PREDICTED ECONOMIC IMPACT OF ADOPTING A GROWING DEGREE DAY MODEL TO MANAGE SPOTTED WING DROSOPHILA (SWD) IN TART CHERRY PRODUCTION IN MICHIGAN

By

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ABSTRACT

Integrated Pest Management (IPM) is a sustainable and crucial pest control strategy that can have a substantial positive impact on tart cherry production in Michigan. This study presents an ex-ante impact analysis of implementing a Growing Degree Day Based (GDD)-IPM model for the management of Spotted Wing Drosophila (SWD), a major pest that affects the production of tart cherries in Michigan. By using a combination of partial budget analysis, daily weather data, and phenological data, this study determines the optimal timing for pesticide application, assuming that future weather patterns will resemble those of the past.

According to the study's findings, implementing an IPM model in Michigan's tart cherry production can result in significant cost savings and increased profitability. Even with a low adoption rate, producers can expect net benefits of around $1.4 million, which can increase to $3.2 million with a medium adoption rate and, $4.9 million for high adoption over a 15-year period between 2023-2037. The cost savings associated with reduced insecticide application requirements prove conclusively that implementing an IPM strategy can result in substantial producer benefits in Michigan's tart cherry production.

The study also considers the research and outreach costs associated with SWD management, emphasizing the significance of extension and outreach efforts in boosting the diffusion of adoption. The study's findings make a compelling case for the adoption of IPM strategies in Michigan's tart cherry production, as they not only increase profitability but also take a more sustainable and environmentally friendly approach to pest control.

Keywords: *Drosophila suzukii*, tart cherry production, Integrated Pest Management, Technology Adoption, Ex-ante Impact Analysis, Growing Degree Days, and Research And Extension Cost.

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INTRODUCTION

The Spotted Wing Drosophila (*Drosophila suzukii Matsumura*), also known as SWD, is a well-known pest that wreaks havoc on berry crops, grapes, cherries, and other tree fruit. The first SWD detection in the USA took place in 2008 in California, and after a few years, it is spotted in the state of Michigan in 2010 (Isaacs, 2011). A response team from the Michigan State University (MSU) Department of Entomology, MSU Department of Horticulture, MSU extension field staff, Michigan Department of Agriculture and Rural Development, and fruit commodity representatives, has been established. Public and private funding is provided to the response team to organize research projects to learn how best to protect the fruit from this new insect's infestation.

SWD is a major threat to fruit crops, causing significant yield losses due to its destructive behavior. Female SWDs lay their eggs on healthy fruit during the fruiting season, which is then consumed by larvae, causing the fruit to rot and become inedible. Fruit quality and quantity degradation can cause significant economic harm to fruit growers, emphasizing the importance of effective pest management strategies to prevent the spread of SWD in agricultural settings. Even after harvesting, some eggs or larvae may still be present in the fruit, and according to MSU Extension staff, even a low level of infestation, such as 1%, can result in the entire harvest being rejected by market buyers. To reduce the negative impact of SWD on fruit production, it is critical to implement Integrated Pest Management (IPM) strategies that can reduce the risk of infestation while ensuring the continued production of high-quality fruit that meets market demand. Therefore, SWD pest management techniques mainly rely on extremely broad-spectrum insecticide applications, primarily organophosphates, spinosads, and pyrethroids, on a calendar-based approach because of the zero-tolerance of crop pest infestations and observational uncertainty about the SWD population (Beers et al., 2011; Fan et al., 2020; Haye et al., 2016; Schoneberg et al., 2020). In the long run, the increasing use of insecticides to SWD populations may have unintended consequences. In the future, the evolution of genetic resistance to these insecticides may result in increased pest management expenses and negative externalities. According to Van Timmeren et al. (2019) the ability of SWD to develop resistance to pesticides can reduce the effectiveness of these chemicals over time, necessitating more frequent or potent insecticide applications. This not only increases the cost of pest control, but also poses potential threats to human health and the environment. Therefore, alternative strategies that reduce reliance on chemical pesticides may be required for the long-term management of SWD.

SWD management involves a range of dimensional measures because the nature and behaviors of the insect and invasive insect management are different from non-invasive insect management(Fan et al. 2020; Ranjan 2007). In a region, the SWD damage differs depending on crop type, location, time of the year management practices, and environmental factors such as relative humidity (Rh) and the temperature is another factor that affects pest population size and the number of application for pesticide (Andika et al., 2019; Tochen et al., 2016; Nik G. Wiman et al., 2016). The rapid increase in population requires an action threshold for early detection and starts controlling as early as possible (Francis Drummond et al., 2019; Fan et al., 2020). Traditional pest management strategies for SWD have relied heavily on broad-spectrum insecticides, such as organophosphates, spinosads, and pyrethroids, applied on a calendar-based schedule. However, the ability of SWD to develop resistance to the pesticides over time undermines their effectiveness, leading to higher pest management costs and potential negative externalities, including human health impacts, pollution, and loss of beneficial insects.

IPM specialists advise employing more ecologically friendly and cost-effective alternatives to traditional pesticide-based treatments. Researchers have found that the Growing Degree Days

(GDD) system is a practical and effective component of IPM approaches for predicting the onset of SWD (Kamiyama et al., 2020; Wilson et al., 2022). The technology predicts the growth of tart cherries and pests using temperature data, allowing for targeted and timely management measures. A GDD-Based IPM strategy has the potential to reduce excessive insecticide use, increase the overall efficiency and effectiveness of pest management efforts, and save money on insecticide spraying costs.

The steady increase of SWD populations and the growing resistance of pests to conventional pesticides have become a global concern. Various stakeholders, including farmers, researchers, and government agencies, must invest in and investigate alternative pest control methods in order to address this problem. This research will aid in advocating and implementing GDD-based Integrated Pest Management strategies to solve this problem. The results will benefit Michigan fruit growers and may help define pest management strategies in other fruit-growing regions with similar difficulties.

The SWD infestation problem is a pressing issue that demands a comprehensive and sustainable solution. The use of GDD-based IPM strategies is a promising approach that addresses the economic challenges growers face and promotes environmental and human health. This study aims to demonstrate the economic feasibility of GDD-based IPM strategies.

1.1. Research Motivation

The United States of America ranks fifth globally in tart cherry production after Russia, Ukraine, Poland, and Turkey. Michigan is the leading producer of tart cherries in the US, with the majority of production occurring in the state's northwest. Michigan is currently home to over 20,000 acres of tart cherry orchards, accounting for approximately 75% of the tart cherries grown in the United

States (USDA/NASS). According to the "Michigan Tart Cherry Cost of Production Study 2022" by the Cherry Marketing Institute and Michigan State University Extension, the average Michigan cherry farm currently encompasses approximately 300 acres, with 150 acres dedicated to tart cherries and the remaining acreage dedicated to other fruit crops such as apples or sweet cherries (Chris Bardenhagen, 2022). Understanding the critical and emerging issues confronting the tart cherry industry is critical for conducting a thorough and insightful analysis. A thorough understanding of these issues is critical to ensuring that our analysis accurately reflects the industry's challenges and opportunities. Lagoudakis et al. (2020) provide an overview of the tart cherry industry in Michigan and examine the industry's strengths, weaknesses, opportunities, and threats. One threat to the tart cherry industry was the damage SWD creates to businesses. According to an industry report, SWD damaged 21% of cherry production in 2016 in Michigan (Fruit Growers News, 2019). Lindsey (2018) has called SWD an "industry killer" and "the worst insect. The Michigan tart cherry industry faces significant economic obstacles due to rising production costs and declining market returns (Fruit Growers News, 2022). In addition, the recent emergence and spread of the invasive pest, the SWD, has increased the need for crop protection measures and the associated costs for cherry growers. Therefore, there is an urgent need for innovative and sustainable approaches to sour cherry production that can help mitigate the negative economic effects of SWD and lower overall production costs.

The adoption of an IPM approach for tart cherry production in Michigan is justified for several reasons. Firstly, such a strategy has the potential to reduce costs for farmers through the reduction of pesticide use. Pesticides can be expensive to purchase and apply, and these chemicals can lead to developing resistance in pests, requiring increased pesticide use over time. By contrast, an IPM approach that reduces the reliance on pesticides can help to lower costs and minimize the risk of resistance.

Environmental and human health can benefit from using an IPM strategy in tart cherry cultivation. Pesticides are known to contaminate water supplies, harm non-target species, and have acute and chronic effects on human health. A method of IPM that decreases pesticide use can mitigate these adverse effects. Finally, adopting an IPM approach in tart cherry production can improve environmental and human health outcomes. Pesticides cause environmental damage through water contamination and harm to non-target species, and they can also have adverse effects on human health through acute and chronic exposure. By reducing pesticide use through an IPM approach, it is possible to address these issues and promote a healthier environment and population. These social benefits can be realized only if farmers adopt this technology, which requires the technology to be economically feasible. This research addresses this urgent question.

1.2. Research Goal and Objectives

This research aims to measure the expected returns to research and outreach for improved management of the SWD in tart cherry production in Michigan. To do this, I will apply the partial budget method to measure the returns to research and outreach activities using a Growing Degree Day (GDD)-based IPM model. This model aims to reduce the number of pesticide applications by determining the optimal timing of pesticide application based on accumulated GDD. Using the degree day model to determine when tart cherry fruits reach a susceptible stage of growth, we can reduce the number of spraying activities and avoid unnecessary spraying when the fruits' phenological level has not reached a certain GDD. However, if producers adopt degree-day-based chemical control measures, some unnecessary spraying activities may be avoided by not spraying when the fruits' phenological level has not reached a certain GDD. Therefore, the economic return to agricultural research and outreach of the GDD-based IPM strategy's potential adoption will be measured using the partial budget method.

2. LITERATURE REVIEW

2.1. The Economic Impact of Spotted Wing Drosophila

The first estimation of SWD damage's economic effects in the US, Bolda et al. (2010) claimed revenue loss for strawberry, blueberry, blackberry, and raspberry cherry production in California, Oregon, and Washington could reach $511.3 million. However, the analysis did not consider the price responses due to quantity changes and welfare effects on the consumer; the analysis is limited only to the effects on producer revenues, as the authors explicitly stated in the paper.

Goodhue et al. (2011) conducted an investigation into the potential revenue losses and control costs associated with SWD damage in California raspberry and strawberry production. They also analyzed the price responses and supply reactions to the impact of SWD on the industry. The analysis revealed that the benefits of controlling the SWD outweigh the estimated costs.

According to a study by DiGiacomo et al. (2019), raspberry growers in Minnesota face substantial yield losses due to SWD (2019). The study surveyed 157 berry growers in Minnesota, and 82 individual grower surveys were returned. The results indicated that raspberry growers were especially susceptible to SWD infestation, with the highest levels of infestation among fruit growers surveyed. In 2017, raspberry growers experienced yield losses ranging from 2% to 100% of planted area, with a median yield loss of 20%. According to the findings, the raspberry industry lost an estimated $2.36 million in sales over the course of one year as a result of SWD damage. Despite the fact that 74% of growers actively managed to control SWD through a variety of methods, yield losses were still substantial. The high yield losses in Minnesota's fruit industry are likely attributable to the delayed detection of SWD and the use of less effective pest control methods. The study emphasizes the significance of investing in effective SWD control measures to assist growers in reducing future losses and maintaining the region's fruit industry's long-term viability.

Farnsworth et al. (2017) aimed to estimate the potential economic impact of the SWD invasion on raspberry production in California. The research team determined the total economic cost of the SWD invasion by factoring in the costs of chemical management programs, labor-intensive sanitation methods, and yield losses at the sector level resulting from infestation. This study provides valuable insights into the economic effects of the SWD invasion on the raspberry industry and emphasizes the importance of implementing effective pest management strategies to mitigate the effects of this destructive pest. In order to protect the raspberry industry and guarantee the production of high-quality fruit, the study's findings highlight the need for continued investments in the research and development of effective and sustainable pest control methods.

In the Italian Trentino region, total revenue losses are estimated at €3.3 million on strawberries, raspberries, blueberries, blackberries, and cherries (Giorgio De Ros et al., 2013). However, the study was limited to aggregate levels, and pest control costs were ignored. A subsequent analysis by G. De Ros et al. (2015) examined the control costs of SWD in the same region and found that before the implementation of an integrated pest management strategy, the projected sales losses amounted to approximately 13% of the output of the raspberry industry. Following the introduction of an integrated plan, this loss decreased to around 7% of the industry's output. The potential damage was estimated to be about one million euros between 2012 and 2013.

Mazzi et al. (2017) describe the various costs of pest control initiatives against SWD in Switzerland's case. Depending on the implemented pest control methods, the damage is estimated to generate an annual loss for growers of 44,000 CHF(Swiss Franc)/ha for the low infestation scenario. However, for the worst-case scenario, where all of the products produced were rejected due to zero tolerance for SWD infestation, the damage would reach 71,000 CHF/ha.

Yeh et al. (2020) conducted a study on the economic impact of SWD without control on the Maine wild blueberry industry. Assuming a 30% yield reduction, their study revealed that SWD could result in a significant loss of sales for the industry, with a worst-case scenario estimate of over $6.8 million. During the harvesting season, growers must choose between various control strategies, and this was the focus of the Monte Carlo simulation-based study. According to the study, in low-infestation-risk scenarios, insecticide applications are not economically optimal. While early harvesting is an option for preventing SWD infestations, the unripe crop results in income loss. In addition, the study revealed that there is no single optimal management strategy applicable to every production method and economic price forecast. Maine wild blueberry growers should not assume that the best approach for managing SWD is the use of an insecticide, even if they are applying a risk-based action threshold. The study provides valuable information for organic farmers when insecticide control may not be a viable option.

Knapp et al. (2019) investigated the perceived costs, expected additional costs, and expected revenue losses associated with the SWD in Swiss cherry, plum, and grape production. Multiple surveys of Swiss cherry, plum, and grape growers were conducted between 2016 and 2018 (N=1572). The research revealed that 76% of cherry, plum, and grape growers incurred additional costs due to SWD. The perceived costs and revenue losses varied considerably across crops, years, and farms, with larger farms experiencing lower additional costs. The study concluded that the economic impact of invasive species, such as SWD, is driven by the costs associated with implementing preventative and control measures, rather than yield reduction alone. The perceived costs and revenue losses varied substantially across crops, years, and farms, with larger farms experiencing lower additional perceived costs. In light of this, the study suggests that policy measures intended to aid farmers should be tailored to specific crops and farm types.

Using a Bayesian state-space bioeconomic model that incorporated observational uncertainty in pest population monitoring via Monte Carlo Markov Chain, Fan et al. (2020) sought to determine the optimal management strategy for SWD. Comparing a monitoring-based IPM strategy to a calendar-based preventative insecticide spray strategy, the study found that the monitoring-based IPM strategy had a slightly lower total cost. The research revealed a disparity between public and private incentives for adopting IPM strategies, with profit-maximizing growers having little incentive to implement such measures. However, IPM strategies were more appealing to growers with a concern for the environment. As trapping efficiency increases, IPM strategies become more appealing to both types of growers, according to the study. The authors suggest a variety of measures to promote the adoption of monitoring-based IPM strategies, including extension efforts, funding for research to improve trapping efficiency, and financial incentives.

SWD management requires a substantial investment, with an emphasis on the cost of increased pest control inputs and labor. However, these estimates fall short of capturing the full extent of the impact on particular regions because they fail to account for the vital resources invested in research and extension activities. These activities are crucial for comprehending the issue, developing effective solutions, and educating growers on the best SWD management practices. The actual cost of managing SWD is significantly higher than current estimates, highlighting the critical need for continued investment in research and extension efforts. This fact demonstrates the significance of considering the total cost of SWD management, including resources spent on research and extension activities, in order to comprehend the total impact on the regions under study.

2.2. SWD Management

SWD has spread to all soft-skinned and stone fruit-producing regions in the last several decades. SWD is a highly adaptable insect capable of dispersing, surviving, and thriving under various environmental situations. SWD infestation has significant economic consequences, including reduced fruit yields, shorter shelf life, and higher production costs, as noted by Tait et al. (2021).

SWD management involves a range of dimensional measures because the nature and behaviors of the insect and invasive insect management differ from non-invasive insect management (Fan et al., 2020; Ranjan, 2007). In a region, the SWD damage differs depending on crop type, location, time of the year management practices, and environmental factors such as relative humidity (Rh) and the temperature is another factor that affects pest population size and the number of applications for pesticide (I. P. Andika et al., 2019; Tochen et al., 2016; N. G. Wiman et al., 2016). The rapid increase in population requires an action threshold for early detection and starts controlling as early as possible (F. Drummond et al., 2019; Fan et al., 2020)

The demand for uninfested tart cherry products has placed a significant strain on the industry's finances, particularly organic businesses. This is due to the limited availability of effective organic pesticides and the sector-mandated threshold for crop acceptance. The zero-tolerance policy in the United States for detectable larvae in fruit or cooling tanks at harvest necessitates a careful and cautious approach to SWD (Wilson et al., 2022). Because of this policy, even a small number of SWD larvae can cause significant economic losses for fruit growers, emphasizing the importance of effective pest management strategies. To meet this strict requirement, tart cherry growers must apply insecticides frequently and intensively, beginning with the first signs of SWD and continuing through harvest. The high level of control required to meet these standards is difficult and leads to a substantial increase in pesticide use, which can have negative effects on the environment and the industry as a whole. This emphasizes the urgent need for more research and innovation in SWD management in order to find sustainable and effective solutions that minimize the use of pesticides and lessen the industry's and environment's impact.

2.2.1. Chemical Control

Many fruit farmers have no choice but to heavily rely on insecticides in order to protect their high-value crops from the pest because their company has a zero-tolerance policy for fruit that is infested with Spotted-Wing Drosophila (Haye et al., 2016). The seasonal behavior, rapid spread, and exponential growth of SWD populations necessitate the implementation of highly effective management strategies (Hamby et al., 2014). According to Van Timmeren and Isaacs (2013) farmers have modified their approach to pest management for SWD, shifting from targeted insecticides based on monitoring and scouting to calendar-based spray programs that rely on broad-spectrum insecticides. Bioassays conducted in a semi-field setting revealed that organophosphate, pyrethroid, and spinosyn insecticides have strong initial activity against flies, but their residual fruit protection varies. It was discovered that the neonicotinoid insecticide acetamiprid was active for up to five days, whereas the organic pyrethrum insecticide was ineffective. Some insecticides were less effective against insects when it rained. Both conventional and organic spray programs provided significant fruit protection compared to untreated fields, with conventionally produced berries containing fewer larvae.

Broad-spectrum insecticides, which are widely used in calendar-based spray programs, are aimed at controlling the adult stage of SWD. However, they can also impact the survival of the early life stages, such as eggs and larvae (Shawer et al., 2018; Wise et al., 2015).

Mermer et al. (2020) investigated the effects of insecticides on immature SWD on cherry and blueberry. Insecticides such as phosmet, spinosad, spinetoram, and methomyl were effective in killing 90-96.6% of SWD immature stages. In immature SWD, malathion, cyantraniliprole, fenpropathrin, acetamiprid, and zeta-cypermethrin caused moderate mortality (85.5-86.3%), while cyclaniliprole caused 70% mortality. Using laboratory mortality data, a SWD population model was parameterized, revealing that insecticide application order and timing are critical for pest control. According to the model simulations, starting with highly effective insecticides and then moving on to medium or low mortality insecticides could optimize population control in cherry and blueberry crops.

The cherry growers in Michigan, typically use insecticides on a weekly basis to control SWD, beginning once adult flies have been identified through traps and the fruit has begun to change color. It is possible that 4-6 preventive sprays will be required. The weather conditions present at the time of application are one of the key factors that can impact the effectiveness of SWD control using current spray technologies such as air-assisted sprayers or aerial applications (Dietrich, 2020).

Since the widespread spread of SWD, the development of pesticide resistance has become a growing concern (Cini et al., 2012). Given the rapid generation times of Drosophila pests, it is crucial to implement effective management strategies in order to minimize the risk of insecticide resistance development. This can be accomplished by investing in educational programs to disseminate research findings to end users and encouraging the use of targeted insecticides based on monitoring and scouting rather than relying solely on calendar-based spray programs that employ broad-spectrum insecticides (Asplen et al., 2015). Additionally, the limited number of pesticide classes that are permitted for use on SWD host crops contributes further to the existing level of selection pressure, and this is true of both conventional and organic production methods (Tait et al., 2021). Despite the fact that pesticide resistance has not been widely identified in the primary growing regions for berries and cherries in North America to date, decreased sensitivity to spinosyns has been identified in both Michigan (Van Timmeren et al., 2018) and California (Gress & Zalom, 2019). On the other hand, a laboratory colony of SWD that was exposed to malathion selection for a total of 30 generations did not end up developing resistance to the chemical (Smirle et al., 2017). Due to the potential for SWD field populations to develop insecticide resistance, the discriminating dosage contact bioassay was developed. This straightforward and rapid bioassay can detect pesticide resistance in the vast majority of commonly used insecticides for SWD management (Van Timmeren et al., 2019).

2.2.2. Cultural Control

Sanitation measures, harvest timing, pruning, watering, mulching, and exclusion netting are all examples of successful cultural management approaches (Schoneberg et al., 2021). SWD reproduction can occur in ripe, ripening, overripe, or fermented fruit. SWD infestations can also be found in fruit compost and discarded fruit (Bal et al., 2017). According to the findings of some studies, there were significantly fewer SWD larvae in raspberries that had been harvested every one to two days as opposed to once every three days (Leach et al., 2016). Consequently, sanitation interventions that eliminate potential hosts can be helpful for SWD management. Temperature and relative humidity impact SWD's development, survival, and reproductive production (Fanning et al., 2019; Green et al., 2019; Kinjo et al., 2014; Ryan, 2016). In some regions, lower SWD infestation levels may be the result of lower canopy densities brought about by excessive pruning. The activity of SWD oviposition may be affected by changes in ecological conditions and oviposition sites caused by crop canopy pruning (Schöneberg et al., 2020).

Drip irrigation in blueberries led to a reduction in relative humidity, which prevented SWD adults from emerging from sentinel pupae and hampered their ability to survive (Rendon & Walton, 2019). According to a study by Rendon et al. (2020), woven weed cloth mats combined with sawdust may be capable of modifying the microclimate, increasing temperatures, reducing the suitability of fields for SWD, and acting as a barrier to prevent larvae from reaching ideal pupation microhabitats beneath.

Fruit can be protected from damage caused by SWD by constructing a barrier made up of screens that are 0.98 millimeters thick and covering the canopies with them (Cini et al., 2012; Kawase et al., 2008; M. A. Rogers et al., 2016). The article by Leach et al. (2016) examines the management of SWD in North American raspberries and other soft fruits. It compares the efficacy of insecticide and exclusion treatments for controlling SWD infestations. The study demonstrates the efficacy of both control methods in reducing the larval infestation of raspberry fruit. However, the combination treatment was found to be more effective, as it led to the lowest overall abundance of larvae in the fruit and delayed the first detectable infestation by 10 days compared to untreated plots. It was discovered that applying exclusion netting to commercial high tunnels significantly reduced overall SWD infestation and delayed the first detectable fruit infestation by three weeks, with no effect on raspberry size or quality. The authors conclude that in temperate climates, Exclusion netting has been shown to be an effective method for protecting soft-skinned fruit crops from SWD infestation. By creating a barrier that physically prevents adult flies from accessing the fruit, exclusion netting can play an important role in growers' efforts to manage the impacts of SWD on their crops.

The implementation of cultural control measures to SWD necessitates both material investment and manual labor, resulting in a cost that is higher than that of various other management strategies

(Schoneberg et al., 2021). Although these strategies may not be effective in reducing SWD damage on their own, they can still provide horticultural benefits. Cultural control methods are an essential component of SWD management, and there are numerous options available, each with its own economic advantages and disadvantages. Techniques such as exclusion netting, drip irrigation, and mulching are popular among growers of high-value crops such as blackberries, raspberries, and strawberries because they can result in increased financial returns despite requiring substantial initial investments.

2.2.3. Biological control

Biological control is a pest management method that employs predators, parasitoids, and entomopathogens (Tait et al., 2021). There has been an interest in biological control instruments since the SWD became a global economic threat for many crops. The biological control of spotted-wing drosophila was examined intensively. The research by Jana C Lee et al. (2019) examined the effectiveness of various biological control agents, such as predators, parasitoids, pathogens, and competitors, against the SWD. The authors analyzed 75 publications and summarized their findings. They discussed the impact observed in the field, the efficacy of currently available commercial products, and other potential future control options. The purpose of the study was to provide a comprehensive summary of the current state of knowledge regarding the use of natural enemies for SWD control.

Woltz et al. (2015) reported that natural predators reduced spotted-wing drosophila larval populations in strawberries and blueberries. In field experiments, when predators consumed infested fruit, strawberry larval infestations were reduced by 19-34 percent and blueberry infestations were reduced by 28-49 percent, according to the study. This highlights the significant role that natural predators play in controlling the spotted-wing drosophila population.

According to Ballman and Drummond (2019) research, predators were able to eliminate 80 to 100 percent of the sentinel spotted-wing drosophila pupae placed on the soil surface in blueberry fields in Maine, United States. This suggests that predators may play a significant role in controlling the population of spotted-wing drosophila.. Woltz et al. (2015) revealed that, while several natural enemies, including predators, entomopathogenic fungi, and entomopathogenic nematodes, were tested for their ability to control SWD in fruit crops, most had limited effectiveness under the tested conditions. Jana C Lee et al. (2019) found that unmanaged or organic farms tend to have greater populations of generalist predators than conventional farms. These predators are capable of suppressing the SWD population through a process known as conservation biocontrol. This means that predators can naturally control the SWD population without the need for additional management practices or chemicals.

There have been reports of levels of parasitism in specific Drosophila populations ranging from 80 to 100 percent, and parasitoids play an essential part in the control of these populations (De Haan et al., 1987; Fleury et al., 2009). There are parasitoid wasps that lay their eggs in larvae of the spotted-winged drosophila, which then pupate, resulting in an adult wasp emerging from the parasitized larva.

Spotted-wing Drosophila has several generalist pupal parasitoids, including *Pachycrepoideus vindemiae, Trichopria drosophilae*, and *Trichopria anastrephae*. However, these pupal parasitoids have not been found to be effective in providing significant suppression of the pest (Gabarra et al., 2015; Mazzetto et al., 2016; Miller et al., 2015; Rossi Stacconi et al., 2019)

Ganaspis brasiliensis and *Leptopilina japonica* are the two predominant larval parasitoids that attack SWD-infested fruits. In China, *G. brasiliensis* is responsible for the parasitization of larval hosts at a rate of 47.8 percent (Giorgini et al., 2019) while in Japan, this rate is 75.1 percent (Girod et al., 2018). Therefore, these two parasitoids would be ideal candidates for traditional biological management strategies (Tait et al., 2021). Properly planned augmentative biological control, in combination with other control strategies, can thus provide an effective control mechanism for producers (Tait et al., 2021).

2.2.4. Manipulation of Behavioral Patterns

The ability of the SWD to locate reproductive hosts is critical for its survival, and it poses a serious threat to soft-skin fruits and berries in many parts of the world. Both short- and long-distance attraction rely on the proper functioning of visual and olfactory cues (Little et al., 2019). In accordance with the visual sensitivity range of the melanogaster subgroup, Little et al. (2019) discovered that the spotted-wing drosophila has a limited capacity to distinguish between red hues. This suggests that SWD's ability to select hosts based on visual cues may be limited, which has substantial implications for fruit growers. In addition, the study revealed that color contrast may play a more important role in orientation and attraction than color appearance. Reflectance differences between light wavelengths that are important for color opposition have been shown to be critical to color discrimination, providing contrast between foreground and background during host-finding, such as between fruit and foliage. These findings emphasize the importance of understanding the role of visual cues in SWD host selection, which could help to develop more effective pest management strategies for this invasive species.

Attractive stimuli are used in mass trapping to suppress a pest population. The manipulations involve luring insects to a trap, where they are imprisoned and are likely to perish (Shaw et al., 2018). A concentrated perimeter of traps baited with attractants is one potential method for reducing the number of SWD that enter a crop. This method claims to reduce the number of SWD pests that enter the crop (Alnajjar et al., 2017; Hampton et al., 2014). It is advised to place 30 to

50 traps per hectare, with a maximum distance of 2 meters between each trap, and to service these traps once per week (J. C. Lee et al., 2011; Spies & Liburd, 2019). Especially for large-scale production, the cost of materials and labor associated with this technology is likely to be a barrier to adoption. Therefore, mass trapping is not a viable stand-alone technique for SWD control; however, it could contribute to integrated management when used in conjunction with other management strategies (Profaizer et al., 2015; Spies & Liburd, 2019).

2.2.5. Developmental Disruption-Sterile Insect Technique (SIT)

The SIT approach is a way of pest management that is both kind to the environment and particular to certain species. This method has proven effective in controlling or eradicating pest populations (Nikolouli et al., 2018). The sterile insect strategy involves mass breeding of the insect sterilized by exposure to ionizing radiation and continuous release of the sterile male insects throughout the affected area on a regular basis (Lanouette et al., 2017). The sterile insect approach may be a promising strategy for controlling SWD, but it requires the development of mass-rearing technologies. Furthermore, it is critical to identify a radiation dose capable of producing competitive sterile males, which are required for effectively reducing SWD populations. Mass-rearing technologies must be developed in order to establish a sterile insect approach for SWD. Furthermore, an adequate dose of radiation should be capable of completely sterilizing females (Tait et al., 2021). Therefore, using exclusively sterile male insects in the sterile insect approach results in greater effectiveness. According to Rendón et al. (2004) sterile females can compete with fertile females for the chance to mate with sterile males. This result has significant implications for the implementation of the sterile insect technique for pest population control, as it demonstrates the potential for competition between sterile and fertile females for access to sterile males.

Understanding the dynamics of competition between sterile and fertile insects is essential for optimizing the efficacy of this strategy.

Controlling *Drosophila suzukii* is notoriously difficult due to the limited number of efficient measures available; thus, farmers are strongly recommended to establish a complete management approach for this extremely adaptable bug. This strategy should involve basic horticultural procedures as well as post-harvest treatments.

2.2. The GDD-Based IPM Approach to SWD Management

Spotted Winged Drosophila is a pest that infects a wide variety of soft-skinned and stone fruits worldwide and has disastrous economic consequences. The use of GDD as a predictor of SWD activity has been recognized as an integral part of the IPM strategy for SWD management. The GDD method is a heat accumulation measurement that is used to determine the development of pests, diseases, and plant growth. Baskerville and Emin's method is utilized to calculate GDD in horticulture and agriculture.

A recent study by Wilson et al. (2022) revealed a strong correlation between SWD infestation in tart cherry orchards and the progression of fruit development as measured by GDD post-bloom. The research revealed that very few larvae developed in fruit before reaching 530 GDD (base 4°C) in no-choice assays, and none were found in naturally infested fruit prior to 800 GDD. This study provides evidence that the risk of SWD infestation in tart cherries increases as the fruit ripens and that a GDD model based on fruit development can be utilized to predict the likelihood of SWD infestation. Furthermore, Kamiyama et al. (2020) developed seasonal prediction models for SWD utilizing four years of data from adult monitoring trap catches in Wisconsin tart cherry orchards. These models properly predicted SWD behavior throughout the year. The models examined the correlations between many factors such as the year, the location of the orchard, relative humidity, degree days (DD), and the amount of prey caught in traps.

Infestations of the SWD are widespread in crops that have reached a specific color and level of softness. Wilson et al. (2022) utilized the findings from Zavalloni et al. (2006) and developed a model based on the GDD. The goal of the model was to acquire a clearer understanding of the relationship between fruit ripening and the presence of SWD infestation. Wilson et al. (2022) found that SWD larval infestation increases predictably as fruit ripens, especially after 800 GDD base 4°C. According to Zavalloni et al. (2006), the timing of 800 GDD coincides with the average diameter of tart cherries reaching 95% of its final size and reaches to a certain point of color and softness that makes it more susceptible to SWD infestation. Growers can use this information to improve the timing of their strategies and reduce the amount of insecticide they use for SWD control by not spraying when unnecessary. The research conducted by Wilson et al. (2022) indicates a strong correlation between fruit ripeness and an increased risk of D. suzukii infestation in tart cherry. Using a growing degree day (GDD) model with a lower threshold of 4°C to predict the risk of infestation, the study determined that 800 GDD is a critical threshold for the increased susceptibility of tart cherry fruit. While this model does not account for all environmental conditions that can influence D. suzukii behavior and infestation risk, it does provide growers with a promising tool to more precisely time control tactics and minimize insecticide applications. This strategy highlights the findings of Wilson et al. and proposes the use of GDD-based chemical control as a potential solution while recognizing the need for additional field testing

Ultimately, the incorporation of a GDD-based IPM strategy is a promising method for controlling SWD in tart cherry orchards. This strategy prioritizes the vulnerability of the fruit over the population of flies, providing growers with a practical and crop-specific SWD management tool.

To confirm that the model can prevent fruit infestation, additional testing under real-world situations is necessary.

3. CONCEPTUAL FRAMEWORK

The conceptual framework for this study aims to investigate the economic benefits of adopting GDD-based IPM models for controlling SWD in tart cherry orchards. The study employs a partial budget analysis approach, a method used to evaluate the economic impact of a change in a specific input or activity on the overall profitability of a farming operation.

IPM is a crucial strategy for cost-effective and sustainable pest control in crop production. In Michigan's tart cherry production, the adoption of an IPM strategy can yield substantial benefits, especially in managing SWD. This study focuses on the economic benefits of adopting GDD-based IPM models for controlling SWD in tart cherry orchards.

The study employs a partial budget analysis approach, which is a reliable and widely used method for evaluating the economic impact of a change in a particular input or activity on the overall profitability of a farming operation. Other variables, such as yield, market value, and production expenses, are held constant during the analysis. By controlling for these other variables, the study can isolate and accurately estimate the potential cost savings associated with adopting the IPM model based on GDD for SWD control in tart cherry orchards. This report provides a thorough analysis of the economic impact of adopting the GDD-based IPM model for SWD management in tart cherry production. The use of a partial budget analysis approach allows for a clear and concise evaluation of the economic impact of adopting GDD-based IPM models. The method considers both the costs and benefits of the new practices and calculates the net change in profits. This approach is a reliable and widely used method for evaluating the economic effects of new pest management practices (Norton et al., 2005).

Adoption of IPM practices at the producer level has the potential to result in substantial improvements to agricultural practices. In addition to reducing pesticide use, it leads to a shift toward a more proactive approach to pest management, including increased monitoring. This shift in practices results in a method of crop production that is more sustainable, cost-effective, and environmentally friendly.

Costs associated with chemicals, labor, and equipment can be significantly reduced by decreasing the number of pesticide spray applications. This reduction in pesticide use is only part of the picture. IPM's increased monitoring also plays a vital role in ensuring that pests are effectively managed and kept under control. This proactive approach to pest management increases the likelihood of preventing pest outbreaks and reducing crop-related economic losses.

Degree days play a crucial role in SWD management by predicting fruit ripening and the time at which fruit becomes more susceptible to infestation, allowing growers to precisely time control strategies. The GDD-based IPM strategy for controlling SWD holds great promise for reducing the need for insecticide applications and optimizing the management of this pest. By accurately determining the timing of insecticide applications using GDD-based IPM, this strategy has the potential to minimize the use of pesticides, thereby reducing costs and promoting more sustainable agricultural practices. The adoption of the GDD-based IPM strategy for managing SWD merits additional research due to its potential to provide benefits to both producers and the environment.

The study conducted by Wilson et al. (2022) utilizes historical weather data and tart cherry production statistics to estimate the potential cost savings of implementing this innovative pest management strategy. The results demonstrate the potential for substantial cost savings and improved pest management outcomes, making this a valuable resource for tart cherry growers and industry stakeholders.

The results of this study will provide valuable information for tart cherry growers and industry stakeholders in Michigan, as well as other regions where SWD is a significant pest problem. In addition, the findings will provide insight into the potential cost savings and economic benefits of adopting GDD-based IPM models for SWD management, which can inform decision-making and support more sustainable pest management practices in tart cherry orchards.

In conclusion, adopting GDD-based IPM models for controlling SWD in tart cherry production is a cost-effective and sustainable solution for pest control that provides both economic benefits and environmental advantages. The results of this study demonstrate the potential for substantial cost savings The results of this study will provide valuable information for tart cherry growers and industry stakeholders in Michigan, as well as other regions where SWD is a significant pest problem. In addition, the findings will provide insight into the potential cost savings and economic benefits of adopting GDD-based IPM models for SWD management, which can inform decision-making and support more sustainable pest management practices in tart cherry orchards.

Table 1: Producer-level Partial Budget Form for SWD Control in Tart Cherry Orchards

COST		**BENEFIT**	
Additional costs		**Additional Returns**	
Reduced returns		Reduced Cost	
		Reduced Pesticide	
		Reduced cost of pesticide application	
Total Cost		Total Benefits	
The net change in profits = Total Benefits - Total Cost			

4. METHODOLOGY

This study aimed to estimate the potential long-term economic benefits of adopting an IPM strategy based on GDD for managing SWD in tart cherry production in Michigan between 2023 and 2037 over a period of 15 years. To achieve this objective, a comprehensive methodology was implemented that utilized multiple data sources and made a number of assumptions to estimate the costs and benefits of the IPM strategy. The study used a partial budget analysis approach to evaluate the economic impact of a change in a specific input or activity on the overall profitability of a farming operation, taking into account both the cost savings from reduced insecticide use and the application costs, labor, and equipment associated with SWD management. In order to provide a comprehensive analysis, the study held other variables, such as the price of tart cherries, the price of other inputs, and yield, constant, ceteris paribus. This allowed for a clear evaluation of the effect of the IPM strategy on SWD management in tart cherry production.

Several crucial steps constituted the methodology for this research. Initially, daily temperature data between 2008-2022 was obtained from MSU Enviroweather from three different regions in Michigan: South West Central Michigan, Traverse City Northwest Michigan, and Hart in the West Central. Then growing degree days are calculated for each year and each day using the Baskerville-Emin method. This data was used to determine the threshold GDD as an action threshold to start for the first cover spray on tart cherry orchards. To achieve this objective, we utilized MSU Enviroweather to collect growing degree day (GDD) information from 2008 to 2022. We then utilized the Baskerville-Emin method to calculate a GDD base of 4°C and to obtain the phenological dates corresponding to the GDD values. It is important to note that this study makes the assumption that future weather will be similar to past weather, which is a common practice in many studies that make projections using historical data (Collins et al., 2012; Dixon et al., 2016;

Knutti & Sedláček, 2013; Stocker et al., 2014). On the assumption that future weather patterns will be similar to those observed in the past, the daily temperature data from MSU Enviroweather for the years 2008 to 2022 can be used to project weather patterns for the years 2023 to 2037. This methodology can be used to assess the potential impact of implementing integrated pest management (IPM) practices in 2023 by calculating avoided sprays using temperature data from the reference period (2008 to 2022). Similarly, temperature data from the final year of the reference period (2022) can be used to forecast potential spray avoidance in 2037. To demonstrate the applicability of this methodology, consider estimating the avoided sprays in 2023 using climate data from the 2008-2022 reference period, which provides a reliable representation of weather patterns in tart cherry growing regions. Using this method, we can determine the potential benefits of implementing IPM practices in 2023. Similarly, if we wanted to predict the avoided sprays in 2037, we would use climate data from the final year of the reference period (2022).

Based on the findings of Wilson et al. (2022), the SWD infestation of tart cherries was most likely to occur at 800 GDD, the point at which fruit becomes susceptible to infestation. As a result, we established an annual GDD threshold of 800, which is the optimal time for the first cover spray within the IPM system.

To estimate spray timing and cost savings, we assumed farmers in the adopter group would implement the GDD-based IPM strategy and apply the initial spray at the annual threshold of 800 GDD, followed by weekly spraying. In the meantime, the non-adopters would continue to use the calendar-based method of chemical spraying. This assumption is consistent with the objective of the study, which is to assess the potential economic advantages of adopting the IPM strategy based on GDD for SWD control in tart cherry production. Farmers who are contemplating switching from the traditional calendar-based spraying method to the GDD-based IPM method can use the study's results as a guide.

The 2019 Tart Cherry Pest Guide Extension Handout provide an estimate of the calendar-based chemical spraying schedule, as we were unable to obtain a spraying schedule from a producer survey due to low participation. This guide is essential for constructing a pesticide application schedule, as it provides comparative benchmarks for making well-informed decisions about the optimal times to apply insecticides. According to the data on the Tart Cherry Pest Guide, we can assume that the calendar-based strategy involved spraying on fixed dates of June 15 for the initial cover, June 29 for the second cover, July 13 for the third cover, and July 29 for the fourth cover for each year between 2023 and 2037. It is important to note that the study assumes that the GDD-based IPM system is just as effective as the traditional calendar-based spraying method at controlling SWD. Based on the assumption that both GDD-IPM and calendar-based spraying have equal efficacy for SWD control, the cost savings from using GDD-IPM come solely from reduced spraying frequency and associated spray costs. Insecticides used for SWD control after the 800 GDD threshold is reached would be expected to provide equivalent control to those used before, but with fewer sprays needed. It is important to note that other factors, such as pest pressure and weather conditions, could still affect the effectiveness of SWD control, even with GDD-IPM.

The baseline counterfactual scenario was constructed to estimate the number of unnecessary sprays by assuming that farmers in Michigan would continue to use their current pest management strategies without adopting the GDD-based IPM model. The "no adoption" scenario represents the actual spraying schedule that farmers would have used if the GDD-based IPM model had not been adopted. We used the calendar spraying schedule provided in the 2019 Tart Cherry Pest Guide Extension Handout as a benchmark for estimating the number of unnecessary sprays because participation in a producer survey was low and we were unable to obtain a schedule from it. We calculated the cost of these unnecessary sprays that would occur before the GDD threshold of 800 by using cherry acreage data from the USDA/NASS QuickStats system, as well as pesticide and application costs per acre from MSU Extension specialists. The pesticides used in both GDD-based IPM and calendar-based spraying are assumed to be equally effective against SWD. This assumption is required to ensure the validity of the comparison between the two scenarios, as it allows for a direct comparison of the number of sprays required and unnecessary in each scenario.

This research seeks to identify more effective and efficient SWD management strategies in tart cherry production while minimizing the use of insecticides. Recent research by Wilson et al. (2022) suggests that spraying before the 800 GDD threshold may be less effective at reducing SWD infestation and controlling the pest. After 800 GDD, when the fruit is more ripe and therefore more conducive to larval development, the tart cherry fruit is significantly more susceptible to SWD infestation, according to the study. As a result, spraying before this threshold may constitute an unnecessary application of insecticides. This study sheds light on the potential advantages of adopting a GDD-based IPM strategy for SWD control in tart cherry production.

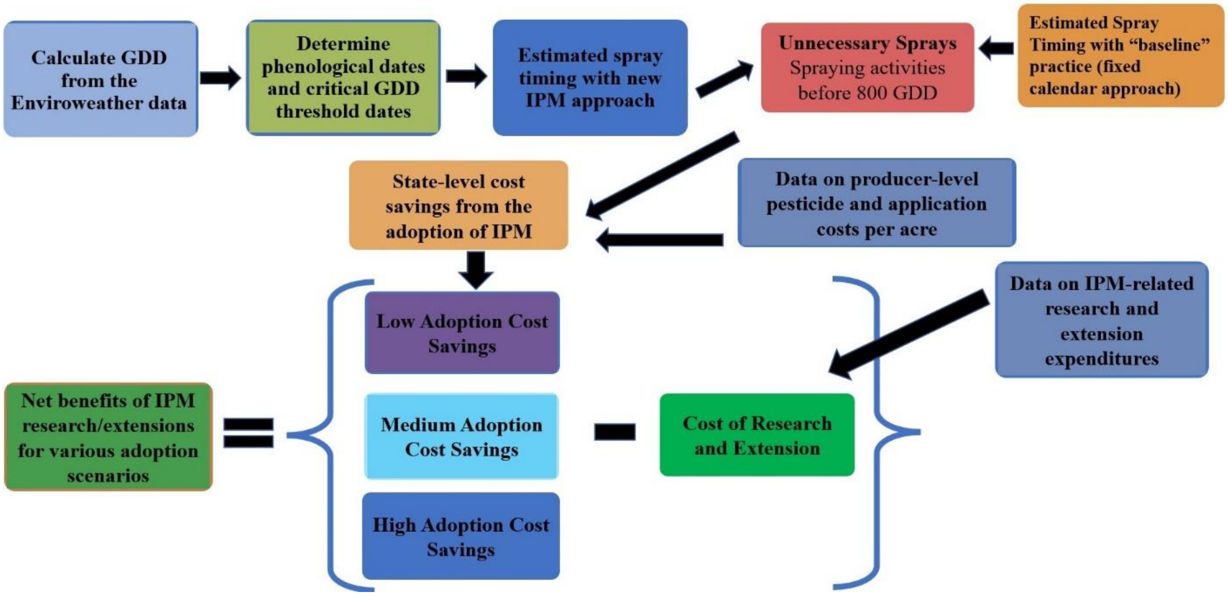
The study acknowledges that some pesticides used in tart cherry production are effective against multiple pests in addition to SWD. For the purposes of the study, it was assumed, however, that the pesticide applications were solely for SWD management. This is a simplification, but it supports the argument that a more targeted approach to insecticide use can be just as effective in controlling SWD, even in the presence of other pests.

Our analysis of the adoption of an Integrated Pest Management (IPM) strategy for Michigan tart cherry production utilized the Net Present Value (NPV) method to calculate the present value of future savings and totaled cost savings across farms, acres, and the 15-year period from 2023 to

2037. Our objective was to calculate the net benefits of implementing this strategy. The GDD threshold was not initially specified when the GDD-based IPM system was introduced in the 2019 MSU Extension handout. Recent research conducted by some of the same researchers Wilson et al. (2022) from the MSU Extension system based at the Northwest Michigan Horticultural Research Center in Traverse City, Michigan, USA, has established the GDD threshold required for effective management of SWD in tart cherry production. In light of this development, we began our analysis in 2022 using a real discount rate of 5% in 2022 dollars. We assume that at that time, MSU Extension specialists were aware of the GDD threshold required for effective SWD management. By utilizing this methodology, we were able to assess the economic viability of adopting an IPM approach for tart cherry production in Michigan and provide valuable insights to regional producers.

To understand the potential adoption of GDD-Based IPM in Michigan tart cherry production, we estimated the adoption rates for the new IPM method using the S-Shaped Diffusion model. The model allowed us to account for three distinct phases of adoption: low, moderate, and high. Then, for each adoption scenario, we determined the potential cost savings that could be realized by adopting GDD-based IPM. The S-Shaped Diffusion model is a prevalent method for estimating the adoption trajectory of innovations over time; it assumes the adoption rate will follow an S-shaped curve, beginning slowly, accelerating to a peak, and then slowing as the innovation reaches saturation. This model enabled us to make insightful projections regarding the potential adoption of GDD-based IPM and the resulting cost savings for tart cherry production in Michigan. Our study provides a comprehensive evaluation of the economic benefits of adopting a GDD-based IPM strategy for managing SWD in Michigan tart cherry production. Farmers, researchers, and policymakers will be able to use the findings of our study to make informed decisions regarding the adoption of IPM practices to manage SWD and reduce the economic costs of traditional spraying methods.

Figure 1: Methodological Process



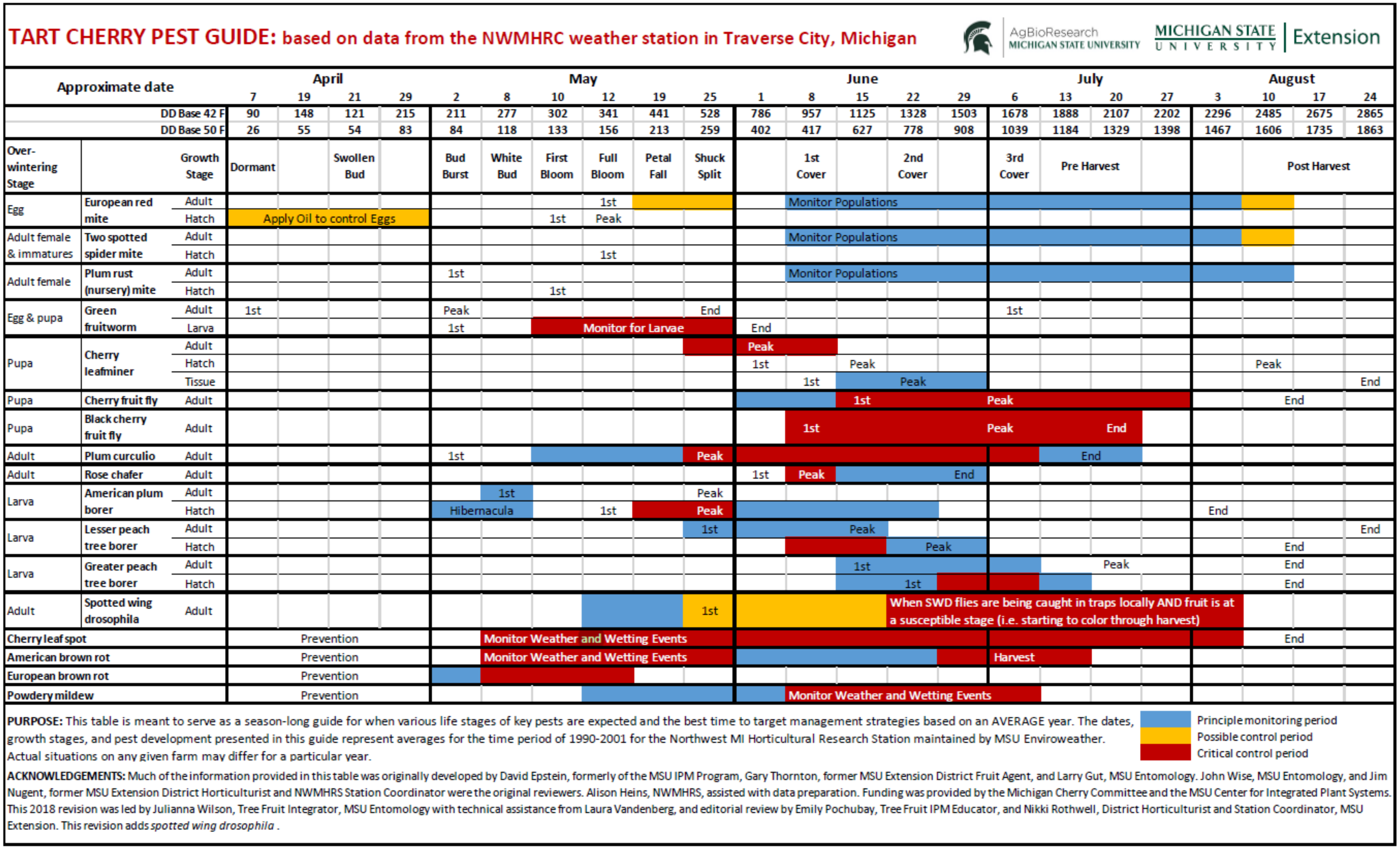
During the data collection and analysis process, we encountered several challenges. One of the main challenges was obtaining accurate information on the current spraying schedule and practices used by tart cherry farmers in Michigan. We attempted to gather this information through a producer survey; however, the survey did not proceed as expected, and we did not receive enough responses. To address this challenge, we turned to other sources of information, such as extension handouts from MSU Extension and data sets obtained from MSU Extension specialists, which helped us understand the potential spraying schedule and quantities. We also used "First action point" data from the cherry pest guide 2019, which considered June 15 for the first cover, June 29 for the second cover, and July 13 for the third cover. This approach is consistent with the guidelines provided in the Tart Cherry Pest Management Guide.

Another challenge we faced was creating an IPM alternative to compare in our analysis. The challenge is mainly caused by the zero tolerance for tart cherry infestation among farmers. To address this challenge, we had to think about a rational IPM model. We considered an area-wide pest management strategy against SWD, and there will be a combination of chemical control and biological control instruments. Chemical will be the first management technique in the orchard; however, we assume that adopting GDD-based chemical control over calendar-based chemical control would be a more effective management strategy.

The lack of empirical data on the adoption rate of the GDD-Based IPM method among Michigan's tart cherry farmers posed a formidable obstacle to this study. This issue was approached by examining a range of adoption rates and analyzing three distinct adoption rate scenarios. This can be viewed as a form of sensitivity analysis, as it allows us to assess the potential impact of varying adoption rates on the overall results. In addition, we gathered as much information as possible about the technology and the environment in which it will be implemented, which enabled us to make more accurate assumptions. By considering a range of adoption rates and utilizing multiple scenarios, we were able to evaluate the potential benefits of adopting the GDD-Based IPM approach for tart cherry production in Michigan in a more comprehensive manner.

Overall, despite these challenges, we were able to gather and analyze relevant data and provide an estimation of the economic benefits of adopting an IPM approach to managing the SWD in tart cherry production in Michigan.

Figure 2: Cherry Pest Guide by MSU Extension 2019



TART CHERRY PEST GUIDE: based on data from the NWMHRC weather station in Traverse City, Michigan

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Approximate date			April				May						June					July				August			
			7	19	21	29	2	8	10	12	19	25	1	8	15	22	29	6	13	20	27	3	10	17	24
		DD Base 42 F	90	148	121	215	211	277	302	341	441	528	786	957	1125	1328	1503	1678	1888	2107	2202	2296	2485	2675	2865
		DD Base 50 F	26	55	54	83	84	118	133	156	213	259	402	417	627	778	908	1039	1184	1329	1398	1467	1606	1735	1863
Over-wintering Stage		Growth Stage	Dormant		Swollen Bud		Bud Burst	White Bud	First Bloom	Full Bloom	Petal Fall	Shuck Split		1st Cover		2nd Cover		3rd Cover	Pre Harvest					Post Harvest	
Egg	European red mite	Adult								1st	🟨	🟨		🟦 Monitor Populations	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨		
		Hatch	🟨 Apply Oil to control Eggs	🟨	🟨	🟨			1st	Peak															
Adult female & immatures	Two spotted spider mite	Adult												🟦 Monitor Populations	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨		
		Hatch								1st															
Adult female	Plum rust (nursery) mite	Adult					1st							🟦 Monitor Populations	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		
		Hatch							1st																
Egg & pupa	Green fruitworm	Adult	1st				Peak					End						1st							
		Larva					1st		🟥 Monitor for Larvae	🟥	🟥	🟥	End												
Pupa	Cherry leafminer	Adult										🟥	🟥 Peak	🟥											
		Hatch											1st		Peak								Peak		
		Tissue												1st	🟦	🟦 Peak	🟦								End
Pupa	Cherry fruit fly	Adult											🟦	🟦	🟥 1st	🟥	🟥	🟥 Peak	🟥	🟥	🟥		End		
Pupa	Black cherry fruit fly	Adult												🟥 1st	🟥	🟥	🟥	🟥 Peak	🟥	🟥 End					
Adult	Plum curculio	Adult					1st		🟦	🟦	🟦	🟥 Peak	🟥	🟥	🟥	🟥	🟥	🟥	🟦 End	🟦					
Adult	Rose chafer	Adult											1st	🟥 Peak	🟦	🟦	🟦 End								
Larva	American plum borer	Adult						🟦 1st				Peak													
		Hatch					🟦 Hibernacula	🟦		1st	🟥	🟥 Peak	🟦	🟦	🟦	🟦						End			
Larva	Lesser peach tree borer	Adult										🟦 1st	🟦	🟦	🟦 Peak										End
		Hatch												🟥	🟥	🟦 Peak	🟦						End		
Larva	Greater peach tree borer	Adult													🟦 1st	🟦	🟦	🟦		Peak			End		
		Hatch													🟦	🟦 1st	🟥	🟥	🟦				End		
Adult	Spotted wing drosophila	Adult								🟦	🟦	🟨 1st	🟨	🟨	🟨	🟥 When SWD flies are being caught in traps locally AND fruit is at a susceptible stage (i.e. starting to color through harvest)	🟥	🟥	🟥	🟥	🟥	🟥			
Cherry leaf spot			Prevention					🟥 Monitor Weather and Wetting Events	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	End		
American brown rot			Prevention					🟥 Monitor Weather and Wetting Events	🟥	🟥	🟥	🟥	🟦	🟦	🟦	🟦	🟥	🟥 Harvest	🟥						
European brown rot			Prevention				🟦	🟥	🟥	🟥															
Powdery mildew			Prevention							🟦	🟦	🟦	🟦	🟥 Monitor Weather and Wetting Events	🟥	🟥	🟥	🟥							

PURPOSE: This table is meant to serve as a season-long guide for when various life stages of key pests are expected and the best time to target management strategies based on an AVERAGE year. The dates, growth stages, and pest development presented in this guide represent averages for the time period of 1990-2001 for the Northwest MI Horticultural Research Station maintained by MSU Enviroweather. Actual situations on any given farm may differ for a particular year.

🟦 Principle monitoring period
🟨 Possible control period
🟥 Critical control period

ACKNOWLEDGEMENTS: Much of the information provided in this table was originally developed by David Epstein, formerly of the MSU IPM Program, Gary Thornton, former MSU Extension District Fruit Agent, and Larry Gut, MSU Entomology. John Wise, MSU Entomology, and Jim Nugent, former MSU Extension District Horticulturist and NWMHRS Station Coordinator were the original reviewers. Alison Heins, NWMHRS, assisted with data preparation. Funding was provided by the Michigan Cherry Committee and the MSU Center for Integrated Plant Systems. This 2018 revision was led by Julianna Wilson, Tree Fruit Integrator, MSU Entomology with technical assistance from Laura Vandenberg, and editorial review by Emily Pochubay, Tree Fruit IPM Educator, and Nikki Rothwell, District Horticulturist and Station Coordinator, MSU Extension. This revision adds *spotted wing drosophila* .

5. DATA

5.1. Data Sources And Collection

This study's data sources and collection were primarily derived from the USDA NASS QuickStats Database, which contains information on tart cherry production, including price, bearing acres, and annual production. This database is a comprehensive and current source of agricultural data for the United States, such as crop production, prices, and acreage information. In addition, we obtained data on pesticide names, prices, and application rates from an MSU Extension specialist, who provided us with data sets containing the names of commonly used pesticides for tart cherry production in Michigan, as well as their prices and application rates. **Table 2** displays the rates, pesticide costs, and application costs for three selected pesticides; these data are assumed to be applicable for all years between 2023 and 2037. It is worth mentioning that the variation of pesticides and application costs may vary from year to year and may not be accurately reflected in our calculations.

Table 2: Pesticide Use Per Acre Cost Breakdown in Tart Cherry Orchards

	Pesticide Name	**Rate**	**Pesticide Cost ($)**	**Application Cost ($)**	**Per Acre cost of spray ($)**
First Spray	Imidan	2.13	11.08	6	29.55
Second Spray	Delegate	6.5	8.74	6	62.81
Third Spray	Mustang MAXX	4	7.56	6	30.24

Source: MSU Extension

The utilization of the the USDA's National Agricultural Statistics Service (NASS), information on Michigan's 2017 fruit production, including tart cherries, blueberries, strawberries, and raspberries, was collected. The acreage of these fruits and the proportion of tart cherry production compared to the total acreage for each year are shown in **Table 3**. This information was used to calculate the amount of time extension specialists devote to managing SWD in tart cherry orchards and the associated research costs. Integrated Pest Management (IPM) models based on Growing Degree Days (GDD) for SWD management in tart cherry orchards. Notably, the table only provides data on the acreage of fruit-bearing plants impacted by SWD, not production figures.

Table 3: Acres of Fruit-Bearing Plants Affected by SWD in Michigan in 2017

Commodity	Acres Bearing
Blueberries	20,228
Cherries, sweet	6,701
Cherries, tart	26,500
Raspberries	410
Strawberries	738

Source: USDA/NASS

Table 4 displays the tart cherry production acreage and proportion by region in Michigan. This information was used to estimate the geographic distribution of tart cherry production in Michigan and to gain a better understanding of the potential effects of adopting the GDD-based IPM strategy on a regional scale.

Table 4: Michigan Tart Cherry Production by Region in 2017

Region	Acres Bearing	Proportion
Northeast	1	0.0%
Northwest	15863	62.0%
Southeast	5	0.0%
Upper peninsula	4	0.0%
Southwest	1887	7.4%
West central	7807	30.5%
Total	25567	100.0%

Source: USDA/NASS

Based on an analysis of tart cherry acreage data for various Michigan regions between 2017 and 2021, it was determined that the overall trend was a decline in acreage. In particular, 2017 and 2018 saw no change, followed by a 3.5% decrease in 2019, an 8% decrease in 2020, and a 2% decrease in 2021.

Given that these were actual reductions in tart cherry acreage across the state, it is reasonable to assume that reductions occurred at the same rates in each region. As a result, it is suggested that a 1% annual decrease in acreage be used for the forecast from 2022 to 2037 across all regions.

Despite the fact that this assumption is based on the observed trend in acreage reduction, it is important to note that unanticipated events such as changes in weather patterns or government policies could influence the trend and cause deviations from the predicted values. It is recommended, therefore, to monitor and reevaluate the trend over time to ensure that any changes in land area are accounted for in planning and decision-making.

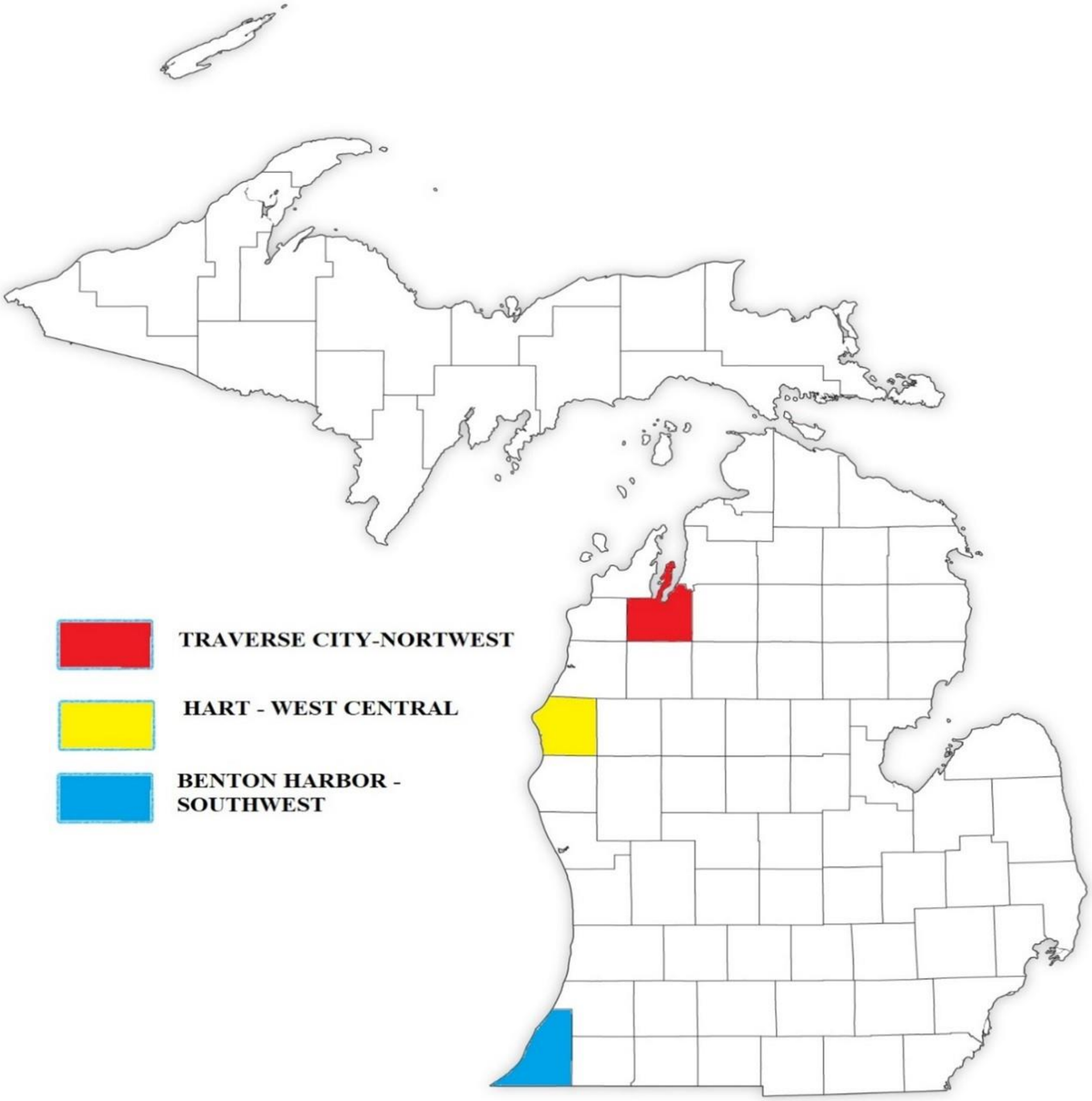
It is possible to predict with a reasonable degree of certainty the future acreage of tart cherries if one considers the observed trend in the reduction of acreage and then applies a reasonable assumption to the upcoming years. This information can be utilized to determine the ex-ante benefits of implementing GDD-Based IPM for SWD management. The projections for tart cherry acreage from 2023 to 2037 are detailed in **Table 5.**

Table 5: Tart cherry acreage forecast between 2023-2037

Year	Tart Cherry Acreage Northwest	Tart Cherry Acreage Southwest	Tart Cherry Acreage West Central
2023	13477.2	1603.2	6632.8
2024	13342.5	1587.2	6566.5
2025	13209.0	1571.3	6500.8
2026	13076.9	1555.6	6435.8
2027	12946.2	1540.0	6371.5
2028	12816.7	1524.6	6307.8
2029	12688.5	1509.4	6244.7
2030	12561.7	1494.3	6182.2
2031	12436.0	1479.3	6120.4
2032	12311.7	1464.5	6059.2
2033	12188.6	1449.9	5998.6
2034	12066.7	1435.4	5938.6
2035	11946.0	1421.1	5879.2
2036	11826.6	1406.8	5820.5
2037	11708.3	1392.8	5762.3

Figure 3 shows a map of Michigan with three highlighted regions denoting the three regions from which weather stations were selected for the study. The colors red, yellow, and blue represent Traverse City, Hart, and Benton Harbor, respectively. The illustration depicts the spatial distribution of weather stations in relation to tart cherry growing regions in Michigan. This information is essential for understanding the geographical scope of the weather data used in the study and its applicability to the various regions of interest.

Figure 3: Location of Weather Stations in Tart Cherry Growing Regions of Michigan: Traverse City, Hart, and Benton Harbor



5.2. Phenological Stages and Growing Degree Days(GDD)

We used the Enviroweather station in Traverse City to determine the daily GDD statistics, and then we determined the dates of critical phenological stages. In the paper by Zavalloni et al. (2006), the phenological stages were described in terms of GDD (2006). To estimate the growth of 'Montmorency' tart cherry fruit before the arrival of the Spotted Wing Drosophila, Zavalloni et al. (2006) developed a model in Michigan based on the accumulation of GDD from full bloom (SWD). This model was developed to assist growers in estimating the potential growth and development of their crop prior to the arrival of SWD, allowing them to plan effective pest management strategies to protect their crop. This model can aid in the prediction and management of pest outbreaks, as well as the reduction of economic losses associated with pest damage. Observations made in the three major tart cherry production zones in the lower peninsula of Michigan, which are located in the northwestern, western central, and southwestern regions, were used to construct and validate the models. Based on daily maximum and minimum temperatures, Zavalloni et al. (2006) developed a simulation model for the 'Montmorency' sour cherry that computes the flower bud phenological stages and fruit growth.

The Baskerville and Emin method for calculating GDD is used in horticulture and agriculture to measure heat accumulation over a certain period. GDD is a measure of heat accumulation that is used to determine the development of pests, diseases, and growth. This method is utilized by MSU Enviroweather to calculate the degree days reported by agricultural weather stations throughout the state. When the minimum daily temperature is greater than the base threshold temperature, the averaging method and the Baskerville and Emin methods produce similar results. To calculate GDD with Baskerville and Emin method;

- Suppose the maximum temperature is lower than the base temperature. If this is the case, the total GDD for the day is 0. If not, continue to the following step.
- Determine the average temperature for the day. In the example, (5C + 15C)/2 =20C.
- Determine if the minimum temperature exceeds the base temperature. If this is the case, then

GDD=Average Temperature-Base Temperature

If not;

TAVE = Average temperature (already calculated in our example at 20C).

BASE = Base Temperature (4C).

W= (Max Temperature-Min Temperature)/2 = In our case, this is (15-5)/2=5

A=Arcsin((Base-Tave)/W)

$$\mathbf{GDD} = (\boldsymbol{W} \times \mathbf{cos}(\boldsymbol{A})) - \left[(\boldsymbol{BASE} - \boldsymbol{TAVE}) \times \left(\left(\frac{\mathbf{3.14}}{\mathbf{2}}\right) - \boldsymbol{A}\right)/\mathbf{3.14}\right] \quad (1)$$

The particular phenological stages of the tart cherry flower bud and the number of growing degree-days GDD(base 4°C) required to attain those stages according to the tart cherry phenological model are presented in Although this extension handout was released in 2019, as seen **Figure 2**, a spraying calendar was created using the dates provided here between 2008 and 2022. This may not be the case in fact; the event may have occurred earlier or later than these dates.

When calculating the total GDD for each of the distinct phenological stages, the accumulation of GDD was begun on the side of green first. Based on previous observations, the side green stage was expected to commence at 120 GDD on March 1 from each of the three sour cherry production sites. GDD accumulations were utilized to define all following flower bud phases, commencing with the side green stage.

We assumed that the information we obtained in the Cherry Pest Guide 2019, based on data from the North West Horticultural Research Center (NWMHRC) weather station in Traverse City, Michigan, an extension document made by MSU Extension, was a spraying schedule from 2008 to 2022. According to the cherry pest guide in 2019, which also contains GDD for each phenological stage, the first cover happens around June 15, the second cover happens to occur around June 29, the third cover is covered by the previous spray on a 14-day interval unless a rain event warranted reapplication, so it is around July 13, and July 29 for the fourth cover.

Recent research by Wilson et al. (2022) sought to enhance the management decision-making process for SWD in tart cherry orchards. The authors sought to develop a more effective and sustainable strategy for SWD management that would enable fruit growers to reduce economic losses caused by pest damage. This research could aid in the development of future pest management strategies for SWD in tart cherry orchards, thereby reducing the negative impact of this invasive species on fruit production. They correlated infection risk with the growth model of tart cherry fruit and utilized no-choice bioassays to identify the threshold at which SWD infestation occurs. This was done so that the starting point for SWD control in tart cherries for a specific season may be precisely predicted. The findings of this study offer farmers with a precise method for determining where to begin SWD management in tart cherry. In addition, Wilson et al. (2022) assessed the fruit infestation caused by SWD using accumulated GDD with a base temperature of 4°C in comparison to an existing fruit development model that employs full bloom as a reference point.

The findings of Wilson et al. (2022) are the first to quantify the relationship between SWD infection and fruit growth. The results, if implemented, can provide a basis for a more environmentally friendly method of managing SWD in tart cherry orchards by identifying the fruit's susceptibility period. There was a clear association between increasing larval infestation and post-bloom GDD fruit development. The results indicated that very few larvae developed on fruit subjected to no-choice experiments prior to 530 GDD (base 4°C), and no larvae were observed on naturally contaminated fruit prior to 800 GDD (base 4°C).

Wilson et al. (2022) discovered that the infestation of SWD in 'Montmorency' tart cherry orchards is closely associated with the ripening of the fruit. The study was able to predict the likelihood of infection by utilizing a growing degree day (GDD) model with a base temperature of 4°C. The laboratory experiments demonstrated that SWD larvae can infest fruit beginning at 530 GDD, when the fruit begins to change color. However, the natural infestation of the orchard fruit was not observed until 800 GDD, when the fruit was completely ripe and red. The study concluded that focusing on the susceptibility of the fruit, as opposed to the presence and density of SWD flies, is the most effective method of pest control. This GDD model could provide tart cherry growers with a crop-specific tool to reduce insecticide use and manage SWD effectively on an annual basis.

The growing degree day (GDD) model with a lower threshold of 4°C is regarded as the optimal method for managing Spotted Wing Drosophila in Michigan tart cherry orchards. Due to the likelihood of risk-averse tart cherry growers continuing chemical spraying in response to the infestation threshold, this is the case. In the early stage of this research, various pest management alternatives were considered, and we came to a solution that we should lower the pesticide usage if farmers continue to spray. Due to heavy insecticide applications, biological control with parasitoids or predators may not work correctly in the orchards. However, biological control in non-crop areas would be more effective. USDA APHIS and the Michigan Department of Agriculture and Rural Development have approved the release of the samba wasp (*Ganaspis brasiliensis*) in areas where it threatens fruit production after years of evaluation and permit review.

According to (Tochen et al., 2016) and (Winkler et al., 2021), environmental parameters such as temperature and relative humidity have a major impact on the behavior, population dynamics, and infection risk of SWD. However, this crucial information has not been incorporated into the model. In addition, despite the fact that cultural management approaches have been shown to be successful in managing SWD (Schöneberg et al., 2020; Schoneberg et al., 2021) this model does not account for this and assumes that producers follow the same cultural practices.

The Baskerville and Emin (1969) approach was used to determine GDD based on daily minimum and maximum temperatures as Zavalloni et al. and Wilson et al. GDD was calculated using daily weather data obtained from a weather station at the Northwest Michigan Horticultural Research Center near Traverse City. Estimating the critical phenological stages for each year was accomplished by utilizing a mixture of the methods proposed by Zavalloni et al. (2006) and Wilson et al. (2022).

Using a model developed by Wilson et al. (2020), which predicts the likelihood of *Drosophila suzukii* infestation based on GDD accumulation, the likelihood of infestation at each stage was determined. Each phenological stage's likelihood of infestation was predicted using the Wilson model (y = 5.47244 + 0.01091*x). According to this model, there is a 0% chance of infestation for all growth stages prior to full bloom. As fruit ripens following full bloom, the likelihood of infestation increases, with varying degrees depending on environmental conditions and pest pressure. This study's GDD model was determined using the Baskerville and Emin method with a 4°C base temperature. At the Northwest Michigan Horticultural Research Center, the model was applied to the fruit growth and phenological stages of 'Montmorency' tart cherry orchards, and GDD accumulation was used to define the stages of flower bud development, beginning with full bloom.

It is important to note that, the characterization of the remaining flower bud stages for sour cherries in the three production regions was based on historical observations. The analysis involved tracking the accumulation of GDD starting from the side green stage. The side green stage, which is the starting point for tracking the accumulation of GDD, was determined to occur after March 1st at 120 GDD. GDD Threshold happens 800 GDD after full bloom.

Figure 4, **Figure 5**, and **Figure 6** provide crucial data for the development of effective pest management strategies for tart cherry production in Michigan, based on growing degree day (GDD) models. These graphs depict the cover dates for the initial three sprays and the associated GDD thresholds for the Northwest, Southwest, and West Central regions of Michigan from 2008 to 2022. The GDD thresholds are set at 800 GDD, and the GDD calculation for each cover in each year is calculated using temperature data to ensure that models are tailored to each region's particular environmental conditions. These figures illustrate that pest management strategies based on GDD models can be an effective means of controlling SWD populations in tart cherry production, given their potential to improve pesticide application timing and reduce pesticide quantity, thereby reducing environmental impact and overall production costs.

In comparison to other years, the patterns observed in the critical phenological stages and accumulation of GDD in 2012, 2016-18, and 2021-22 can be explained by variations in weather conditions. In these years, warmer temperatures in early phenological stages caused the critical stages to occur earlier, resulting in an earlier accumulation of 800 GDD following full bloom. These findings highlight the importance of adapting pest management practices to yearly variations in weather conditions, particularly in light of climate change and its potential impact on crop growth and pest infestation.

Figure 4: Northwest Region Tart Cherry Cover Dates and Corresponding GDD Thresholds (2023-2037)

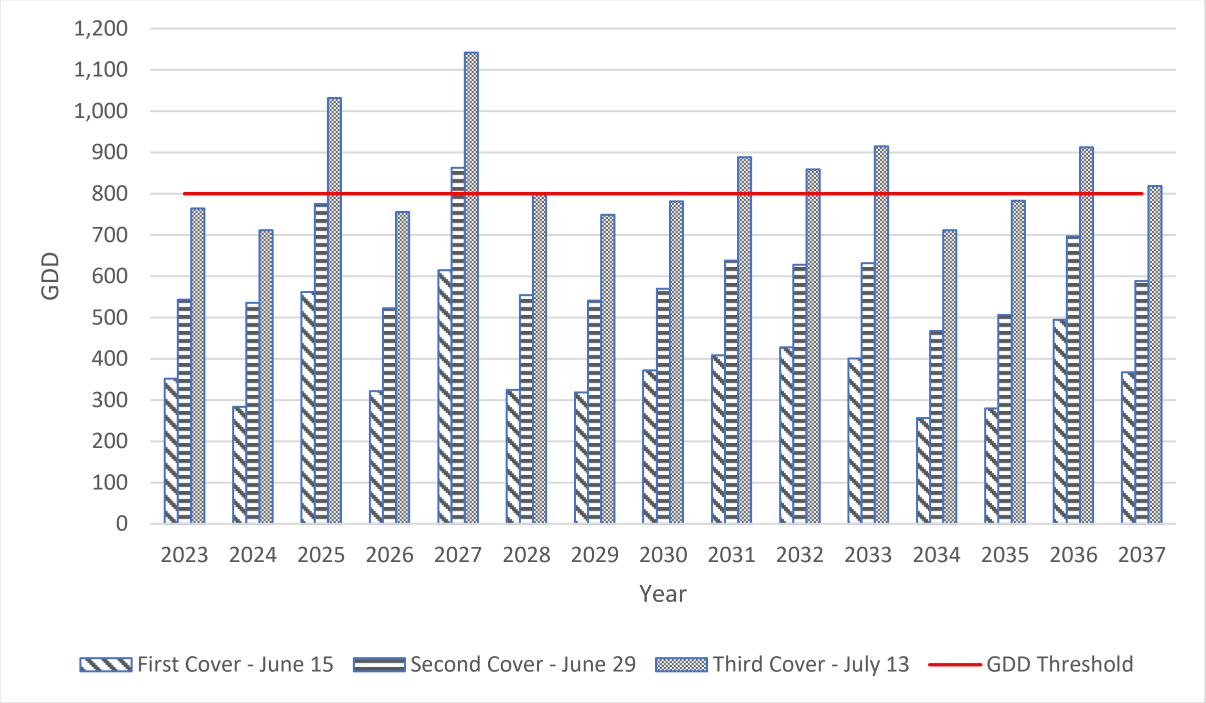


Figure 5: Southwest Region Tart Cherry Cover Dates and Corresponding GDD Thresholds (2023-2037)

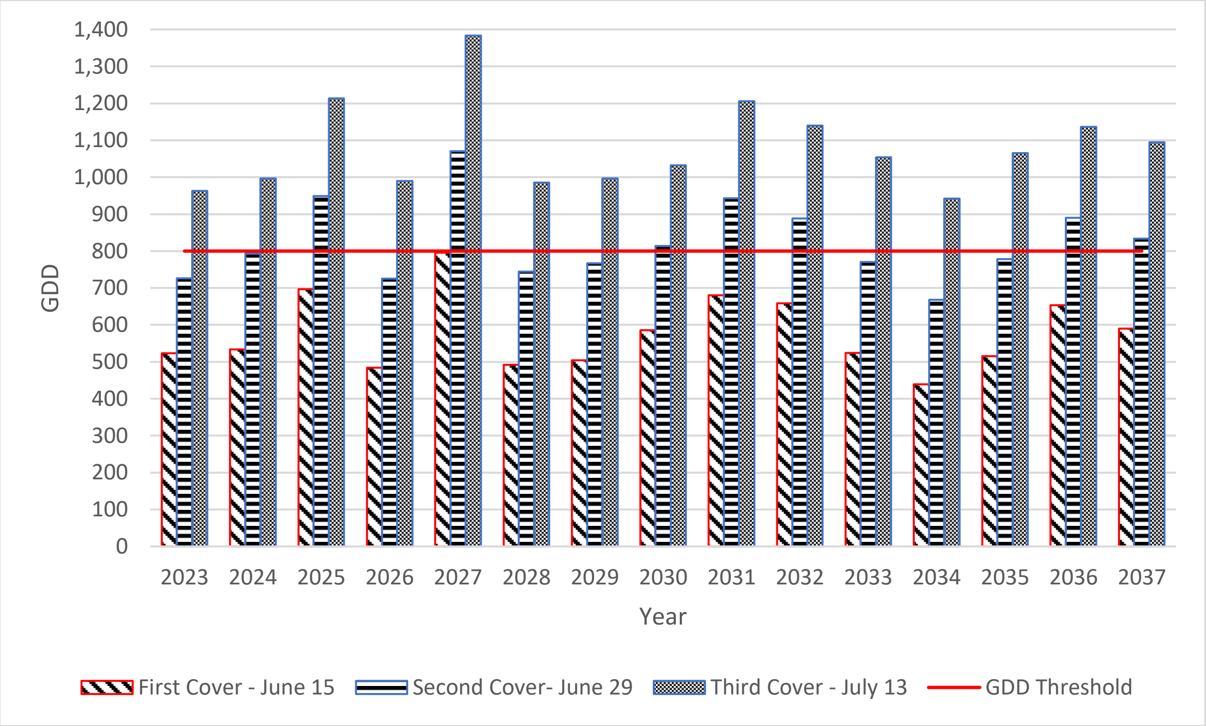
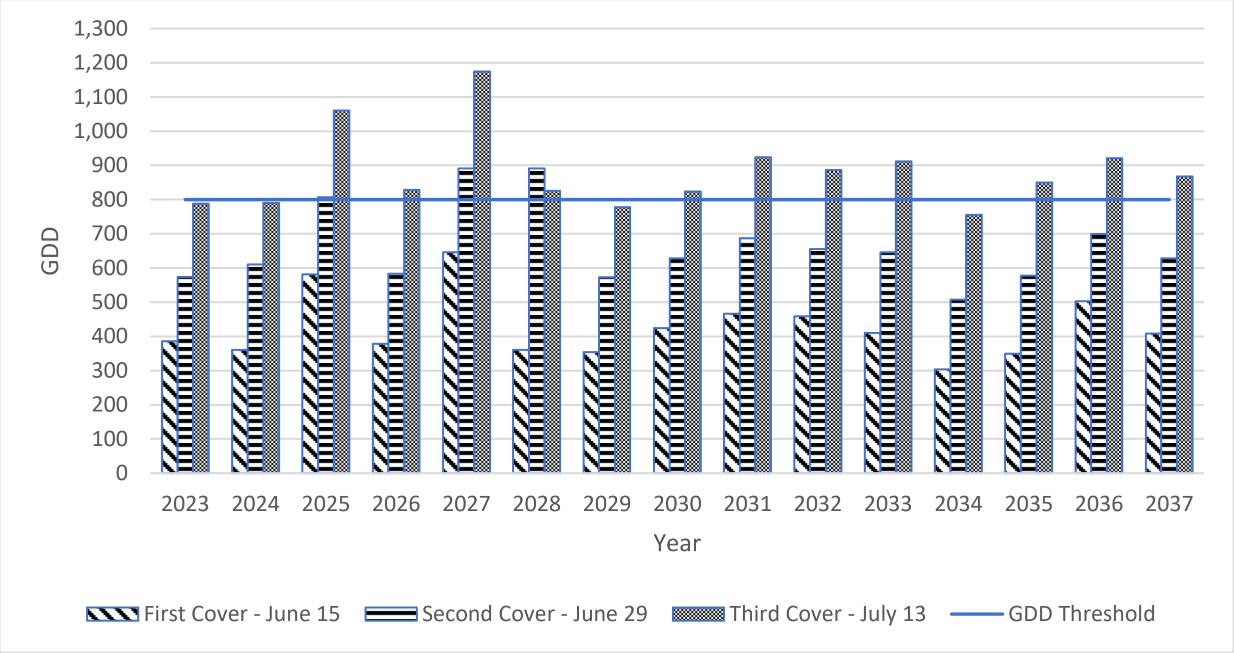


Figure 6: West Central Region Tart Cherry Cover Dates and Corresponding GDD Thresholds (2023-2037)



Based on the findings of Wilson et al. (2022) and other studies, it is likely that spraying activities for SWD control would be more effective if scheduled according to the 800 GDD threshold rather than a specific calendar date. This is due to the fact that the likelihood of SWD infestation increases as fruit ripens, and the GDD threshold provides a more accurate method for predicting when this will occur. By comparing the cover dates to the respective GDD thresholds depicted in Figures 4-6, it is possible to determine if the cover was sprayed in a timely manner to effectively control SWD. If the cover was sprayed before the corresponding GDD threshold was reached, this indicates that the spraying was done proactively and could aid in preventing SWD infestation. If, however, the cover was sprayed after the GDD threshold was reached, this suggests that the spraying was reactive and may not have been as effective at preventing infestation. These conclusions can aid in guiding future management decisions and enhancing the overall efficacy of IPM strategies. It is essential to note, however, that this assumption must be verified under local conditions, and that the effectiveness of any IPM program will also depend on other variables, such as pest pressure, weather conditions, and the use of other control measures.

5.3. Research Costs

SWD infestations present a significant obstacle to the Michigan tart cherry industry. Significant investments have been made in research and development to discover new and effective pest control methods in order to effectively manage this pest. Significant research expenses are associated with the management of SWD in Michigan's tart cherry orchards, and ongoing research is required to ensure the industry's sustainability.

To determine the extent of these research costs, I analyzed data from the USDA Research, Education, and Economics Information System (REEIS) and Michigan State University Extension-supported research projects (MSU PROJECT GREEN). In this research, I have gathered the costs associated with managing SWD in tart cherry orchards in Michigan since 2012. The data was obtained from the Research, Education, and Economics Information System (REEIS) - USDA, which has a database for grants for specific issues, and expenditures on SWD research activities can be estimated from these datasets. We have also looked into research projects supported by the Michigan State University Extension (MSU PROJECT GREEN) to comprehensively view the research costs associated with SWD management in tart cherry orchards.

We also estimated the total research cost of SWD management in tart cherries by attributing a proportion of each project to tart cherries based on its direct relevance. Projects that are directly related to tart cherries are attributed 100% of their award, while those related to tree fruit are attributed 50%, and those related to other berries are attributed 10%. This approach gives us a comprehensive view of the research costs associated with SWD management in tart cherry orchards in Michigan.

Table 6 summarizes the research investments made by various organizations in Michigan tart cherry orchards from 2011 to 2023. The National Institute of Food and Agriculture (NIFA) and Michigan State University Extension funded these projects (MSU PROJECT GREEN). These projects range in price from $50,000 to more than $2 million. We calculated the net present value (NPV) of the costs at a discount rate of 4% to evaluate the total research investment. The net present value (NPV) of these research expenses in 2022 dollars is approximately $970 thousand. This shows the present value of the net returns on these projects over time, as well as the significant research costs associated with managing SWD in Michigan's tart cherry orchards. These research investments are critical for developing new and effective control methods and ensuring the long-term viability of the industry in Michigan.

In conclusion, the research costs associated with managing Spotted Wing Drosophila in tart cherry orchards in Michigan are significant, and ongoing research is essential to develop new and effective control methods. Furthermore, these research costs are crucial to ensure the sustainability of the tart cherry industry in Michigan.

Table 6: Research Costs for SWD Management in Michigan between 2011-2023.

Project Title	Sponsor Agency	Year	Award	NPV at 5% (2022 dollars)	The proportion of tart cherries	Total Research Cost
Tree Fruit IPM/ ICM Management and Measurement Systems and Pesticide Regulatory Policy in Michigan	NIFA	2011	$50,000	$85,517	50%	$42,758
Optimizing Protective Culture Environments for Berry Crops	NIFA	2012	$2,000,000	$3,257,789	10%	$325,779
New Arthropod Pest Controls and Management Strategies for Michigan Tree Fruit Production Systems	NIFA	2012	$50,000	$81,445	10%	$8,144
Holistic Integration of Organic Strategies and High Tunnels for Midwest/Great Lakes Fruit Production	NIFA	2012	$625,000	$1,018,059	45%	$458,127
New Arthropod Pest Management Approaches and Control Tactics for Michigan Tree Fruit Production Systems	NIFA	2019	$50,000	$57,881	50%	$28,941
Evaluating the Samba Wasp as a Promising New Biocontrol Agent for Spotted Wing Drosophila in Michigan Cherries	PROJECT GREEN	2022	$50,000	$50,000	100%	$50,000
Predicting the effectiveness of spotted wing drosophila biocontrol across space and time	PROJECT GREEN	2022	$50,000	$50,000	50%	$25,000
Testing a promising new biocontrol agent for spotted-wing drosophila in Michigan	PROJECT GREEN	2022	$50,000	$50,000	50%	$25,000
Training program on sampling berries for SWD to improve blueberry IPM	PROJECT GREEN	2022	$50,000	$50,000	10%	$5,000
						$968,749

When evaluating the impact of SWD control on tart cherry in Michigan, the issue of research costs and spillover effects must be taken into account. Although it may be difficult to determine the exact costs associated with research on SWD control conducted in other countries, it is essential to analyze the possibility of spillover effects and avoid double counting when estimating research costs. This is especially crucial in a global market model, where projections for other nations must be made based on historical yield growth and technology spillover trends.

Additionally, it can be difficult to determine the actual impact of research spillovers on the production and adoption of new technologies, particularly when research results are transferred rather than embodied in technologies. However, taking research costs and spillover effects into account can provide insights into the potential benefits and limitations of research in this area.

In addition, while it may be difficult to measure the precise effects of spillovers from SWD control research conducted outside of Michigan, it is possible that the research conducted in other regions and countries influenced the development of control methods in Michigan. Similarly, research conducted in Michigan may have positive implications for SWD control in other regions. When analyzing the costs and benefits of SWD control research in Michigan, it is therefore essential to consider the possibility of spillover effects.

5.4. Extension cost

Implementing IPM strategies in tart cherry production in Michigan can significantly reduce SWD management costs and increase profitability. In addition to the cost savings, IPM is a more sustainable and environmentally friendly method of pest management. To ensure widespread adoption of IPM strategies, outreach and extension efforts are essential This study aimed to determine the economic benefits of implementing IPM technology for managing SWD in tart cherry orchards in Michigan. As part of this analysis, we also evaluated the costs associated with implementing IPM technology, specifically the costs of extension services.

Extension specialists at Michigan State University (MSU) play a crucial role in providing producers with information and training on pest management techniques. We estimated the annual extension cost based on the proportion of tart cherry production in Michigan relative to other crops impacted by SWD, assuming seven MSU Extension specialists worked on SWD management and earned approximately $70,000 per year. By applying a 5% discount to the annual extension cost, we determined that the estimated cost of extension for SWD management over the fifteen-year period from 2023 to 2037 was over $1 million. This investment in extension and outreach is essential for increasing adoption rates and ensuring the long-term success of IPM strategies in tart cherry production in Michigan.

It should be noted that our estimates of the SWD management extension cost are based on certain assumptions. One such assumption is that extension specialists from MSU Extension are working on SWD management and spend 30% of their time doing so. While this assumption may not fully capture the actual amount of time spent by MSU Extension specialists on SWD management, it does provide a reasonable estimate of the extension cost associated with implementing IPM technology for managing SWD in tart cherry orchards in Michigan. Furthermore, our calculations assume that tart cherries account for approximately 51% to 59% of all crops affected by SWD damage in Michigan. This estimate is based on tart cherry production as a percentage of total acres of all crops that are affected from SWD in the state, and it provides a reasonable basis for estimating the extension cost of managing SWD in tart cherry orchards.

The additional extension costs will depend on the extent of the training workshops, field demonstrations, and fact sheets required to promote the adoption of the GDD-based IPM model.

More detailed data and analysis would be required to accurately estimate these costs. The estimates in the table are only meant to provide a useful indication of the extension cost of managing SWD in tart cherry orchards in Michigan and can be used to inform a cost-benefit analysis of this pest management strategy

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Table 7 illustrates the estimated cost of tart cherry production extension in Michigan from 2023 to 2037, based on the proportion of tart cherry production relative to total acres of all crops affected by SWD damage in the state. It should be noted that this table only includes the cost of hiring extension specialists and excludes the costs of other extension activities such as training workshops, field demonstrations, and fact sheets, all of which are required to promote the adoption of the GDD-based IPM model. As a result, additional research is needed to accurately estimate the total cost of implementing IPM technology in Michigan tart cherry orchards.

The additional extension costs will depend on the extent of the training workshops, field demonstrations, and fact sheets required to promote the adoption of the GDD-based IPM model. More detailed data and analysis would be required to accurately estimate these costs. The estimates in the table are only meant to provide a useful indication of the extension cost of managing SWD in tart cherry orchards in Michigan and can be used to inform a cost-benefit analysis of this pest management strategy.

Table 7: Extension Costs for Tart Cherry Production in Michigan between 2023-2037

Year	Number of staff	Salaries	Total	Total NPV at 5%	Proportion of their time devoted to SWD	Proportion of Tart Cherry Acre to other crops	Cost of Extension
2023	7	$70,000	$490,000	$466,667	30%	50%	$70,000
2024	7	$73,500	$514,500	$466,667	30%	50%	$70,000
2025	7	$77,175	$540,225	$466,667	30%	50%	$70,000
2026	7	$81,034	$567,236	$466,667	30%	50%	$70,000
2027	7	$85,085	$595,598	$466,667	30%	50%	$70,000
2028	7	$89,340	$625,378	$466,667	30%	50%	$70,000
2029	7	$93,807	$656,647	$466,667	30%	50%	$70,000
2030	7	$98,497	$689,479	$466,667	30%	50%	$70,000
2031	7	$103,422	$723,953	$466,667	30%	50%	$70,000
2032	7	$108,593	$760,151	$466,667	30%	50%	$70,000
2033	7	$114,023	$798,158	$466,667	30%	50%	$70,000
2034	7	$119,724	$838,066	$466,667	30%	50%	$70,000
2035	7	$125,710	$879,970	$466,667	30%	50%	$70,000
2036	7	$131,995	$923,968	$466,667	30%	50%	$70,000
2037	7	$138,595	$970,166	$466,667	30%	50%	$70,000
							$1,050,000

5.5. Adoption and Diffusion of IPM

Adoption and diffusion of innovations are essential components of the successful application of new agricultural technologies. IPM is a prime example of an innovative agricultural practice that has the potential to transform crop management. Understanding the factors that influence the adoption and diffusion of IPM technologies is essential for the research of adoption behavior. The word "adoption" is used to describe individual behavior towards innovation and "diffusion" in terms of collective behavior, and diffusion can be interpreted as total adoption (Sunding & Zilberman, 2001).

The "diffusion of innovations theory" developed by Everett M Rogers et al. (2014) has been an important contributor to both extension theory and practice, as De Tarde (1903) demonstrated that the introduction of new ideas within a social system results in an S-shaped growth curve. Everett M. Rogers (2010) defined diffusion as "the process by which an innovation is communicated to the members of a social system over time through specific channels." The diffusion of IPM technology follows the same pattern, beginning slowly, accelerating to a peak, and then reversing course as the innovation reaches saturation (Alston et al., 2009; Alston et al., 1995). The S-shaped curve is a recognizable pattern in the diffusion of innovations and has been observed in the adoption of IPM technologies (Grieshop et al., 1988). The slope of the S curve varies depending on the rate of adoption, with a steep slope indicating a relatively quick diffusion rate, and a lower slope indicating a slower rate of adoption (Pannell & Zilberman, 2020).

Adoption and diffusion of IPM technologies are crucial determinants of the widespread use of these innovative practices in agriculture. The adoption and diffusion process is complex and influenced by a number of variables, including the timing and extent of a farmer's adoption of a new technology. Understanding the factors that influence the decision to adopt IPM technologies is essential to the field of research on adoption behavior.

Investing in research and development (R&D) can yield a steady stream of benefits over time, but this process is frequently characterized by lengthy and uncertain delays. For instance, the development of new crop varieties through traditional breeding techniques can take five to ten years or longer, and even biotech crop varieties require years of regulatory approval before they can be widely adopted.

There is a recognizable pattern associated with the adoption and diffusion of innovations. The transmission of a particular innovation across most nations follows an S-shaped curve over the course of time. This curve is characterized by a slow start, acceleration towards a peak, and then a slowing as the innovation reaches saturation.

The process of adopting IPM practices can follow a logistic "S"-shaped curve, which is a common pattern in the diffusion of new technologies (Alston et al. 1995; Griliches 1957). The following equation determines the degree of adoption for a given year:

$$\boldsymbol{A_t = A^{max}\left(1 + e^{-(a+bt)}\right)^{-1} = \frac{A^{max}}{\left(1+e^{-(a+bt)}\right)}} \qquad (2)$$

Where $\boldsymbol{A_t}$ $[\boldsymbol{A_t} \in (0,1)]$ is the actual adoption rate at year $\mathbf{t}$ after the release of the new technology, $\boldsymbol{A^{max}}$ is the long-run maximum adoption rate, $\boldsymbol{a}$ and **b** are the long-run maximum adoption rate, and a and b are parameters that determine the asymptotically maximizing path of the adoption rate. It is typically fair to conclude that adopting a single point on the curve is low in the first years of dissemination. Various approaches have been used to determine the parameters of a logistic adoption curve. It is essential to select the strategy that is the most intuitive and straightforward to estimate. A prevalent notion is that adoption within the first year of a product's release is extremely low, such as 1%. This offers a point of departure for the curve. In addition, it is useful to predict the maximum adoption rate that can be anticipated over time.

To effectively anticipate the rate of adoption for a new technology, it is necessary to consider both its beginning point and its ultimate adoption limit. This can be accomplished by designating two points on the logistic adoption curve: the beginning low adoption rate point and the maximum adoption limit point. Scientists and extension personnel can provide valuable advice by calculating the most likely adoption rate at a specific moment or the number of years required for the technology to attain 50% of its full potential. These estimations will aid in defining the parameters of the logistic curve and provide a more precise estimate of the adoption rate of the technology. (Alston et al., 1995)

In this study, we determined the maximum adoption rate for each scenario, with a maximum adoption period of 15 years. The ceilings for low, medium, and high adoption scenarios, respectively, were set at 40%, 60%, and 80%. It was assumed that the technology would be released in 2022 and that its adoption rate would reach 50 percent within six years. In the first year, it was assumed that the initial adoption rate would be 1% for low adoption, 2% for moderate adoption, and 3% for high adoption.

Despite the lack of actual data on the subject, this approach provides a theoretical framework for understanding the potential adoption of IPM technologies. In the absence of concrete data, the use of hypothetical scenarios is a necessary limitation, but it provides valuable insights into the potential adoption and diffusion of IPM technologies. Using this method, we can guide future research and investment in this field, as well as refine our predictions as more data becomes available. This study's findings provide a comprehensive summary of the potential adoption of IPM technologies and future projections for their widespread use.

With this knowledge of the logistic "S"-shaped curve, the curve can be described as a linear function of the logarithmic odds ratio, making it simpler to quantify the adoption of IPM practices;

$$\ln\left(\frac{A^{max}}{1+e^{-(\alpha+bt)}}\right)=\alpha+bt \tag{3}$$

Since A^{max} is known, and two combinations of A_t and $\mathbf{t}$. Substituting those values into equation (3) is straightforward to solve for α and b.

The parameters of the curve can be easily determined by employing the information. Taking the logarithms of Equation (3) yields a dependent equation for A^{max}, A_t, and t:

$$\boldsymbol{b} = \left[\ln\left(\frac{\boldsymbol{A_t}}{\boldsymbol{A^{max}} - \boldsymbol{A_t}}\right) - \boldsymbol{\alpha}\right]\frac{\mathbf{1}}{\boldsymbol{b}} \qquad (4)$$

With the available information, it is straightforward to set the parameters of the curve. We may determine the value of b in respect to a, $\boldsymbol{A^{max}}$, $\boldsymbol{A_t}$ and **t**. By substituting the values of $\boldsymbol{A^{max}}$ and two sets of $\boldsymbol{A_t}$ and **t** into equation (4), the values of a and b can be determined. It is possible to do it for each adoption scenario to derive the values for a and b. **Table 8** shows the corresponding values for each adoption scenario.

Note that the values in Table 8 are the result of a procedure described in "**APPENDIX I: ADOPTION TRAJECTORY CALCULATION**"**.** This process involved determining the values of b relative to **a,** $\mathbf{A^{max}}$**,** $\mathbf{A_t}$, and **t** by substituting the values of $\mathbf{A^{max}}$ and two sets of $\mathbf{A_t}$ and **t** into the equation (4). For each adoption scenario, these calculations were repeated to determine the values for a and b. The values in Table 8 represent the parameters of a hypothetical adoption trajectory for low, medium, and high adoption scenarios. These parameters can be used to model the potential adoption of IPM practices in tart cherry orchards.

Table 8: Hypothetical Adoption Trajectory Parameters

	Low Adoption Trajectory	**Medium Adoption Trajectory**	**High Adoption Trajectory**
a	-4.19	-3.85	-3.71
β	0.52	0.48	0.46
$\boldsymbol{A^{max}}$	0.40	0.60	0.80

Multiple variables influence the adoption of IPM technologies. To better comprehend the potential adoption of these innovative practices, it is necessary to consider a variety of scenarios based on assumptions. The adoption scenarios presented in the provide valuable insight into the adoption and diffusion dynamics of IPMs.

The Low Adoption Phase assumes a slower rate of IPM adoption with a low rate of change. The Medium Adoption Phase is characterized by a moderate rate of adoption and change. The High Adoption Phase assumes a rapid adoption rate and a high rate of change for IPM.

These scenarios are intended to represent various levels of IPM adoption and diffusion and are presented as a snapshot of the various adoption rates. Despite not being based on actual observations, the data follows the typical S-shaped diffusion curve observed in the diffusion of innovations. This curve provides valuable information on the initial period of low adoption rate and high rate of change, which can be used to inform policies and programs designed to promote the adoption of IPM practices and speed up their diffusion.

Adoption and diffusion of IPM technologies is a complex process influenced by a variety of variables, such as the timing and scope of an individual's use of the technology. Although it would be ideal to find actual data on the adoption rate of comparable technologies to serve as a proxy, such data are unavailable in this instance. To estimate the adoption limit of IPM technologies, we have adopted a hypothetical approach based on three different adoption scenarios - low, medium, and high. These hypothetical scenarios are based on the general pattern of innovation diffusion, which follows an S-shaped curve with a gradual beginning, an acceleration towards the peak, and a deceleration when the technology reaches saturation. The adoption rate assumptions we have made are shown in **Table 9**.

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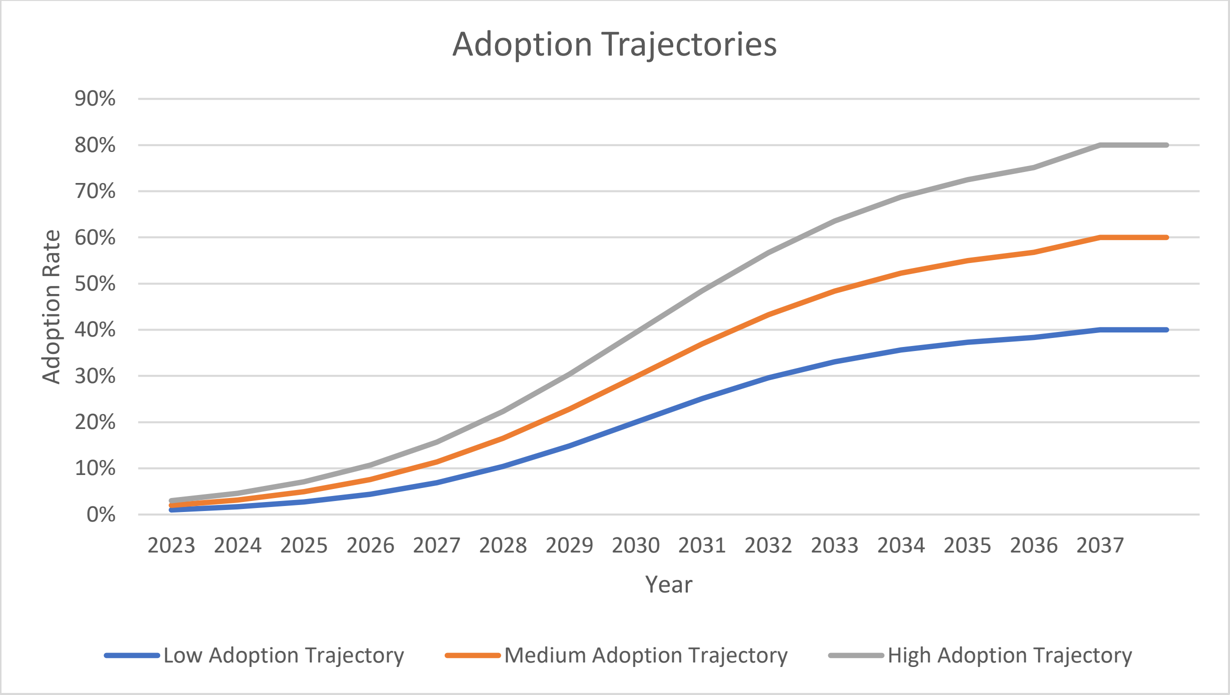
Table 9: The Adoption Rate of GDD-Based IPM, 2023-2037

Year	Low Adoption Trajectory	Medium Adoption Trajectory	High Adoption Trajectory
1	1%	2%	3%
2	2%	3%	5%
3	3%	5%	7%
4	4%	8%	11%
5	7%	11%	16%
6	10%	16%	22%
7	15%	23%	30%
8	20%	30%	39%
9	25%	37%	48%
10	30%	43%	57%
11	33%	48%	64%
12	36%	52%	69%
13	37%	55%	73%
14	38%	57%	75%
15	40%	60%	80%

Adoption and diffusion of IPM technologies are crucial determinants of the widespread application of these innovative agricultural practices. Commonly observed in the diffusion of innovations, the S-shaped diffusion curve provides valuable insight into the potential adoption of IPM technologies. Understanding the factors that influence the adoption and spread of IPM technologies is crucial for future research and investment in this field. In the absence of actual data, the use of hypothetical adoption scenarios is a necessary limitation, but it nevertheless provides valuable insights into the potential adoption of IPM technologies and guides future research and investment in this field. **Figure 7** depicts the phases of adoption for all three scenarios.

Figure 7: Adoption Trajectories for 2023-2037



6. RESULTS AND DISCUSSION

The objective of the research presented in this dissertation was to examine the economic benefits of adopting GDD-based IPM models to control SWD in tart cherry orchards. Adoption of a growing degree-day (GDD)-based IPM model for managing SWD in Michigan tart cherry orchards revealed substantial economic benefits for the industry. By reducing the use of unnecessary pesticides, the GDD-based IPM model has the potential to save tart cherry growers money. The GDD-based IPM model has been demonstrated to result in significant net industry benefits, with estimated cost savings of $3.4 million for low adoption, $5.2 million for medium adoption, and $6.9 million for high adoption. The results demonstrate that the savings increase as the adoption rate of the GDD-based IPM model rises as it can be seen in **Table 10**.

Table 10: Projected Cost Savings of IPM Adoption in Michigan Tart Cherry Production by Region between 2023-2037

Region	Cost Savings from Low Adoption	Cost Savings from Medium Adoption	Cost Savings from High Adoption
Northwest	$ 2,312,921	$ 3,485,865	$ 4,636,763
Southwest	$ 153,075.82	$ 231,358	$ 308,116
West Central	$ 963,495.71	$ 1,448,747	$ 1,925,468
Total	**$ 3,429,492.33**	**$ 5,165,970**	**$ 6,870,347**

The analysis demonstrates that adoption of the IPM model based on GDD can result in net industry benefits. **Table 11** displays the estimated net benefit based on the three adoption rates (low, high, and full). Adoption of the GDD-based IPM model for SWD control in Michigan's tart cherry orchards can result in industry-wide net benefits, particularly at medium and full adoption rates. At a low adoption rate, for instance, the estimated net benefit is over $1.4 million, whereas at a medium adoption rate and at a high adoption rate, the estimated net benefits are approximately

$3.2 million and $4.9 million, respectively. Therefore, the findings suggest that the adoption of the GDD-based IPM model for SWD control in Michigan's tart cherry orchards can provide significant economic benefits to producers and the industry as a whole.

The results also suggest that adopting an IPM model based on GDD can help to promote sustainable agricultural practices. Growers can reduce their environmental impact and enhance the sustainability of their operations by using fewer pesticides. In addition, the savings from reduced pesticide use can be re-invested in other areas of their business, such as increasing crop yields or expanding operations. The findings of this study highlight the economic and environmental benefits of adopting the GDD-based IPM model for SWD control in tart cherry orchards in Michigan.

A sensitivity analysis was conducted to examine the impact of changes in adoption rates on the overall net benefits of the GDD-based IPM model to evaluate the robustness of these results. The sensitivity analysis was based on the net benefits presented in **Table 11**, which considers the total cost for research, extension, and net benefits.

Table 11: Net Benefit per Adoption Phase

Adoption Rate	Total Producer level benefits (2023-2037)	Total Cost for Research	Total Cost for Extension	Net Benefit (2023-2037)
Low Adoption	$ 3,429,492	$ 968,749	$ 1,050,000	$ 1,410,743
High Adoption	$ 5,165,970	$ 968,749	$ 1,050,000	$ 3,147,221
Full Adoption	$ 6,870,347	$ 968,749	$ 1,050,000	$ 4,851,598

7. CONCLUSION

Based on the results presented in **Table 10** and **Table 11**, it is clear that adopting a GDD-based IPM model for SWD control in tart cherry orchards can result in significant cost savings for growers. Depending on the adoption phase, the Michigan tart cherry industry could save between \$3.9 million and \$6.7 million due to the implementation of GDD-Based IPM.

It is important to note that these cost savings are in addition to the benefits of reduced pesticide use and improved crop yields expected from this IPM model. Furthermore, the total cost for research and extension required to implement this model is relatively low compared to the potential cost savings, around \$0.97 million and over \$1 million, respectively.

It is also worth considering the net benefit of adopting this IPM model, which can be calculated by subtracting the total cost of research and extension from the total benefit of cost savings. Using this metric, low adoption rate would result in net benefits of around \$1.9 million, while medium and high adoption rates would result in net benefits of approximately \$3.2 million and \$4.9 million, respectively.

In conclusion, adopting a GDD-based IPM model for SWD control in tart cherry orchards can result in significant cost savings for growers and the social benefits of reduced pesticide use. The total cost for research and extension required to implement this model is relatively low compared to the potential cost savings. The data indicate that adopting the GDD-based IPM model will likely result in significant cost savings for tart cherry producers in Michigan. Growers and policymakers can use these results to optimize pest management strategies and reduce unnecessary spraying costs. Additionally, this analysis shows that the total cost of preventable pesticide sprays can be reduced by adopting a GDD-based IPM model. Even in the low adoption rate scenario, a significant amount of savings could be achieved, and the savings increased as the adoption rate increased.

Furthermore, this analysis demonstrates that using a GDD-based IPM model can reduce the total cost of preventable covers. Even with a low adoption rate, significant savings could be realized, and the savings increased as the adoption rate increased. These findings emphasize the importance of incorporating GDD-based IPM models into pest management strategies in tart cherry production, and additional research is required to investigate the model's impact on other states and regions.

7.1. Real-World Implications

This analysis demonstrates the potential for cost savings for Michigan tart cherry growers by adopting a GDD-based IPM model for controlling Spotted Wing Drosophila" (SWD). Nevertheless, it is essential to consider potential obstacles that may arise when implementing this model in practical orchard settings.

One of the main challenges is the need for growers to invest in new equipment or training to monitor GDD levels and accurately make informed pest management decisions. This can be expensive for growers, especially those with smaller operations. Additionally, pesticide and application costs may vary yearly and may not be accurately reflected in our calculations.

Another challenge is the need for more communication among farmers to inform them when the 800 GDD threshold has been reached in a season. MSU Extension has a system called Enviroweather that shows GDD stats, but it is sometimes unclear how farmers would know when the threshold has been reached. To address this challenge, MSU Extension could consider implementing a text message-based communication system to alert farmers when the 800 GDD threshold has been reached. This system could be built into an existing weather data service, such as Enviroweather, and would send automated text messages to farmers once the threshold has been reached. Although implementing this system would involve some cost for MSU Extension, it could be a valuable investment in the long run, as it would help farmers to be more efficient in controlling SWD and reduce unnecessary spraying costs. This could be a cost for MSU Extension, but it would be a valuable investment in the long run as it will help farmers to be more efficient in controlling SWD. In addition to the text message-based communication system, human interaction and interpretation could further optimize the system's effectiveness. MSU Extension could provide farmers with additional materials to help them comprehend the significance of the 800 GDD threshold and how to interpret and respond to automated text messages. These resources may consist of training sessions, educational materials, or access to pest management specialists who can answer questions and offer guidance. By providing these resources, MSU Extension could ensure that farmers have the knowledge and support necessary to make informed pest management decisions and further reduce unnecessary spraying costs.

Despite these challenges, the results of this study provide a strong case for the adoption of GDD-based IPM models for SWD control in Michigan tart cherry orchards. To fully validate this study's findings and explore the potential benefits of GDD-based IPM models, additional research is required in multiple areas. To test the efficacy of GDD-based IPM models in different crops and regions, field trials should be conducted. A comprehensive economic analysis is required to determine the costs and benefits of adopting IPM models based on GDD. It is necessary to develop implementation strategies to facilitate the cost-effective implementation of these models in real-world scenarios. The evolution of technology should continue to refine and improve the precision and usability of GDD-based IPM models. Lastly, education and outreach efforts are required to educate growers and extension agents on the benefits and best practices of GDD-based IPM models and to facilitate their adoption in the field. Growers can optimize pest management strategies, reduce unnecessary spraying costs, and improve the sustainability of their operations with additional research and the right tools and resources.

7.2. Future Implications

The results of this research have important implications for the management of SWD in tart cherry orchards in Michigan, as well as for similar pest management challenges faced by other fruit producers. The GDD-based IPM approach developed in this study represents a promising alternative to traditional pesticide-based methods, as it offers a more sustainable and cost-effective solution for managing SWD.

One important implication of this research is the potential to reduce the use of pesticides in tart cherry orchards. Pesticides have been linked to several environmental and health concerns, including the decline of beneficial insect populations, the contamination of water and soil, and the emergence of pesticide-resistant pests. By reducing the need for pesticides, the GDD-based IPM approach developed in this study could help to mitigate these negative impacts and protect the environment.

Another key implication of this research is the potential for cost savings for tart cherry producers. The results of this study indicate that adopting the GDD-based IPM approach could lead to significant reductions in the cost of managing SWD, particularly as adoption rates increase. These cost savings could help to make tart cherry production more economically viable for farmers and could also help to lower the price of tart cherries for consumers.

It is also important to consider the implications of this research in the context of climate change. As temperatures continue to rise, the occurrence and severity of pest infestations will also increase.

The GDD-based IPM approach developed in this study could be adapted to manage other pests and diseases, and could thus be an important tool for helping farmers to adapt to a changing climate.

In addition, the adoption of the GDD-based IPM approach could help to reduce the carbon footprint of tart cherry production, as it would require less energy-intensive inputs such as pesticides and fuel for spraying.

In the future, it would be important to continue to monitor the effectiveness and adoption of the GDD-based IPM approach developed in this study, to evaluate its long-term impact on SWD management, environmental and social impact, and economic viability for farmers. Furthermore, more research is needed to evaluate the potential of this approach to be applied to other pests and crops and to understand the potential for this approach to be integrated into other conservation practices and conservation programs. Additionally, future research should focus on developing a GDD model that considers the phenological stages of the fruit and the development of insects, to further improve the effectiveness of the GDD-based IPM approach.

Overall, the results of this research have the potential to improve the sustainability and profitability of tart cherry production in Michigan and could serve as a model for other regions and crops facing similar pest management challenges. The adoption of the GDD-based IPM approach is not only beneficial for the environment and farmers, but also for the consumers who can enjoy safe and healthy fruits.

8. CAVEATS

It is important to note that the results of this study are based on several assumptions and should be taken as estimates rather than as definitive conclusions. In addition, the following limitations should be considered when interpreting the results.

This research is primarily concerned with the control of SWD, a major pest in tart cherry production. Nonetheless, it is essential to recognize that some pesticides used in tart cherry production, such as Imidan and Exirel, target multiple pests. Despite the fact that these pesticides are effective against both SWD and other pests, for the purposes of this study, we will assume that the pesticide applications are intended solely for SWD management. This simplification permits a more concentrated examination of the effect of SWD management strategies on the tart cherry production system. Nonetheless, future research and implementation of pest management strategies in tart cherry production must take the potential impact of multiple pest management into account.

The analysis assumes that the information in the Cherry Pest Guide represents the actual spraying schedule for tart cherry orchards in Michigan and that spraying activities before the 800 GDD threshold since full bloom are unnecessary. However, the actual spraying practices may vary from orchard to orchard and may not be accurately reflected in the analysis. The pesticides and application costs may vary yearly and may not be accurately reflected in our calculations. Therefore, the cost savings presented in this study should be considered estimates.

The adoption rate assumptions used in this study are based on hypothetical and may not reflect the actual adoption rate of the GDD-based IPM model. The actual adoption rate may be higher or lower than the assumptions made in this study. Future research may seek to collect more specific information on adoption rates in order to provide a more precise estimate of the potential impact of the GDD-based IPM model.

The study focuses on the cost savings associated with controlling SWD in tart cherry orchards, but it is important to note that there may be other benefits associated with adopting the GDD-based IPM model, such as improved fruit quality and yield.

Despite these limitations, the results of this study suggest that adopting a GDD-based IPM model for controlling SWD in tart cherry orchards in Michigan can result in significant cost savings for growers. Growers and policymakers can use the results of this analysis to optimize pest management strategies and reduce unnecessary spraying costs. Furthermore, it is essential to consider the additional benefits of adopting this model beyond cost savings and regional specificities. Future research is needed to investigate further the impact of the GDD-based IPM model on other states and regions.

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APPENDIX A: TART CHERRY PEST GUIDE BY MSU EXTENSION

This an extension handout from MSU Extension that provides a pest management guide for multiple pests in tart cherry production.

APPENDIX B: PROGRAM COMPARISON BY MSU EXTENSION

Pesticide application rates, prices, and costs were obtained from the "Cost Calculations-Producer Level" sheet. This data was used to calculate the per acre cost of spray for each cover in a year and the total unnecessary spray cost per acre.

APPENDIX C: NORTHWEST CALCULATIONS

This supplementary document contains region-specific daily temperature data and Growing Degree Day (GDD) calculations for each year between 2008-2022 for Traverse City Northwest Michigan.

APPENDIX D: SOUTHWEST CALCULATIONS

This supplementary document contains region-specific daily temperature data and Growing Degree Day (GDD) calculations for each year between 2008-2022 for Southwest Michigan.

APPENDIX E: WEST CENTRAL CALCULATIONS

This supplementary document contains region-specific daily temperature data and Growing Degree Day (GDD) calculations for each year between 2008-2022 for Hart West Central Michigan.

APPENDIX F: STATE-WIDE CALCULATIONS

The state-wide calculation document contains the aggregated results of the cost analysis for implementing integrated pest management (IPM) strategies in Michigan's tart cherry production.

APPENDIX I: ADOPTION TRAJECTORY CALCULATION

To define the entire adoption curve corresponding to a particular technology (or results from a particular program of research), it is necessary to choose a functional form. A linear form for adoption response is widely used as a component of a trapezoidal lag structure. Appendix A5.1.2 describes in detail how to specify a trapezoidal research lag structure, including a linear adoption phase (following an initial research lag) and a linear decline. The main alternative is an S-shaped (usually logistic) curve that involves a similar number of parameters. The logistic curve can be specified as;

$$A_t = \frac{A_{Max}}{1 + e^{-(a+bt)}}$$

where;

$\boldsymbol{A_{Max}}$**:** is the maximum adoption rate (commonly expressed as a fraction of the total area ultimately planted to a crop),

$\boldsymbol{A_t}$: is the actual adoption rate t years after the release of the new technology, and "a " and "b" are parameters that define the path of the adoption rate that asymptotically approaches the maximum. Thus, a logistic adoption curve can be defined completely by three parameters: $\boldsymbol{A_{Max}}$, a, and b. The entire curve can be generated, also, by defining any three points on the curve (preferably with two near-extreme values).

A variety of approaches has been used to elicit values that will define the parameters of a logistic adoption curve. A wise choice would be dictated by judgments about which points on the curve are easier to guess. It is usually reasonable to assume very low adoption in the year of release (say, A_0 = 0.01, or 1 %) to define one point on the curve. It is also reasonable to try to elicit an estimate of the ceiling rate of adoption.

One more point is needed. The scientists and extension workers could be asked either

(a) to estimate the most likely adoption rate in a particular year, say seven years after release of the technology or

(b) to give a best estimate of the number of years required after the release of the technology before adoption reaches 50% of the maximum (e.g., if it takes 11 years, A_11 = 0.5A_Max).

Using such information, it is easy to parameterize the curve as follows. Taking logarithms of equation 5.16 yields an equation for b as a function of a A_{Max}, A_t, and t:

$$b = \left[\ln\left(\frac{A_t}{A_{Max} - A_t}\right) - a\right]\frac{1}{t}$$

We know A_{Max} and two combinations of A_t and t. Substituting those values into equation 5.17, we can solve for values of a and b.

Example:

Low Adoption

$$b = \left[\ln\left(\frac{A_1}{A_{15} - A_1}\right) - a\right]\frac{1}{1} = \left[\ln\left(\frac{0.01}{0.4 - 0.01}\right) - a\right]$$

$$b = \ln(0.034482759) - a$$

$$b = -3.66356 - a$$

$$a + b = -3.66356$$

$$b = \left[\ln\left(\frac{A_8}{A_{11} - A_8}\right) - a\right]\frac{1}{6} = \left[\ln\left(\frac{0.2}{0.4 - 0.20}\right) - a\right]\frac{1}{8}$$

$$b = [\ln(1) - a]\frac{1}{8}$$

$$b = -\frac{a}{8}$$

$$a = -8b$$

By plugin this to a+b=-3.36729583

$$-8b + b = -3.66356$$

$$b = 0.523366$$

$$a = \ -4.19$$