Assessing the adaptation potential of pest Cultural Management Practices (CMPs) for spotted wing Drosophila on tart cherry orchards in Michigan

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1. <u>Abstract</u>

Spotted wing Drosophila (*Drosophila suzukii)*, or SWD, a fruit fly native to East Asia, has become pervasive on fruit farms across North America in the past decade, laying its eggs inside thin-skinned fruits. Its short generation time, release from native predators, and modified, serrated ovipositor make infestation rates difficult to control. Many tart cherry growers in Michigan combat increasing populations with broad spectrum pesticides like pyrethroids and organophosphates, risking increased pesticide resistance and declines in populations of natural enemies of SWD. In response to these threats, cherry growers have applied cultural management practices (CMPs) and considered supporting native and introduced parasitoids in their integrated pest management programs to more effectively control SWD infestation. Our research evaluated the effect of four cultural management treatments (factorial combinations of mowing and pruning) on SWD and parasitoids (Hymenoptera) in the trees and grasses of four Montmorency tart cherry orchards in West Central Michigan. We vacuum-sampled arthropod communities twice before harvest, when cherries were susceptible to SWD infestation, and once three weeks after harvest, to assess community dynamics throughout the growing season. We also performed semi-structured interviews with Michigan tart cherry growers to understand their adaptive responses to SWD and feelings about CMPs as behaviors for adapting to the threats of SWD. We found no difference in SWD or parasitoid abundances between the cultural management treatments across sampling events. SWD and parasitoid abundances peaked at opposite times in relation to the day of harvest, suggesting potential phenological mismatches between the two groups. Overall abundance of SWD was low for the season compared to previous years, likely due to significant drops in temperature over the 2017-2018 winter season, killing populations of overwintering adults. These results were comparable to growers' perceptions of the low efficacy of CMPs as effective methods for reducing SWD abundance. Growers generally saw CMPs as supplementary to chemical sprays but without potential to replace or reduce spraying. Alternatively, many growers recognized the risk of pesticide resistance and regulation that could reduce the efficacy of chemical pesticides, their primary method of response to SWD. Integrating a diversity of pest management practices into current regimens should continue to be explored for its ability to replace chemical pesticide application, support diverse native natural enemy populations, and sustain economically viable agricultural systems now and in the future.

2. **INTRODUCTION**

2.1 Michigan Tart Cherries

Michigan is the number one grower of Montmorency tart cherries (*Prunus cerasus)* in the nation, accounting for 75% of US tart cherry production (Michigan Ag Council, 2016). From 2013 through 2016, the U.S. Department of Agriculture's Economic Research Service reported over $250 million in cash receipts from tart cherry production, placing it in the state's top 15 commodities ("Michigan Agricultural Statistics 2016-2017"). Bred for their cold resiliency, Montmorency tart cherries are best suited to be grown in northern regions with moderate summers and cool winters. However, these trees are susceptible to dramatic changes in temperature, such as very cold winters, spring frosts, and early freezes in the fall (Fogle, Cochran, and Keil, 1974; Wang et al., 1999). In addition to the crop's climatic vulnerability, an invasive fly species, spotted wing Drosophila, is placing mounting pressures on the viability of this crop in the region (Zavalloni et al., 2004).

2.2 Spotted Wing Drosophila and Management

Spotted wing Drosophila (SWD, *Drosophila suzukii)*, an invasive pest species originating from Southeast Asia, first appeared on Michigan farms in 2010 and has since spread to all cherry-growing counties in the state. This fly specializes on thin-skinned fruits and a female may oviposit around 300 eggs in cherries (or similar fruits) in her lifetime. Larvae feed on the inside of the fruit, leaving the fruit unfit for sale (Wilson et al., 2017). In addition to economic losses from other pests, climate sensitivity and international market competition, US thin-skinned fruit production has incurred over $500 billion dollars in losses since the arrival of SWD (Bolda, Goodhue and Zalom, 2010).

Extension services, including Michigan State University's extension service, recommends the use of a variety of registered insecticides to manage invasive populations and avoid pesticide resistance, but this may come at a significant economic and health costs to growers (Longstroth, 2017). In addition to the financial costs of spraying chemical pesticides frequently and abundantly to effectively control fly populations in the short term, there is an association between high pesticide exposure and nervous system damage, with implications for both physical and emotional well-being to the growers (Freire 2013). Additionally, pesticides have negative effects on the physiology and behavior of beneficial arthropods, suggesting potential degradation of the predatory ecosystem services they provide (Desneux, 2007; Michaud and Grant, 2003). The use of non-chemical management strategies may reduce the impact of this pest and also the risks to growers and the entire ecosystem (through reduction in pesticide application), as well as the likelihood of pesticide resistance.

Biocontrol by parasitiods (Hymenoptera) is also being considered as an alternative to pesticides for reducing SWD on tart cherries in North America. Non-native parasitic wasps from the SWD native ranges could be introduced on farms infested with SWD. However, the introduction of non-native parasitoids requires a lengthy period for research and approval, and these could potentially parasitize other beneficial arthropods in the community (Hawkins et al., 1994). Thus, it is essential to also assess the potential for native predators and parasitoids to control SWD. Native larval and pupal parasitoids, i.e. the pupal parasitoids *Trichopria drosophilae* and *Pachycrepoideus vindemiae*, and the larval parasitoids *Leptopilina boulardi, Asobara tabida,* and *Leptopilina heterotoma,* have been identified as potential parasitoids for SWD (Burrack and Diepenbrock n.d.). While few field observations have supported the effectiveness of these generalist natural enemies on the biological control of SWD, they may still be an important component of a diversified pest management regimen (Haye et al., 2016).

The current rate of pesticide usage threatens the efficacy of parasitoids or other natural enemies in contributing to the control of SWD. Broad spectrum pesticides do not selectively kill pests but kill beneficial arthropods as well. They also disrupt parasitoid development, creating phenological mismatches between parasitic wasps and their host flies (Desneux, 2007). Alternatively, the integration of sustainable pest management strategies (e.g. exclusion nets, cultural management, etc.) may reduce the frequency or intensity at which pesticides are applied, mitigating harm to native natural enemies. SWD has low tolerance for high heat and is attracted to environments with higher humidity (Ryan et al., 2016; Tochen et al., 2016). Cultural management practices (CMPs), like pruning, can increase canopy air flow and sunlight, reducing humidity, temperature and ultimate suitability for SWD. Nearby grasses may maintain moisture in the shade of the tree canopy, potentially serving as suitable habitat for SWD. Previous work by Northwest Michigan Horticulture Research Center showed that on controlled research blocks, frequent mowing and annual pruning reduced SWD incidence (Jones and Rothwell, 2018). These cultural management practices may reduce the impact of this pest and reduce the risks to growers and the entire ecosystem if pesticide application is reduced. One of the goals of our study was to expand that work to commercial cherry orchards by investigating natural enemy communities associated with these CMPs as well as the potential of CMPs to promote grower adaptation to SWD.

2.3 Threat Response

CMPs may provide an alternative management strategy for SWD, but understanding practitioner response to the threat of SWD and use of CMPs is equally important in creating an effective management plan. Frameworks that explain individual responses to threats of climate change have recognized the importance of psychological and social drivers to an individual's threat response (Riser and Swim, 2011). This includes how individuals perceive the probability

and severity of the threat (i.e. threat appraisal) as well as how they perceive their ability to respond to the threat with the tools at hand (i.e. coping appraisal). While cognitive mechanisms that influence an individual's response to invasive species are rarely studied, rhetoric used to explain the unpredictability and uncontrollability of invasive species is often used in models for explaining individual adaptive responses to climatic and weather threats (Bubeck et al., 2012; Crowley et al., 2017). Applying climate adaptation frameworks, like Grothmann and Patt's model of private proactive adaptation to climate change (Grothmann and Patt, 2005; Fig. 1), to invasive species adaptation could promote more robust understanding of the barriers to and mechanisms for growers' potential for adaptation to SWD.

The goal of this project was to assess the ability of CMPs to serve as adaptation behaviors to SWD by examining the following three questions: 1) how well do CMPs control SWD?; 2) how do CMPs influence parasitoid populations?; and 3) how do growers' appraisals of the threat of SWD and their ability to cope with it influence their adaption responses to SWD? For the first and second questions we measured the abundances of SWD and parasitic wasps on four different cultural management regimens on tart cherry orchards in West Central Michigan. For the third question we interviewed tart cherry growers to understand how their perceptions of the risks of SWD and their perceived ability to respond to SWD influenced their ability to adapt to the pest. Because mowing and pruning may reduce habitat suitability for parasitoids and SWD, we expected to see fewer arthropods in treatments with more mowing and pruning. Due to the high adherence to pesticide application in the tart cherry community, we also expected few farmers to be using mowing and pruning as adaptation behaviors to SWD.

3. <u>METHODS</u>

3.1. Arthropod Data

3.1.1. Study location and treatments

The data on SWD and parasitoids were collected on four Montmorency tart cherry orchards in West Central Michigan in Mason and Oceania counties, located between 43.9137° to 43.5475° north to south and -86.1928° to -86.4316° east to west. The orchards varied in size, tree age, and chemical pest management schedules. The managers of each of the tart cherry orchards in the study were asked by Michigan State University Extension to implement different combinations of cultural management practices to assess the effects of management on the weekly trap abundance of SWD. Pruning trees reduces canopy density and humidity, increasing spray coverage and decreasing the tree's hospitability for SWD, and mowing may decrease the amount of suitable refuge habitat for SWD. Such practices could have the same negative effects on native parasitoids but may be incorporated into more robust integrated pest management regimens and could encourage reductions in pesticide use. The treatments included: 1) pruning the trees before the growing season and following a standard mowing procedure (mowing once at the start of the season and once just before harvest); 2) pruning the trees before the growing season and mowing every two weeks during the growing season; 3) not pruning the trees before the growing season and following a standard mowing procedure; and 4) not pruning the trees before the growing season and mowing every two weeks during the growing season (Figure 2).

3.1.2. Sampling

In order to capture both SWD and natural enemies, we vacuum-sampled cherry trees and grasses in each of the treatment plots using a reverse leaf blower and fine mesh bags fitted with rubber bands to the end of the vacuum. In rows in the middle of each treatment plot, we sampled arthropods from the lower and middle canopy of four trees spaced equidistance from one another. We vacuumed each sample tree for 30 seconds on both the north and south-facing sides of the trees. We then sorted the samples into separate bags. In the tree alleys we vacuum-sampled three grassy patches the width of the sample-tree block (about 12 paces) for one minute per patch in the alley one row away from the row of sample-trees. This reduced the potential of disturbance to grasses from foot traffic in the grasses adjacent the sample-trees. For each unit (tree or grass patch) sampled, we inverted the contents of the vacuum net into a gallon Ziplock containing a cotton pad soaked in 98% ethyl acetate to quickly kill the insects and stored the bags over dry ice in the field. We recorded humidity and temperature every hour and estimated vegetative cover and plant diversity of sample-tree blocks. We also measured the heights of three random pieces of grass in the grassy patches as a potential covariate and averaged the heights per patch. We sampled different trees within the same sampling row two weeks

before harvest (June 17-21) when cherries were first becoming susceptible to SWD, one week before harvest (June 29-30), and three weeks after harvest began (July 28). Using the android app Canopy, we estimated canopy cover from the bottom of the cone of the tree (i.e. where the main branch diversions from the trunk began) for the trees from the first sampling event (two weeks before harvest).

3.1.3. Sorting and identification

We stored the Ziplock bags in the freezer until insects could be carefully sorted from grasses and tree debris. We emptied all contents of the tree sample bags onto a tray for careful viewing under a stereoscope and sorted the arthropods into vials of 70% ethyl alcohol. For the tree samples, we brushed larger pieces of debris for any attached insects and systematically skimmed the remaining debris under the microscope for SWD and parasitic wasps, also sorting these into vials of 70% ethyl alcohol.

3.1.4. Data analyses

We assessed the implementation of treatments by comparing the canopy cover and grass height across treatments. We ran two-sample t-tests to make these comparisons, combining treatments with the same mowing and pruning practices. We evaluated the effects of each of the cultural management treatments on parasitoid abundance and SWD abundance using a zero-inflated Poisson model. In the first iterations of the model we used treatment type, temperature, canopy cover, humidity, vegetative ground cover, plant diversity, harvest time (a binary variable denoting before or after harvest), and the product of harvest time and days from harvest (harvesttime*DFH) as fixed effects. We used the Deviance Information Criterion (DIC) to decide which model to use. DIC is a hierarchical model generalization of the Akaike Information Criterion (AIC) that is particularly useful in Bayesian model selection. To estimate incomplete temperature data, we sampled missing data using the mean and precision of sampled temperatures. We included farm as a random effect to account for differences across farms other than the measured predictor variables. Due to the large number of zeros in the data we used four submodels following a zero inflated Poisson likelihood to analyze SWD abundance and predicted parasitoids. In the final models we included treatment, temperature, predicted parasitoid abundance and harvest time*DFH in the process model for SWD abundance. We predicted parasitoid abundance as a function of observed parasitoids, treatment and harvest time*DFH. For parameter estimation for both submodels we used a Bayesian framework from non-informative priors. We gave harvesttime*DFH, temperature, and observed parasitoids normal distributions with means of 0 and variances of 0.0001, and gave treatment priors lognormal likelihoods with a mean of 1 and variance of 0.0001. We used harvest time as a covariate to predict the probability of measuring a zero. We ran analyses in OpenBUGS (Surhone,

Tennoe, & Henssonow, 2010) with 200,000 iterations over two burn-in periods.

3.2 Qualitative Interview Data

3.2.1. Interview methods

We collected qualitative data via semi-structured interviews with 12 tart cherry growers from Mason, Oceana, Grand Traverse and Leelanau counties in Michigan to better understand drivers of their decision making and response to SWD (Figure 3). Each interview was performed over the phone with growers who were the primary decision-makers for their respective orchards, ranging from recently retired growers or growers who had just retired their tart cherry plots, to growers who were new to tart cherry management. Using theory from climate change adaptation literature, in the first cycle of coding we coded interviews for quotes related to threat appraisal, coping appraisal and objective adaptive capacity. Under these higher order themes, we divided codes into subthemes of perceived probability and perceived severity within threat appraisal and response appraisal, self-efficacy, and response cost within coping appraisal (Table 1). Coded quotes also informed emergent codes, which were more specific trends or concepts that arose from quotes within the subthemes. After the first 5 interviews, we organized and consolidated while following loose entry for the remaining seven interviews, cleaning, consolidating and re-binning along the way. We also listed interesting quotes to be considered for inclusion in analysis later, or to create new codes in second cycle coding. We edited code definitions continually based on new data (i.e. quotes) acquired with continual interview coding. During second cycle coding we edited, consolidated and re-binned selected quotes to come up with the final set of codes. Finally, we adapted Grothmann and Patt's process model of individual drivers of adaptation to climate change to model growers' responses to SWD.

4. <u>RESULTS</u>

4.1. Treatments

When pruning treatments were combined the canopy cover was significantly different between the two groups (t-statistic =39.7; $p < 0.0001$; Fig. 4). Additionally, when mowing treatments were combined the average grass heights were significantly different between the two groups (t-statistic = 5.1; $p < 0.0001$; Fig. 4).

4.2. Arthropods

4.2.1. Model fit

The model with the best fit (DIC for SWD submodel = 151.7; DIC for parasitoid submodel = 348.3) included parasitoid abundance, treatment, temperature and the harvest time coefficient as predictors of SWD abundance, and treatment, the harvest time coefficient and observed parasitoid abundances as predictors of predicted parasitoid abundance.

4.2.2. Predicted SWD abundances

There were no significant differences in SWD abundances across treatments (95% critical interval; Fig. 6). SWD did show an opposite trend in peak abundance when compared to parasitoids, with the majority of zeros occurring before harvest and non-zero counts occurring after harvest (Fig. 7). There were no significant relationships between SWD and temperature or SWD and predicted parasitoids (95% critical interval). There was an average of 0.24 SWD per sampling unit in the grasses. One grass sample from the second sampling event in the no-prune, 2-week mow treatment contained 11 SWD, an outlier compared to all of the other samples. We found no significant differences in SWD grass abundances across treatments nor any significant relationships between SWD abundance and other environmental variables (95% critical interval; Fig. 8).

4.2.3. Predicted parasitoid abundances

There were no significant differences in parasitoid abundances across treatments, although parasitoids showed more variability in counts when compared to SWD (Fig. 9). There was a significant difference in the abundance of parasitoids before and after harvest (with significantly more before than after; Fig. 10). We found no significant differences in parasitoid abundances across treatments, although there was a significant difference in the abundance of parasitoids in grasses before as compare to after harvest (Fig. 11). The number of parasitoids in grasses increased significantly from before to after harvest, which is the opposite of the pattern seen in parasitoids in trees.

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4.3. Qualitative Interviews

4.3.1. Threat appraisal

Cherry growers' perceptions of the severity of the threat of SWD varied from the idea that "it may not be a problem" to growers equating it to "holding a gun to your head." The three subthemes that emerged within perceived severity were intensity, priority and zero tolerance. Most growers agreed that SWD's fast generation time contributed to the intensity of the threat of SWD and made it a high priority among current tart cherry pests. Anomalies within this discussion were from an organic grower who said his biggest concern was plum curculio, a native beetle pest (Bessin, 2010), and another grower who had just retired his tart cherries but suggested that SWD may have just incited a crisis narrative:

> *All it did was scare the growing community into spraying more often, and we don't... I guess I don't know if you can have justified that or not.*

The severity of SWD is also exacerbated by USDA regulation that maintains zero tolerance for larval infestation of the fruit (Figure 12). Growers mentioned that the detection of larvae in the fruit by the processing facility not only jeopardized their entire crop for that season but tarnishes their reputation and makes them subjects of higher speculation. One grower said it was a "really big conundrum," explaining:

> *If you bring them in then you've kind of been marked as somebody who has wormy fruit, then they'll be checking you twice as hard in the future. And so, you just can't get yourself in that position.*

Subthemes that emerged within the theme of perceived probability (i.e. specific factors that influenced growers' perceived likelihood of exposure to SWD) included environmental factors and the risk of pest resistance. Environmental factors that were commonly cited as increasing the probability of SWD included the humidity and limited light exposure and airflow in the tree; surrounding landscapes like woods with non-crop hosts or abandoned orchards; and unpredictable weather that would influence spray schedules or temperature and humidity. Commonly cited sources of this information, specifically SWD's affinity for high-humidity and low-temperature, were Michigan State University Extension and more specifically the Northwest Horticulture Research Station.

4.3.2. Coping Appraisal

A small variety of methods for responding to SWD emerged from the response appraisal code, including pesticides, CMPs like mowing and pruning,

biological control, trapping, and other miscellaneous strategies (Table 2). Growers felt that the only way to effectively control SWD was through chemical pesticides and that all other practices were merely supplemental and would not allow for reducing spray frequency or intensity. CMPs were often already being utilized for tree health and productivity before SWD became an issue and were not being considered for partial replacement of chemical pesticides:

> *I would highly doubt it. I would be very surprised if that happened. I think it's just going to increase your efficacy of the spray program that you're already on, but I don't ever see reducing the spray because you've pruned or because you mowed.*

Alternatively, some growers were engaging in adaptation behaviors, like mitigating the effects of wind and sun on dispersal and evaporation of pesticides by spraying at night or stretching pesticide application by spraying alternate rows. A significant limiting factor for response to SWD was costs of methods to growers, which included time, machinery and fuel investment, and mental and emotional burdens of juggling spray schedules. Reflecting on the stress of scheduling pre-harvest sprays, one grower commented:

> *So, if we get to day nine, I'm ... or I mean, even on day eight, I'm starting to think like, man, this is not a good thing. And if it gets to day nine, I'm like, I don't really want to look at the first few tanks that come in. Somebody else look and make sure they're good. Then I can breathe a sigh of relief.*

Most of growers' feelings of self-efficacy were determined by their ability to afford and employ their primary form of defense against SWD: chemical pesticides. This elicited negative emotional responses in growers as they recognized the negative effects of pesticides on natural enemies and the vulnerability of the chemicals they currently use to the threat of regulation and pesticide resistance. One grower talked about his conflicting interests when faced with SWD:

> *I tried to get colleagues that I don't think took resistance seriously enough, I tried to get them to think in terms of save the best materials for when they are really needed. Save your guns for when you really need them. In this damn pest, we've seen pressure so high for so long that we are using about anything we've got.*

Other growers echoed similar sentiments, recognizing the heavy costs of use and disuse of chemical pesticides against SWD. Many also spoke about how difficult it was to determine which control mechanisms to use when the abundances of SWD vary tremendously from year to year:

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This past year was probably the biggest shocks in seeing what these damn things can actually do on the negative side. I was really surprised at the lack of SWD activity this year.

Such unpredictability is complicated by climatic variability, as weather and temperature not only influence SWD abundances but can also reduce the efficacy of sprays, for example if it rains immediately after application. Growers suggested that the solution to these issues is more research on the life cycles and triggers of SWD, which they hoped MSU and other researchers would achieve (Figure 12). Alternatively, the short-term solution posed by MSU researchers is a disease management approach which includes spraying just as soon as the fruit begins to yellow, and many growers said that they ascribe to these recommendations despite variability in abundance (Jones, 2017).

5. <u>DISCUSSION</u>

As SWD continues to increase in range and abundance across small-fruit crops in North America, the acquisition of sustainable pest management options is critical. Such options should effectively reduce pest populations, limit the risk of pesticide resistance to chemical pesticides, support diverse populations of natural enemies, like parasitoids, and be strategies that growers are willing and able to implement.

Contrary to predictions, we found no differences in SWD abundance across CMP treatments, and thus no evidence that CMPs were effective in controlling SWD. Assuming canopy cover and grass height serve as appropriate indicators of proper treatment implementation, the differences in these indicators between treatments suggest that growers did implement the treatments appropriately. Low abundances of SWD may be easily controlled with standard applications of pesticides, hiding evidence of even marginal differences in arthropod abundances between CMP treatments. Pruning and mowing are often employed to decrease microclimate humidity and subsequently reduce SWD habitat suitability, but, based on our results, should be assessed more critically for their ability to produce the desired low-humidity environment to reduce SWD abundance.

In this study, overall counts of SWD and parasitoids were considerably lower than anticipated for this region, contributing to the zero-inflation of our data. Counts of SWD in West Central during July 2017 averaged about 146 individuals per 5 traps (Jones and Rothwell, 2018), but we found a maximum of 17 individuals per 3 traps in July of 2018. Low SWD abundances may have been due to warmer and drier weather in the 2018 summer than the summer of 2017, as well as cold spells during the 2017-2018 winter that killed overwintering populations of SWD. Mean parasitoid wasp abundances on south eastern conventional Michigan apples orchards in August of 2009 reached 18 wasps per tree (Mates, 2012), compared to a maximum per-tree parasitoid abundance on 2018 West Central tart cherries of 6 individuals. Such low counts could be attributed to the rate and power of pesticides applied to tart cherries versus apples. Because SWD is a novel pest with fast generation times, tart cherry growers are encouraged to apply high-efficacy pesticides frequently, posing higher risks to non-target arthropods. While we cannot pinpoint a singular cause of lower abundances during our sampling year, the variability in SWD between years suggests variation in the ability of management techniques to reduce populations from year to year.

The lack of significant differences in parasitoid abundance across treatments suggests parasitoids are not heavily responsive to differences in mowing and pruning regimens. Parasitic wasps are also known for their substantial sensitivity to pesticides, are likely to avoid environments with heavy pesticide applications, or may have reduced rates of parasitism after sprays (Thomson and Hoffmann, 2006; Vianna et al., 2009). This is supported by the

significant increase in parasitoids in neighboring alley grasses after harvest. As pesticide application increases closer to the tart cherry harvest, parasitoids may move from trees to grasses to seek refuge from pesticides. Growers may therefore consider using alley grass as refuge habitat for beneficial parasitoids of SWD.

Unsurprisingly, given the low abundances of each, we found no effect of parasitoids on SWD abundance. Of all the native parasitoid species in North America, only five are known to parasitize SWD, none of which were found in the 2009 apple study, although they are native to Michigan (Mates, 2012). Parasitoids were not identified to species in this study, but the lack of SWD parasitoids found in Michigan by Mates indicates that few if any of our parasitoids may have been controlling SWD. If any of these known SWD parasitoids were captured in our samples, the overall abundance of parasitoids (total of 95 across all three sampling events) was likely too low to provide effective control over SWD.

In addition to low abundances of parasitoids, temporal mismatches in peak abundance of the two groups suggest that phenological mismatches may also prevent native parasitoids from serving as effective control agents of SWD. While the majority of SWD counts before harvest were zero and increased after harvest, parasitoid counts were at their highest before harvest and declined thereafter. Shortened spray windows (or increased frequency of pesticide applications), which are generally followed closer to harvest when the cherries are most susceptible to infestation by SWD, likely contributed to steady declines in parasitoid abundances. Therefore, if native or introduced parasitoids are to be considered for biological control of SWD, adjustments to chemical material use (including chemical type and frequency of application) should be considered for the protection of parasitoid populations and effective control of SWD. It is also important to continue field research on the efficacy of these native parasitoids for controlling SWD. While controlled lab experiments provide important insight into the potential regulation of SWD by parasitoids, the behaviors of both groups may be dramatically altered in less realistic conditions.

While our results from the field experiment do not support the efficacy of CMPs for reducing SWD abundances, many growers recognized the utility of mowing and pruning to increase the efficacy of their spraying programs and for keeping healthy and productive cherry trees. Few growers felt that CMPs could allow for reductions in pesticides applications and primarily relied on pesticides to respond to SWD, suggesting that grower responses are not sustainable adaptations (Figure 12). Researchers seemed to place significant influence on growers' coping appraisal, and some growers expressed hope in the ability of researchers to offer alternative solutions to SWD that may allow for reduction in pesticide application in the future (Figure 12). Others have removed their tart cherries from production, accepting that the low price of

cherries, restrictive regulations and international market competition make the crop no longer profitable or worth the costs of SWD control.

While the dominate narrative among growers is that SWD is a "game changer" for the tart cherry industry that requires an aggressive chemical spray program, some growers feel confident in their ability to control SWD with the available tools and question the validity of game changer rhetoric. This contradiction warrants careful critique of narratives surrounding SWD as well as who promotes them and who benefits from them (Figure 12). For example, chemical companies who provide scouts for growers may not consider the long-term costs of pesticides in reducing robust natural enemy communities, compromising the ecological health of the landscape for future crops and the farmer who tends them.

Many growers mentioned that they received most of their advice for SWD control from Michigan State Extension and associated researchers. These sources of objective adaptive capacity have a strong influence over the adaptive mechanisms of growers, specifically on how they perceive the risk of SWD (Figure 12). Collaborating with growers to understand the diversity of response mechanisms they implement and sharing these ideas with the broader growing community may provide more robust options for growers when responding to SWD rather than being solely reliant on chemical pesticides. More research on different combinations of these diverse practices, including reduced pesticide applications, should be explored. This might include conducting more interviews and surveys with growers to understand the mechanisms they find effective for controlling SWD and experimentally testing factorial combinations of these strategies to explore more sustainable options for managing SWD on tart cherries and other susceptible crops.

6. <u>CONCLUSION</u>

This research contributes to the body of knowledge on the phenological compatibility of SWD and North American parasitoids as native biological control agents as well as the impact of current management practices and social discourse on sustainable adaptation to invasive species. While the maintenance of native natural enemy populations would serve as the most sustainable pest management strategy, during the 2018 growing season we found no evidence that native parasitoids can control SWD due to low counts of both groups, likely attributable to climate and pesticide application. The integration of a variety non-chemical control tactics for SWD should still be considered for the reduction of broad-spectrum pesticides, including further exploration of the utility of CMPs on commercial orchards. Reductions in chemical controls may appeal to growers' desires for long-term control mechanism and allow for more clear detection of benefits from different cultural pest management practices, encouraging sustainable adaptation for prolonged ecological and social vitality.

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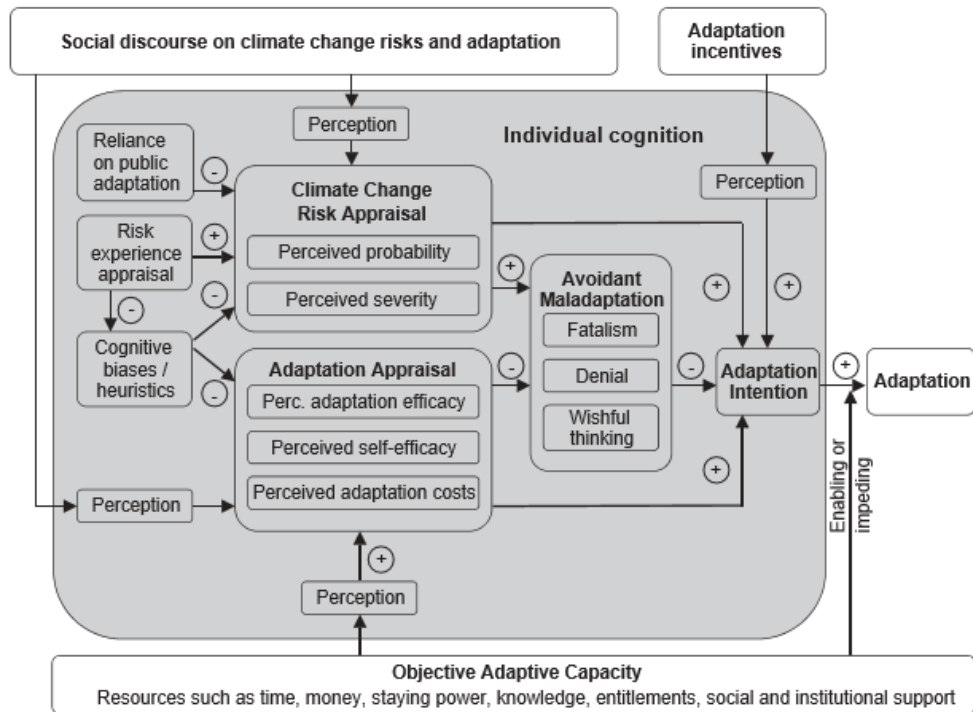
Figures & Tables

Figure 1. Grothmann and Patt model of private proactive adaptation to climate change (MPPACC) (2005).
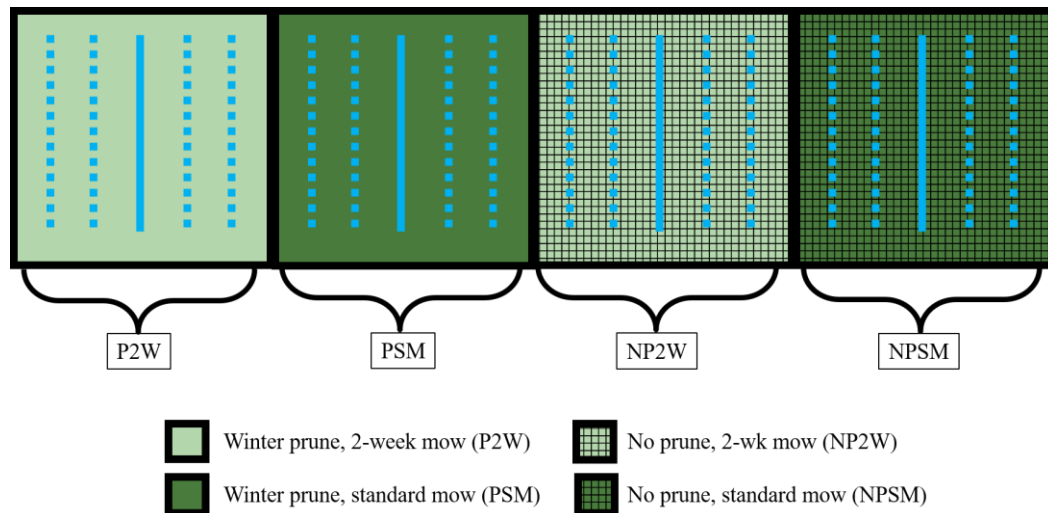

Figure 2. Conceptual diagram of experimental design. Dashed lines indicate rows of trees within treatment blocks and solid lines indicate rows on which tree samples were taken. Note that this illustration is not to scale and that plots varied in size and shape.
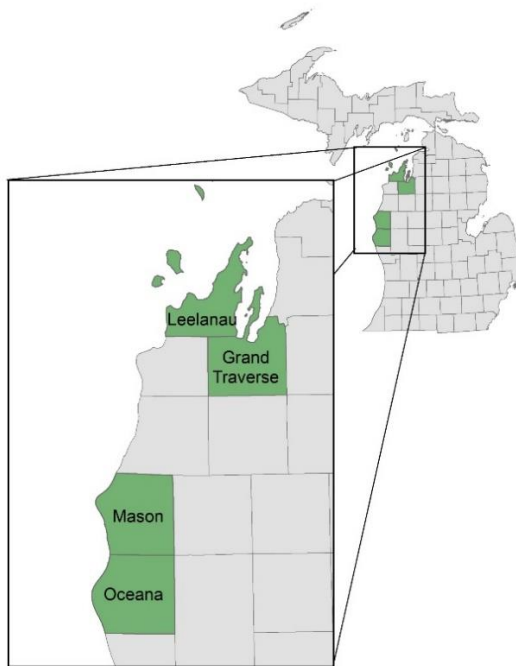
Figure 3. Map of study area for grower interviews including Leelanau, Grand Traverse, Mason and Oceana counties.

a.   b.
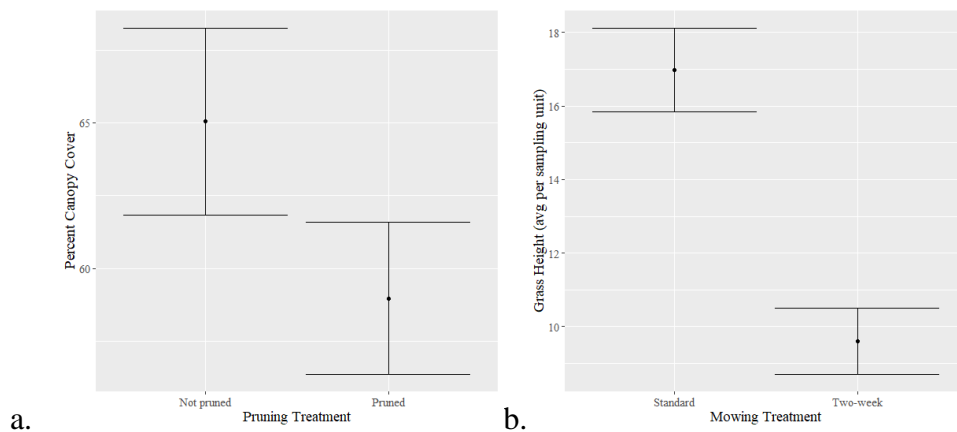
Figure 4. Box plots of pruning and mowing treatments against percent canopy cover and grass height (respectively). Canopy cover is compared between pruned (PSM and P2W) treatments and not-pruned (NPSM and NP2W) treatments ($p < 0.05$). Grass height is compared between standard mowing (PSM and NPSM) treatments and two-week mowing (P2W and NP2W) treatments ($p < 0.05$). Grass heights are averages of three random measurements within each sampling unit.
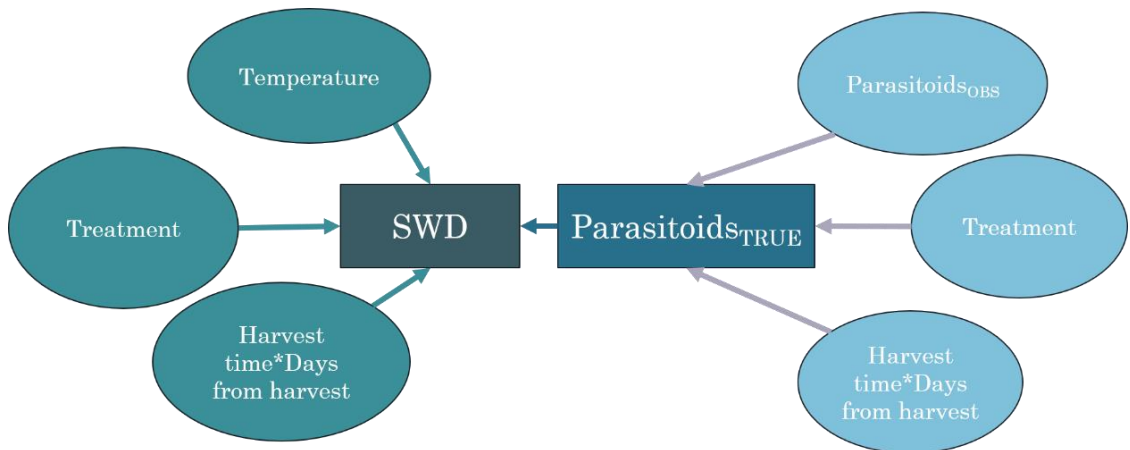
Figure 5. Conceptual framework of final model. The observed number of parasitoids, treatment and the harvest coefficient predict the "true" number of parasitoids in the parasitoid sub-model. Temperature, treatment, the harvest coefficient, and predicted (or "true") parasitoids predict SWD.
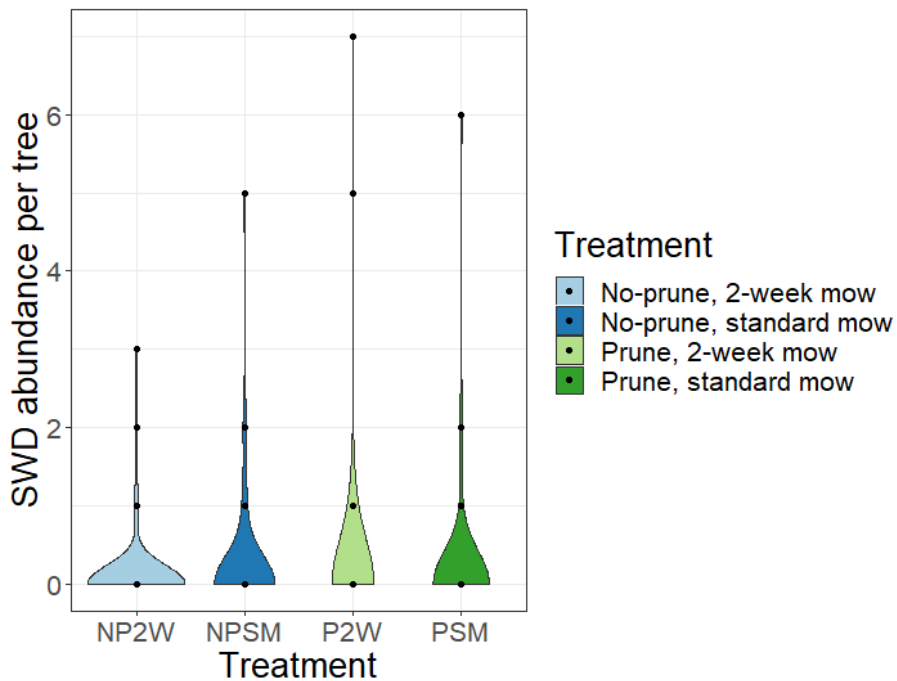

Figure 6. Violin plot of SWD abundance per tree per treatment. The plot shows frequency of counts with wider sections indicating counts of highest frequency. The highest frequency of counts for SWD were no counts, or zero (critical interval of 95%).
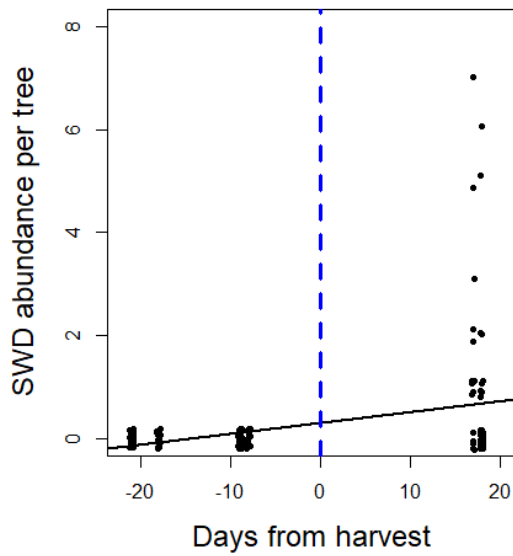
Figure 7. SWD abundance in relation to harvest. SWD abundance in trees increased significantly after the start of harvest (critical interval of 95%).
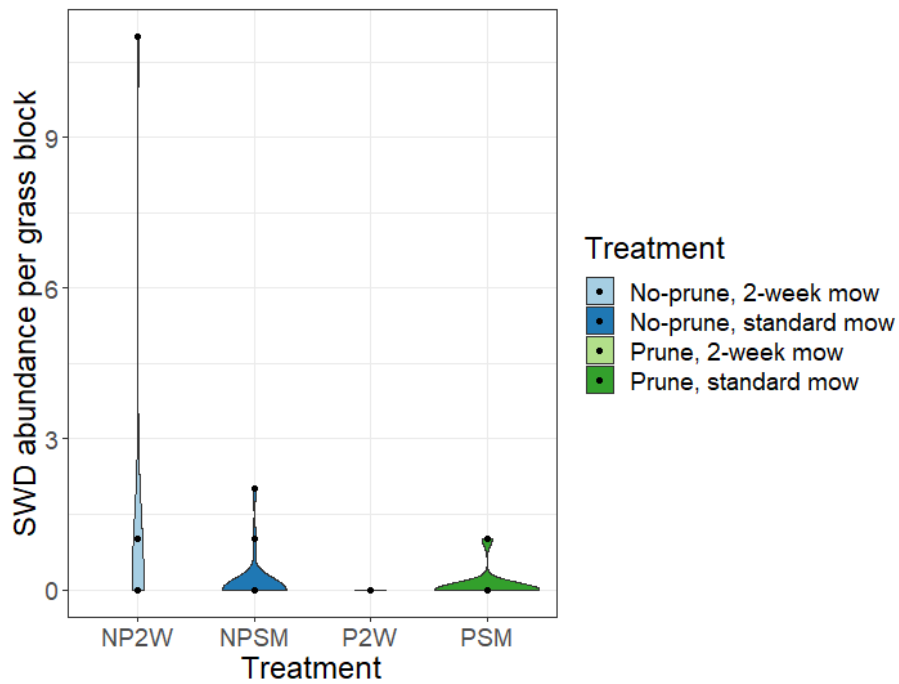

Figure 8. Violin plot of SWD abundances per grass sampling unit per treatment. The plot shows frequency of counts with wider sections indicating counts of highest frequency. The highest frequency of counts for SWD were no counts, or zero (critical interval of 95%).
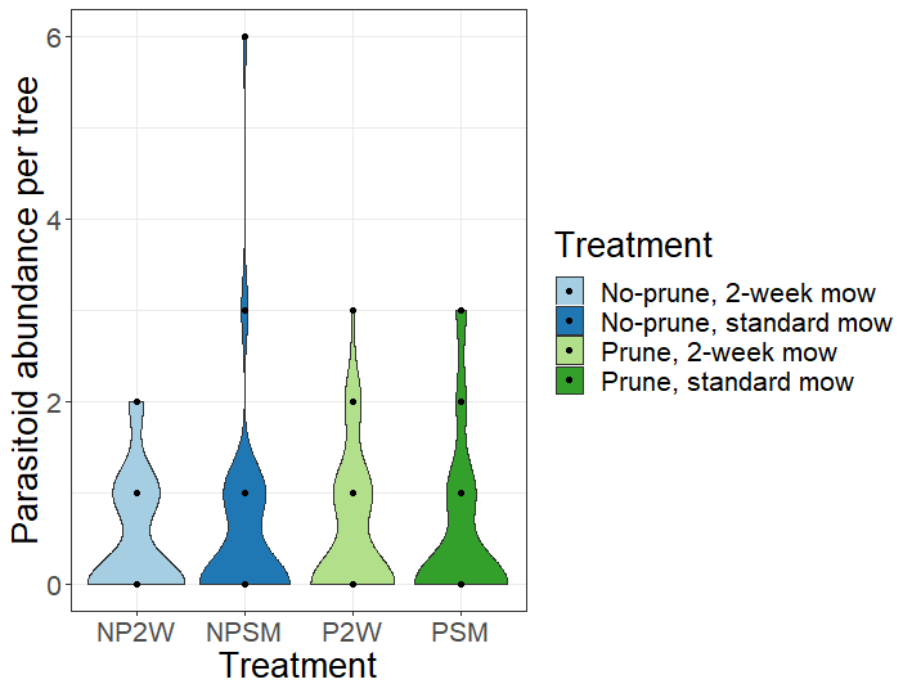
Figure 9. Violin plot of parasitoid abundance per tree per treatment. The plot shows frequency of counts with wider sections indicating counts of highest frequency. The highest frequency of counts for parasitoids were no counts, or zero (critical interval of 95%).
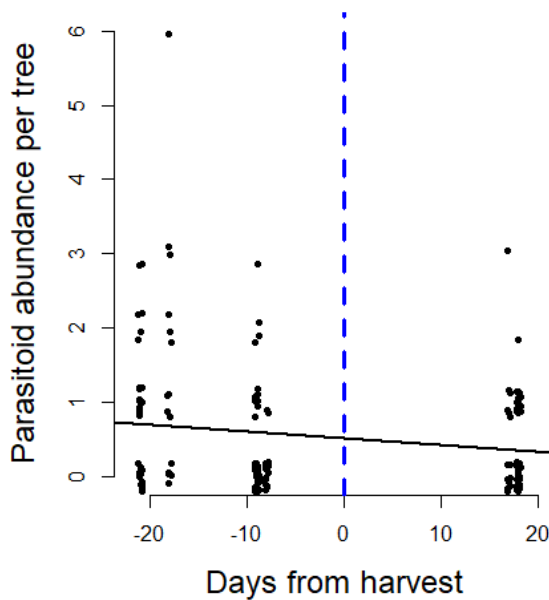

Figure 10. Parasitoid abundance in relation to harvest. Parasitoid abundance in trees decreased significantly after the start of harvest (critical interval of 95%).
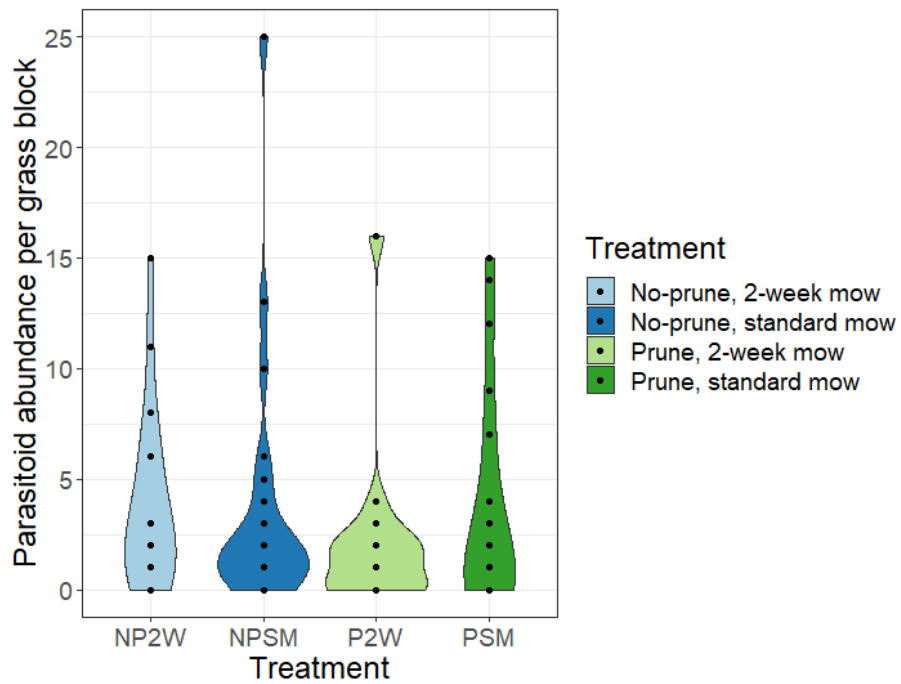
Figure 11. Violin plot of parasitoid abundances per grass sampling unit per treatment. The plot shows frequency of counts with wider sections indicating counts of highest frequency. The highest frequency of counts for parasitoids were no counts, or zero, with higher frequencies of non-zero parasitoid counts in grasses than in trees (critical interval of 95%).
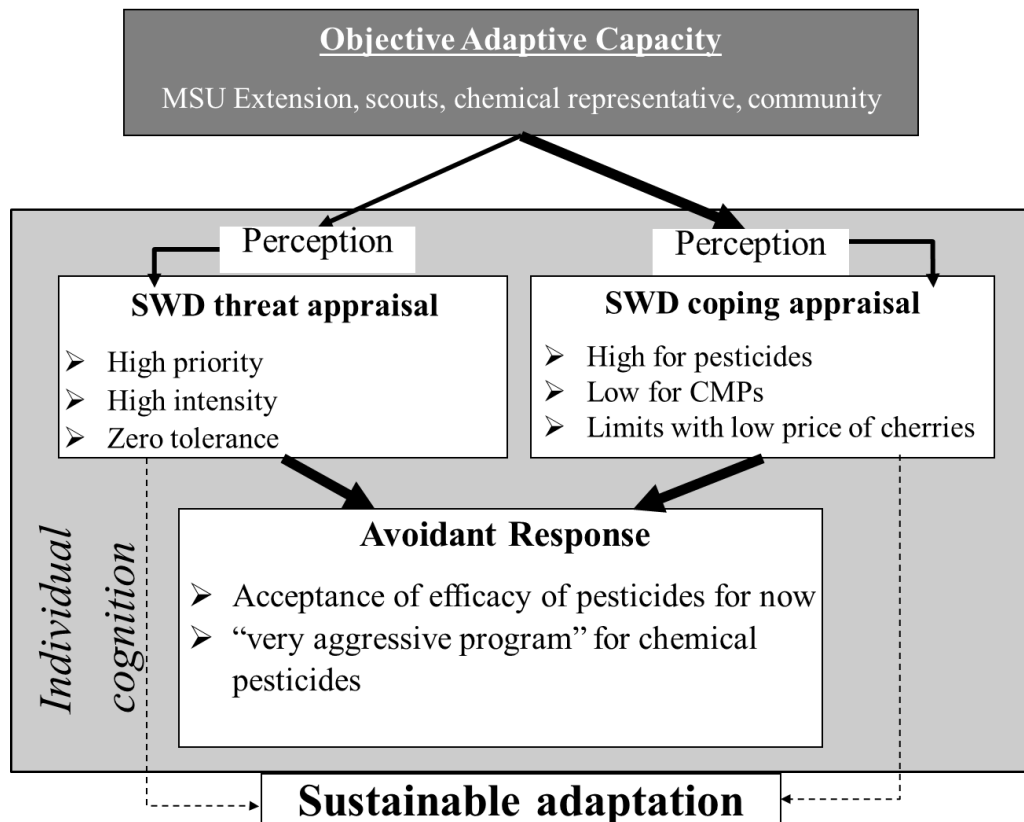
Figure 12. Process model of growers' responses to SWD, adapted from Grothmann and Patt 2005. Everything within the lighter grey box represents the cognitive processes of the grower, and outside of the box are external influencers of decision making. Thicker solid arrows indicate a stronger influence on perception and response.

Code	Description
1. Coping Appraisal	Perceived ability to respond to SWD
1.1. Response Appraisal	Perceived ability of response or management practice to reduce the threat
1.1.1. Biological Control	Non-chemical control of SWD other than CMPs or traps
1.1.2. CMPs	Cultural management to control SWD (e.g. pruning and mowing)
1.1.3. Pesticides	Chemical pesticides for SWD
1.1.4. Trapping	SWD traps for tracking incidence
1.1.5. Other	Ambiguous hope in "other" control options that may be discovered in the future, as well as methods that are not included in any of the previous codes
1.2. Response Cost	Costs of responding to SWD
1.2.1. Costs of Control	Costs of time, labor, equipment, pesticides, etc. for managing SWD
1.3. Self-efficacy	Growers' perceived ability to perform response or management practice
1.3.1. Ability to control	General perceptions of growers' abilities to control SWD
1.3.2. Adaptability	Growers' willingness to or anticipation of their management adaptability
1.3.3. Price of cherries	Market price of cherries that influences growers' profit
1.3.4. Regulation	Regulation of pesticides
1.3.5. Unpredictability	Conditions and characteristics of SWD that make the severity of their incidence hard to predict
2. Threat Appraisal	Growers' perceived threat of SWD
2.1. Perceived Probability	Factors that influence the perceived vulnerability or likelihood of exposure to SWD
2.1.1. Environment	Environment surrounding orchard, environment and microclimate of the tree that influence SWD incidence
2.1.2. Pesticide Resistance	SWD resistance to pesticides
2.2. Perceived severity	Factors that influence the perceived intensity of the threat and how it may impact grower
2.2.1. Intensity	Perceived intensity of the threat of SWD and how it may impact the grower
2.2.2. Priority	Perceived priority of SWD as a threat compared to others (e.g. other pests)
2.2.3. Zero Tolerance	Perceived impact of zero tolerance from processors for any eggs or larvae in the cherries

Table 1. Descriptions of the different first, second and third order codes from interview transcript analysis. The darker the color, the higher the order of the code. Continued on next page.

3. Objective Adaptive Capacity	Resources (e.g. time, knowledge, support) outside of growers' cognitive processes
3.1.Community	Influence of family and other growers on interviewed growers' threat responses
3.2.Chemical Industry	Influence of scouts and chemical representatives
3.3.Processors	Influence of processors
3.4.Researchers	Influence of researchers
3.5.Scouts	Influence of scouts not associated with chemical companies

Table 1 (continued). Descriptions of the different first, second and third order codes from interview transcript analysis. The darker the color, the higher the order of the code.

Method	Application	Grower Appraisal	Costs and Challenges	Current Effectiveness	Future Potential	Researcher Explanations
Pesticides (56 references)	according to label and regulation	±	• "soft chemicals" less costly, but encourage resistance • spray coverage and intervals difficult to manage • mental and financial exhaustion:" It's so discouraging now" • threat to natural predators	• the only way to manage SWD • no way to reduce application	• "In the long term I don't envision a day when we're not gonna be spraying" • limited potential for increasing spray windows	Growers felt that pesticides were the only solution to SWD and that no other supplementary mechanisms could replace or reduce pesticide application. They found this dependence discouraging and a barrier to potential implementation of natural enemies.
Mowing & Pruning (i.e. CMPs; 41 references)	Employed to decreases habitat suitability for SWD, increase spray coverage, and maintain productivity	±	• labor • machinery (maintenance, fuel, etc.) • time • "I'm not sure where you're going to find the savings"	• already considered general good practice for productive trees • no change to spraying • "certainly [CMPs are] not a primary management strategy"	• "I don't ever see reducing the spray because you've pruned or because you mowed." • limited hope for even reducing spray (maybe reduce one spray over the season	The CMPs (mowing and pruning/trimming) were considered inherently good practices for tart cherries, regardless of SWD. Growers' willingness to increase these were limited by their cost-effectiveness and limited ability to replace pesticides to any degree.
Biological Control (17 references)	natural predators/enemies, pheromones, gene changers	+	• doubts regarding affordability	• no current application	• hope that researchers will discover an effective strategy	Many growers mentioned the unrealized potential of natural enemies and had hope that researchers would come up with a plan for use and implementation.
Traps (13 references)	listening to regional catches; spraying on sight; potential to save sprays at the beginning	±	• "not a user-friendly trap"	• saved sprays • "by the time traps find SWD you've already got them in your fruit" • not as control	"So I think traps someday will help us avoid wasting sprays by spraying too early"	Regional trap catches are used by growers to determine when they need to start spraying. Traps are difficult to for growers to use, warranting the need for scouts, which may be chemical representatives. The traps have little to no utility for direct control of SWD.
Other (10 references)	cutting down hosts; dwarfing root stocks for smaller canopy; earlier-maturing cultivars; younger trees; burning residue; herbicide strips; nighttime spraying	+	• younger trees cost to older growers • no other costs mentioned	• good enough for growers to continue to implement	• include ideas for limiting threat of SWD in the future	These are either specific behaviors employed on a case-by-case basis by different growers or haven't yet been implemented yet. They tend to exhibit characteristics of adaptive innovation in response to SWD, although some deflect responsibility of innovation to researchers and others in the industry.

Table 2. Matrix of response appraisal. This table illustrates the potential for different SWD control methods to serve as mechanisms for grower adaptation to SWD. The methods are listed in the order of number of coded references from grower interviews. Grower appraisal of the method is either positive (+) or mixed (±).