as well as the most accurate mapping of a major problem in the valley, the invasive plant *Arundo donax*.

This report also discusses relevant issues in two further sections:

- THE KSHB HAS NOT SUBSTANTIALLY REINVADED THE RECOVERING FORESTS – Here I show why this is unexpected and suggest three possible reasons for this surprising finding; and

- RECOMMENDATIONS – Here I list vital research and management recommendations based on this year's results.

This work is unusual in that it covers five years of repeated surveys within one valley. The five-year period has been long enough to document both the spread of the KSHB in the valley and the recovery of the hardest-hit forests. Many researchers will survey a site just once and provide a "*snapshot in time*" (Coleman et al 2019); here the frequent and long-term surveys instead present an *epic tale* of death, destruction, survival and remarkable recovery.

The three sections dealing with GIS technology have been written by Kellie Uyeda and the rest have been written by John Boland (see Section 9 for Author Bios).

This report is designed to be most useful to managers of the parks inside the Tijuana River Valley, but it should also be useful to other scientists and land managers who deal with invasive ambrosia beetles in other parts of southern California.

3. BACKGROUND

3.1. THE TIJUANA RIVER VALLEY

The Tijuana River Valley in San Diego County, California, is a coastal floodplain of approximately 3,700 acres at the end of a 1,730 square mile watershed (Figure 1). The Tijuana River is an intermittent stream that typically flows strongly in winter and spring and is mostly dry in summer (Boland 2014b). Many of the forests were established in the massive flood years of 1980 and 1993, making them 39 and 26 years old respectively – young by riparian forest standards (Faber et al 1989). Because the stream has changed course many times over the years (Safran et al. 2017), the riparian forests in the valley are a mosaic of forests of different ages and at different distances from the current flows. The forests can be divided into: **Wet Forests**, which are growing in the current river beds; **Dry Forests**, which are growing in older river beds that get some current flows; and **Scrub Forests/Woodlands**, which are growing far from current river flows (Figures 2 and 3).

For decades, the Tijuana River has been polluted with sewage and industrial waste as it has flowed through the city of Tijuana, Mexico; when the river flows through the Tijuana River Valley it is one of the most polluted rivers in California (Boland and Woodward 2019). The riparian willows in the valley have therefore been frequently exposed to high nutrient levels and they grow more quickly than willows elsewhere (Boland 2018). Furthermore, the forests in the valley can be considered valuable “treatment wetlands” because they filter some of the pollutants from the flows before the water reaches the ocean.

The riparian forest and scrub habitats are preserved within three adjoining open-space parks: the San Diego County Tijuana River Valley Regional Park, the Border Field State Park, and the federal Tijuana Slough National Wildlife Refuge. The riparian habitats are relatively undisturbed and support numerous reptile, mammal and bird species (Concur 2000), most notably the federally endangered least Bell's vireo (*Vireo bellii pusillus*) for which most of the riparian habitats are designated critical habitat (U.S. Fish and Wildlife Service 1994).

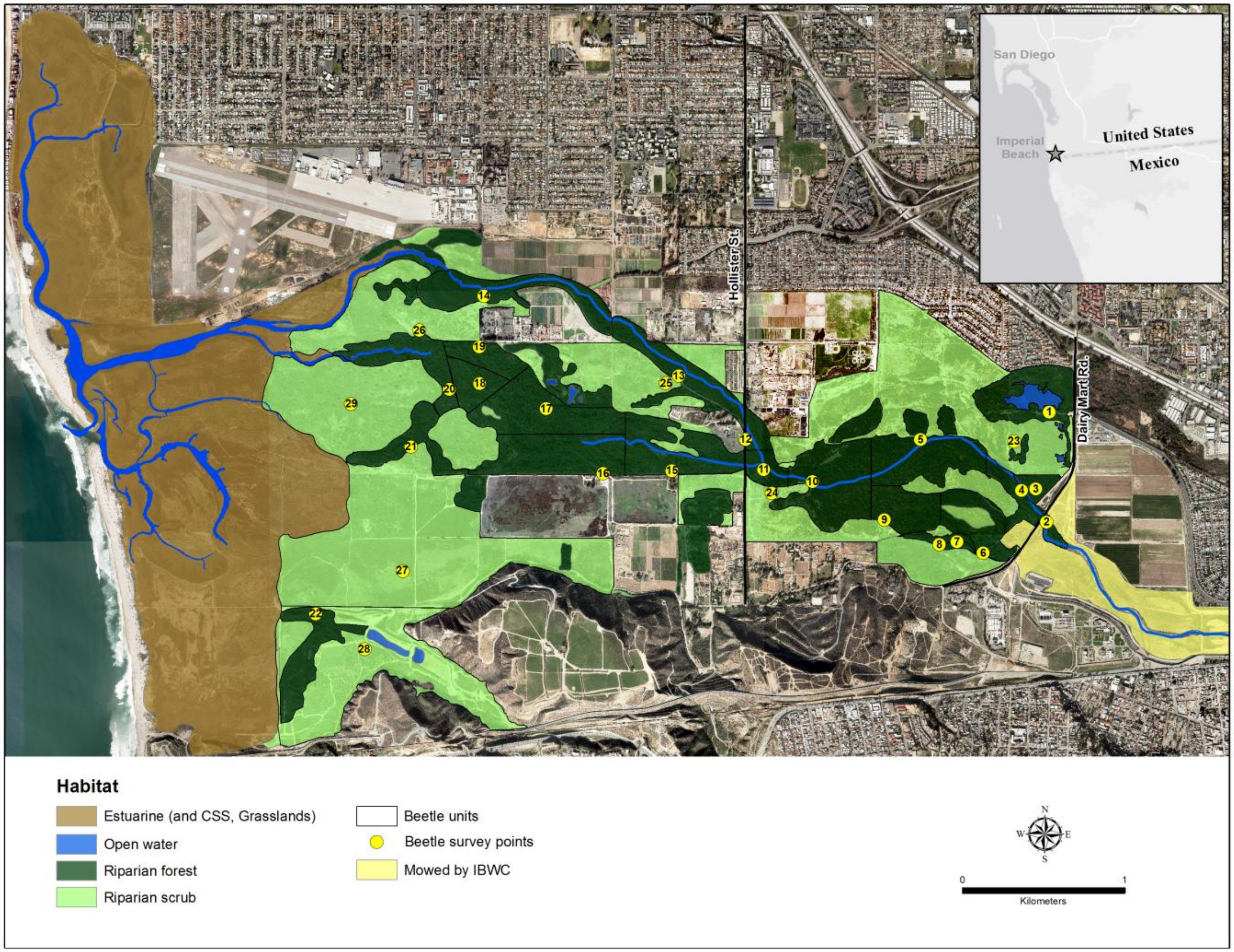
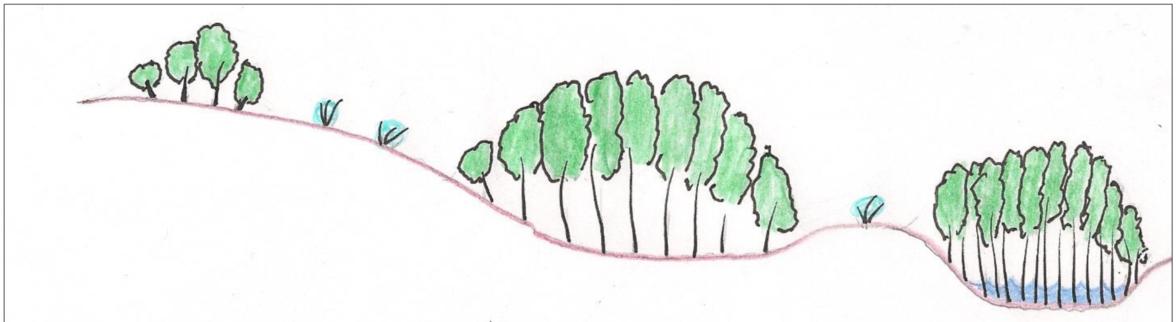


Figure 1. The location of the riparian forest and riparian scrub habitats within the Tijuana River Valley (from Boland 2016). Riparian forest units are numbered 1-22 and riparian scrub units are numbered 23-29. [Map created by John Boland and Monica Almeida, January 2016.]

3.2. THE DOMINANT WILLOW SPECIES

All the forests in the valley are dominated by just two tree species: the black willow (*Salix gooddingii*, SAGO) and the arroyo willow (*Salix lasiolepis*, SALA). SAGO is usually a single-trunked tree that occurs in the wettest sites, whereas SALA is usually a multi-trunked shrub or tree that occurs in slightly higher, dryer sites (Boland 2014b). Both species occur abundantly in all three forest types: the Wet, Dry and Scrub Forests; they grow fastest in the Wet Forests and slowest in the very dry Scrub Forests. Both willow species are pioneer species that establish in disturbed wet areas and their different zonation is due to their different timing of seed production (Boland 2014b). Both willow species resprout vigorously from adventious buds when damaged; SAGO produces resprouts from the trunk well above ground level, whereas SALA produces resprouts at or below ground level. The riparian scrub woodlands surrounding the forests are dominated by the perennial shrub, mule fat (*Baccharis salicifolia*; Boland 2014b, 2017a).



	SCRUB FOREST	DRY FOREST	WET FOREST
spp.	SAGO + SALA	SAGO + SALA	SAGO + SALA
age (yrs)	10 - 51	35 - 51	5 - 35
girth (cm)	35 - 135	67 - 130	18 - 83
density (#/40m^2)	1 - 12	2 - 5	1 - 72

Figure 2. A diagram of a bisect through the Tijuana River Valley showing the elevations of the Scrub Forest, Dry Forest and Wet Forests. The same willow species (black willow and arroyo willow) dominate all three forest types. The ranges of forest stand characteristics (age, girth, and density of trees) are given for the willows (data from Boland 2016). Girth is the trunk circumference at breast height.

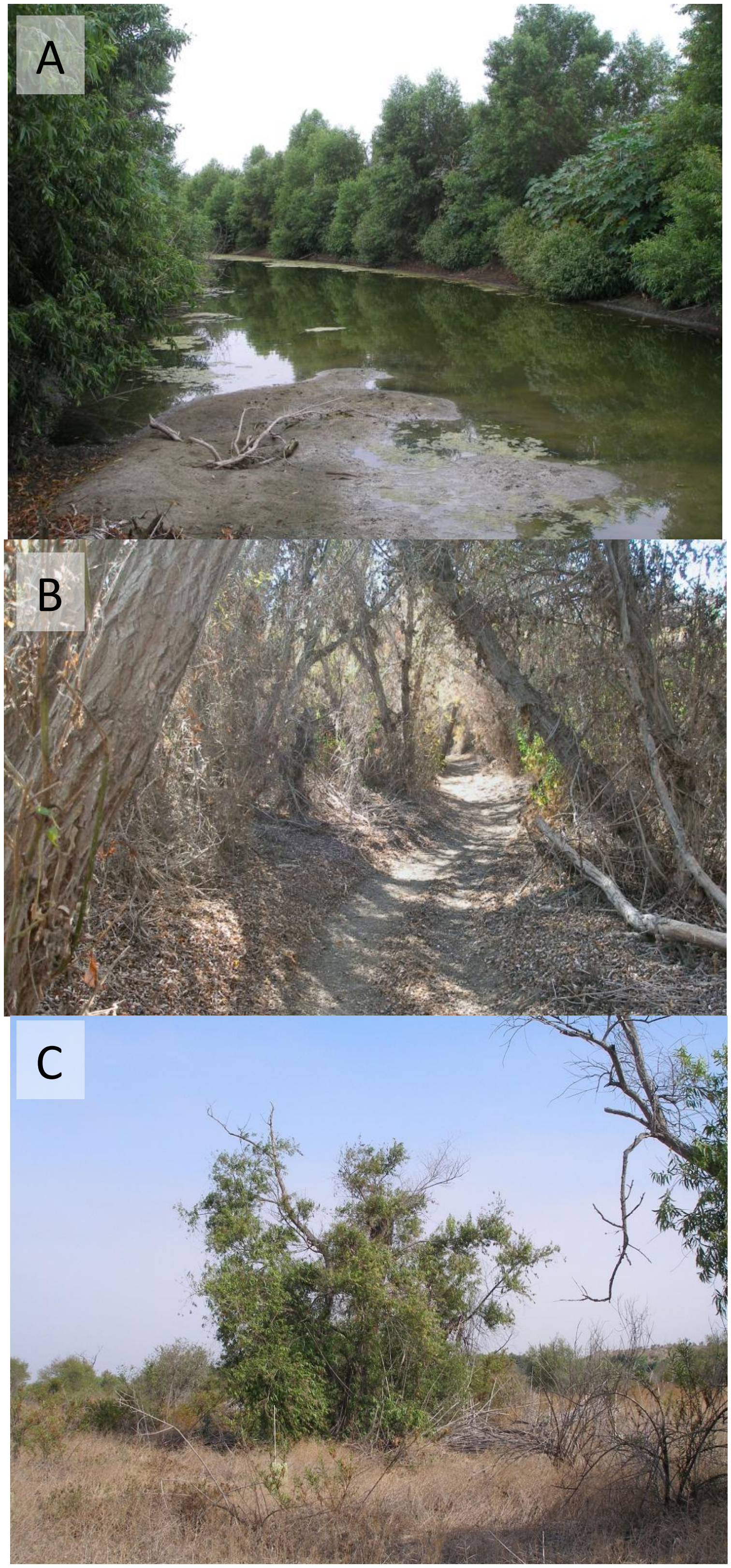


Figure 3. Typical views of the riparian forest habitats in the Tijuana River Valley. ***A****: Wet Forest showing the proximity of the willow trees to water;* ***B****: Dry Forest showing a typical dry trail; and* ***C****: Riparian Scrub showing a few scattered black willows surrounded by mule fat.*

3.3. THE KUROSHIO SHOT HOLE BORER

The KSHB (*Euwallacea kuroshio*) is one of two ambrosia beetles currently attacking live trees in southern California. The other is the Polyphagous Shot Hole Borer (PSHB; *E. whitfordiodendrus*; Gomez et al. 2018). The two species are morphologically identical and are distinguished by their DNA sequences and by their associated fungi (Eskalen 2019). The PSHB was first documented in Los Angeles County in 2003, and the KSHB was first observed in San Diego County in 2012 (Eskalen et al. 2013; Eskalen 2019; Umeda et al. 2016). Both beetles attack many tree species in southern California, including native species, landscape trees, and the economically important avocado (*Persea americana*; Freeman et al. 2013; Eskalen et al. 2013). The ever-increasing list of reproductive host plants used by these two species currently stands at 65 host species (UCR 2020). The authorities have sometimes referred to the two species together as the Invasive Shot Hole Borers (ISHB).

When shot hole borers attack a tree, the females drill into the trunk or branch and create galleries of tunnels in the xylem by pushing sawdust 'tailings' out of the entrance hole (Figure 4). They inoculate the tunnel walls with a fungus (e.g., *Fusarium* sp.), and live in the tunnels eating the fungus and reproducing (Eskalen 2009). Within a few weeks new females emerge, and start another gallery in either the natal tree or a new tree (Rudinsky 1962). The beetles are tiny (~2 mm in length) and seldom seen, however they can damage and even kill trees via their tunneling activities, which undermine the structure of the tree trunks (Boland 2016). This occurred in many Wet Forest sites within the Tijuana River Valley in winter 2015-16, when many heavily-infested willow trunks snapped and their dense canopies fell to the ground (Figure 4). One of these snapped trees, a 13 m tall black willow, had an estimated 26,900 KSHB holes along its trunk and had been severely undermined by KSHB tunnels (Boland 2017).

When surveying a forest for KSHB, trees that are actively-infested with KSHB are identified by the distinctive sawdust tailings being extruded from tiny KSHB holes, which have the diameter of the ball of a ball-point pen (Figure 4).

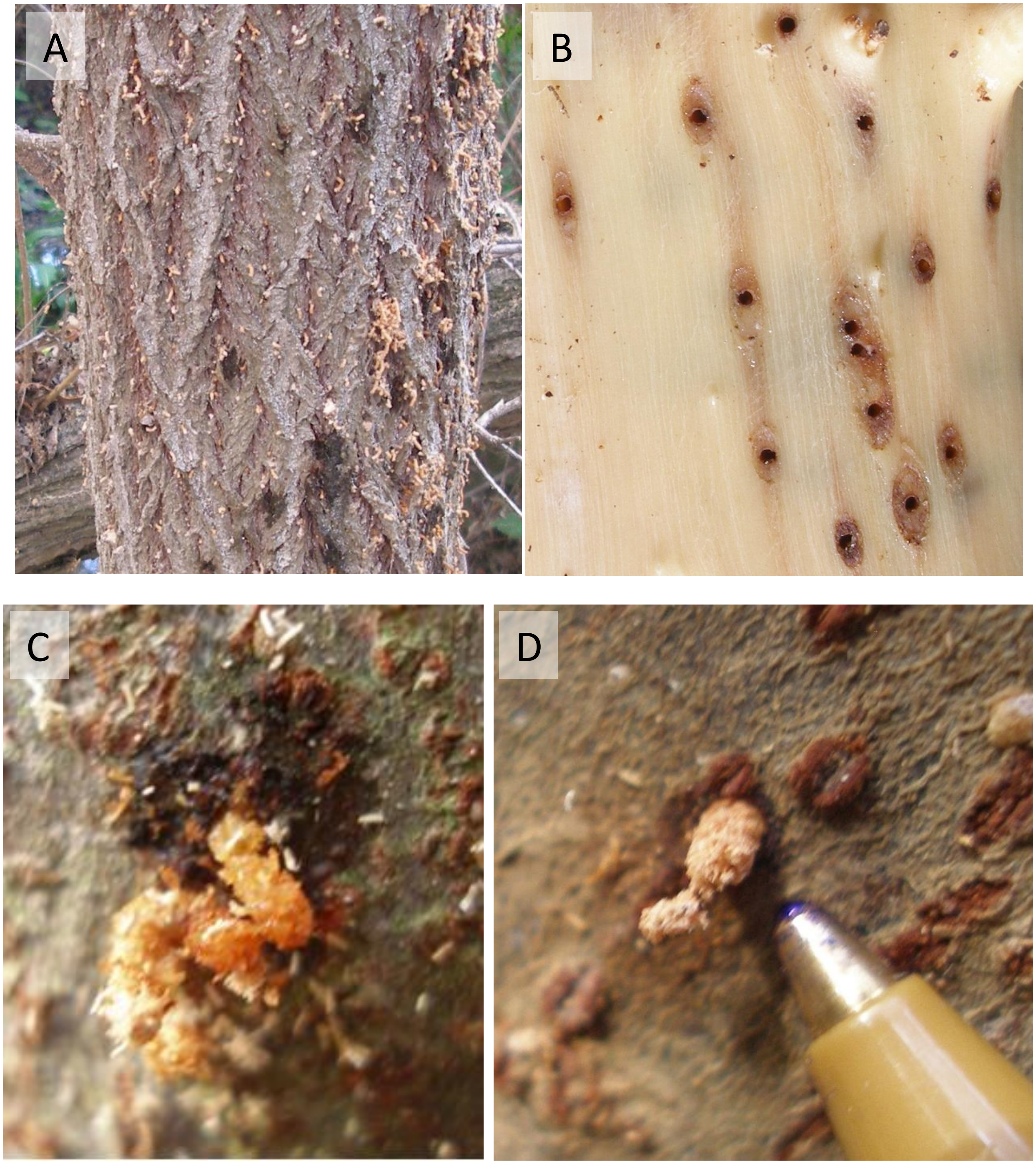


Figure 4. KSHB as seen on willows. ***A****: A heavily-infested black willow trunk showing sawdust tailings coming out of the many KSHB entrance holes in the bark.* ***B****: A heavily-infested black willow trunk with its bark removed showing the KSHB holes within the xylem.* ***C****: A lightly-infested arroyo willow with moist sawdust coming out of a KSHB hole.* ***D****: A lightly-infested arroyo willow with dry sawdust coming out of a KSHB hole. A ball-point pen is used for scale. The mouth-like structure in the bark next to the KSHB hole is a lenticel.*

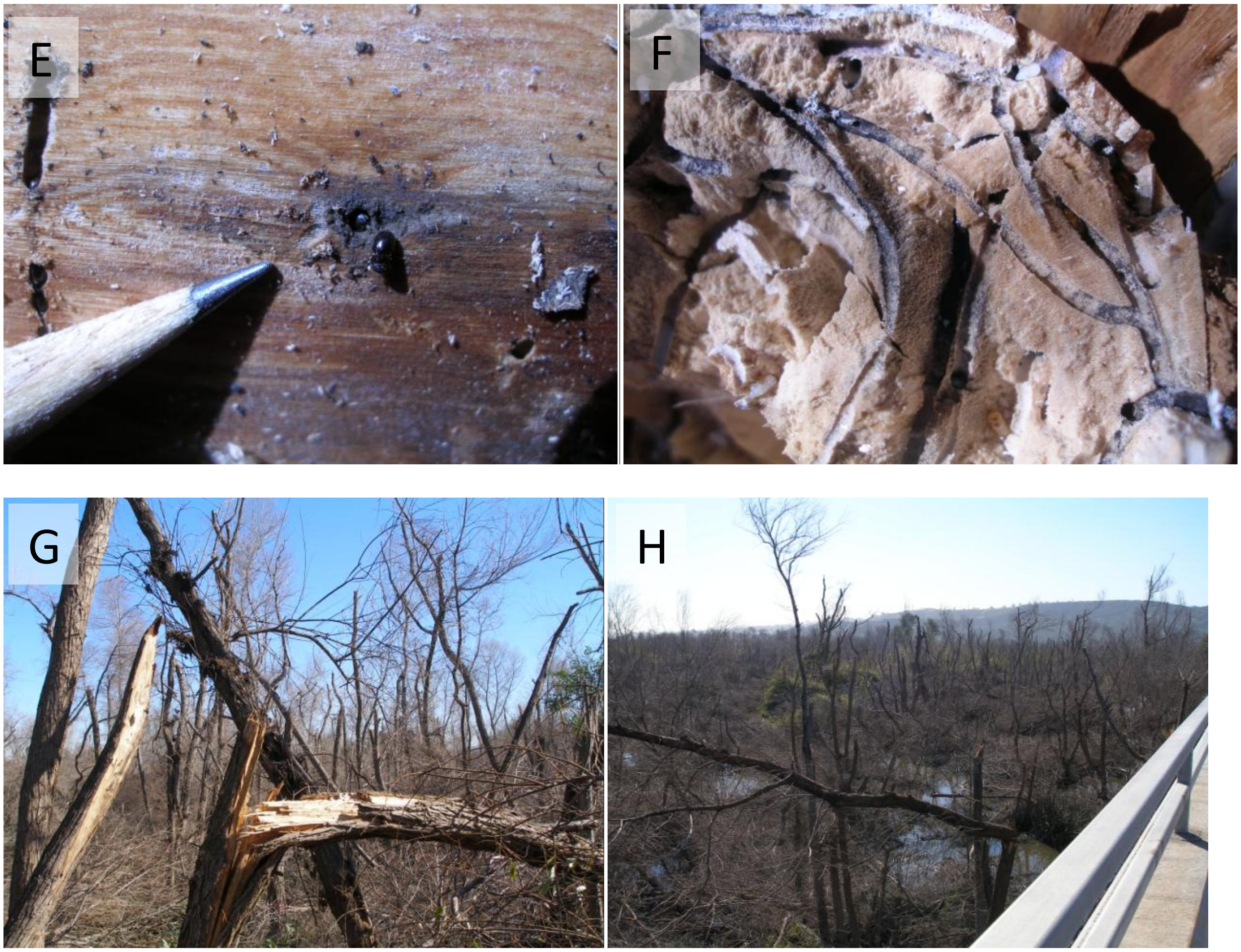


Figure 4 (continued). ***E****: Two KSHB at the entrance to a tunnel (bark removed).* ***F****: KSHB tunnels and associated fungus (black staining) in a cross section through a black willow trunk. Extensive tunneling has undermined the trunk, which snapped at this point.* ***G and H****: Two views of the KSHB-infested and heavily-damaged Wet Forest at Hollister Ave. in February 2016. Notice that the trunks of the willow trees have been recently snapped by wind and the canopy is now laying on the ground.*

4. KSHB IMPACTS IN THE TIJUANA RIVER VALLEY

We report the impact of the KSHB in the valley by describing the following:

- Infestation rates of the willows in all units;
- Canopy damage caused by the KSHB using GIS technology;
- Mortality rates of the willows in all units; and
- Survivorship of tagged willows.

4.1. KSHB INFESTATION RATES OF WILLOWS (2015-19)

The willows SAGO and SALA are the preferred hosts of the KSHB in the Tijuana River Valley (Boland 2016) and, as these willows are also the dominant trees in the forests in the valley, the KSHB has caused considerable damage in the valley in the past few years (Boland 2016, 2017b, 2018, 2019). Here I address the question:

- **What is the current extent of the KSHB infestation in the valley?**

Methods

In 2015, the Tijuana River Valley forests were divided into survey units so that each unit was homogenous in terms of tree age and tree density (Boland 2016). A sample taken inside a unit could then be extrapolated to the entire unit. There was a total of 29 units, consisting of 22 forest units dominated by willows, and seven scrub units dominated by mule fat (Figure 1). The annual surveys have continued to use these units (Boland 2017b, 2018, 2019). The units were grouped into three general categories – the Wet Forests, the Dry Forests and the Scrub Woodlands (Figures 3 and 4) and their locations are shown in Figure 5. The Wet Forests are always inundated by polluted flows each year, whereas the Dry Forests are rarely inundated by those flows, and the Scrub Woodlands are seldom, if ever, inundated (Figure 6). The two willow species occur as dense stands in the Wet and Dry Forests, and as outliers in the riparian Scrub Woodland (Figures 2 and 3).

To determine the KSHB infestation rates in 2019, I conducted the same type of surveys as in previous years, using the same survey units and survey points (Figure 1; Boland 2016, 2017b, 2018, 2019). In each unit, I started at the survey point, examined as many live SAGO and SALA trees as I could in two hours and classified each tree as either ‘currently infested’ or ‘not currently infested’. A tree was counted as ‘currently infested’ if it showed evidence of active tunneling by the KSHB, i.e., extrusion of sawdust from KSHB holes (Figure 4), or as ‘not currently infested’ if it had no evidence of KSHB attack or had only old, non-active KSHB holes. Surveys were conducted September-November 2019 and a total of 1,807 willows were examined. Within the Wet Forest units I further categorized each tree encountered as either a seedling (<3 years old), young tree (3-5 years old), Big Tree (relatively undamaged adult tree >5 years old), or resprouting adult tree (damaged adult tree >5 years old). The results for all of the annual surveys (2015-2019) are presented and the highest annual rate (the maximum) is used to estimate the total number of willows infested by the KSHB in each unit.

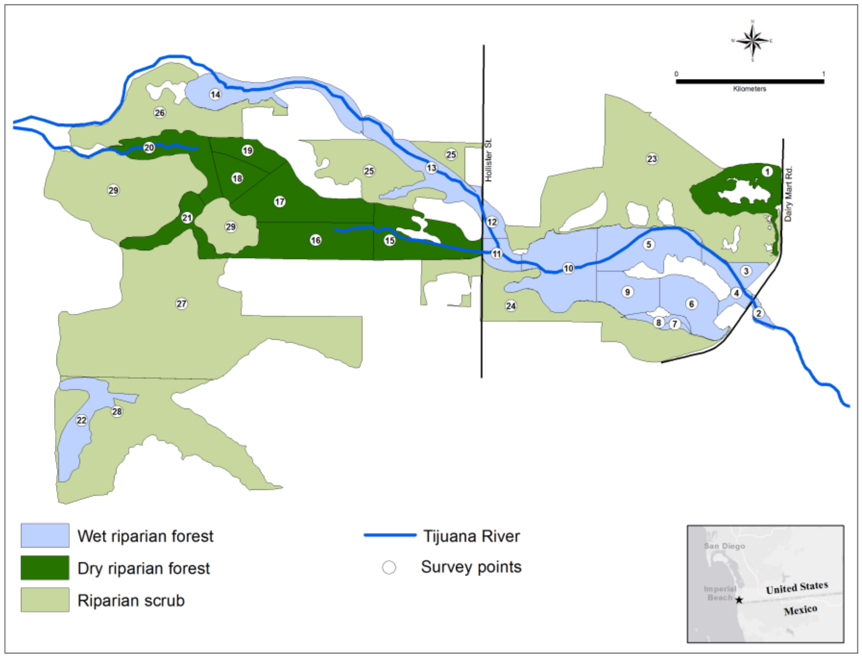


Figure 5. The identification of the three main riparian habitats in the Tijuana River Valley – Wet Forest, Dry Forest and Scrub Woodland. [Map created by John Boland and Monica Almeida, February 2019.]

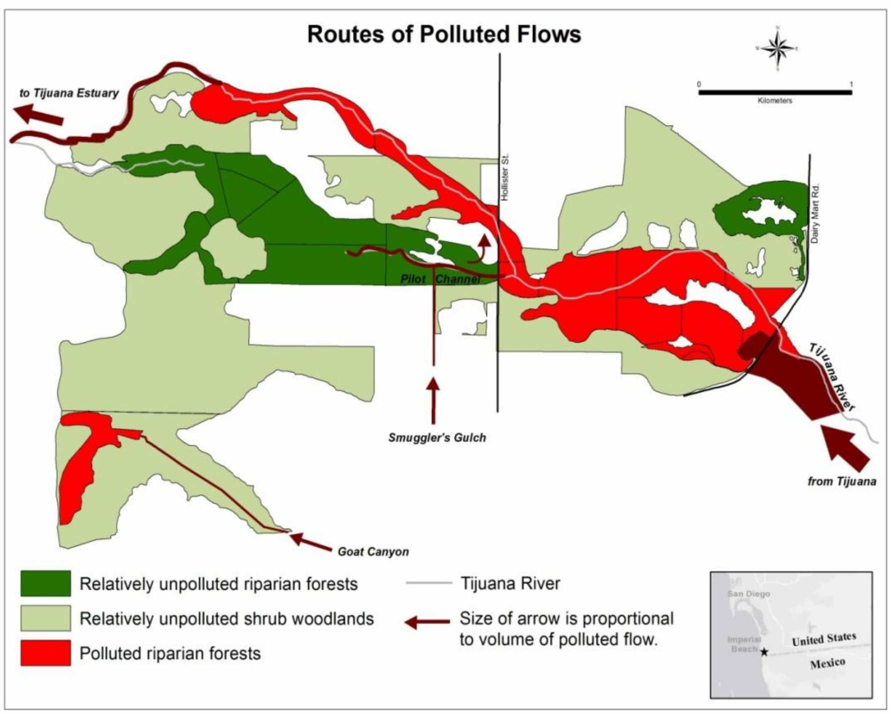


Figure 6. The main routes (shown in red) taken by the polluted flows through the Tijuana River Valley.The sizes of the arrows are proportional to the volume of polluted flows. [Map created by John Boland and Monica Almeida, February 2018.]

Results

Infestation overview 2015 – 2019

Willow infestation rates for the years 2015-2019 show several interesting features:

- Infestation rates peaked in 2015 and 2016, and have been declining ever since (Table 1). In 2015 and 2016 the overall infestation rates were 75% and 80% respectively, whereas in 2019 the overall infestation rate was only 9%.
- Of all the willows in the valley an estimated total of 375,558 willows, or 91%, have been infested by the KSHB (Table 2).
- Maximum infestation rates over the five years differed among forest types; they averaged 99% in the Wet Forest units, 82% in the Dry Forests and 3% in the Scrub Woodlands (Table 2).
- Trajectories of the KSHB infestations differed among forest types (Figure 7). Wet Forest infestation rates peaked early then declined considerably in the subsequent years. Dry Forest infestation rates were mixed some peaked early then declined while others were more sustained. Scrub Forest remained low. These results show that there is no typical infestation trajectory.

Infestation rates within different willow trees by types and sizes

Within the Wet Forests, the 2019 infestation rates differed among tree types and sizes (Table 3A):

- Seedlings (<3 years old) had a mean infestation rate of 0%;
- Young trees (3-5 years old) had a mean infestation rate of 0%; only 3 of the 220 young trees examined were infested;
- Big Trees (relatively undamaged adult trees >5 years old) had a mean infestation rate of 3%; and
- Resprouting adult trees (damaged adult trees >5 years old) had a mean infestation rate of 1%; only 6 of the 358 resprouting trees examined were infested.

Infestation rates within different forest types

During 2019, the infestation rates of the willows differed among the various forest types (Table 3):

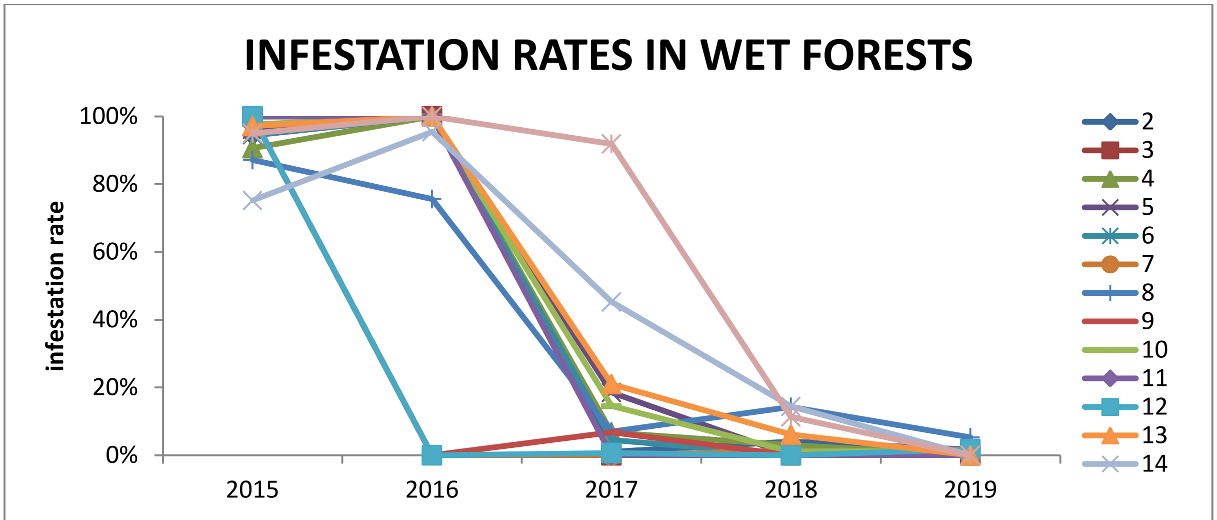
- In Wet Forests, 1% of the willows were infested;
- In Dry Forests, 29% of the willows were infested; and
- In Scrub Forests, 0% of the willows were infested.

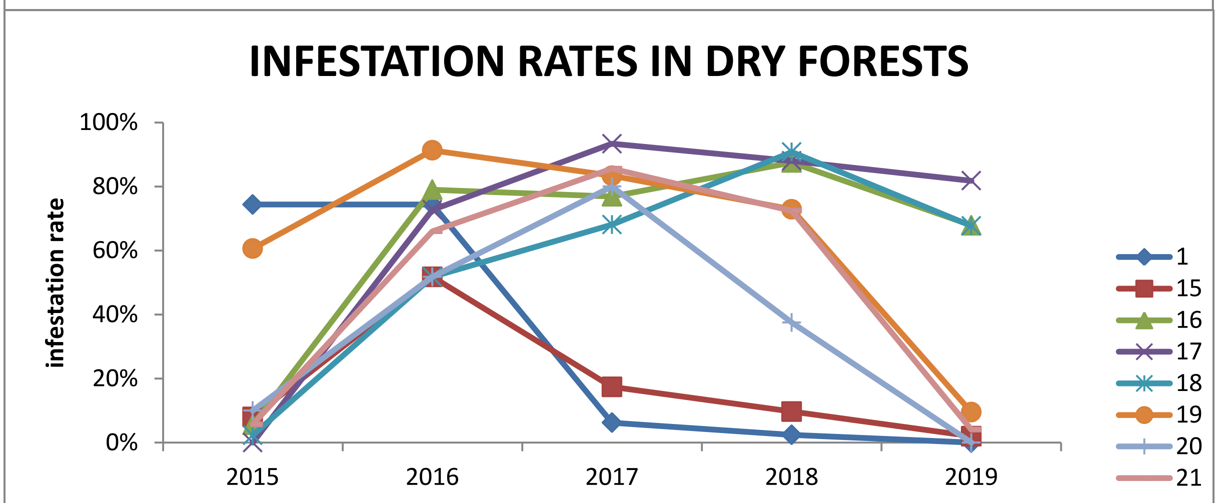
Table 1. Overall willow infestation rates in the Tijuana River Valley during the past five years.

year	# infested	TOTAL	% infested	source
2015	973	1,306	75%	Boland 2016
2016	466	584	80%	Boland 2017
2017	631	1,464	43%	Boland 2018
2018	284	1,901	15%	Boland 2019
2019	160	1,807	9%	this report

*Table 2. Willow infestation rates in the Tijuana River Valley survey units during the five survey years. * = no adult trees available, called 0% infestation; ** = no data collected during survey period, infestation rate estimated later; and nd = no data.*

SITES			INFESTATION RATES						
UNIT	AREA	WILLOWS	2015	2016	2017	2018	2019	MAX	
#	acres	est #	%	%	%	%	%	%	TOTAL #
A. Wet riparian forests									
2	4.4	16,026	94%	100%	1%	4%	2%	100%	16,026
3	7.5	5,517	100%	100%	0%	0%	0%	100%	5,517
4	12.7	1,282	91%	100%	7%	3%	0%	100%	1,282
5	44.7	13,561	96%	100%	19%	0%	0%	100%	13,561
6	30.3	9,194	95%	100%	5%	0%	0%	100%	9,194
7	2.0	4,407	100%	0%*	0%	1%	0%	100%	4,407
8	5.2	37,953	87%	76%	7%	14%	5%	87%	33,063
9	25.2	10,211	100%	0%*	7%	0%	2%	100%	10,211
10	56.9	17,280	98%	100%	15%	1%	1%	100%	17,280
11	11.6	9,365	100%	100%	0%	0%	0%	100%	9,365
12	7.8	9,421	100%	0%*	1%	0%	2%	100%	9,421
13	37.1	37,526	97%	100%	21%	6%	0%	100%	37,526
14	44.1	84,717	75%	95%	45%	14%	0%	95%	80,866
22	31.7	48,124	95%	100%	92%	11%	0%	100%	48,124
mean			**95%**	**77%**	**16%**	**4%**	**1%**	**99%**	
total	**321.1**	**304,583**							**295,843**
B. Dry riparian forests									
1	36.2	7,319	74%	74%	6%	2%	0%	74%	5,442
15	45.8	16,204	8%	52%	17%	10%	2%	52%	8,386
16	51.3	25,936	6%	79%	77%	88%	68%	88%	22,694
17	52.9	16,069	0%	73%	93%	88%**	82%	93%	14,997
18	17.5	7,062	2%	52%**	68%	91%	68%	91%	6,410
19	16.9	8,524	61%	91%	83%	73%	10%	91%	7,783
20	31.8	9,643	10%	52%**	80%	38%	0%	80%	7,714
21	23.6	7,172	6%	66%	86%	72%	4%	86%	6,134
mean			**21%**	**67%**	**64%**	**58%**	**29%**	**82%**	
total	**275.8**	**97,929**							**79,562**
C. Riparian shrub									
23	189.3	6,184	nd	nd	0%	0%	0%	0%	0
24	94.0	1,436	nd	nd	0%	9%	0%	9%	131
25	97.9	253	nd	nd	0%	0%	0%	0%	0
26	78.3	70	nd	nd	10%	0%	0%	10%	7
27	262.7	1,360	nd	nd	0%	0%	0%	0%	0
28	169.6	384	nd	nd	0%	4%	0%	4%	16
29	142.9	850	nd	nd	0%**	0%**	0%	0%	0
mean			**nd**	**nd**	**1%**	**2%**	**0%**	**3%**	
total	**1,034.8**	**10,537**							**154**
Grand	**1,631.7**	**413,050**							**375,558**
% total infested									**91%**





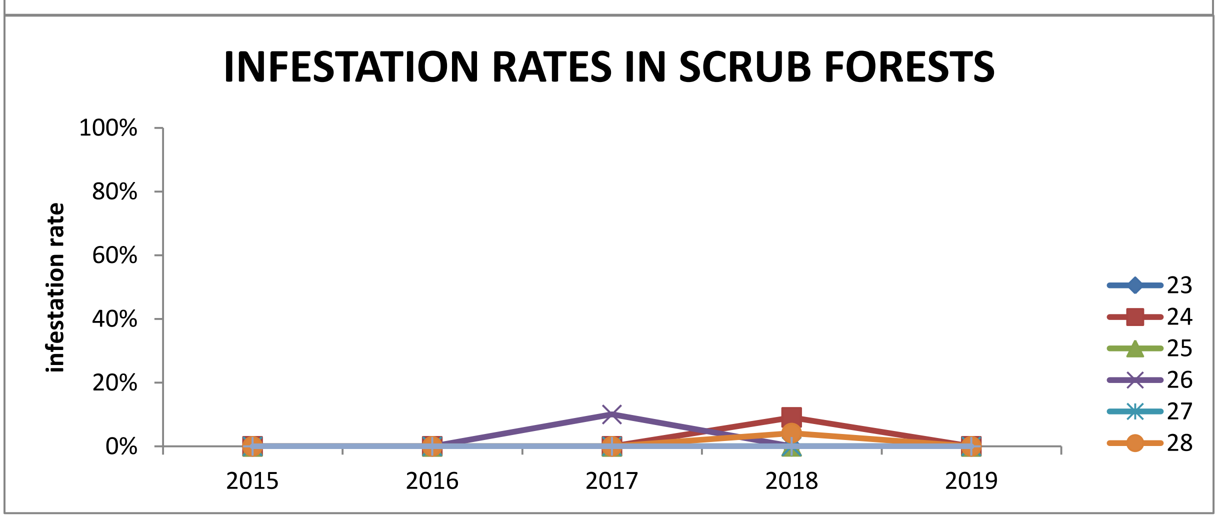


Figure 7. Infestation rates of willows within the Tijuana River Valley riparian survey units from 2015 to 2018. This is a graphic representation of the unit data in Table 2.

*Table 3. Willow infestation rates in: **A**: the Wet Forest; **B**: Dry Forest; and **C**: Scrub units during 2019.*

A. INFESTATION RATES IN WET UNITS															
UNIT	SEEDLINGS			YOUNG TREES			BIG TREES			RESPROUT. TREES			TOTAL		
	#INF	TOTAL	% INF	#INF	TOTAL	% INF	#INF	TOTAL	% INF	#INF	TOTAL	% INF	#INF	TOTAL	% INF
2	0	124	0%				3	131	2%	2	47	4%	5	302	2%
3	0	57	0%	0	60	0%				0	8	0%	0	125	0%
4	0	15	0%	0	2	0%	0	4	0%	0	36	0%	0	57	0%
5							0	3	0%	0	29	0%	0	32	0%
6							0	6	0%	0	19	0%	0	25	0%
7										0	11	0%	0	11	0%
8	0	4	0%	0	6	0%	3	15	20%	0	32	0%	3	57	5%
9										1	49	2%	1	49	2%
10	0	12	0%	0	8	0%	0	1	0%	1	56	2%	1	77	1%
11	0	27	0%	0	16	0%				0	54	0%	0	97	0%
12	0	31	0%	3	128	2%				0	7	0%	3	166	2%
13	0	4	0%				0	20	0%	0	10	0%	0	34	0%
14							0	5	0%	1	80	1%		85	0%
22							1	24	4%	1	39	3%		63	0%
Total	0	274		3	220		6	180		6	358		15	1032	
mean			0%			0%			3%			1%			1%

B. INFESTATION RATES IN DRY UNITS			
UNIT	BIG TREES		
	# INF.	TOTAL	% INF.
1	0	38	0%
15	2	101	2%
16	38	56	68%
17	54	66	82%
18	44	65	68%
19	4	42	10%
20	0	49	0%
21	3	74	4%
Total	145	491	
mean			29%

C. INFESTATION RATES IN SCRUB UNITS			
UNIT	BIG TREES		
	# INF.	TOTAL	% INF.
23	0	26	0%
24	0	42	0%
25	0	38	0%
26	0	25	0%
27	0	47	0%
28	0	76	0%
29	0	30	0%
Total	0	284	
mean			0%

Discussion
The KSHB population in the Tijuana River Valley, as indicated by the percent of willow trees infested with KSHB, grew quickly in 2015 and 2016 and has been declining steadily ever since. At one time 80% of the surveyed willows were infested and now only 9% are infested. It appears that the KSHB population has gone through a rapid boom-and-bust cycle. Outbreaks of other ambrosia beetles have sometimes also declined unexpectedly; Browne (1961) said of outbreaks of the tea shot-hole borer *Euwallacea fornicates* (Eichhoff, 1868) in Java that they "*often come to a sudden end for unknown reasons*."

Over the past five years an estimated 375,558 of the willows in the valley have been infested by the KSHB, this is 91% of the willows in the valley. Most of the willows in the Wet and Dry Forests have been infested, whereas the scattered willows in the Scrub Forests remain largely uninfested.

The spread of the KSHB infestation in the valley has been interesting. The infestation started in the Wet Forest units in 2015, and later, in 2016 and 2017, moved into the Dry Forests. So far the KSHB has not substantially infested the willows in the Scrub Forests, which are growing in marginal willow habitat that could be called "Very Dry Forests."

Superimposed on this forest type pattern was the KSHB's preference for young trees with a trunk diameter at breast height of > 4.5 cm (Section 9.1 in Boland 2017b); trees with smaller trunk sizes (seedlings) were generally avoided by the KSHB, and trees with very large diameter trunks (> 30 cm, i.e., Big Trees) appear to be able to survive a KSHB attack. Therefore, intermediate-sized willow trees have been most susceptible to the KSHB.

Within the different riparian habitats in the Tijuana River Valley, infestation rates have proceeded along very different trajectories (Figure 7). In the Wet Forests, the KSHB infestation progressed rapidly over the course of only a few months from barely noticeable to heavy infestation and dramatic canopy collapse, i.e., the infestation had a steep trajectory. In the drier forests, the KSHB infestation progressed more slowly over several years and the canopy remained mostly intact, i.e., the infestation displayed a shallow trajectory. In the very dry Scrub Forests, infestation remained extremely low, i.e., the infestation had a very shallow trajectory.

This result means that the old idea that *all trajectories are similar from site to site* is incorrect; one cannot presume that an infestation will progress from mild to serious in all sites. Likewise, the idea that *a light infestation must be a recent infestation while a heavy infestation must be an old infestation* is incorrect; the degree of infestation is not necessarily tied to age of infestation.

4.2. PROGRESSION OF FOREST DAMAGE USING GIS TECHNOLOGY (2014-19; Uyeda)

The goal of this analysis was to estimate annual canopy loss caused by the KSHB in order to determine where and when the KSHB had the greatest impact. To do this I used a satellite-based index of vegetation health from the years 2015 to 2019.

Methods

Monitoring forest canopy loss due to insect outbreaks using satellite imagery has been fairly common for the past several decades (Iverson et al. 1989). In recent years, the availability of higher resolution satellite imagery such as RapidEye has allowed for these patterns of forest loss to be monitored at finer spatial scales (Marx and Kleinschmit 2017).

I downloaded 5 m spatial resolution imagery from the RapidEye constellation of satellites from Planet (Planet Team 2017). This imagery includes five spectral bands: blue, green, red, red edge, and near-infrared. The level 3B product was used, which is already radiometric, sensor and geometrically corrected. Cloud free dates were selected from the spring (ranging from April 28th - June 17th) of each year from 2014 - 2019. I calculated Top of Atmosphere reflectance using the Apparent Reflectance tool in ArcGIS Pro.

The normalized difference vegetation index (NDVI) was calculated for each image. NDVI is calculated as the difference of near-infrared and red reflectance divided by the sum of those values (Rouse et al. 1973). NDVI ranges from -1 to 1, with higher values corresponding to areas of healthy green vegetation, values close to 0 lack green vegetation, while values close to -1 are typically areas of water. NDVI loss was calculated by subtracting current year NDVI from previous year NDVI. For example, the loss reported in 2015 was the difference between the 2014 and 2015 NDVI values. By comparing NDVI patterns to field observations of canopy loss, I have determined that the loss of about 0.15 indicates that the green canopy has been replaced by a brown ground, i.e., the canopy has been heavily damaged.

In order to focus on the riparian forests in the valley, I show the results only for areas with a canopy height of at least 6 m in 2014. Canopy height was calculated using the light detection and ranging (lidar) dataset collected by the U.S. Geological Survey in December 2014.

Annual riparian forest loss in hectares was calculated as the cumulative area of NDVI loss of at least 0.1 in each year from 2015 - 2019.

Extensive ground surveys during the past five years allow me to interpret all canopy losses in the Wet and Dry Forests as due to the KSHB, and most of the canopy losses in the forested parts of the Scrub Woodlands as due to drought.

Results

- The NDVI losses show the progression of the KSHB-induced damage in the valley (Figure 8). High NDVI losses (red areas) were first observed in the eastern portion of the river valley in 2015. Then, in 2016, the high NDVI losses occurred particularly around Hollister Street and in the large triangular area near Dairy Mart (Unit 3). The high NDVI losses then progressed westward during 2017 and 2018. In 2019 the losses were more scattered in many forests.
- Negative NDVI losses (blue areas) show the areas where the forests have been regrowing (Figure 8); these areas of regrowth were particularly widespread during 2018 and 2019.
- The total NDVI losses for all years show that all forests in the valley have been damaged by the KSHB invasion to some extent and many areas were severely damaged (Figure 9).
- The total acreage of KSHB-damaged canopy peaked during 2016-17 at 38 hectares, or 94 acres (Figure 10). The damage has declined substantially since then.

Discussion

The use of satellite-based NDVI difference images provides an efficient method of tracking the spread of KSHB and documenting the total area infested. The KSHB caused dramatic vegetation loss in the Tijuana River Valley that was easily captured in the satellite imagery.

These analyses support the results seen in the other sections of this report. First, in the early years of the KSHB infestation, the most dramatic vegetation losses were observed in the Wet Forests and in later years the vegetation losses were observed in the Dry Forests, with lower levels of vegetation loss. Second, the KSHB's impact was **greatest in 2016-17** and since then it has been tapering off. It appears that the KSHB has gone through a rapid **boom-and-bust outbreak** in the valley.

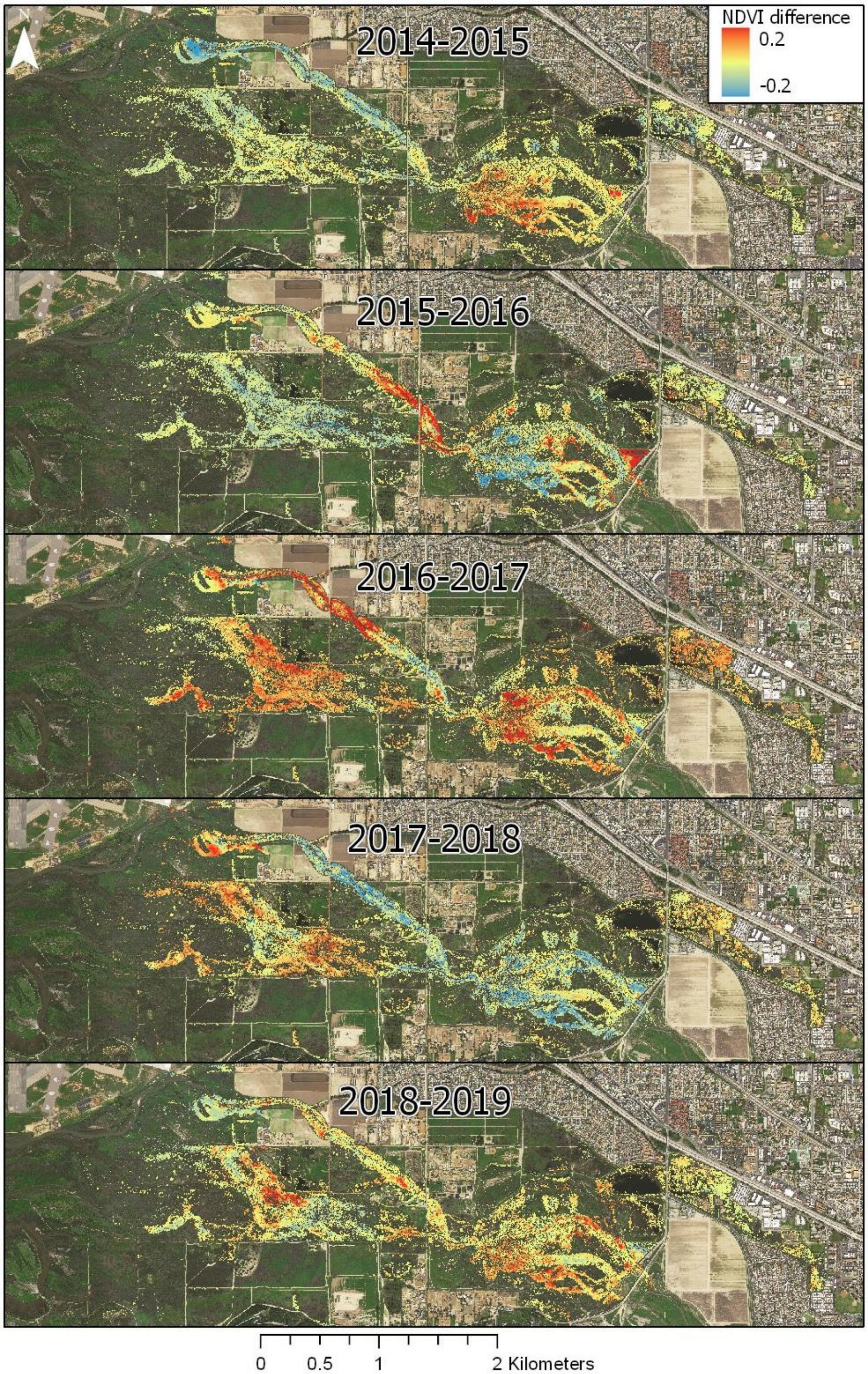


Figure 8. Canopy damage caused by the KSHB. NDVI difference image showing current year spring NDVI subtracted from previous year spring NDVI. Only areas with a canopy height of 6 m or greater in 2014 are shown. [Maps created by Kellie Uyeda, January 2020.].

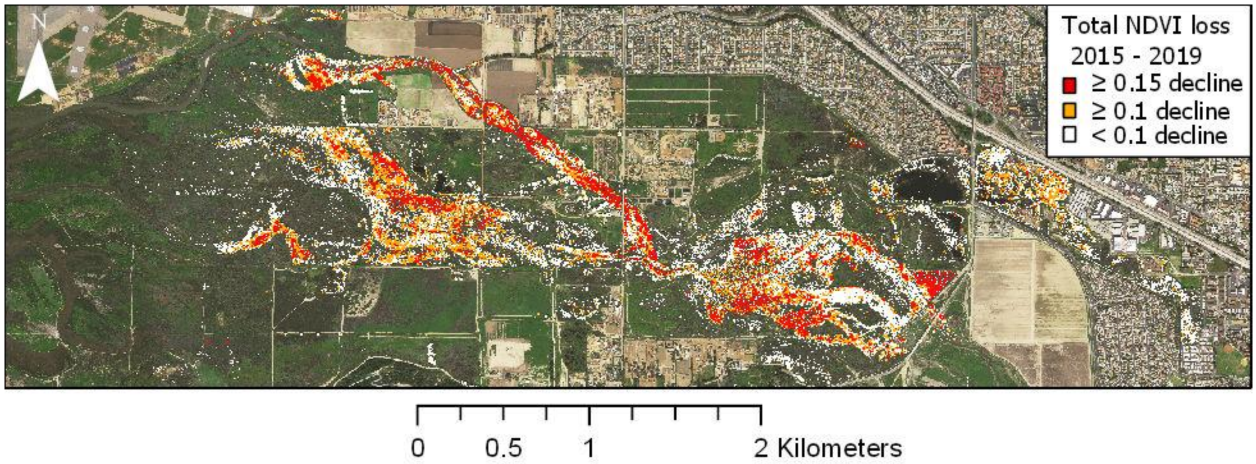


Figure 9. Cumulative NDVI loss observed in riparian forests (canopy height of at least 6 m in 2014) from 2015 - 2019. [Map created by Kellie Uyeda, January 2020.]

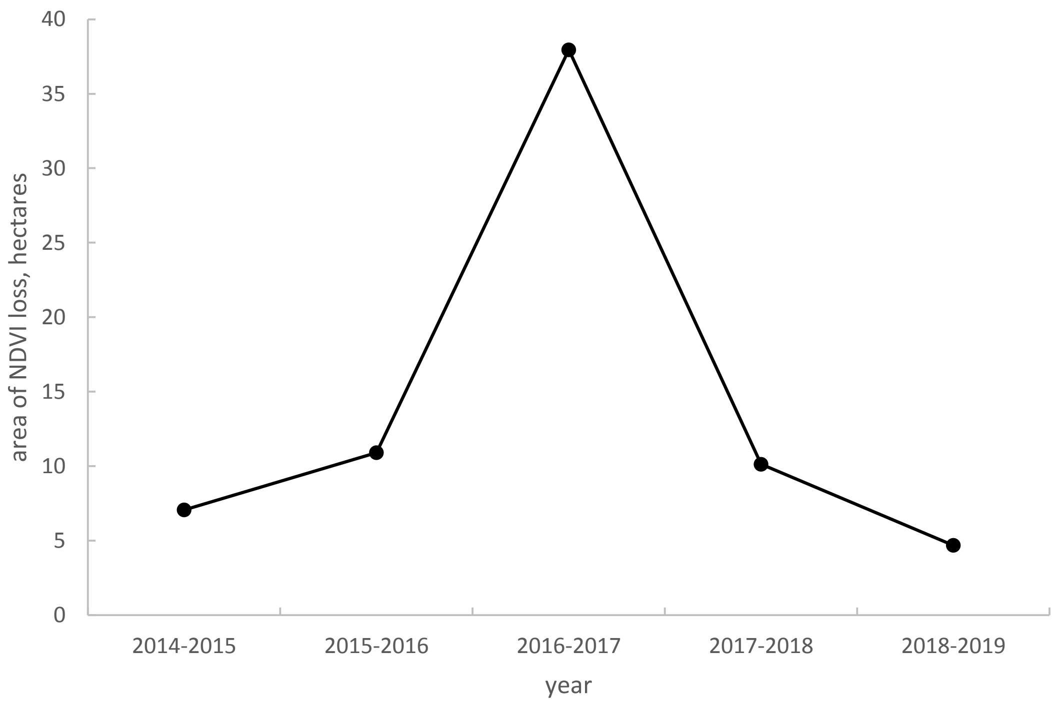


Figure 10. Annual canopy loss caused by the KSHB, i.e., *area of annual NDVI loss of at least 0.1 within riparian forests.*

4.3. KSHB-INDUCED MORTALITY RATES OF WILLOWS (2015-18)

It is important to distinguish between infestation and mortality because not every infested tree dies (Boland 2018). Here I address the question:

- **How many trees have been killed by KSHB infestation?**

It was relatively easy to determine mortality rates in the years immediately following the KSHB invasion in 2015 – all or part of each KSHB-killed tree was still standing and could be counted. But now those dead trees have fallen and been swept away by river flows and so, in 2019, it was impossible to count KSHB-killed trees. However, for completeness, I include here mortality rates estimated in 2018 as first reported in Boland (2019).

Methods

One way to determine mortality rates within a survey unit is to inspect each tree at a survey point and count the number living or recently dead; this is the method used in 2016 and 2017 (Boland 2017b, 2018). In 2018 I did this kind of survey in the Dry Forest and Scrub units; in these units, as many willows as could be in two hours and classified each as either 'alive', 'recently dead from KSHB attack', or 'dead from some other cause'. An average of 45 ± 27.3 trees (n = 13 units) was surveyed in each of these units. From these data, the mortality rate and the estimated total number of trees killed were then calculated. This kind of survey could not be done in most of the Wet Forest units in 2018 because most of the recently dead trees had been swept away by river flows during the winters of 2016-17 and 2017-18; for Wet Forest units, therefore, my earlier surveys are used as the best mortality estimates (Boland 2017b, 2018), as each survey is an estimate of mortality since the KSHB invasion in 2015. When two or more surveys were conducted in a unit, the highest (maximum) rate is used to estimate the total number of willows killed by the KSHB in that unit.

Results

- Mortality rates were highest in 2016 and have declined since then (Table 4).
- An estimated total of 122,987 willows, or 30%, have been killed by the KSHB.
- Mortality rates within units were positively and significantly correlated with infestation rates within units ($n = 29$; $r = 0.756$; $p < 0.01$); the correlation was curvilinear – sites with maximum infestation rates of 0% to 75% had low mortality rates (<10%), whereas sites with maximum infestation rates of greater than 95% had very high mortality rates (up to 97%; Figure 11).
- Mortality rates have been considerably higher in Wet Forest units than in Dry Forest and Scrub Forest units. In Wet Forest units mean maximum mortality rate was 49%, compared with only 9% in Dry Forest and 2% in Scrub Forest units (Table 4, Figure 12). Of all of the willow deaths in the valley, 93.8% occurred in the Wet Forests, 6.1% in the Dry Forests and 0.1% in the Scrub Forests.
- The remarkable differences in mortality rates between the Wet and Dry Forest units can be seen in the photos taken in Wet Unit 3 and Dry Unit 15 (Figure 13). The KSHB was destructive in the Wet Forest and less destructive in the Dry Forest, even though the sites contain the same willow species.

Table 4. Willow mortality rates in the Tijuana River Valley survey units during the three survey years 2016 - 2018. nd = no data.

UNIT	AREA	WILLOWS	WILLOW MORTALITY RATES				
#	acres	est total #	2016	2017	2018	MAX %	MAX # trees
source	Boland 2016		Boland 2017	Boland 2018	this report	3 years	
A. Wet Rip. Forests (2 willow spp.)							
2	4.4	16,026	67%	nd	nd	67%	10,738
3	7.5	5,517	97%	nd	nd	97%	5,352
4	12.7	1,282	57%	nd	nd	57%	731
5	44.7	13,561	29%	nd	nd	29%	3,933
6	30.3	9,194	44%	nd	nd	44%	4,045
7	2.0	4,407	55%	nd	nd	55%	2,424
8	5.2	37,953	29%	nd	nd	29%	11,006
9	25.2	10,211	42%	nd	nd	42%	4,288
10	56.9	17,280	51%	nd	nd	51%	8,813
11	11.6	9,365	26%	nd	nd	26%	2,435
12	7.8	9,421	78%	nd	nd	78%	7,349
13	37.1	37,526	41%	nd	nd	41%	15,386
14	44.1	84,717	13%	22%	15%	22%	18,826
22	31.7	48,124	10%	41%	29%	41%	19,970
mean			**46%**	**32%**	**22%**	**49%**	
total	**321**	**304,583**					**115,294**
B. Dry Rip. Forests (2 willow spp.)							
1	36.2	7,319	6%	8%	1%	8%	563
15	45.8	16,204	0%	0%	0%	0%	0
16	51.3	25,936	6%	1%	0%	6%	1,556
17	52.9	16,069	0%	3%	nd	3%	434
18	17.5	7,062	0%	3%	0%	3%	228
19	16.9	8,524	15%	12%	13%	15%	1,279
20	31.8	9,643	2%	33%	11%	33%	3,214
21	23.6	7,172	0%	4%	0%	4%	272
mean			**4%**	**8%**	**4%**	**9%**	
total	**276**	**97,929**					**7,547**
C. Riparian scrub (2 willow spp.)							
23	189.3	6,184	nd	0%	0%	0%	0
24	94.0	1,436	nd	0%	9%	9%	131
25	97.9	253	nd	0%	0%	0%	0
26	78.3	70	nd	0%	0%	0%	0
27	262.7	1,360	nd	0%	0%	0%	0
28	169.6	384	nd	0%	4%	4%	16
29	142.9	850	nd	0%	nd	0%	0
mean			**nd**	**0%**	**2%**	**2%**	
total	**1,035**	**10,537**					**147**
Grand Tot.	**1,632**	**413,050**					**122,987**
% total mortality							**30%**

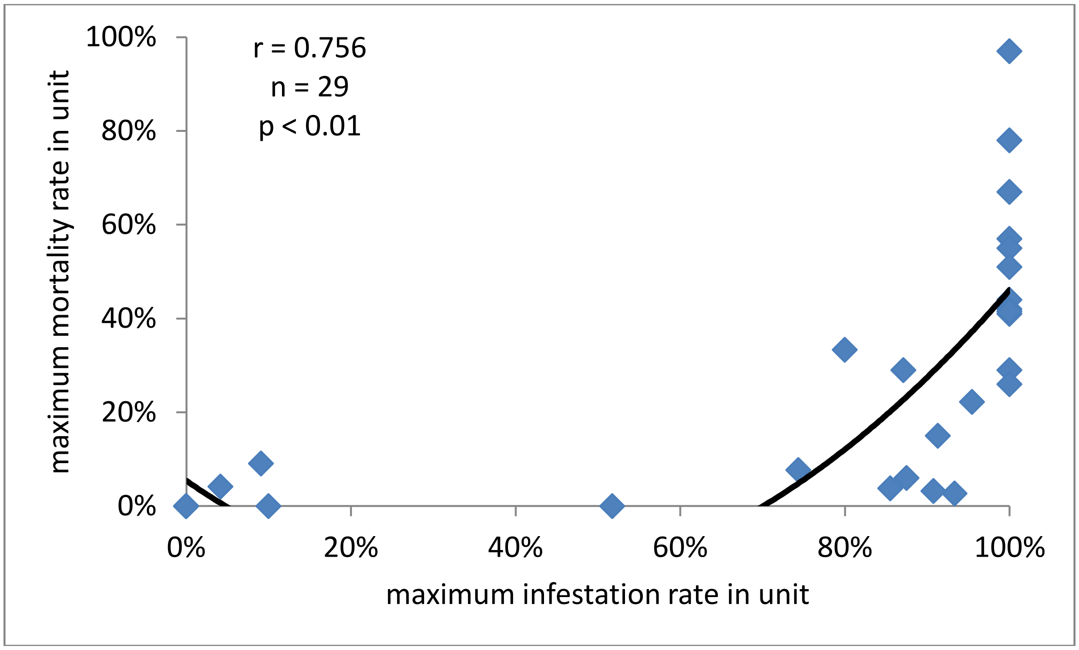


Figure 11. The relationship between maximum infestation rates and maximum mortality rates of willows in the Tijuana River Valley survey units.

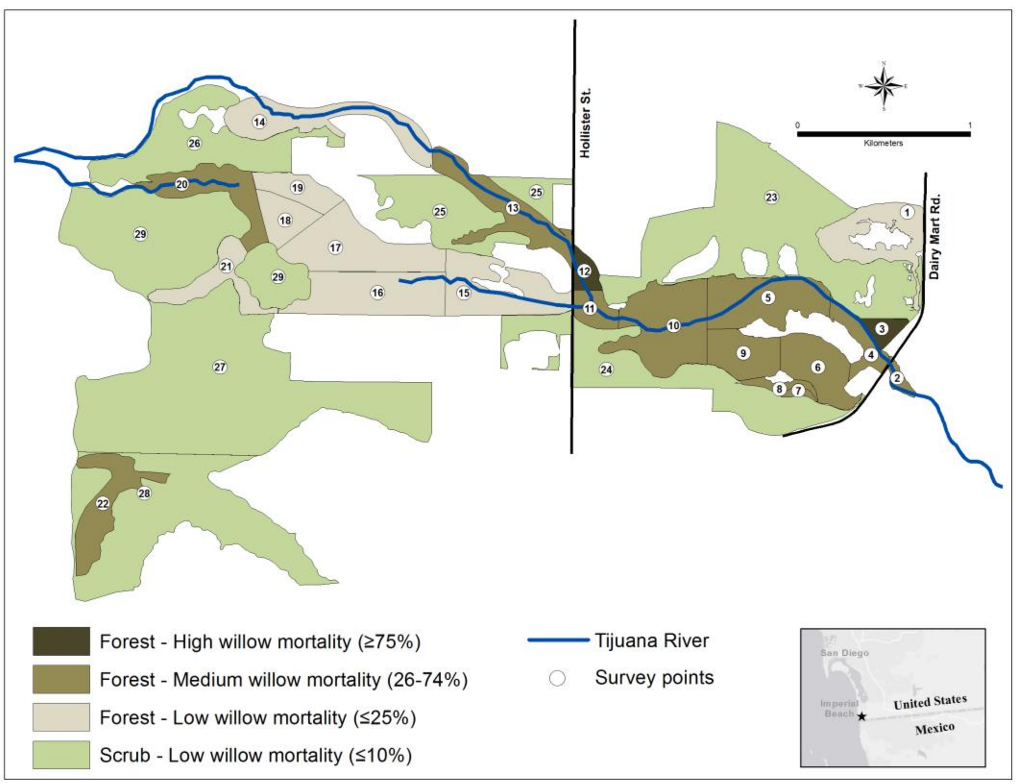


Figure 12. The distribution of willow mortality within the Tijuana River Valley. [Map created by John Boland and Monica Almeida, February 2019.]

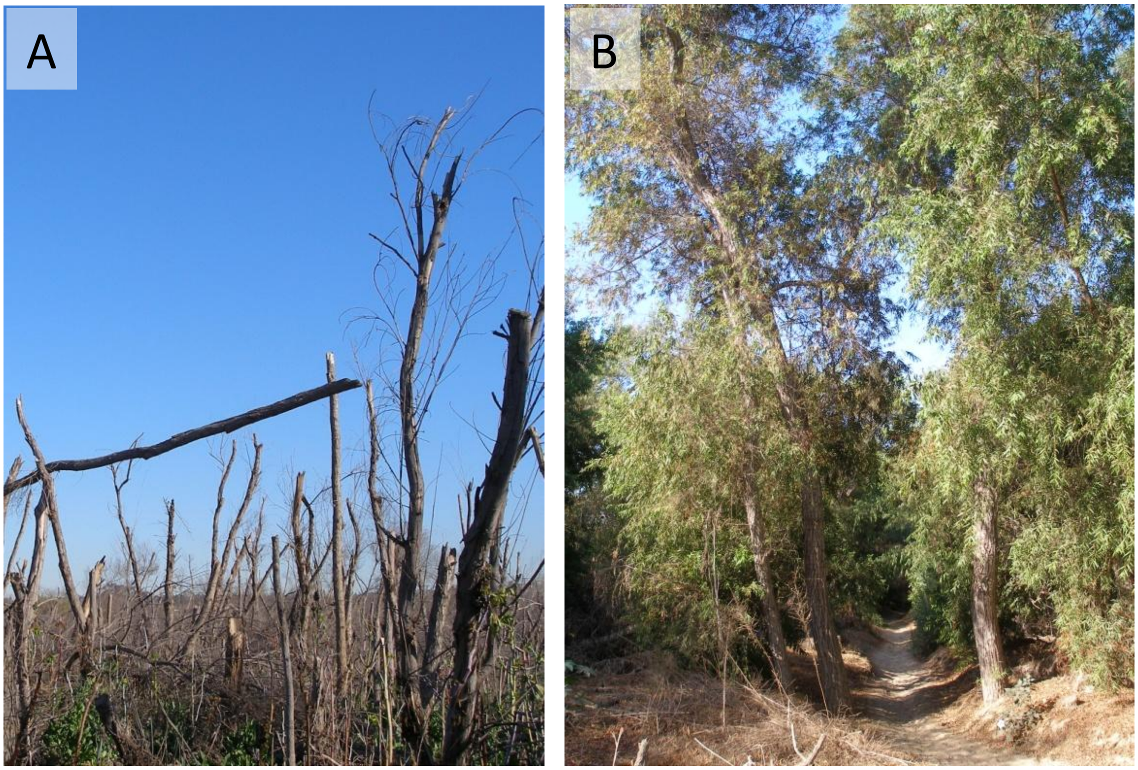


Figure 13. The large differences in KSHB impact within the valley. ***A****: Wet Forest Unit 3 where the mortality rate was highest.* ***B****: Dry Forest Unit 15 where the mortality rate was among the lowest. In both units, black willow was the most abundant tree species.*

Discussion

The total number of willows in the valley estimated to have been killed by the KSHB grew each year and in 2018 stood at 122,987 trees, or 30% of all the willows in the valley. This is the highest mortality figure for any site in southern California. Even so this number is likely to be an underestimate because in the extensively-damaged Wet Forest units, KSHB-killed trees that were snapped at ground level could not be accurately surveyed in the last year of surveys, 2018.

As expected the infestation and mortality rates were significantly correlated – a high infestation rate led to a high mortality rate. But unexpectedly, the infestation rate had to be very high (>75%) before a substantial number of deaths (>10%) were recorded.

As with the infestation rates, the mortality rates were not equal everywhere; the KSHB has mainly killed willow trees in the Wet Forests and not killed the willow trees of the same species in the drier units. This within-Tijuana River Valley pattern in KSHB impact was investigated further in Boland and Woodward (2019) and hypothesized to be due to the KSHB having a preference for fast-growing, nutrient-enriched trees. As the Wet Forests were the fastest growing, most nutrient-enriched trees in the valley they were the ones the KSHB infested first and damaged the most (see Section 4.5). Later the KSHB moved into the slower growing, less nutrient-enriched Dry Forests, and the KSHB have all but ignored the slowest growing, non-nutrient-enriched willows in the Scrub Woodlands.

4.4. SURVIVORSHIP OF TAGGED WILLOWS (2016-19)

In order to determine how quickly a tree could be killed by the KSHB, I followed the speed of deterioration in many individual trees. I asked:

- **How long does it take a typical Dry Forest tree to go from being 'not infested' to 'infested' to 'dead'?**

Methods

I tagged more than 200 willows during February 2016 and revisited them in November 2019 to see how the infestation was progressing. The tagged trees were scattered in Units 13, 14, 16, 17, 18, 19, 20 and 21, i.e., mainly Dry Forest units. When revisiting the trees I classified each tree as either: 'not infested–alive'; 'not infested–dead'; 'infested–alive'; or 'infested–dead'. The 'infested–alive' included trees that had been heavily damaged by the KSHB and were resprouting, as well as trees that were undamaged live trees showing signs of active KSHB infestation.

Results

- Of the 135 tagged willows that were not infested at the start in February 2016, most of the trees (66 trees, or 49%) were 'infested–alive' in November 2019 (left side of Figure 14). This means they became infested during the nearly four year period but did not die. Only a few of these 135 trees became infested and died (17 trees, 13%).
- Of the 58 tagged willow trees that were infested at the start in February 2016, most of the trees (44 trees, or 76%) were still 'infested–alive' in November 2019 (right side of Figure 14). This means they continued to live, even though infested, throughout the nearly four year period. Only a few of these infested trees died (14 individuals, 24%).

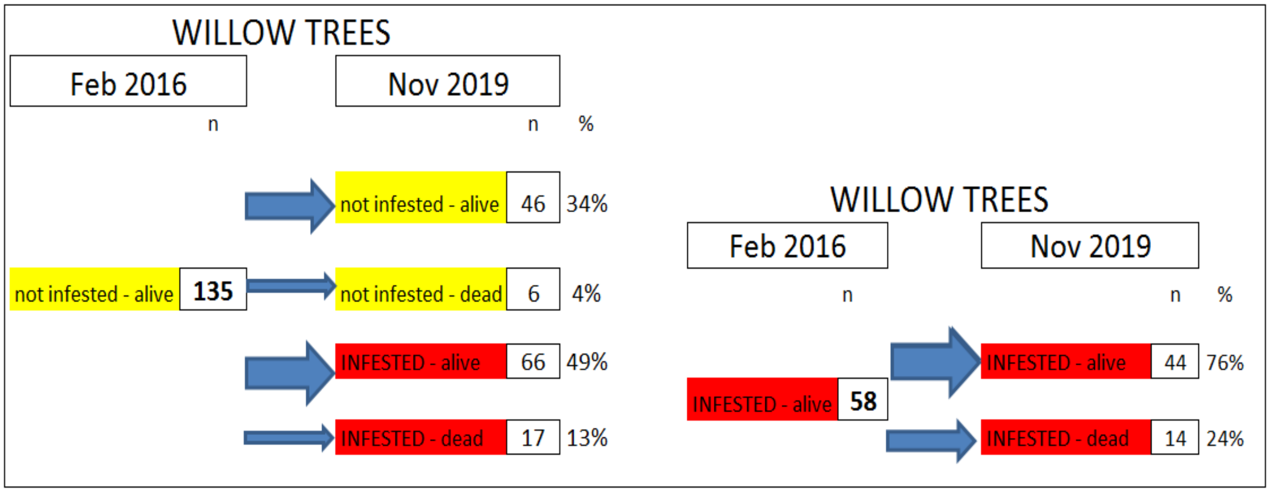


Figure 14. The change in condition of tagged trees from February 2016 to November 2019. One set of trees started as 'not infested' (n = 135; on the left), another set started out 'infested' (n = 58; on the right). These trees were mainly in the Dry Forests.

- All together, only a few of the tagged willows have been killed by the infestation during the four years. A total of 31 (17 + 14) out of 193 (135 + 58) have been killed by the KSHB during the four years; this amounts to 16% of the tagged trees.
- Putting the timelines together to approximate a hypothetical eight year period, the results suggest that an uninfested tree at the beginning of Year 1 had a 62% (49% + 13%) chance of becoming infested by the end of Year 4, and that an infested tree at the start of Year 4 had a 76% chance of surviving until the end of Year 8. Therefore, over the course of an eight year period, a typical tree would likely be infested by KSHB but survive the attack.

Discussion

The results from the tagged trees showed that, although Dry Forest trees were being infested, only a small percent were being killed by the infestation. The low mortality rates mean that, at the moment, the Dry Forests continue to look generally sound (Figure 13B).

4.5. CONCLUSIONS AND REVIEW OF KSHB ECOLOGY

In this section we have shown the impact of the KSHB in the valley in four ways: by examining infestation rates of the willows in units; by following the canopy damage caused by the KSHB using GIS technology; by examining mortality rates of the willows in units; and by monitoring survivorship of tagged willows. Our studies have shown that **the KSHB can be very destructive**. The surveys show that 91% of the willows in the valley have been infested by the KSHB and that 30% of the willows have been killed by the KSHB. The estimated number killed was 122,987 willow trees, which is the largest number of trees reported killed by the KSHB anywhere in southern California.

These data also show that the KSHB **impact was not the same throughout the valley.** The highest KSHB infestation and mortality rates were in the Wet Forest units, and the lowest infestation and mortality rates were in the Dry Forest and Scrub Forest units. As the willow species in all the units are the same two species, the KSHB appears to be responding to the condition of the trees, which changes with nutrient levels (Boland and Woodward 2019); trees in the Wet units were frequently inundated by the river and were healthy and fast-growing, but as one moved away from the river into the Dry Forest and Scrub Forest units the sites were drier and the trees less-vigorous and slower-growing. Therefore the environment and the preexisting condition of the trees play major roles in determining the impact of the KSHB within the Tijuana River Valley (Boland and Woodward 2019).

Review of KSHB ecology

Ecology deals with "*the distribution and abundance of organisms – where organisms occur, how many there are and what they do*" (Begon et al 1996). Through studies of the ecology of a species, one gains a deeper understanding of the species and, if it is a newly-arrived exotic pest, one can make predictions as to where the pest is likely to invade next. Since 2015, I have been studying the distribution and abundance of the KSHB at three spatial scales: within the host tree, within the valley, and within the county. These are my main findings involving the ecology of the KSHB:

1. Host trees: KSHB prefers certain tree species. The five species most infested and impacted by the KSHB in the Tijuana River Valley were: arroyo willow, black willow, red willow, western cottonwood and California sycamore (Boland 2016). The damage to the Tijuana River Valley forests was extensive because these species, particularly arroyo willow and black willow, made up the majority of the trees in the forests when the KSHB invaded (Boland 2014b). Other species in the Tijuana River Valley that were not infested or only light infested included several trees (the Blue elderberry, Peruvian pepper and *Eucalyptus* spp.), all shrubs, and *Arundo donax*. This list of host species has been confirmed, and added to, by others who have examined ISHB infestation rates elsewhere (Eskalen et al. 2013; Coleman et al. 2019).

2. Host trees: KSHB prefers moderate to large diameter willow trunks and branches. Surveys of 302 resprouting branches and 78 trees showed that the KSHB preferred to attack moderate to large diameter willow trunks and branches (> 4.5 cm; Boland 2017b). KSHB did not attack small branches or very young willow trees. In addition, a survey along the length of a heavily-infested, 13 m-tall, black willow tree showed the same pattern: KSHB made tunnels along the entire length of the large-diameter trunk but not into the small diameter branches. The holes in the trunk extended from 0 to 10 m with the greatest density at 4 m (39 holes per $40cm^2$; Boland 2017b). I estimated a total of 26,900 holes on the entire tree. This study showed why the heavily-infested tree trunks snapped in the wind between 1 and 5 m, i.e., where the KSHB's tunneling undermined the trees the most.

3. The valley: KSHB prefers nutrient-enriched trees. The distribution of KSHB within the Tijuana River Valley was not random; they infested willows growing in or near the main channel significantly more than willows growing far from the water (Boland 2016). Further investigation showed that the main channel in the Tijuana River Valley carried many millions of gallons of raw sewage each month and sewage contains the most important plant nutrients – nitrogen, phosphorus and potassium (Boland and Woodward 2019). The willows growing in or near the nutrient-enriched channel water were growing quickly and vigorously, and had wood characteristics that were significantly different to the willows growing far from the nutrient-enriched channel water (Boland and Woodward 2019). Therefore, trees of the same species growing under different conditions have different wood characteristics, and the most enriched trees among them were the most susceptible to KSHB infestation.

This link between nutrient enrichment and susceptibility to KSHB attack is formalized in the Enriched Tree Hypothesis (Boland and Woodward 2019; Figure 15). The link is suggested to be due to the sap in the enriched trees being nutrient loaded in two ways – phloem sap being loaded with sugars from the fast-growing leaves, and xylem sap being loaded with nutrients from the enriched soil – and these extremely high nutrient conditions in the trunks and branches promote fast growth of the symbiotic fungi and ideal conditions for the KSHB.

Some kind of link between the environment and susceptibility to shot hole borer attacks has been suspected but not previously identified. Hulcr and Stelinski (2017) noted that "*in ambrosia beetle research, the role of the environment and preexisting conditions of the trees has not yet been well appreciated, even though it appears to determine the impact of these beetles.*" The Enriched Tree Hypothesis directly links the environment (enriched water) and the preexisting condition of the trees (vigorous, fast growing willows) with the impact of the KSHB (tens of thousands of KSHB per host tree, which cause the trunk to snap and the canopy to collapse).

4. The county: The KSHB infestation in the Tijuana River Valley is in a class of its own; similar riparian forests in San Diego County are not infested or only lightly infested. By conducting surveys at nine riparian sites outside the influence of the Tijuana River, I found that the Tijuana River Valley stands out as an extreme case in two ways: it is the most severely KSHB-infested natural site in southern California; and the most polluted with sewage. These findings are consistent with the Enriched Tree Hypothesis described above. The severe infestation and damage seen in the Tijuana River Valley should not be expected to occur at other natural, unpolluted riparian sites.

The five years of repeated surveys has allowed me to add two temporal characteristics of the KSHB.

5. The trajectory of a KSHB infestation varies from site to site. A view commonly encountered in southern California is that the severity of a shot hole borer infestation reflects the age of an infestation, i.e., a stand with many infested trees is said to be an older infestation, and a stand with few infested trees is said to be a younger infestation. This 'age of infestation' view presumes that the trajectory of a shot hole borer infestation will be the same in all stands, i.e., a mild infestation with little tree damage will quickly turn into a severe infestation with heavy tree damage. My results do not support this view. The trajectory of infestation varied among units (Section 4.1). In the Wet Forests the KSHB infestation progressed rapidly over the course of only a few months from barely noticeable to heavy infestation and dramatic canopy collapse, i.e., the infestation had a steep trajectory. In the drier forests, the KSHB infestation progressed more slowly over several years and the canopy remained mostly intact, i.e., the infestation displayed a shallow trajectory. In the very dry Scrub Forests, infestation remained extremely low, i.e., the infestation had a <u>very</u> shallow trajectory. This result means that one cannot presume that an infestation will progress from mild to serious in all sites. Likewise, the idea that *a light infestation must be a recent infestation while a heavy infestation must be an old infestation* is incorrect; the degree of infestation is not necessarily tied to age of infestation.

6. The KSHB invasion went through a boom-and-bust cycle in the valley. In the Tijuana River Valley the KSHB population went through a rapid outbreak and a rapid decline over a five-year period, as measured by KSHB-infested trees, KSHB-induced tree damage and KSHB-induced willow mortality. The early outbreak was characterized by the KSHB presence in the Wet Forests and the swift damage to these habitats. The later decline was characterized by the KSHB presence in the Dry Forests and the slower damage to these habitats. The decline appears to be due to the KSHB depleting the original trees and not reinvading the recovering Wet Forests. [More about this in Section 6.] There have been no management interventions to limit the spread or impact of the KSHB in the valley.

Apart from my research summarized above, little ecological work has been done on the ISHB in southern California. There has been a heavy focus on the host species list (Eskalen et al. 2013; Coleman et al. 2019; UCR 2020) and little else. One researcher conducted an extensive data collection effort in more than 260 one-hectare sites, but had to conclude that air temperature and relative humidity do not determine the distribution, establishment, and spread of the ISHB (Lynch et al 2018).

As for predictions, only host species is currently used by the authorities to predict likely impacts of the shot hole borers (McPherson et al. 2017). As their model uses only host species and considers all host individuals equal and all sites equal, their analyses should be considered just a rough first step that greatly exaggerates the likely impact. These models need to include more information about the sites and the ecology of the KSHB, like the findings listed above, in order to make them more useful. [More about this in Section 7.1.]

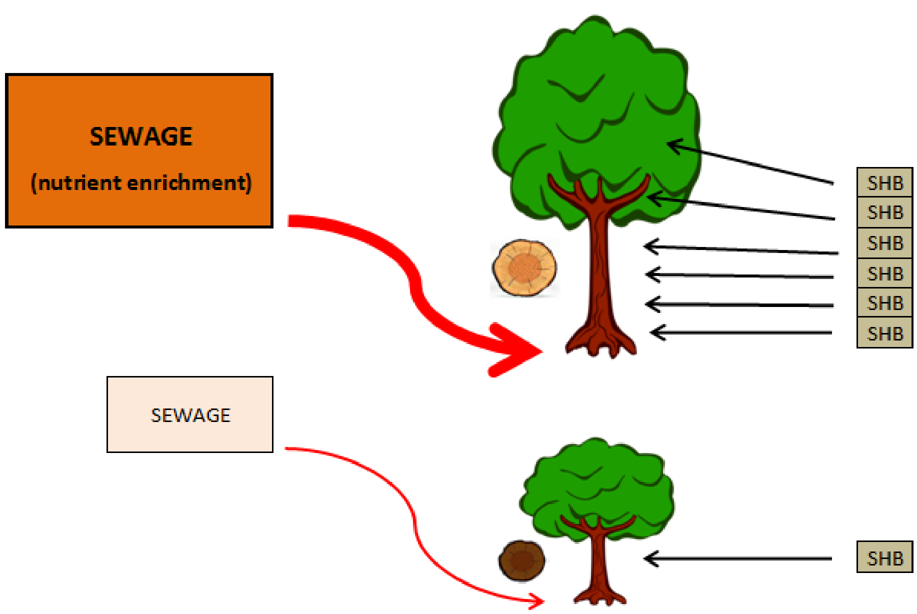


*Figure 15. The Enriched Tree Hypothesis illustrated. **A**: When excessive sewage flows into a site it stimulates the growth of trees and the trees are susceptible to a mass attack by Shot Hole Borers (SHBs). **B**: At other sites not influenced by excessive sewage, trees grow more normally and the trees are not abundantly attacked by SHBs.*

5. RESPONSE OF VEGETATION IN THE KSHB-DAMAGED RIPARIAN HABITATS

The initial KSHB infestation in the Tijuana River Valley in 2015 was alarming because it caused the quick, dramatic collapse of the tall willow canopy in many of the Wet Forest units. The photos A and B in Figure 16 were published in Boland (2016) to illustrate this remarkable collapse. Since then something equally remarkable has occurred in those heavily-damaged Wet Forest units: the canopy has recovered considerably (Figure 16 C and D). In some places the forests are almost back to their pre-KSHB condition, whereas in other places they have failed to return because of the dramatic expansion of *Arundo donax*. In this section we describe how the most heavily-damaged forests in the Tijuana River Valley – the Wet Forests – have responded to the KSHB infestation.

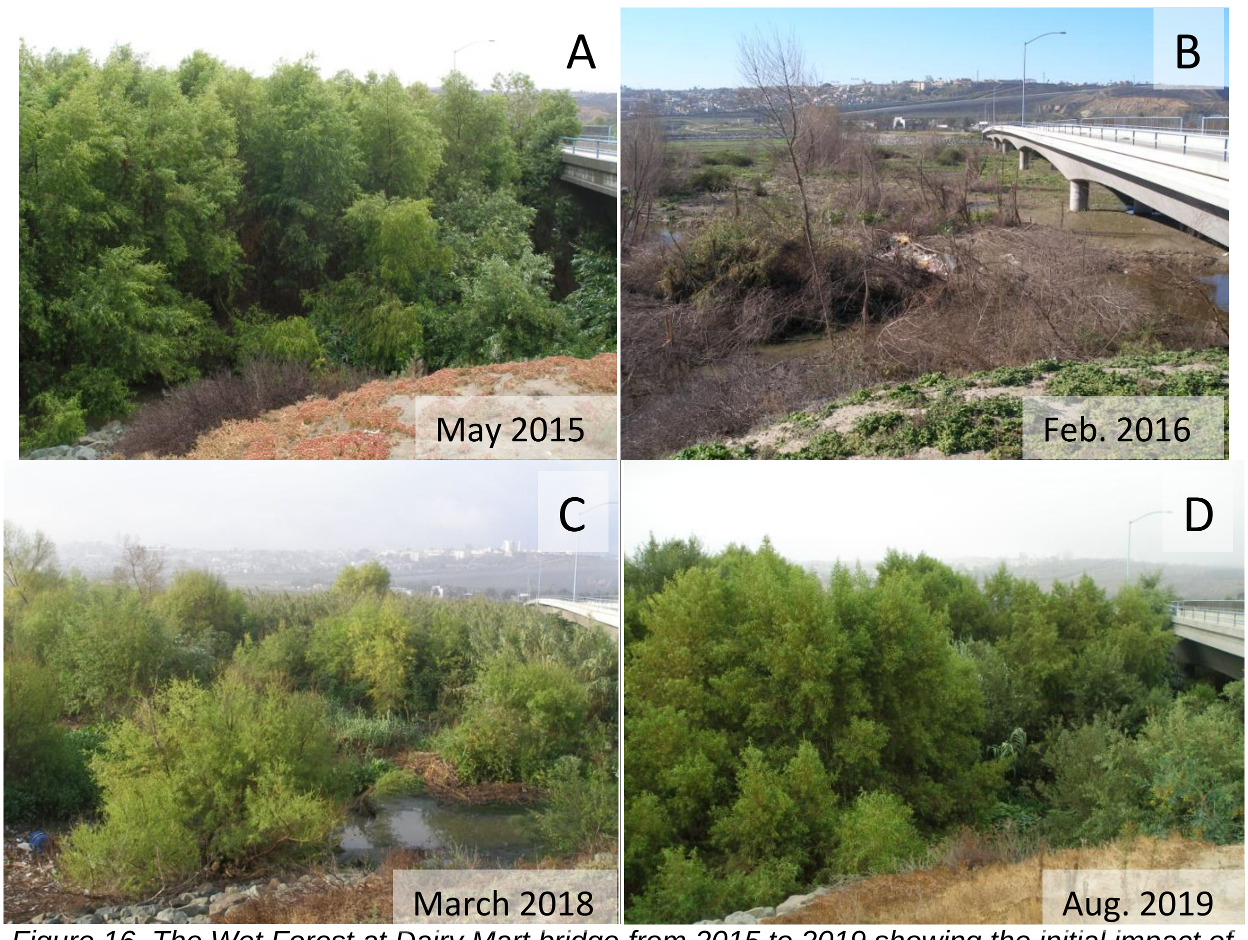


Figure 16. The Wet Forest at Dairy Mart bridge from 2015 to 2019 showing the initial impact of the KSHB on the willow canopy followed by the considerable forest recovery. ***A****: Before the KSHB infestation.* ***B****: After the KSHB infestation.* ***C*** *and* ***D****: During forest recovery.*

We documented the response of the vegetation in the KSHB-damaged riparian habitats by:

- Monitoring growth and survivorship of resprouting willow trees;
- Monitoring growth and survivorship of willow seedlings;
- Conducting belt transects of the vegetation in the recovering riparian forests;
- Estimating willow canopy cover in the recovering riparian forests;
- Mapping the distribution of the surviving original willows in the valley; and
- Mapping the distribution of *Arundo donax* in the valley.

5.1. GROWTH AND SURVIVORSHIP OF RESPROUTING WILLOW TREES (2016-19)

A damaged willow tree produces resprouts, i.e., new upright branches that grow from adventious buds on the surviving trunk. Resprouts are an important means by which the willows in the Tijuana River Valley have recovered after the KSHB attack (Boland 2017b, 2018, 2019). Here I give details on the monitoring of individual resprouting trees and answer the question:

- **What are the rates of survivorship and growth of resprouting willows in areas that were previously heavily infested with KSHB?**

Methods

In October–November 2016, I tagged 34 resprouting willow trees for monitoring over time. The trees had been attacked by the KSHB in 2015, severely damaged by winds in winter 2015-16 and started resprouting in spring 2016. These resprouting tree stumps were scattered throughout the heavily-damaged Wet Forest, in Units 2, 8, 10, 11, 12 and 13. At that time, I measured the characteristics of each tree stump, i.e., height, circumference and number of KSHB holes per 45 cm^2 (Table 5). In addition, I examined all the resprouts on each tagged tree for signs of KSHB infestation, and I measured the diameter of each resprout. I also measured the length of the largest resprout on each tree, tagged it and named it the ‘focal’ resprout. I reexamined and remeasured these resprouts during fall 2017, fall 2018 and fall 2019. During these revisits, I looked for signs of KSHB infestation, measured the diameter of all of the live resprouts, and measured the length of the focal resprouts. In addition, I measured the total height and width of the ‘new’ tree created by the resprouting stump and calculated its volume (as a cone). These surveys therefore address the growth and survivorship of the resprouting willow trees.

Results

- The KSHB was not a problem for the resprouts. None of the resprouts was infested with KSHB in 2019 (Table 5 and Figure 17); none of the resprouts had been killed by KSHB; and the resprouts that had been lightly infested with KSHB in 2016 (Figure 7 in Boland 2018) had all survived and were growing strongly in 2019.
- Of the 34 resprouting willows tagged in 2016, 33 were alive and growing in 2019 (Table 5). One tree had died; it was growing on an embankment high above the

water line and appeared to die from lack of water rather than due to the earlier KSHB infestation.

- The resprouts on the surviving willows exhibited vigorous growth over the three years; they all started out as tiny buds in 2016 and in fall 2019 the focal resprouts (n = 33) had a mean length of 6.0 m and a mean diameter of 9.7 cm (Table 5).
- The average diameter of all the resprouts on the tagged trees in fall 2019 was 6.5 cm (Table 5 and Figure 17). This is three times the average diameter in 2016.
- The resprouting willows were large trees or shrubs (Figure 18). The average 'new' tree had 6.6 resprouts, was 5.8 m tall and 6.5 m wide, and occupied a total volume of approximately 57.3 m^3 (Table 5).

Table 5. Survivorship and growth of tagged willow tree stumps with resprouts.

Characteristic	2016	2017	2018	2019
source	Boland 2017	Boland 2018	Boland 2019	this report
ORIGINAL TREES				
Number of labeled resprouting trees	34			
Labeled trees location -- Units	2, 8, 10, 11 and 13			
Stump height in m -- mean (std dev)	4.1 (2.1)			
Stump circumference in cm – mean (std dev)	92.3 (43.0)			
Number of KSHB holes per 45 cm^2 – mean (std dev)	27.4 (12.0)			
FOCAL RESPROUTS				
Number of labeled focal resprouts	34	34	33	33
Resprout length in m -- mean (std dev)	3.0 (0.7)	4.4 (1.3)	5.1 (1.2)	6.0 (2.1)
Resprout diameter in cm -- mean (std dev)	3.1 (1.0)	5.9 (1.9)	7.7 (2.9)	9.7 (4.1)
ALL RESPROUTS - SIZE				
Total number of resprouts	302	316	264	217
Resprout diameter in cm -- mean (std dev)	2.2 (1.2)	3.4 (2.2)	5.1 (3.3)	6.5 (4.0)
ALL RESPROUTS - INFESTATION BY KSHB				
Number of resprouts infested with KSHB	27	0	2	0
Percent of resprouts infested with KSHB	9%	0%	1%	0%
Number of resprouts killed by KSHB	0	0	0	0
NEW TREE - SIZE				
Number of resprouts per tree -- mean	8.9	9.3	8.3	6.6
Width of new tree in m -- mean	nd	4.0	5.0	5.8
Height of new tree in m -- mean	nd	5.2	5.9	6.5
Volume of new tree in m^3 -- mean	nd	21.8	38.6	57.3

- The resprouting trees are now old enough and vigorous enough to flower; I observed flowers on all of the living resprouting trees (33/33) during spring 2018.

- Many of the resprouting trees in 2019 were larger than they were before the KSHB attack. For instance, the willow tree R30 was originally composed of two main branches/trunks whose diameters totaled 15.4 cm prior to the KSHB, and in 2019 the diameters of the five new resprouting branches/trunks totaled 42.6 cm, more than twice the original total diameter (Figure 18).

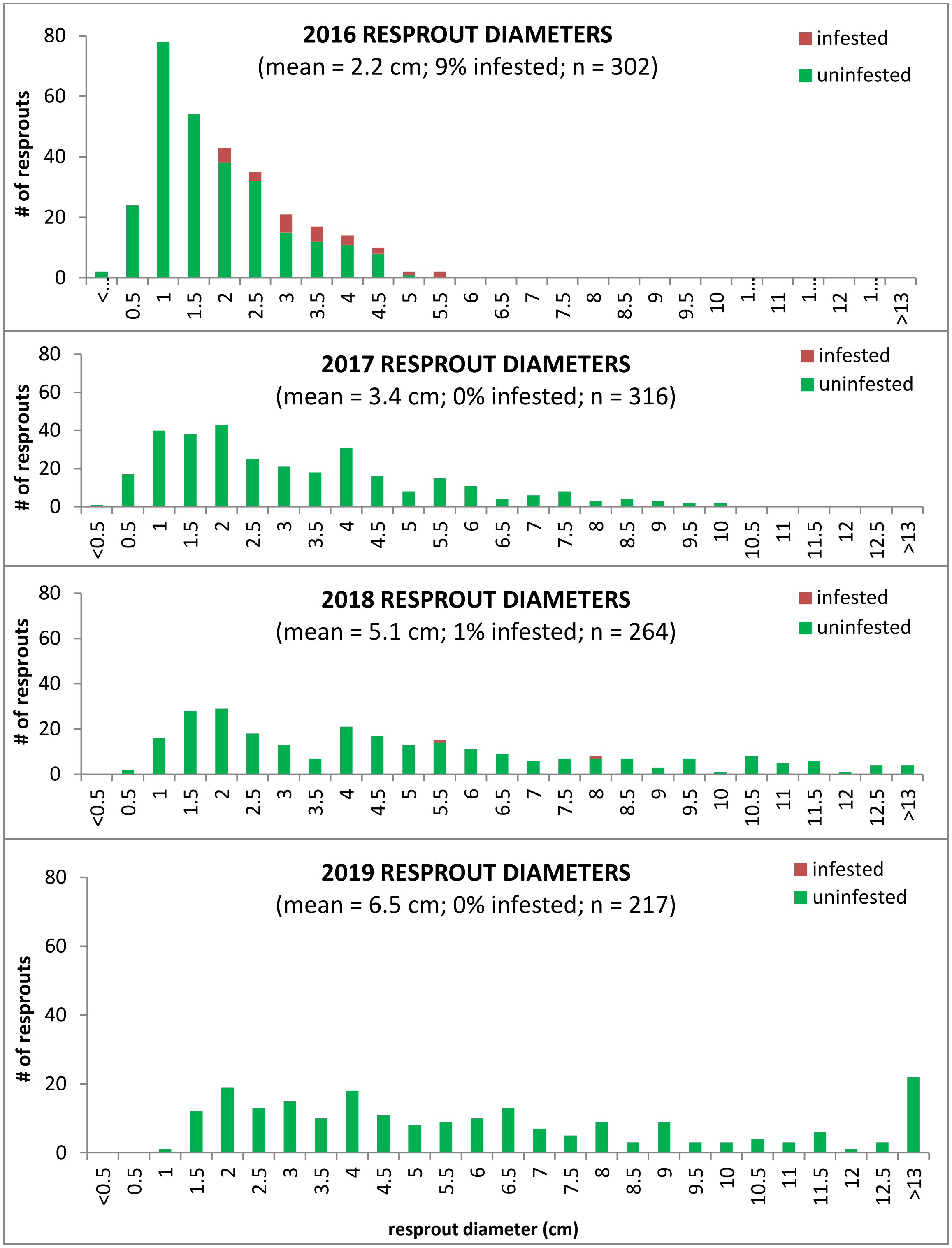


Figure 17. The size frequency of resprouts growing on tagged KSHB-infested willow trees (fall 2016-19). Data included for each year are mean resprout diameter, percent resprouts infested with KSHB, and number of resprouts measured (n).

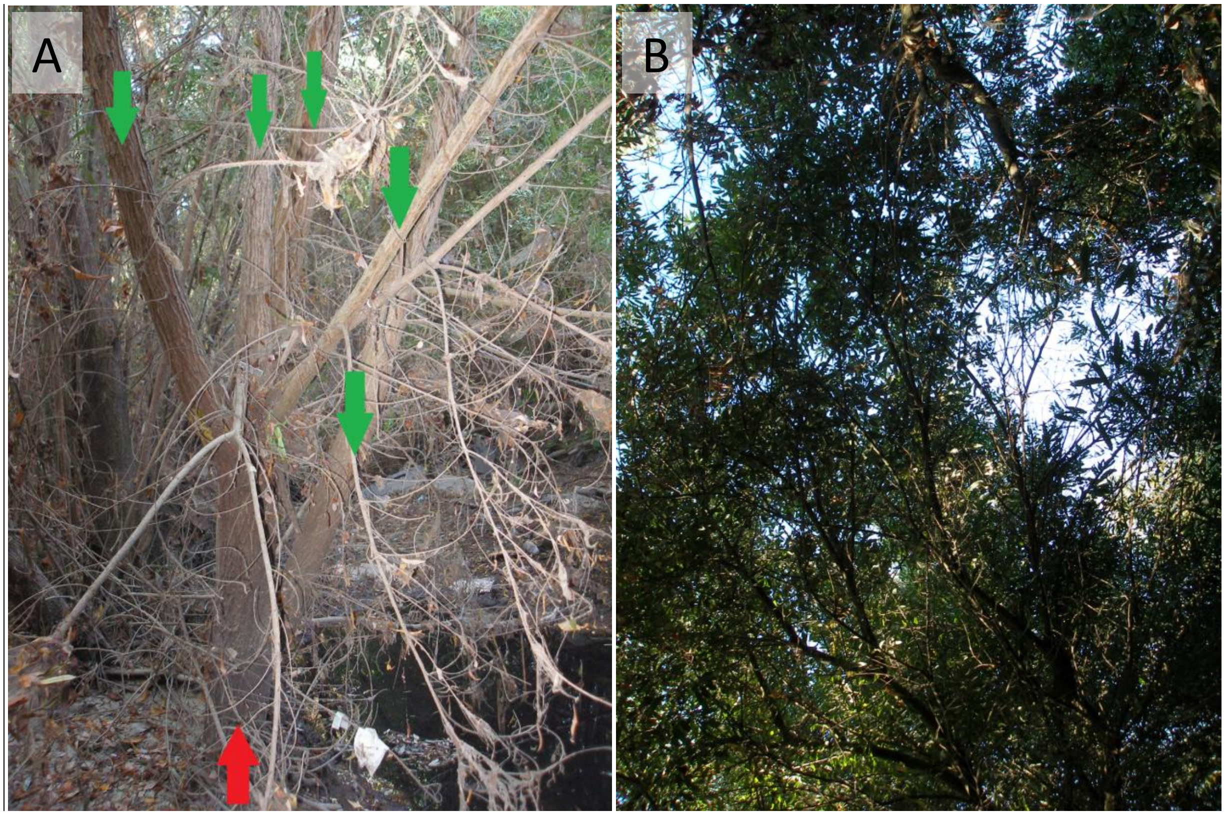


Figure 18. Two views of a resprouting arroyo willow (R30) in fall 2019. ***A:*** *The base, showing the old, previously-infested, main trunk (red arrow) and the new resprouts it has produced (green arrows).* ***B:*** *the canopy, showing the new, tall (9.2 m), almost completely-closed canopy. This tree was severely infested in 2015 (29 KSHB holes per 45 cm^2), but it sent up resprouts in 2016 and has been growing vigorously ever since. It is now larger than it was when first infested with KSHB in 2015.*

Discussion

Most of the willows that are recovering in the heavily-damaged Wet Forests are recovering by producing resprouts and the resprouts continued to grow rapidly in 2019. This growth of resprouts is informative for several reasons.

1. An infested tree is not necessarily going to die when it has > 18 holes per 232 cm^2. Managers are currently being advised that trees that are heavily-infested with KSHB will die and therefore these trees should be removed before they lose branches and before they add more beetles to the population. A tree is considered heavily-infested when there are **> 18 holes per 232 cm^2** (Coleman et al 2019) or > 150 holes on a tree (Nobua-Behrmann 2020). I do not agree with their assessment because these Tijuana River Valley data show that even a very heavily-infested willow can survive and recover. The resprouts that I was monitoring were growing on tree trunks that had an average of 27.4 KSHB holes per 45 cm^2 (Table 5) or **141.2** ± 61.9 **holes per 232 cm^2**, seven times the number Coleman et al. 2019 use for their cut-off. In addition, in June 2018, I carefully examined some old KSHB holes on a living SALA Big Tree and found that the trunk had healed after the KSHB attack and that new wood had grown over the old KSHB tunnels (Figures 12 and 13 in Boland 2019). The density of old KSHB holes on that tree was 10 per 45 cm^2 or **52 holes per 232 cm^2**, and this tree was still alive and well in February 2020. To claim that all heavily-attacked trees will die is certainly not the case and to set such a low threshold as18 holes per 232 cm^2 (Coleman et al 2019) is unfounded and will lead to the removal of many valuable trees that would have survived.

2. Rapid willow regrowth after KSHB attack, pollarding and coppicing. The rapid growth of resprouts shows how quickly the heavily-damaged willow trees can recover. Damaged willows went from dead-looking stumps riddled with many KSHB holes to voluminous, 6.5 meter tall trees or shrubs in less than four years. A KSHB-damaged forest therefore has the ability to rapidly restore itself. The speed of willow recovery is remarkable but is typical of willow trees all over the world. In England, willows growing on land near water are regularly harvested knowing that they will resprout, grow and be available for harvesting again in a few years (Figure 19). They have been harvested that way for hundreds of years. The English call it 'pollarding' when the tree is cut high above the ground and 'coppicing' when the tree is cut at ground level (Figure 19). Both methods take advantage of the willow's natural ability to recover quickly after damage.

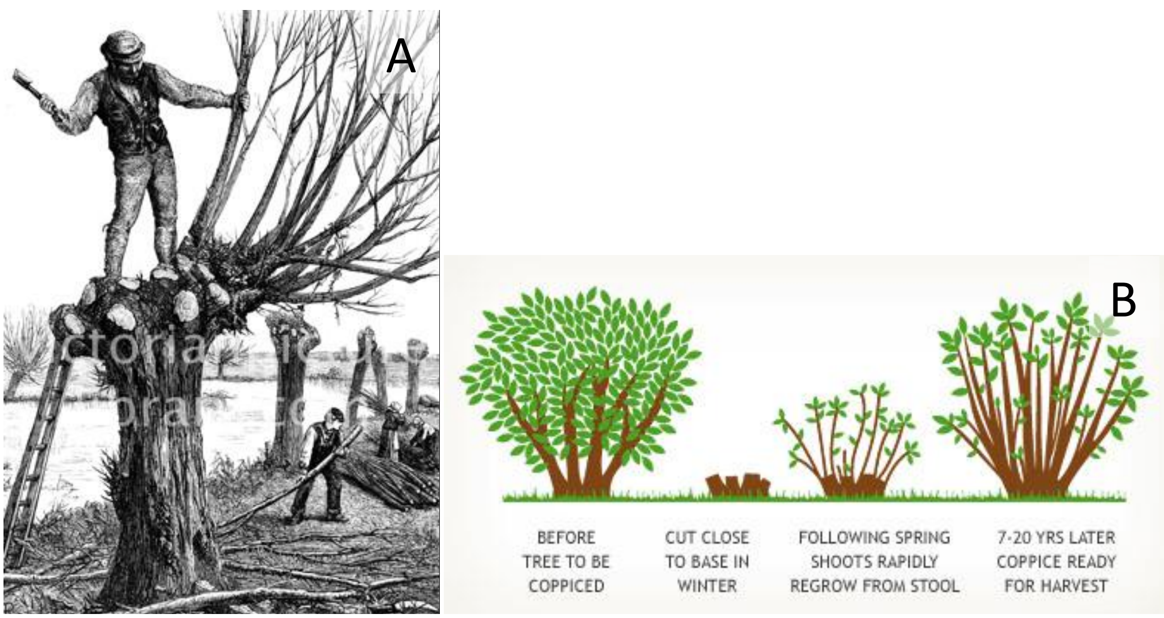


*Figure 19. KSHB attacks on willow trees cause damage and recovery that is similar to willows being harvested by humans. **A**: Harvesting willows by pollarding. **B**: Harvesting willows by coppicing.*

3. Resprouting trees are not being reinfested. Fortunately these resprouting trees are not being reinfested by KSHB. This surprising finding is discussed further in Section 6. It is not known if or when the KSHB will return to these areas, attack the resprouts, and interrupt the forest recovery. But, at present, the resprouting willows are growing and flowering vigorously and providing essential habitat for the animals in the valley.

5.2. GROWTH AND SURVIVORSHIP OF WILLOW SEEDLINGS (2016-19)

After the KSHB-induced damage to the Wet Forests in 2015-16, many willow seedlings recruited onto the newly-opened, and therefore sunny, river beds and banks. Most of the seedlings were scattered within the forest, but three large stands of seedlings became established in three units. Since 2017 I have been following these three stands of willow seedlings to see whether they have become successfully established. Here I answer the question:

- **Are the three large stands of willow seedlings first described in Boland (2018) surviving and growing?**

Methods

The stands of seedlings (now saplings) were revisited during fall 2019, photographed and their maximum heights measured.

Results

- All three of the stands of seedlings were surviving and growing (Figure 20).
- The stand of seedlings in Unit 2, which was established in spring 2017, was 143 m^2 in area and the trees were up to 6.7 m tall (Figure 20B).
- The stand of seedlings in Unit 3, which was established in spring 2016, was 390 m^2 in area and the trees were up to 8.2 m tall (Figure 20D).
- The stand of seedlings in Unit 12, which was established in spring 2015, was 613 m^2 in area and the trees were up to 10.2 m tall (Figure 20F). The mean trunk diameter at breast height was 11.7 cm (std dev = 2.0 cm; n = 8).
- None of these trees was being attacked by KSHB in fall 2019.

Discussion

These three large stands of willow seedlings were all surviving and growing and not being attacked by the KSHB.

These stands illustrate how willows typically establish via seeds: during winter a ‘disturbance’ creates bare, sunny sediment on the river bank (usually the disturbance is extreme water flows but in this case it was the KSHB); during spring many thousands of willow seeds land on the moist sediment and germinate immediately (Boland 2014b); the young seedlings grow very quickly and within a year the once bare area is covered by a dense stand of tall, young trees. As the stand develops it is thinned by the deaths of the shortest trees, and within a few years the stand looks like a typical stand in the Tijuana River Valley – tall and dense and consisting of same-aged trees.

The ease with which native willows became densely established in these sites illustrates the effectiveness of natural restoration projects (Briggs 1996, Boland 2014a). In natural restoration projects riparian revegetation is allowed to recruit and develop with little or no human intervention. Natural restoration is superior to the more commonly conducted horticultural restoration because it produces a forest community with a high density of trees, the tree species are in the appropriate down-slope zonation, and the trees are of

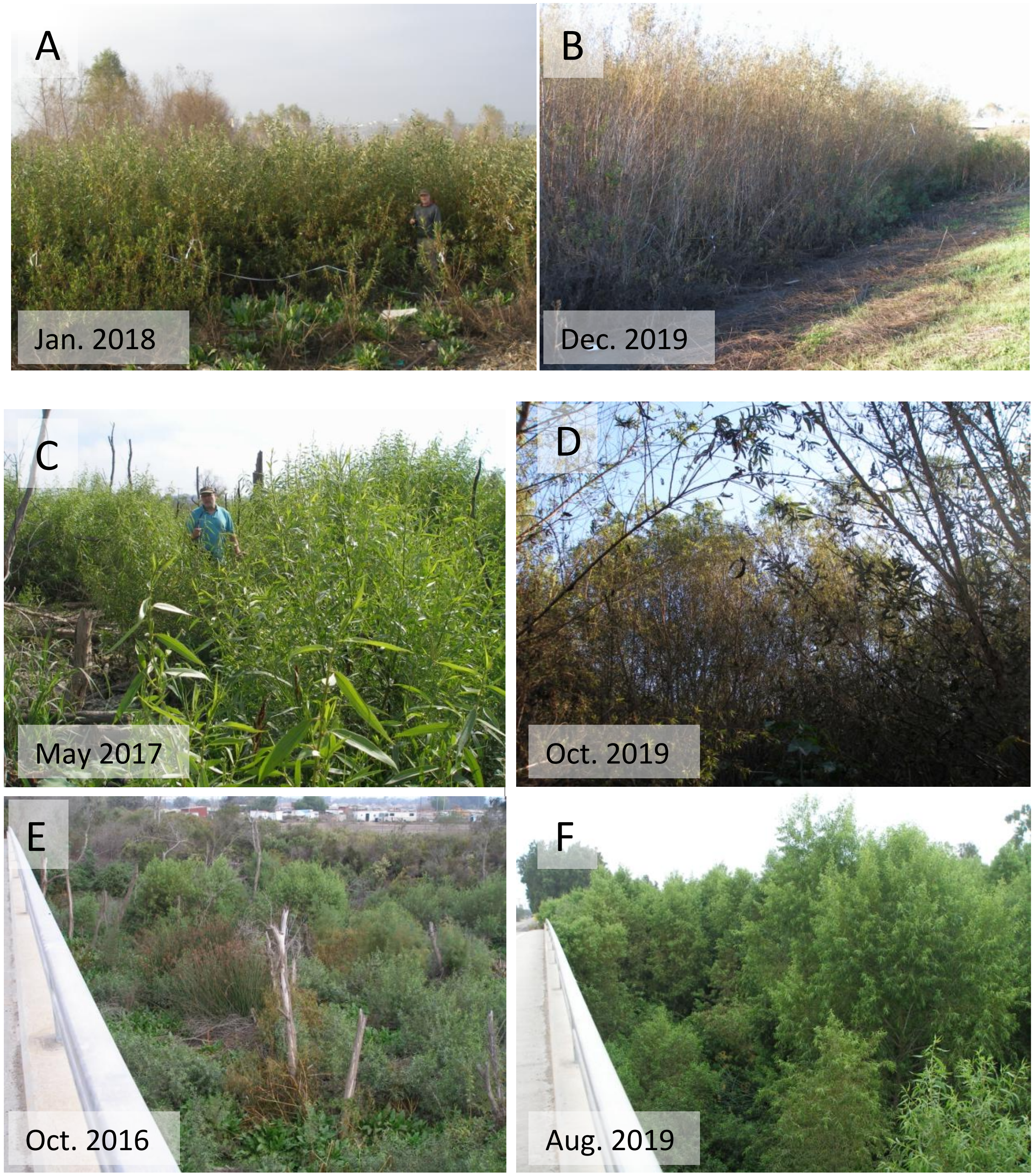


Figure 20. The continued survivorship and vertical growth of three stands of willow seedlings in the Wet Forests. Photos on left were taken early in their development and those on right were taken in fall 2019. ***TOP PAIR****: Arroyo willows in Unit 2.* ***MIDDLE PAIR****: Black willows in Unit 3.* ***BOTTOM PAIR****: Black willows in Unit 12 at Hollister Bridge. These seedlings were not being attacked by KSHB.*

the appropriate sex ratio and genetic diversity (Boland 2014a). Natural restoration is the most suitable method for riparian sites that are inundated by floods during winter and have natural seed sources nearby, like the Wet Forests in the Tijuana River Valley. Natural restoration is therefore the easiest and best method for restoring the Wet Forests after the cover of *Arundo donax* is reduced.

5.3. BELT TRANSECTS OF THE VEGETATION IN THE RECOVERING RIPARIAN FORESTS (2019)

The Wet Forests are green and densely vegetated and are obviously rebounding after they were heavily impacted by the KSHB in 2015-16 (Figure 16A-D). But:

- **What plant species are growing in these heavily-damaged sites?**
- **Are they mostly native or non-native species?**

Methods

During fall 2019, I conducted vegetation surveys to determine plant species composition in each of the Wet Forest units using the same methods as in my earlier annual surveys, i.e., percent cover measurement of species inside belt transects (25 m x 2 m = 50 m^2; Boland 2016, 2017b, 2018, 2019). I then assigned each species present to one of the following categories: willow seedlings, willow Big Trees, willow resprouting trees, native annuals, or non-native plants. I also walked through the accessible parts of each unit to note the presence of unrecorded species outside the belt transects.

Results

- Sixteen native species and 13 non-native species were present in the belt transects (Table 6).
- Native species were more abundant than non-native species; the mean percent cover of natives was 83% and of non-natives was 27% (Table 7).
- Resprouting willow trees were the most abundant native plants, with a mean percent cover of 60% (Table 7). In three units (7, 8 and 13) resprouting willows formed a tall, full canopy with > 90% cover.
- Two of the three native species that were found for the first time in the Tijuana River Valley following the willow-canopy collapse – sticktight (*Bidens frondosa*) and false daisy (*Eclipta prostrata*) – were still present in a few sites during 2019 (Table 6). Each formed a dense ground cover in places where sunlight reached the moist ground.
- Native bulrushes, *Schoenoplectus americanus* and *S. californicus*, were common outside of the belts – at sites where there was plenty of light and perennial water.
- Of the non-native species, castor bean was the most abundant single species in the belts, with a mean percent cover of 10% (Table 7).
- Arundo, had a mean percent cover of only 6% in the belt transects (Table 7), but was more abundant outside the belts. Arundo was abundant and expanding in two of the units (4 and 5) and had a percent cover of >30% in each.

*Table 6. Plant species that occurred in the belt transects in fall 2019. An *** indicates a species that had not been recorded in the Tijuana River Valley prior to the KSHB-induced collapse of the willow canopy.*

NATIVE SPECIES	
Main forest species	
Salix gooddingii	Goodding's black willow
Salix lasiolepis	Arroyo willow
Native annuals	
*Bidens frondosa****	Sticktight
*Eclipta prostrata****	False daisy
Helianthus annuus	Western sunflower
Persicaria lapathifolia	Willow weed
Solanum americanum	White nightshade
Stephanomeria sp.	Wreath-plant
Xanthium strumarium	Cocklebur
Other natives	
Baccharis salicifolia	Mule fat
Datura wrightii	Jimson weed
Salix exigua	Narrow-leaf willow
Sambucus nigra	Blue elderberry
Schoenoplectus americanus	American tule
Schoenoplectus californicus	Southern bulrush
Urtica dioica	Stinging nettle
NON-NATIVE SPECIES	
Non-natives of greatest concern	
Arundo donax	Giant reed
Ricinus communis	Castor bean
Tamarix ramosissima	Tamarisk
Other non-natives	
Araujia sericifera	Cruel vine
Atriplex prostrata	Spearscale
Ficus carica	Edible fig
Fraxinus uhdei	Shamel ash
grasses, e.g, *Pennisetum clandestinum*	Kikuyu grass
Lepidium latifolium	Perennial pepperweed
Phytolacca icosandra	Tropical pokeweed
Rumex conglomeratus	Whorled dock
Schinus terebinthifolius	Brazilian pepper tree
Tropaeolum majus	Garden nasturtium

Table 7. The percent cover of plants along the belt transects within the Wet Forests in fall 2019.

UNIT	NATIVE PLANTS						NON-NATIVE PLANTS				
	willow seedlings	willow Big Trees	willow resprouting trees	native annuals	other natives	TOTAL NATIVES	Tamarisk	Castor Bean	Arundo	other non-natives	TOTAL NON-NATIVES
2	0%	0%	80%	7%	0%	87%	0%	0%	0%	0%	0%
3	83%	0%	0%	32%	0%	115%	0%	1%	0%	0%	1%
4	0%	0%	29%	0%	2%	31%	0%	48%	30%	0%	78%
5	0%	0%	62%	0%	10%	72%	0%	8%	40%	0%	48%
6	0%	33%	19%	24%	0%	76%	0%	32%	10%	4%	46%
7	0%	0%	100%	10%	0%	110%	0%	2%	0%	0%	2%
8	0%	0%	100%	0%	0%	100%	0%	1%	0%	0%	1%
9	0%	0%	66%	3%	1%	70%	0%	7%	0%	18%	25%
10	0%	18%	29%	45%	0%	92%	0%	2%	0%	17%	19%
11	0%	0%	66%	1%	11%	78%	0%	25%	0%	26%	51%
12	0%	0%	58%	3%	7%	68%	0%	13%	0%	35%	48%
13	0%	0%	92%	0%	18%	110%	0%	1%	0%	14%	15%
14	0%	0%	69%	0%	0%	69%	0%	1%	0%	0%	1%
22	0%	2%	73%	0%	14%	89%	0%	1%	0%	45%	46%
mean	**6%**	**4%**	**60%**	**9%**	**5%**	**83%**	**0%**	**10%**	**6%**	**11%**	**27%**

Discussion

In 2019, native plants, particularly resprouting willows, were abundant in most of the belt transects inside the recovering Wet Forest units. This year the resprouting willows were so tall (> 6 m) and their canopy so thick that they were shading the river bed, such that species that had been doing well in the light gaps in previous years were now being shaded out. The species that were conspicuously absent on the heavily-shaded ground were the annuals, tules, bulrushes, and castor bean. In some ways the Wet Forests are returning to their pre-KSHB condition in which the two main willow trees create a dense forest canopy and shade out all of the other plant species (Boland 2014b). The only species preventing a full recovery is *Arundo donax*. It is an abundant and persistent problem that is detailed more fully in Section 5.6.

5.4. WILLOW CANOPY COVER IN THE RECOVERING RIPARIAN FORESTS (2015-19)

The most obvious damage by the KSHB to the riparian forests in the Tijuana River Valley was to the willow canopy in the Wet Forests. Before 2015 this canopy was high and dense but the KSHB attack in the Wet Forests caused the willow canopy to collapse (Figure 16A and B; Boland 2016). Here I ask the question:

- **What is the current willow canopy cover in the Wet Forests in the valley?**

Methods

During each year I have estimated the percent cover of the willow canopy in each of the Wet Forest units (Boland 2018, 2019). This year I did the same: I observed each unit from as many accessible places as possible and estimated the percent cover of willow canopy.

Results

- The willow canopy declined rapidly from 2015 to 2017 in most of the Wet Forest units, but since 2017 the canopy in most units has shown a general increase (Figure 21).
- The mean canopy cover rose from 5% in 2017 to 56% in 2019 (Figure 21).
- Two photo sequences illustrate this canopy recovery – the photographs taken from Dairy Mart Bridge (Figure 16) and photographs taken from Hollister Bridge (Figure 22).
- The willow canopy in most sites is made up of two layers: a sparse, emergent layer created by the few remaining Big Trees, at a height of 15 – 25 m (50 – 80 feet), and a dense, lower layer composed of resprouting willow trees and willow seedlings at a height of 6 – 10 m (20 – 35 feet; Figure 23).

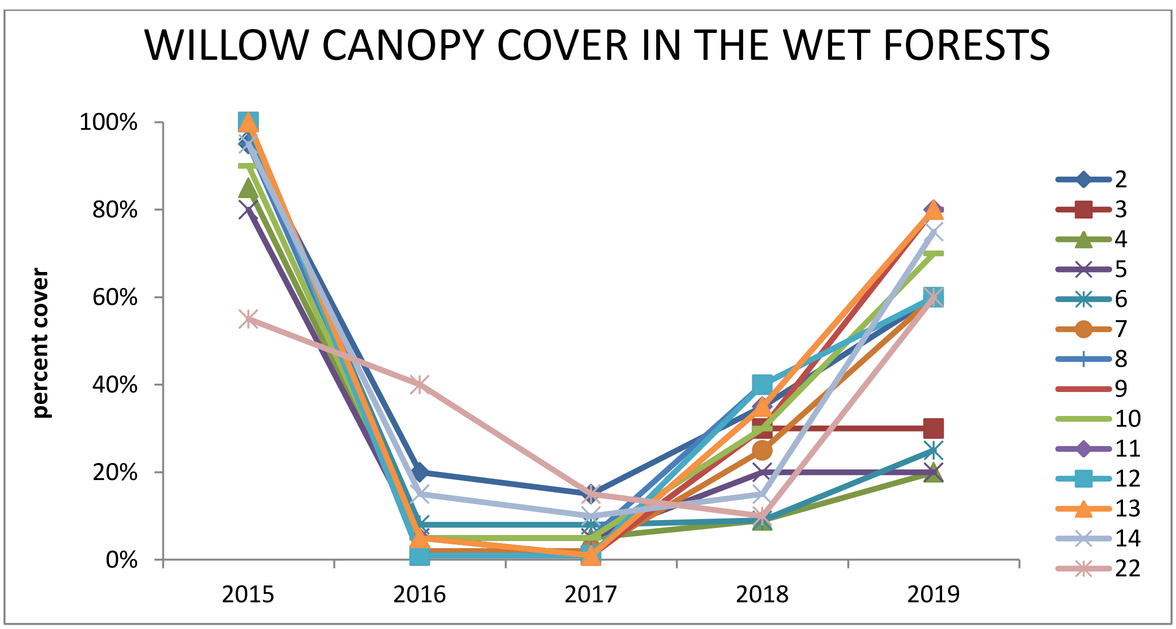


Figure 21. Estimates of willow canopy cover in the Wet Forest units from 2015-19.

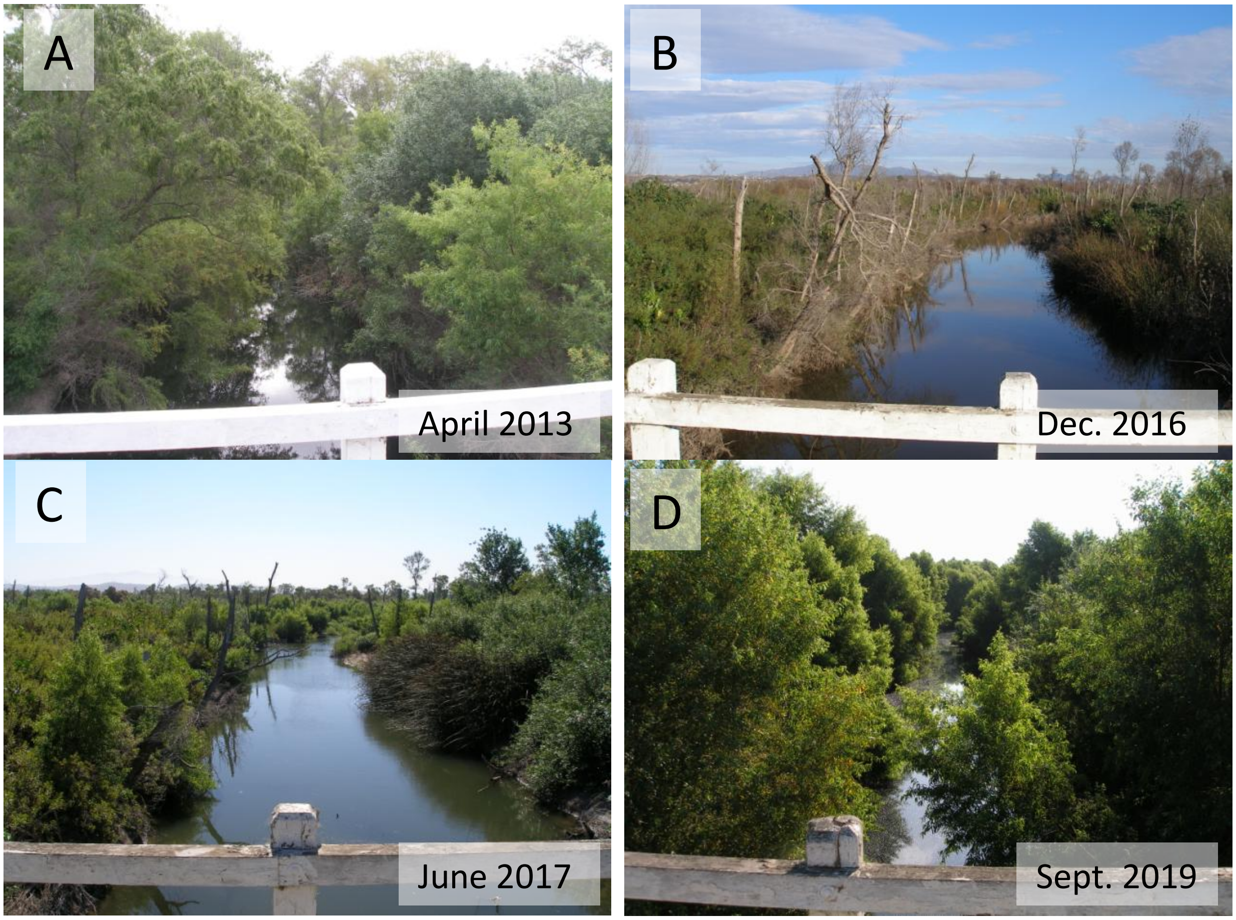


Figure 22. The Wet Forest at Hollister Bridge from 2013 to 2019 showing the initial impact of the KSHB on the willow canopy and the later forest recovery. ***A****: Before the KSHB infestation.* ***B****: After the KSHB infestation.* ***C*** *and* ***D****: During forest recovery.*

Discussion

The KSHB attack in 2015-16 caused most of the willows in the Wet Forests to lose their upper trunks and branches, so that in 2016 and 2017 there was virtually no canopy in the Wet Forest units (Boland 2016, 2017b). Only a few, scattered Big Trees remained. Since then, through the production of resprouts and seedlings, the willows have started to create a new canopy. This young canopy is developing very quickly in the recovering Wet Forests. The Big Trees and the young canopy create two canopy layers in most of the Wet Forest sites.

It is likely that these recovering willow forests will provide good breeding habitat for the endangered least Bell's vireo because the vireo requires dense, young riparian forests for breeding (Kus 2002), exactly what makes up the lower forest layer.

The Big Trees deserve more attention than they have received. They should be considered 'Plus Trees.' A Plus Tree is a tree *whose outward appearance (phenotype) is superior to the average tree of the same species grown at the same or a similar site; their visibly superior characteristics may include morphology, vigor, and pest or disease resistance* (Burns and Honkala 1990). It would certainly be worthwhile to do more research on these Big Trees and determine what characteristics they have that have allowed them to remain standing tall in the wake of the devastating 2015 – 18 KSHB infestation.

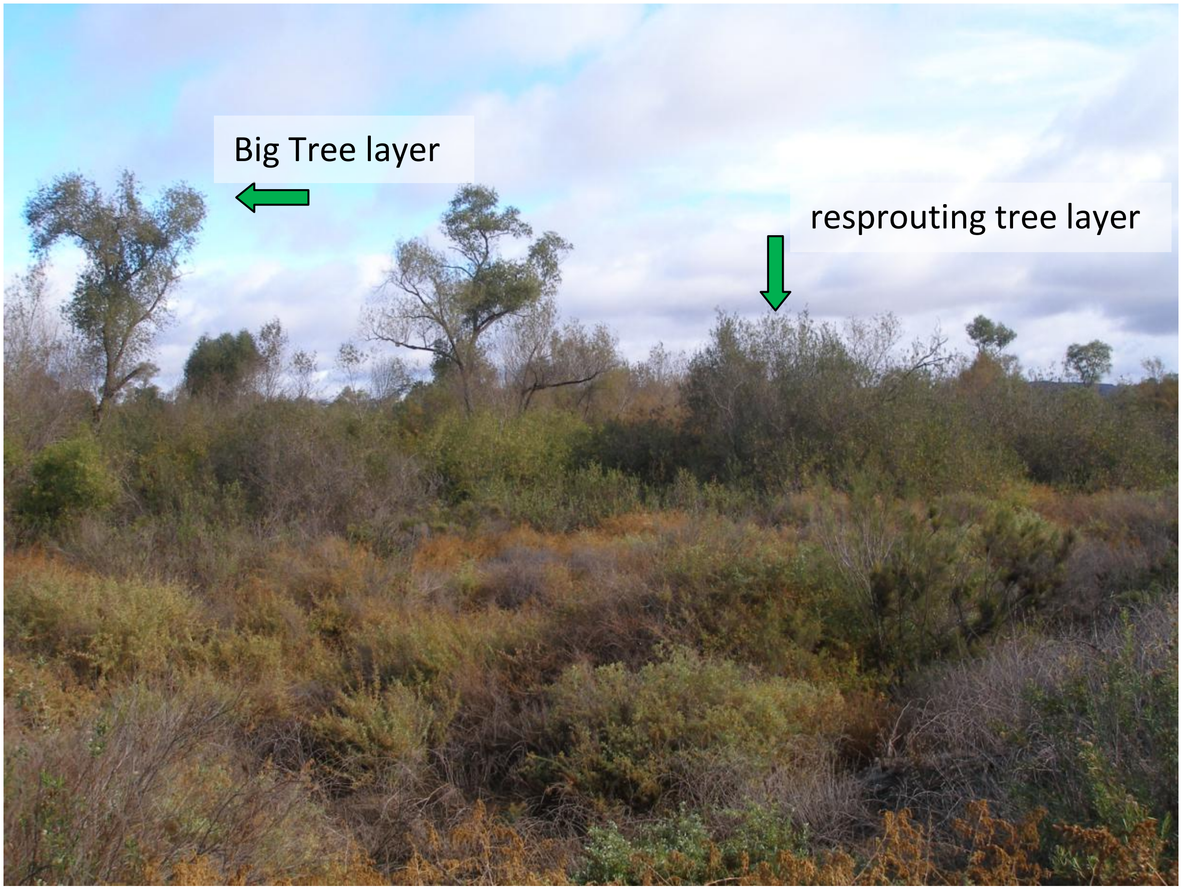


Figure 23. An overview of a Wet Forest (Unit 9) showing the two-layered canopy: the sparse, emergent layer created by the few remaining Big Trees (SAGO in this case), and the denser, lower layer composed of resprouting willow trees and willow seedlings.

5.5. DISTRIBUTION OF THE SURVIVING ORIGINAL WILLOWS IN THE VALLEY (2014-19; Uyeda)

The goal of this analysis was to map the surviving original willows in the Tijuana River Valley. These are the Big Trees that form an important part of the current forest canopy.

Methods

The surviving original willows in the Tijuana River Valley were identified using canopy height based on 2016 aerial imagery with 15 cm spatial resolution. This imagery was flown with sufficient overlap to produce a digital surface model (DSM) using the image processing technique structure from motion (SfM). While less accurate than lidar, the DSM produced using SfM is far less expensive, making it possible to repeat imaging at a higher temporal frequency (Wallace et al. 2016). I used the 2014 lidar as the digital elevation model (DEM) in order to take advantage of the higher accuracy of this ground elevation source. The lidar-based DEM was subtracted from the SfM-based DSM to determine the canopy height in 2016.

Next I removed all areas with canopy normalized difference vegetation index (NDVI) decline of at least 0.1 in 2017 - 2019. Some of these areas possibly experienced only a reduction in canopy health, not a full loss of the canopy structure. However, in the absence of recent canopy height information, the decline in NDVI served to identify likely areas of KSHB infestation. I also removed areas that had been mapped as *Arundo donax*, as well as areas that were clearly *Eucalyptus spp.* groves. Occasional *Eucalyptus spp.* individuals might remain within the riparian forest canopy.

Results

- The Big Trees were originally most common in the Wet Forests; in 2014 the Wet Forests contained 53% of the Big Trees in the valley and the Dry Forests only 38% (Table 8).
- The KSHB invasion damaged so many of the trees in the Wet Forests that now the Big Trees are most common in the Dry Forests; in 2019 the Dry Forests contained 58% of the Big Trees in the valley and the Wet Forests only 24% (Table 8).
- The remaining tall riparian forest trees are located throughout the valley, particularly outside the main route of the polluted flows (Figure 24).
- In many Dry Forests the remaining tall trees form a continuous canopy layer, whereas in the polluted Wet Forests they are usually only single Big Trees.

Table 8. The area of Big Trees remaining from the original forests.

HABITAT	TOTAL AREA	AREA OF BIG TREES			
		original	% tot. original	remaining	% tot. remaining
		2014	2014	2019	2019
	hectares	hectares	%	hectares	%
Wet Forests	120.8	67.6	53%	8.6	24%
Dry Forests	111.6	48.5	38%	20.8	58%
Scrub Forests	418.8	12.4	10%	6.3	18%
Total	651.1	128.5	100%	35.7	100%

Discussion

The KSHB heavily damaged the Wet Forests with the result that now most of the remaining Big Trees are found outside the polluted river flows, i.e., in the Dry and Scrub Forests. These remaining Big Trees will likely play an important role in the recovery of willows in the river valley.

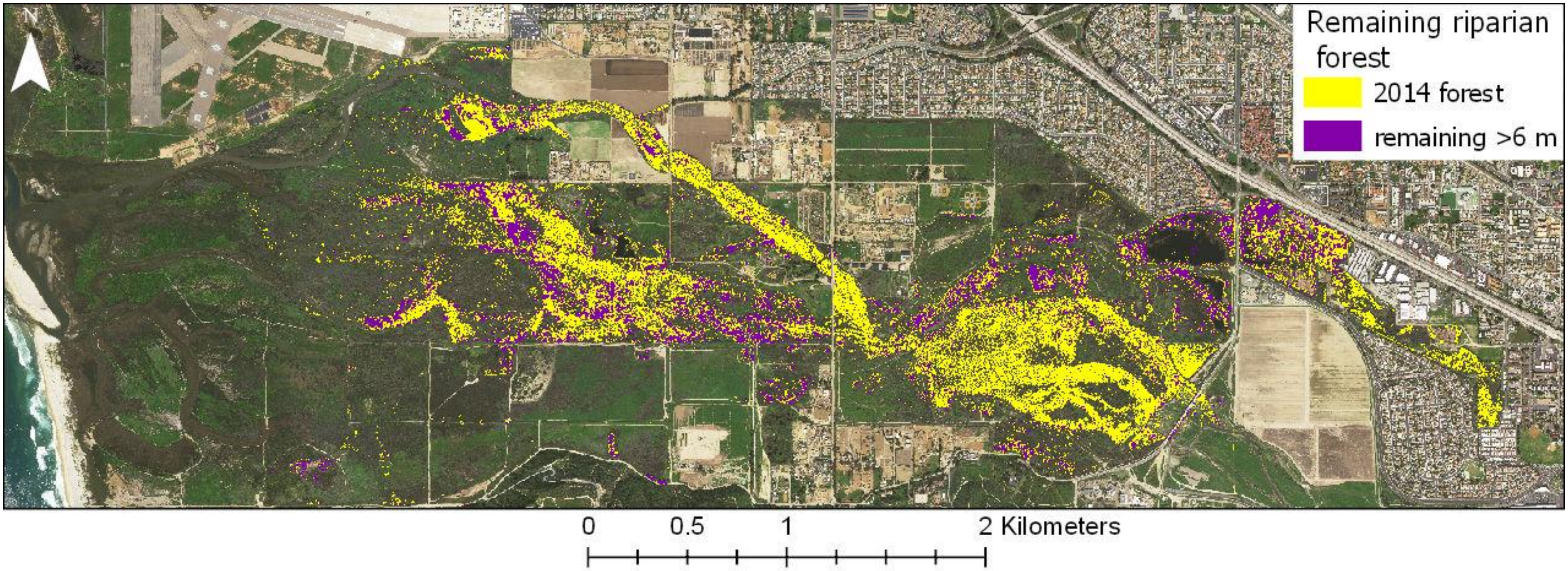


Figure 24. The remaining Big Trees (> 6m tall) in the riparian forests of the Tijuana River Valley as of spring 2019. [Map created by Kellie Uyeda, March 2020.]

5.6. DISTRIBUTION OF ARUNDO IN THE VALLEY (2019; Uyeda)

The goal of this analysis was to map the extent of arundo (*Arundo donax*) in the Tijuana River Valley. Arundo is the worst invasive plant in the valley and one of the worst in California (Cal-IPC 2006). It is a tall perennial grass (family Poaceae) that typically forms dense stands in riparian areas and disturbed sites. It severely degrades wildlands by altering vegetation structure, displacing native plant species, reducing habitat quality for native animal species, and increasing fire frequencies (Boland 2006).

Methods

Arundo was mapped using a combination of automated and manual techniques. I used the object-based imagery analysis (OBIA) software eCognition to identify likely arundo patches, then manually corrected the patches as necessary. In contrast to traditional pixel-based approaches to automated mapping that are based on the values of individual image pixels, OBIA techniques first group the image into spatially contiguous segments. These segments can then be classified based on their spectral or contextual characteristics. Initial imagery inputs include 15 cm spatial resolution, 4 band (red, green, blue, near-infrared) imagery collected in 2016, as well as canopy height from 2014 lidar. Although it was not the most recent imagery available, the 2016 imagery was selected because it was the highest spatial resolution product available after the start of the KSHB infestation in 2015. I used a combination of supervised classification and user-defined rulesets within eCognition to produce the initial map.

The arundo map was manually revised using the original 2016 imagery as well as National Agriculture Imagery Program (NAIP) imagery collected in March 2019. The NAIP imagery has a spatial resolution of 60 cm and includes 4 bands (red, green, blue, near-infrared). The NAIP imagery was viewed as a false color-infrared image (near-infrared, red and green bands displayed as RGB) to allow for easier visual interpretation of arundo.

Results

- Arundo is widespread in the river valley, with the highest concentrations occurring in the eastern portion and along the Pilot Channel in the south west (Figure 25).
- I estimate that arundo covers a total of 29 hectares, or 71 acres, in the river valley.

Discussion

Arundo is unfortunately abundant in the valley, particularly in the eastern portions of the valley. Arundo has benefited from the increased light that followed the KSHB-damage to the willow canopy, and is now growing strongly in the heavily-damaged forests.

Arundo is the most persistent and difficult invasive plant in the valley. It is spread mainly by bulldozers and other heavy equipment; bulldozers break-up rhizomes and make the rhizomes available for downstream spread by water flows (Boland 2008). That is the reason arundo is most abundant in the eastern forests immediately downstream of

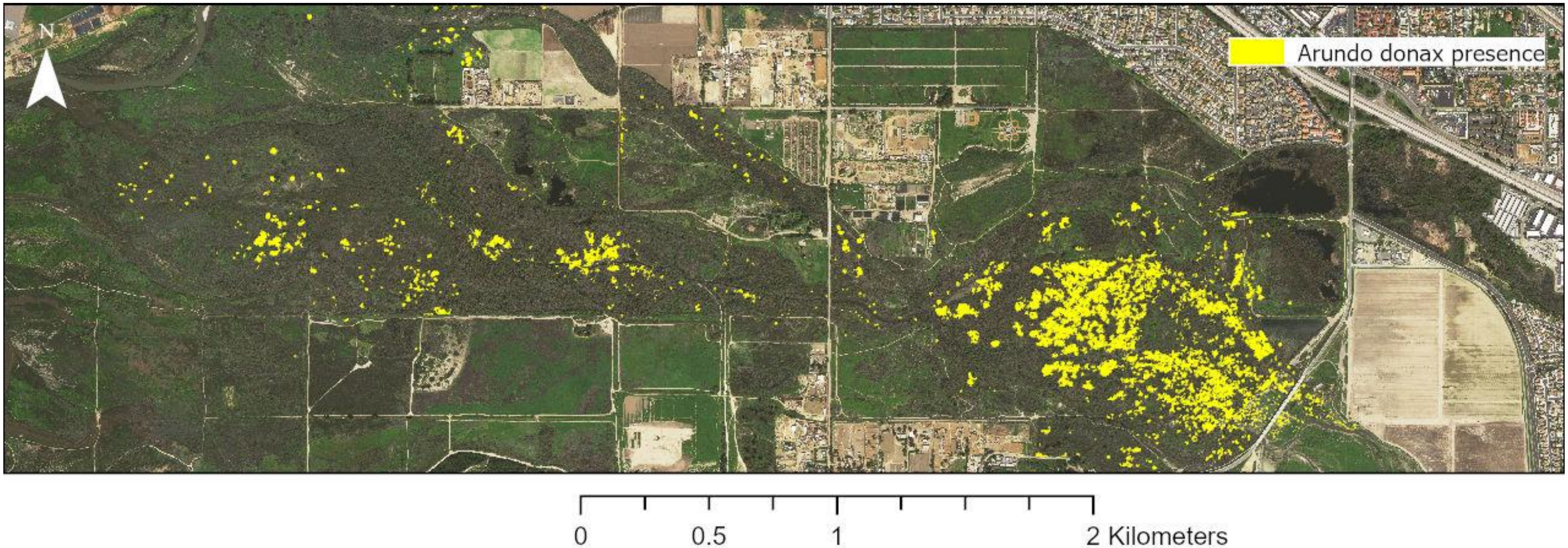


Figure 25. The distribution of Arundo donax in the Tijuana River Valley. [Map created by Kellie Uyeda, January 2020.]

where the International Boundary and Water Commission (IBWC) has been bulldozing, disking, and mowing the arundo on its property for decades (Boland unpublished data).

The control of arundo would greatly reduce its abundance in the valley and thereby greatly assist the recovery of the native forests. As shown in Section 5.2 above the willows are adept at reestablishing themselves in open spaces and will do so abundantly if given the chance. The treatment of arundo should be the highest priority for all managers of properties in the Tijuana River Valley in order to restore these valuable riparian forests.

5.7. CONCLUSIONS

While the first storyline coming out of the KSHB's invasion of the Tijuana River Valley was the boom-and-bust nature of the KSHB outbreak, the second main storyline is that **the vegetation in the damaged forests has responded rapidly**. Willows have responded in three ways: by surviving the KSHB attack mostly intact and appearing now as Big Trees; by being heavily damaged initially but then resprouting and now occurring as vigorously growing resprouting trees; and by the seeding of new trees.

The Big Trees are interesting because they are Plus Trees, i.e., *a tree that in its outward appearance (phenotype) is superior to the average tree of the same species grown at a similar site*; it would certainly be worthwhile to determine what characteristics have made them superior. The resprouting willows are important because they show that even heavily-infested and heavily-damaged trees can survive a KSHB attack and recover. The successful establishment of the willow seedlings shows the ease with which native willows became densely established in clearings, a feature that can be used in natural restoration projects.

Some invasive species are unfortunately thriving in the recovering Wet Forests in the Tijuana River Valley. Arundo, in particular, degrades the forest and reduces the value of the habitat for native species. The best way for a manager of a parks in the Tijuana River Valley to manage the KSHB invasion is to control arundo thereby greatly assisting the natural restoration of the native forests.

6. THE KSHB HAS NOT SUBSTANTIALLY REINVADED THE RECOVERING FORESTS

6.1. THE UNEXPECTED SITUATION

The recovering willows in the Wet Forests are forming forests similar to what was present before the KSHB invasion (Figures 16 and 22), and the trees are not being substantially reattacked by the KSHB.

Many scientists have predicted that the recovering willows would be quickly reinfested. For example, Eskalen said that the resprouts would be reinfested by the time they reached 1 inch in diameter (Eskalen quote in Sahagun 2017). But, in the 2019 surveys of the recovering Wet Forests I found:

- 0% of the resprouts were infested (i.e., 0 of 217; Table 5);
- 0% of the seedlings were infested (i.e., 0 of 274; Table 3);
- 1% of the young trees were infested (i.e., 3 of 220; Table 3);
- 2% of the resprouting trees were infested (i.e., 6 of 358; Table 3); and
- 3% of the Big Trees were infested (i.e., 6 of 180; Table 3).

This unexpected and fortunate situation begs the question: **Why are the recovering willows not being substantially attacked by the KSHB?**

It is especially surprising that the Wet Forests have not, so far been reinfested because the conditions we know the KSHB require are all present (Section 4.5):

1. **Host species**. The trees recovering in the Wet Forests are the preferred host species of the KSHB, i.e., black willow and arroyo willow (Boland 2016; Coleman et al 2019; UCR 2020).
2. **Host size**. The recovering willows are now at the size that the KSHB preferred during the initial KSHB attack in 2015-16, i.e., trunk diameters > 4.5 cm (Boland 2017b). In fall 2019 the trees in the recovering Wet Forests included many resprouting trees with mean diameters of 6.5 cm (Section 5.1), and many new seedlings with mean diameters of 11.7 cm (Section 5.2).
3. **Nutrients in water**. The recovering forests are located in the preferred sites of the KSHB, i.e., where the willows are nutrient-enriched by sewage spills (Boland and Woodward 2019). Sewage spills into the Tijuana River Valley continued unabated during 2019 and, in fact, increased in volume and frequency (Figure 26).
4. **Host condition**. The trees in the recovering forests are in the condition preferred by the KSHB, i.e., the trees are fast-growing and vigorous (Boland and Woodward 2019).
5. **KSHB present**. The KSHB is present – some are infesting a few of the trees in the Wet Forests (Table 3) and many more are in the Dry Forests, less than 1 km away (Section 4.1).

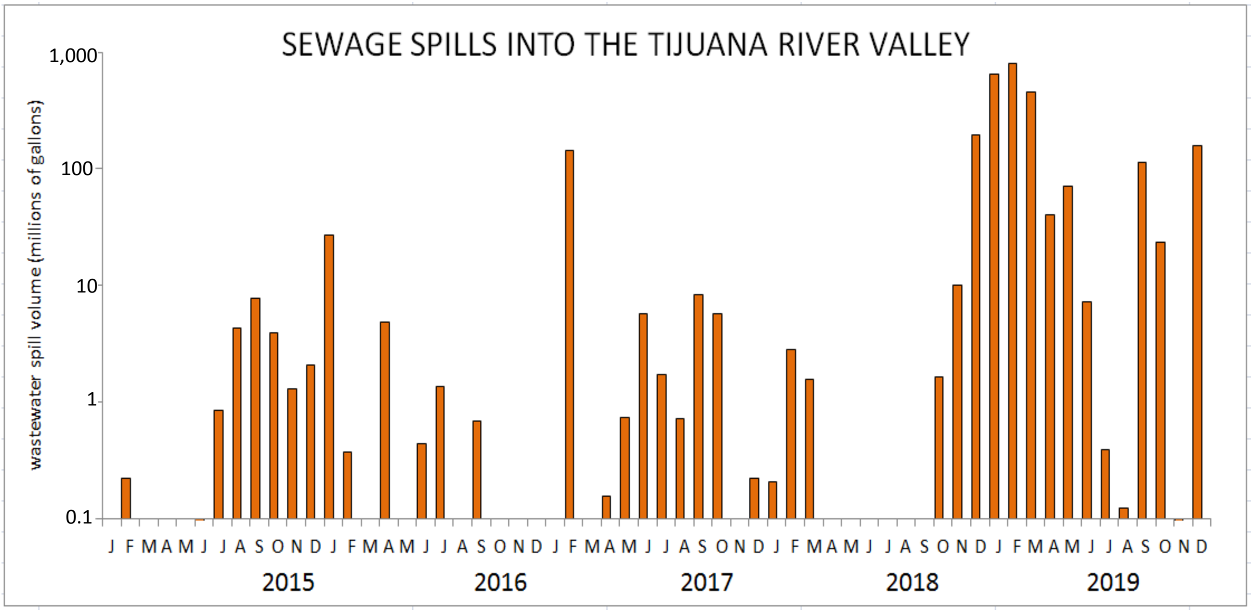


Figure 26. The magnitude of sewage input into the Tijuana River Valley during 2015 – 19. The data are monthly totals in millions of gallons; 2015-17 data are from Boland and Woodward (2019), and 2018-19 data are from San Diego Regional Water Quality Control Board (2020).

Here I present three possible reasons why the recovering Wet Forests are not being substantially reinvaded.

6.2. THREE POSSIBLE REASONS

As all of the requirements that have an influence on the severity of an KSHB attack have been met ***there must be another factor***, or factors, preventing the substantial return of the KSHB to the recovering forests. I suggest three possible factors here.

1. Induced response of hosts. It is possible that the infested willows have changed their chemistry as a result of the borer attack, and this has increased the resistance of the surviving trees to further borer attacks (first suggested in Boland 2019). Herbivore-induced change in chemistry is common and called an "induced response" (Karban and Myers 1989). Amazingly this induced response can be passed from an infested adult to its offspring (Balogh et al. 2018). Therefore induced response may explain why the surviving Big Trees, surviving resprouting trees *and* seedlings in the Wet Forests have not been substantially attacked by a second wave of KSHB.

2. Overall forest structure. It is possible that the willows, though individually suitable, no longer present a suitable group target for the KSHB. Previously the willows were densely-packed in pure, single-aged stands (Boland 2014a) but now, in the developing forests, willows are less dense and mixed with other species, particularly reeds and arundo. This change in forest structure over the past few years is the kind of change that forest entomologists recommend in order to make a forest less susceptible to an insect outbreak (Knight and Heikkenen 1980). They call it "preventive control by silvicultural" practices, in which pure, dense, single-aged stands are changed to stands of mixed age-classes, mixed species, and lowered densities. Just thinning stands has been consistently noted as a tool to reduce a stand's susceptibility to many pest species, e.g., Southern Pine Beetle (*Dendroctonus frontalis* Zimmermann; Coulson and Klepzig 2011). Certainly there have been changes in the structure of the Wet Forests including thinning, and this could be the reason the KSHB has not reinvaded the otherwise apparently suitable Wet Forest trees.

3. A disease or predator. It is possible that the KSHB population in the valley is now being kept low by a pathogen, parasite, parasitoid or predator. The boom-and-bust cycles of insect outbreaks are frequently linked to one of these causes (Dwyer et al 2005) and it has been recently shown that even viruses play an important role in the dynamics of trophic webs (Monterroso et al 2016). It is possible that during the abundant phase of the KSHB in the valley one of these population regulators became established and is now keeping the KSHB population in check. No such pathogen, parasite, parasitoid or predator has been identified, but then the cryptic nature, small size and current rarity of the KSHB means that finding such an agent would require a determined effort.

6.3. CONCLUSION

It will take work and imagination to answer the question *Why are the recovering willows not being attacked by the KSHB?* But successfully answering this question would provide essential information about the KSHB invasion in southern California and about shot hole borers in general.

7. RECOMMENDATIONS

7.1. RESEARCH RECOMMENDATIONS

The data and research presented in this report suggest the following areas for valuable future research:

1. Why are KSHB not substantially reinvading the recovering willow forests?
The recovering willows in the Wet Forests were not being substantially reinfested by the KSHB in 2019-20, even though all of the conditions we suspect KSHB require were present – correct host species, host condition and host size (Section 6.1). I recommend testing the three hypotheses I suggested in Section 6.2 because, as I say above, successfully answering this question would provide essential information about the KSHB invasion in southern California and about ISHB in general.

2. ISHB dispersal by air.
I suggest that the dispersal of the ISHB (i.e., KSHB and PSHB) within southern California is most likely through the air. If willow seeds can land in abundance in

suitable sites using wind (Boland 2014a, 2017a) then the ISHB can too. The borers have brains, small bodies, and functional wings – all characteristics that make dispersal by wind likely. Long-distance dispersal by wind is notoriously difficult to study, but that doesn't mean it doesn't occur. I recommend searching for ISHB in the air high above infested trees; this could involve the use of nets or traps attached to aircraft, hot-air balloons, helium balloons or drones (e.g., Milius 2019).

3. Nutrients and tannins inside enriched trees.
Understanding the mechanism behind the Enriched Tree Hypothesis (Boland and Woodward 2019, and Section 4.5) would be valuable. I suggest two avenues of research. The first has to do with the growth of KSHB's symbiotic fungi. All fungi require sugars and nutrients, such as nitrogen and phosphorus, for growth (Kendrick 1992), the symbiotic fungi in enriched trees are likely to be heavily nutrient loaded in two ways – phloem sap loaded with sugars from the fast-growing leaves, and xylem sap loaded with nutrients from the enriched soil. The research question would be: Do these extremely high nutrient conditions in the host trees promote the fast growth of the symbiotic fungi and, ultimately, the fast growth of the beetles?

A second possible explanation for the Enriched Tree Hypothesis pattern has to do with tannins, which are compounds that protect woody plants from herbivores and diseases. The amount of tannin within quaking aspen (*Populus tremuloides*) varies from site to site in a predictable way; trees growing in fertile soils produce fewer tannins and are more vulnerable to insect attack, whereas trees growing in non-fertile soils produce more tannins and are less vulnerable to insect attack (Thomas 2014). Therefore the mechanism underlying the Enriched Tree Hypothesis may be that the willows growing in the nutrient-enriched sites within the Tijuana River Valley produced fewer tannins and were more susceptible to KSHB attack than those growing outside the sewage-enriched sites. We need to determine whether there is a pattern in the tannin content of the willows and whether their concentration of the tannins can influence the abundance, growth and survivorship of the KSHB.

4. Cost-benefit analysis of infested-tree removal.
Managers are currently being advised to remove trees that are heavily-infested with ISHB, partly because removing an infested tree removes a source of beetles and might reduce the beetle's spread (Coleman et al 2019). But the costs, particularly the ecological costs, of removing the trees are not mentioned and actually there is only anecdotal evidence that removal is beneficial. To convince a manager that a valuable, but infested, sycamore should be removed from a natural woodland we need (a) experimental field data on the effectiveness of removing an infested tree in slowing the spread of ISHB, and (b) a cost-benefit analysis that weighs the whole cost (economic and ecological) against the measured benefits. Only with all this information on hand can a manager be expected to make an informed decision on removal.

5. Improve numerical models.
So far only one model has been used to estimate the impact of the ISHB in southern California; this model estimated that 11.6 million trees could be lost from the urban

forests in southern California at a cost of $15.9 billion (McPherson et al. 2017). Unfortunately this model greatly exaggerates the likely impact of the ISHB because it uses a long list of host species (55 species), most of which are not killed by the ISHB, and presumes that 50% to 80% of these host individuals will be killed. In addition, it presumes that to the ISHB all host individuals and all host sites are equal, which is clearly not the case (see Enriched Tree Hypothesis in Section 4.5). A more accurate numerical model should be developed to predict the impacts of an ISHB infestation in a natural riparian habitat. More reasonable criteria should be incorporated into the model including a more accurate host species list and all of the ecological criteria listed in Section 4.5. The predictions of such a model would provide something worthwhile to the managers of natural habitats.

These five areas of research would provide valuable information about the ecology, behavior and management of the KSHB in southern California.

7.2. MANAGEMENT RECOMMENDATIONS

The results reported here and in previous reports (Boland 2017b, 2018, 2019) support the following management actions.

<u>Parks in the Tijuana River Valley</u>

- **Little can be done about managing the KSHB itself because it is so well-established in the entire valley**. To quote Greer et al (2018): "*current strategies for management of this pest species are inadequate for large scale infestations like the one observed in the Tijuana River Valley*." The best thing to do is to continue to prune any KSHB-infested branches that hang over public places in order to reduce the hazard.

- **Control *Arundo donax*.** Arundo is flourishing in the valley partly because the KSHB attacked the willows, arundo's main competitor. Arundo significantly degrades a site and reduces the value of the habitat. The best way for park managers in the valley to manage the KSHB problem is to control arundo and to allow the natural restoration of the riparian forests. We have provided a map of the current distribution of arundo using OBIA software (Figure 25).

<u>Trees currently infested with KSHB</u>

- **Do not remove infested trees thinking that they are going to die.** Managers are currently being advised that trees that are heavily-infested with KSHB will die and therefore these trees should be removed before they lose branches and before they add more beetles to the population. A tree is considered heavily-infested when there are > **18 holes per 232 cm^2** (Coleman et al 2019) or > 150 holes on a tree (Nobua-Behrmann 2020). As discussed in Section 5.1, willows can survive very heavy infestation rates: a Big Tree healed a branch that had **52 holes per 232 cm^2** and lived; and the resprouting willows have survived an attack that left an average of **141 holes per 232 cm^2** on their trunks. To claim that all heavily-attacked trees will die is certainly not the case and to set such a low threshold as18 holes per 232 cm^2 (Coleman et al 2019) is unfounded.

<u>Urban forests</u>

- **Do not over-fertilize or over-water trees.** Park rangers and city managers can lower the risk of KSHB infestation by not over-fertilizing or overwatering their landscape trees. Nutrient-enriched and fast-growing trees are more vulnerable to KSHB infestation.

<u>Restoration projects</u>

- **Continue to plant willows in new riparian restoration sites if the water quality is good.** Willows are not being attacked by KSHB in most sites in San Diego County and the worst willow attacks have occurred only where the worst sewage pollution occurs, so willows can and should be planted in most new riparian restoration sites in San Diego County, particularly where water quality is good.

- **Use 'natural restoration' methods to restore riparian sites**. Natural restoration is superior to the more commonly conducted horticultural restoration because it produces a forest community with a high density of trees, the appropriate down-slope zonation of species, and the appropriate sex ratios and genetic diversity (Briggs 1996, Boland 2014a).

<u>Searching for KSHB impacts in other parts of San Diego County</u>

- **Search in nutrient-enriched areas.** When searching for KSHB-infested trees in other riparian systems in San Diego County it is advisable to search the trees in sites where the water might be nutrient enriched, e.g., near storm drain outfalls.

8. ACKNOWLEDGEMENTS

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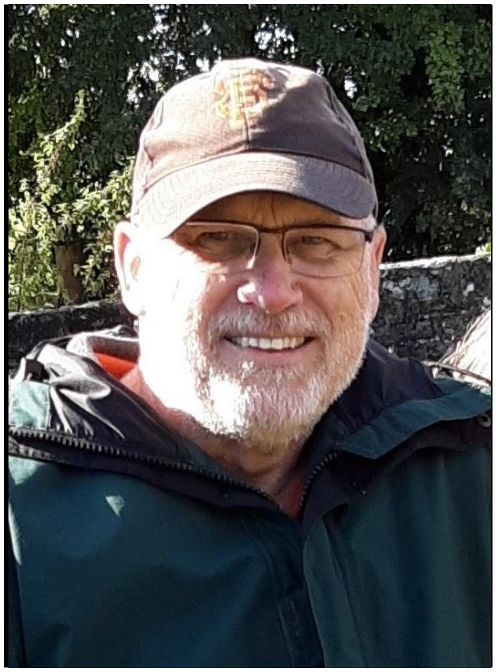
We thank the US Navy, US Fish & Wildlife Service, California State Parks, County of San Diego Department of Parks and Recreation, IBWC, and the City of San Diego for allowing one of us (JMB) access to their properties.

We also thank Monica Almeida at TRNERR for assisting with the mapping, Deborah Woodward for editing, and Jeff Crooks at TRNERR for helpful advice. We thank Mayda Winter, Lisa Lyren, Joyce Sisson, Tracy Ellis and Jeff Crooks for constructive comments on the report. We've had very useful conversations with Greg Abbott, Tracy Ellis, Lawrence Kirkendall, Elizabeth Onan, Mayda Winter, Jeff Crooks and Deborah Woodward – we thank them all.

9. AUTHOR BIOS



John Boland is a plant ecologist. He has conducted research within the Tijuana River Valley for more than 20 years, and has published papers on the KSHB invasion (Boland 2016, Boland and Woodward 2019), riparian community development (Boland 2014a, 2014b, 2017a), arundo (Boland 2006, 2008) and tamarisk (Whitcraft et al. 2007).

Kellie Uyeda is a post-doctoral researcher at the Tijuana River National Estuarine Research Reserve and the Department of Geography at San Diego State University. She specializes in remote sensing of vegetation patterns.

10. PHOTOGRAPH DETAILS AND CREDITS

Here are the particulars for each photo used in the report.

Frontispiece	
= Figure 16A-D	
Figure 3A	
Date	August 24, 2018
Location	Unit 11, Tijuana River Valley
Subject/activity	Trees in the Wet Forest
Names of people	None
photographer	John Boland
Figure 3B	
Date	August 27, 2016
Location	Unit 18, Tijuana River Valley
Subject/activity	Trees in the Dry Forest
Names of people	None
photographer	John Boland
Figure 3C	
Date	June 30, 2016
Location	Unit 28, Tijuana River Valley
Subject/activity	Trees in the Riparian Scrub habitat
Names of people	None
photographer	John Boland
Figure 4A	
Date	October 5, 2015
Location	Unit 2, Tijuana River Valley
Subject/activity	Sawdust tubes coming out of KSHB holes
Names of people	None
photographer	John Boland
Figure 4B	
Date	October 5, 2015
Location	Unit 2, Tijuana River Valley
Subject/activity	KSHB holes
Names of people	None
photographer	John Boland
Figure 4C	
Date	October 18, 2019
Location	Unit 2, Tijuana River Valley
Subject/activity	Sawdust tubes coming out of KSHB hole
Names of people	None

photographer	John Boland
Figure 4D	
Date	October 18, 2019
Location	Unit 2, Tijuana River Valley
Subject/activity	Sawdust tubes coming out of KSHB hole
Names of people	None
photographer	John Boland
Figure 4E	
Date	November 25, 2015
Location	Unit 2, Tijuana River Valley
Subject/activity	KSHB coming out of KSHB hole
Names of people	None
photographer	John Boland
Figure 4F	
Date	November 11, 2015
Location	Unit 2, Tijuana River Valley
Subject/activity	KSHB tunnels in a snapped willow trunk
Names of people	None
photographer	John Boland
Figure 4G	
Date	February 4, 2016
Location	Unit 12, Tijuana River Valley
Subject/activity	Broken trunks in forest
Names of people	None
photographer	John Boland
Figure 4H	
Date	February 4, 2016
Location	Unit 12, Tijuana River Valley
Subject/activity	Broken trunks in forest
Names of people	None
photographer	John Boland
Figure 13A	
Date	February 4, 2016
Location	Unit 3, Tijuana River Valley
Subject/activity	Heavily damaged willows
Names of people	None
photographer	John Boland
Figure 13B	
Date	September 12, 2018

Location	Unit 15, Tijuana River Valley
Subject/activity	Lightly damaged willows
Names of people	None
photographer	John Boland
Figure 16A	
Date	May 15, 2015
Location	Unit 2, Tijuana River Valley
Subject/activity	The forest before the KSHB infestation
Names of people	None
photographer	John Boland
Figure 16B	
Date	February 4, 2016
Location	Unit 2, Tijuana River Valley
Subject/activity	The forest after the KSHB infestation
Names of people	None
photographer	John Boland
Figure 16C	
Date	March 23, 2018
Location	Unit 2, Tijuana River Valley
Subject/activity	The forest during recovery
Names of people	None
photographer	John Boland
Figure 16D	
Date	August 21, 2019
Location	Unit 2, Tijuana River Valley
Subject/activity	The forest during recovery
Names of people	None
photographer	John Boland
Figure 18A	
Date	August 25, 2019
Location	Unit 8, Tijuana River Valley
Subject/activity	Growth of resprouts on old stump
Names of people	None
photographer	John Boland
Figure 18B	
Date	August 25, 2019
Location	Unit 8, Tijuana River Valley
Subject/activity	Growth of resprouts on old stump
Names of people	None
photographer	John Boland

Figure 20A	
Date	January 19, 2018
Location	Unit 2, Tijuana River Valley
Subject/activity	Recruitment of stand of seedlings
Names of people	John Boland
photographer	Deborah Woodward
Figure 20B	
Date	December 20, 2019
Location	Unit 2, Tijuana River Valley
Subject/activity	Survival and growth of stand of seedlings
Names of people	None
photographer	John Boland
Figure 20C	
Date	May 22, 2017
Location	Unit 3, Tijuana River Valley
Subject/activity	Recruitment of stand of seedlings
Names of people	John Boland
photographer	Deborah Woodward
Figure 20D	
Date	October 21, 2019
Location	Unit 3, Tijuana River Valley
Subject/activity	Survival and growth of stand of seedlings
Names of people	None
photographer	John Boland
Figure 20E	
Date	October 28, 2016
Location	Unit 12, Tijuana River Valley
Subject/activity	Recruitment of stand of seedlings
Names of people	None
photographer	John Boland
Figure 20F	
Date	August 21, 2019
Location	Unit 12, Tijuana River Valley
Subject/activity	Survival and growth of stand of seedlings
Names of people	None
photographer	John Boland
Figure 22A	
Date	April 16, 2013
Location	Unit 11, Tijuana River Valley

Subject/activity	The forest before the KSHB infestation
Names of people	None
photographer	John Boland
Figure 22B	
Date	December 29, 2016
Location	Unit 11, Tijuana River Valley
Subject/activity	The forest after the KSHB infestation
Names of people	None
photographer	John Boland
Figure 22C	
Date	June 26, 2017
Location	Unit 11, Tijuana River Valley
Subject/activity	The forest during recovery
Names of people	None
photographer	John Boland
Figure 22D	
Date	September 17, 2019
Location	Unit 11, Tijuana River Valley
Subject/activity	The forest during recovery
Names of people	None
photographer	John Boland
Figure 23	
Date	November 22, 2018
Location	Unit 10, Tijuana River Valley
Subject/activity	Forest consists of two layers
Names of people	None
photographer	John Boland

11. LITERATURE CITED

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