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Advances in cranberry insect pest management: A literature synthesis

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Over the past three decades, an increasing body of entomological research has been published on integrated pest management (IPM) in cranberries (*Vaccinium macrocarpon* Aiton). However, no paper has been published that synthesizes the existing literature. This paper fills this gap by analyzing 139 peer- and editor-reviewed articles that were data driven and had direct relevance to the subject of insect pests or insect pest management of *V. macrocarpon*. Results show that the top three studied insect pests of cranberries have been Sparganothis fruitworm (*Sparganothis sulfureana* Clemens), blackheaded fireworm (*Rhopobota naevana* Hübner), and cranberry fruitworm (*Acrobasis vaccinii* Riley). The regions with the most published entomological papers on cranberry IPM research have been New Jersey, Massachusetts, and Wisconsin in the United States, followed by British Columbia in Canada. Among IPM tactics, published research on chemical control, as well as on host-plant resistance, has increased likely due to recent advances on newer, reduced-risk insecticides and high-yielding cultivars; while published research focusing on behavioral control has declined likely due to the cost of these tactics. There are no consistent trends in published research on natural and biological control or cultural control. These historical research trends are important when considering regulatory changes on insecticide use, such as the Food Quality Protection Act of 1996 in the United States, which resulted in the banning and restrictions of certain broad-spectrum insecticides. As more insecticides are banned or restricted and global and organic cranberry production increases, we anticipate further advances in research related to sustainable IPM tactics.

KEYWORDS

Vaccinium macrocarpon, IPM, entomology, literature trends, globalization

Introduction

The concept of Integrated Pest Management (IPM) was first used in the late 1950s by [Stern et al. \(1959\)](#) in response to the overuse of insecticides for pest control in agriculture. Since then, IPM programs have been developed and implemented in various urban, medical and veterinary, forest, and agricultural settings. These IPM programs are, however,

constantly evolving due to regulatory, environmental, economic, and societal factors (Dara, 2019; Magarey et al., 2019; Hu, 2020). Thus, knowledge of historical trends in IPM research can help us identify past priorities and existing gaps that may guide future activities related to insect pest management in agroecosystems.

The American cranberry (*Vaccinium macrocarpon* Aiton) (Figure 1) is an ericaceous, woody, perennial crop native to North America that is grown commercially on acidic peat, loamy sand, and mineral sandy soils (Eck, 1990). This crop, which has only been domesticated for around 200 years, is grown using a unique method of agriculture, being farmed in beds (Figure 1A), also known as bogs or marshes, which are flooded in the autumn for harvest (Kennedy et al., 2016). These beds frequently remain underwater over winter to protect the dormant plants from frost (Averill et al., 1997; Kennedy et al., 2016), and thus require copious amounts of water, often utilizing nearby surface and ground water (Kennedy et al., 2016).

Cranberries have the highest world production in their native North American range, particularly in certain regions of the United States of America (USA) and Canada, such as Wisconsin, Massachusetts, New Jersey, Oregon, British Columbia, and Québec (USDA NASS, 2022) (Figure 2A). In recent years, however, worldwide production has been increasing, with this crop now being grown in countries like Chile and Turkey (FAOSTAT, 2022) (Figure 2B). In their native region, cranberries often face injury from several insect pests both aboveground and belowground that can be economically devastating to growers (Averill and Sylvia, 1998; Fitzpatrick, 2009). Along with the global expansion of cranberry production, there has been increasing research devoted to IPM to prevent injury from insect pests, especially over the last three decades. Notably, there have been major regulatory changes such as the Food Quality Protection Act of 1996 (Wheeler, 2002; Rajabi, 2014) and new emerging insect pest problems (Steffan et al., 2013; Jaffe et al., 2021a; Jaffe et al., 2021b) that have affected cranberry IPM in a direction towards more sustainable or environmentally friendly methods of pest control. Moreover, there has been a push to practice IPM and a desire from

cranberry growers to learn more about possible methods and approaches (Blake et al., 2007).

In this literature review, we provide a synthesis of cranberry insect IPM research over the past three decades. In particular, we aim to identify knowledge gaps and research accomplishments, provide a framework to guide future research programs, and provide information that can be immediately applied in IPM.

Global cranberry production

Cranberries are a unique crop because of their farming practices and the fact that they grow in acidic beds that utilize a lot of water for various management purposes (Averill et al., 1997; Kennedy et al., 2016). As such, there are likely limited places around the world that are capable of mass producing this crop partly due to environmental conditions (Gareau et al., 2018). The primary areas of production are found in the crop's native ranges of the USA and Canada, which have generated on average around 376,000 and 139,000 metric tons of cranberries annually in the past 10 years, respectively (FAOSTAT, 2022) (Figure 2). Within the USA, Wisconsin is the largest producer of cranberries, producing on average ~229,000 metric tons of cranberries every year for the past decade (USDA NASS, 2022) (Figure 2A). In the USA, after Wisconsin, Massachusetts on average produces ~96,000 metric tons annually (USDA NASS, 2022) (Figure 2A). Over the past 10 years, New Jersey and Oregon produced an annual average of around 25,000 and 21,000 metric tons, respectively; although Oregon very recently overtook New Jersey in annual production (USDA NASS, 2022) (Figure 2A). In Canada, Québec and British Columbia account for ~94% of the national cranberry production, producing a respective average of around 89,500 and 40,000 metric tons in the past decade (Agriculture and Agri-Food Canada, 2021; Statistics Canada, 2022). Other US states and Canadian provinces that produce cranberries include Washington, Maine, New Brunswick, and Newfoundland and Labrador.



FIGURE 1

The American cranberry (*Vaccinium macrocarpon* Aiton). A cranberry bed in a commercial farm (A), and a close-up of the cranberry plant during bloom and early fruit set (B).

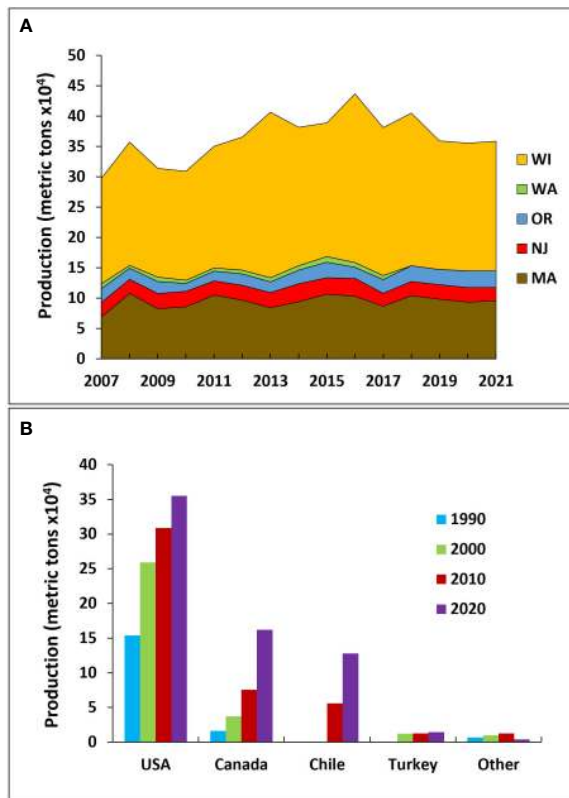


FIGURE 2
Trends in cranberry production (in metric tons) within the United States of America (USA) (A) and global cranberry production (B). US states: WI, Wisconsin; MA, Massachusetts; NJ, New Jersey; OR, Oregon; WA, Washington. Data obtained from USDA NASS (2022) and FAOSTAT (2022).

The largest cranberry producer outside of North America has been Chile, producing an average of 97,000 metric tons over the past 10 years (FAOSTAT, 2022) (Figure 2B). The southern regions of Chile have acidic soils from redistributed volcanic ash and similar temperatures to the northwestern USA, which are suitable conditions for cranberry production, as well as minimal insect pest pressures (Stang, 1997). The country began growing

cranberries in the 1990s, experiencing a significant increase in production in the early 2000s, reaching 19% of the global market in 2020 (FAOSTAT, 2022) (Figure 2B). After Chile, Turkey is the fourth biggest producer of cranberries, responsible for an average of 11,500 metric tons annually in the past decade (Figure 2B), followed by a range of countries mostly across Europe (FAOSTAT, 2022).

Brief history of cranberry IPM

The first cultivation of cranberries from the wild began in the early 1800s in Massachusetts (Figure 3), resulting in varieties like 'Early Black,' although wild fruit was still being collected and sold (Eck, 1990; Vorsa and Johnson-Cicalese, 2012). The first major breeding program took place ~100 years later in 1929 (Figure 3), intended to select for higher resistance against the blunt-nosed leafhopper, *Limotettix vaccinii* Van Duzee (Hemiptera: Cicadellidae) (Vorsa and Johnson-Cicalese, 2012). *Limotettix vaccinii* is a native pest that vectors a phytoplasma that causes cranberry false blossom disease, which is characterized by the malformation of the flowers, resulting in reduced yields (Beckwith and Hutton, 1929; Dobrosky, 1931; Pradit et al., 2020). Around a decade later, shortly after the successful breeding of resistant varieties like 'Stevens,' the popularization of broad-spectrum insecticides, that were inexpensive, fast-acting, and effective, reduced the necessity for these breeding programs (Vorsa and Johnson-Cicalese, 2012). Insecticide classes such as organochlorines, like DDT, as well as organophosphates and carbamates, which are acetylcholinesterase inhibitors, were being developed and sold (Figure 3), all of which were effective against many insect pests, including leafhoppers (Wheeler, 2002). These chemicals had, however, negative side effects, killing nontarget organisms and harming the environment, which led to a ban on organochlorines in the 1970s and the implementation of the Food Quality Protection Act of 1996 (FQPA) by the Environmental Protection Agency (EPA) (Figure 3) (Wheeler, 2002; Rajabi, 2014). The EPA FQPA eliminated and restricted the usage of certain broad-spectrum insecticides (organophosphates and

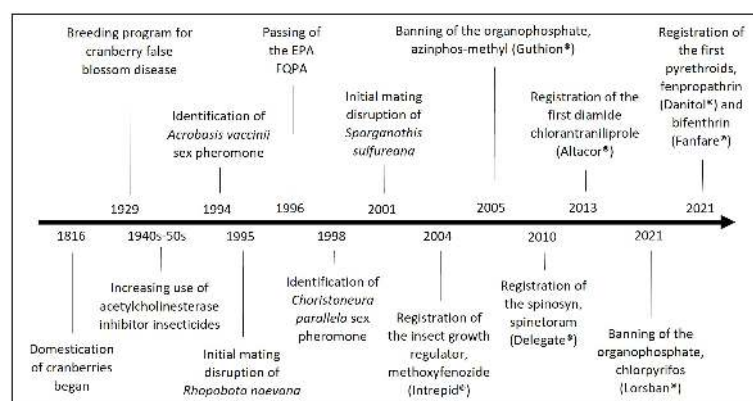


FIGURE 3
Timeline of some of the most important breakthroughs regarding cranberry insect IPM.

carbamates) and led to a reevaluation of these insecticides, many of which were important in cranberry production (Wheeler, 2002; Rajabi, 2014). As a result, new methods of pest control needed to be developed, such as target-specific and more environmentally-sustainable chemical control classes with different modes of action (Rodriguez-Saona et al., 2016) (Figure 3). Additionally, behavioral control methods, such as mating disruption, have been evaluated (Figure 3), with newer technologies allowing for better identification of pheromones of cranberry insect pests (Rodriguez-Saona et al., 2020a). Furthermore, there has been increasing research on biological and natural control, particularly on the use of entomopathogenic nematodes for soil insect pests (Hayes et al., 1999; Koppenhöfer et al., 2008; Ye et al., 2018; Foye and Steffan, 2019).

Because of increased insecticide restrictions since the passing of the EPA FQPA, cranberry growers have been incorporating new tools that are more compatible with IPM to manage insect pests, such as more selective, reduced-risk insecticides and natural and biological or cultural controls (Blake et al., 2007). Despite a societal demand for fewer pesticides, there is still only a relatively small market for organic cranberry farming (Zeldin, 2005). This may be at least in part because most cranberries are used for processing (e.g., juices, sauces) instead of sold fresh, potentially influencing market price and making organic cranberries less profitable. Growing cranberries organically is also challenging because of high pest pressure, particularly from fungal pathogens that cause fruit rot, especially in humid regions (Zeldin, 2005). Due to market demand and suitable environmental conditions, the majority of organic cranberry production occurs in Quebec, followed by Wisconsin (Zeldin, 2005; Rioux, 2018; Drolet et al., 2019). Since cranberries are considered a specialty crop that are not widely grown, there is limited federal support and support from the private industry for research on new pest management strategies (Alston and Pardey, 2008).

Literature search

Our literature search focused on data-driven entomological research on IPM tactics for cranberries over the last 30 years (1990–2021). To meet our selection criteria, and thus be included in this review, the paper had to be published in a peer- or editor-reviewed journal and needs to have direct relevance to the subject of insect pests or insect pest management of the American cranberry, *V. macrocarpon*. For this, the Web of Science Core Collection Database was used because it is the oldest and most widely used and authoritative database of research publications and citations (Birkle et al., 2020). To do so, various keyword combinations were searched in the database. These keyword combinations were: cranberry* (the asterisk accounts for the potential plurality or different forms of the word) and one of the following: insect*, bug*, pest*, IPM, integrated pest management, and monitor*. Other than Web of Science, another database we used was Arthropod Management Tests, which gave editor-reviewed (instead of peer-reviewed) records, and that represent data-driven entomological publications largely focusing on pesticide trials. The keyword used in the Arthropod Management Tests search was: cranberry*. Because our paper focuses on research trends, we only included peer- and editor-reviewed publications and excluded extension publications, such as abstracts, proceedings, newsletter articles, and fact sheets, that are for the most part not data-driven and not easily accessible to search in an open source database.

We created a PRISMA flow chart diagram, following Page et al. (2021), to document the steps taken for the inclusion of publications in our literature review (Figure 4). Our initial search resulted in 897 publications, and after removing duplicates from the search process, we began screening the records. In addition to the records from our database search, five studies were discovered through the citations of the utilized papers that were not present on either Web of Science or Arthropod Management Tests. In the

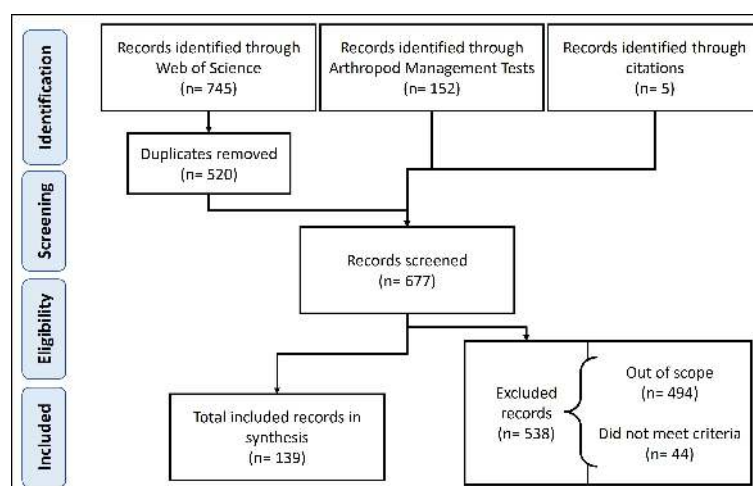


FIGURE 4

PRISMA flow diagram depicting the steps to the literature review. The scope of our paper was on cranberry insect IPM, and to meet our criteria for inclusion the article had to be published in a peer- or editor-reviewed journal and in the years 1990 to 2021.

screening process, we removed the records that were out of scope and irrelevant to cranberry insect IPM, as well as those that did not meet our criteria of being a peer- or editor-reviewed papers published in the years 1990 to 2021, yielding a total of 139 papers used in our literature review (Supplemental Table 1). Because we were interested in examining trends and gaps in the existing literature on entomological IPM research in cranberries over the past three decades, the data extracted from these selected papers included the year of publication, location of the study, the insect pest(s) studied, and the IPM strategy used. It should be noted that only 25 relevant studies were indexed in the databases from prior to 1990, ranging in publication date from 1909 to 1989, and were not included in our data set. Since there were such few publications before 1990, we believe that omitting these records would not affect the findings of our analyses. Moreover, our focus was on the last three decades because this period has the most consistent IPM research and it captures research before and after the implementation of the EPA FQPA, a key regulatory event that impacted pesticide use and insect IPM in cranberries.

Geographical region

Almost the totality of our current knowledge on cranberry insect IPM comes from studies conducted in the USA and Canada (138 of 139 publications within the past three decades) (Figure 5A). The USA accounts for about 84% of the world's publications, with most of the research coming from three states (New Jersey, Massachusetts, and Wisconsin) (Figure 5B). Since 1990, Canada accounts for ~16% of the total research on cranberry insect IPM, with the majority (75%) coming from British Columbia (Figure 5B). Other North American regions with published cranberry IPM research include Québec, Washington, Oregon, and to a lesser extent, Newfoundland and Labrador and Maine (Figure 5B). Across North American regions, the number of publications tends to match the cranberry production (Figure 5C), indicating that funding for research likely depends on the financial support from regional stakeholders such as cranberry grower organizations; except for New Jersey, where the number of publications is much greater than the state's crop production, and Quebec, where

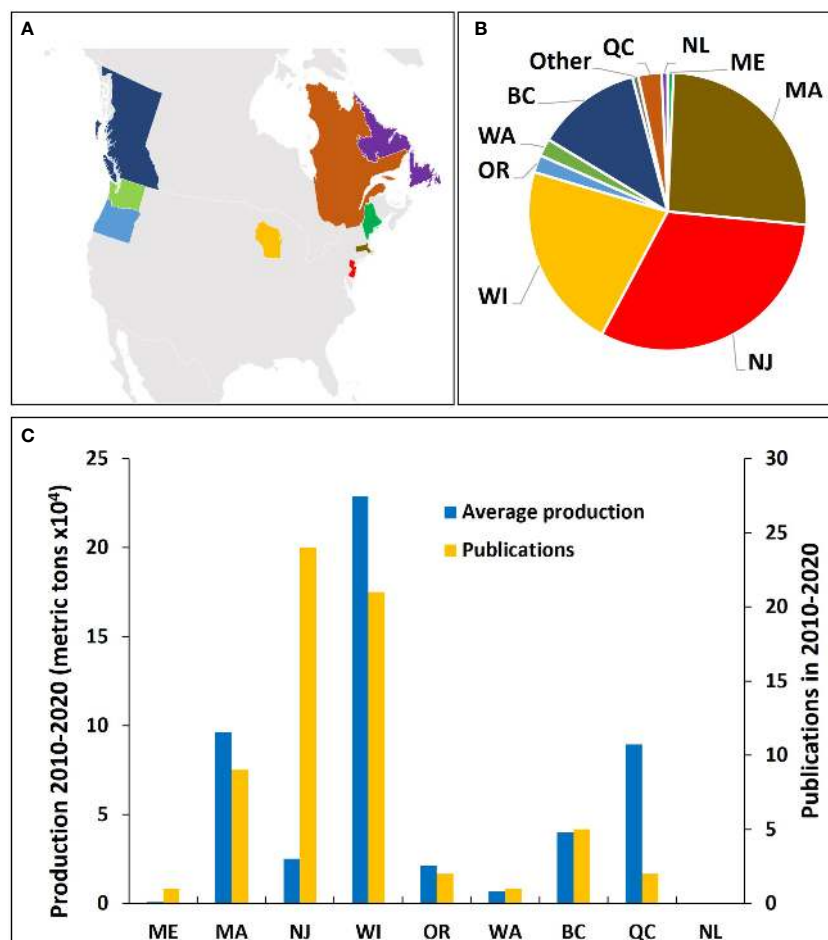


FIGURE 5

Regions in North America where most scientific publications about cranberry entomology topics have been conducted (A), and proportion of scientific publications by region (B) from 1990 to 2021. Publication counts compared to average production in the years 2010 to 2020 (C). US states: WI, Wisconsin; MA, Massachusetts; NJ, New Jersey; OR, Oregon; WA, Washington; ME, Maine. Canadian provinces: BC, British Columbia; QC, Québec; NL, Newfoundland and Labrador. Data obtained from USDA NASS (2022) and Statistics Canada (2022).

production acreage is much greater than the number of publications. Outside North America, the only publication on IPM of cranberry insects came from New Zealand, describing the endemic and polyphagous manuka moth, *Declana floccosa* Walker (Lepidoptera: Geometridae) (Miller et al., 2006). Although insect pest pressures might not be as strong in the newer regions of cranberry production, like Chile (Stang, 1997), as compared to the crop's native regions, we expect research on the subject to increase as insect pests adapt to the introduced crop.

Cranberry insect pests

In the past three decades, there were 31 insect pests or potential pests with varying degrees of importance in cranberries that were researched; out of which 15 were Lepidoptera, 8 Coleoptera, 4 Hemiptera, 2 Diptera, 1 Hymenoptera, and 1 Orthoptera (Supplemental Table 1). The three most researched insect pests of cranberry have been Sparganothis fruitworm (*Sparganothis sulfureana* Clemens; Lepidoptera: Tortricidae), cranberry fruitworm (*Acrobasis vaccinii* Riley; Lepidoptera: Pyralidae), and blackheaded fireworm (*Rhopobota naevana* Hübner; Lepidoptera: Tortricidae)—all of which are native pests of *Vaccinium* spp. All together, these three species account for almost 40% of the studies on cranberry insect IPM (Figure 6A); although the research focus on them has fluctuated over time (Figure 6B).

The other top studied insect pests are spongy moth (formerly known as gypsy moth) (*Lymantria dispar* Linnaeus; Lepidoptera: Erebididae), cranberry tipworm (*Dasineura oxycoccana* Johnson; Diptera: Cecidomyiidae), spotted fireworm (*Choristoneura parallela* Robinson; Lepidoptera: Tortricidae), cranberry girdler (*Chrysoteuchia topiaria* Zeller; Lepidoptera: Crambidae), cranberry weevil (*Anthonomus musculus* Say; Coleoptera: Curculionidae), blunt-nosed leafhopper (*Limotettix vaccinii* Van Duzee; Hemiptera: Cicadellidae), and red-headed flea beetle (*Systema frontalis* Fabricius; Coleoptera: Chrysomelidae) (Figures 6A, B).

Most of these cranberry pests are native to North America, with only a few notable invasive species, such as *L. dispar* and the black vine weevil (*Otiorhynchus sulcatus* Fabricius; Coleoptera: Curculionidae) from Europe, and the oriental beetle (*Anomala orientalis* Waterhouse; Coleoptera: Scarabaeidae) from Asia. These invasive pests are generalist herbivores that can likely cope with a variety of hosts with different chemistries, allowing them to survive on plants with high phenolics, such as cranberries (Rodriguez-Saona et al., 2011b). Furthermore, these invasives feed on the less defended parts of cranberries, particularly *O. sulcatus* and *A. orientalis* that feed on the roots, which are likely less apparent than the rest of the plant due to being underground. Although *L. dispar* feeds on cranberry leaves, cranberries are not a preferred host (Rodriguez-Saona et al., 2011b).

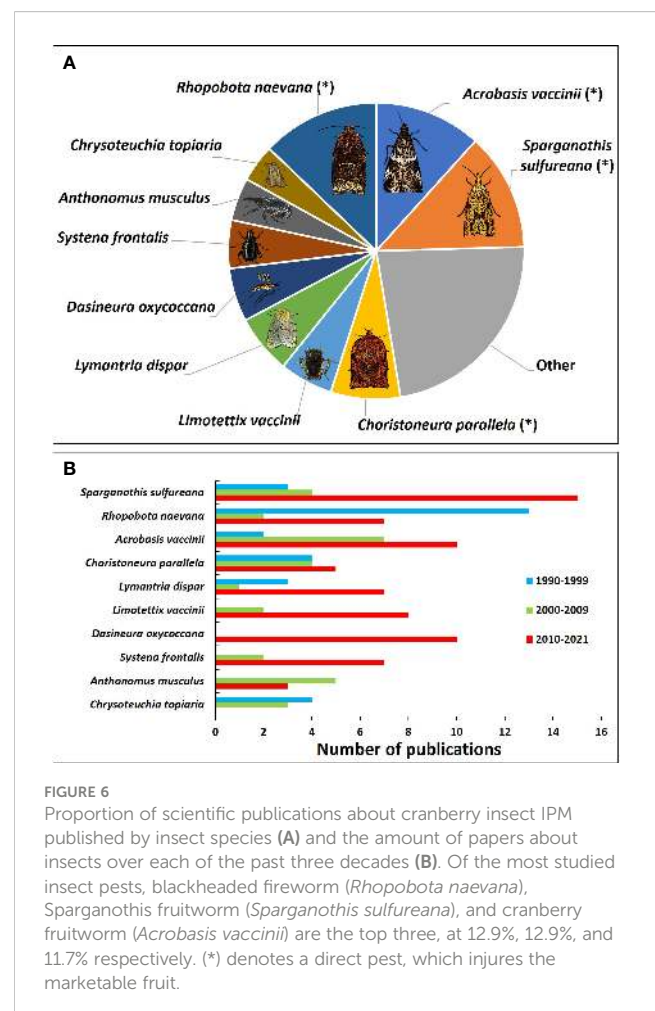
Of these top studied cranberry pests, larvae of *S. sulfureana*, *A. vaccinii*, and *C. parallela* are direct pests, causing damage to the berries. *Sparganothis sulfureana* larvae, *R. naevana* larvae, and adult *S. frontalis* preferentially feed on new plant growth and foliage, whereas *D. oxycoccana* is a gall midge that destroys the apical

meristems of the cranberries. *Limotettix vaccinii* is a phloem feeder that vectors a phytoplasma that causes a disease known as cranberry false blossom. Larvae of *C. topiaria* and *S. frontalis* are crown and root pests, which can kill the plant early in the season.

Considering that many of the cranberry-producing regions in North America are widely separated geographically, they probably experience different insect pest complexes and pressures, which is evident when looking at regional research. For instance, published research coming from Wisconsin, British Columbia, Washington, and Oregon often pertains to *R. naevana* and *O. sulcatus*, whereas all the literature on *A. musculus* and *L. vaccinii* came from Massachusetts and New Jersey, respectively (Supplemental Table 1). By contrast, *S. sulfureana* tends to be a major pest that is widely distributed across North America (Deutsch et al., 2014; Deutsch et al., 2015), and has thus been studied in many regions.

IPM tactics

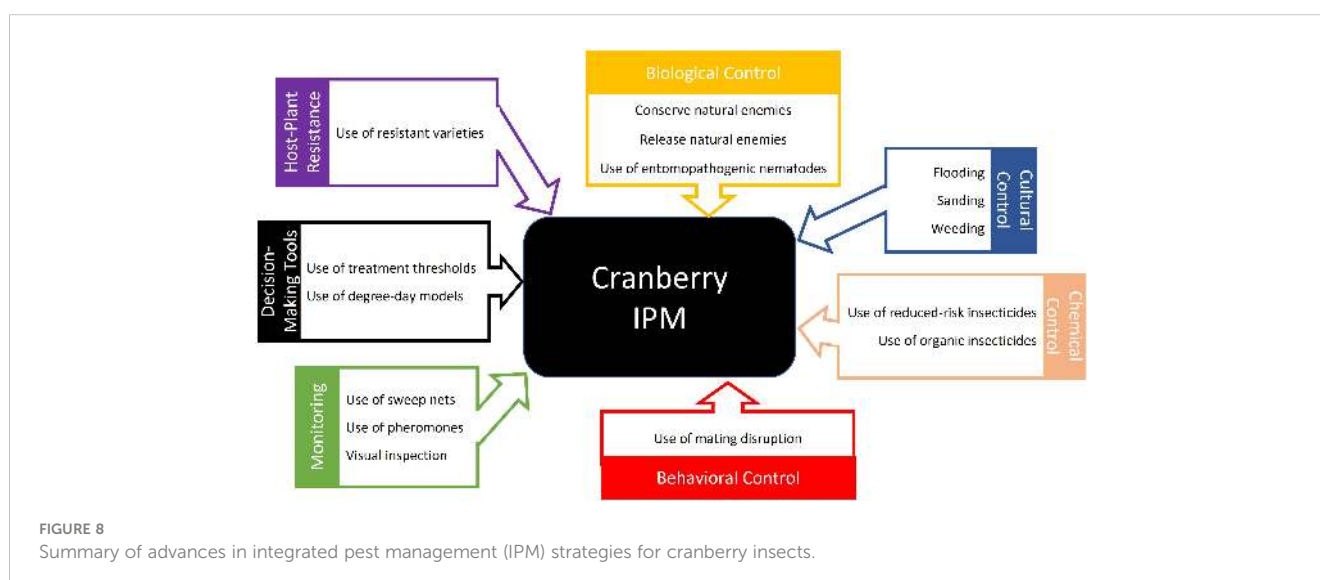
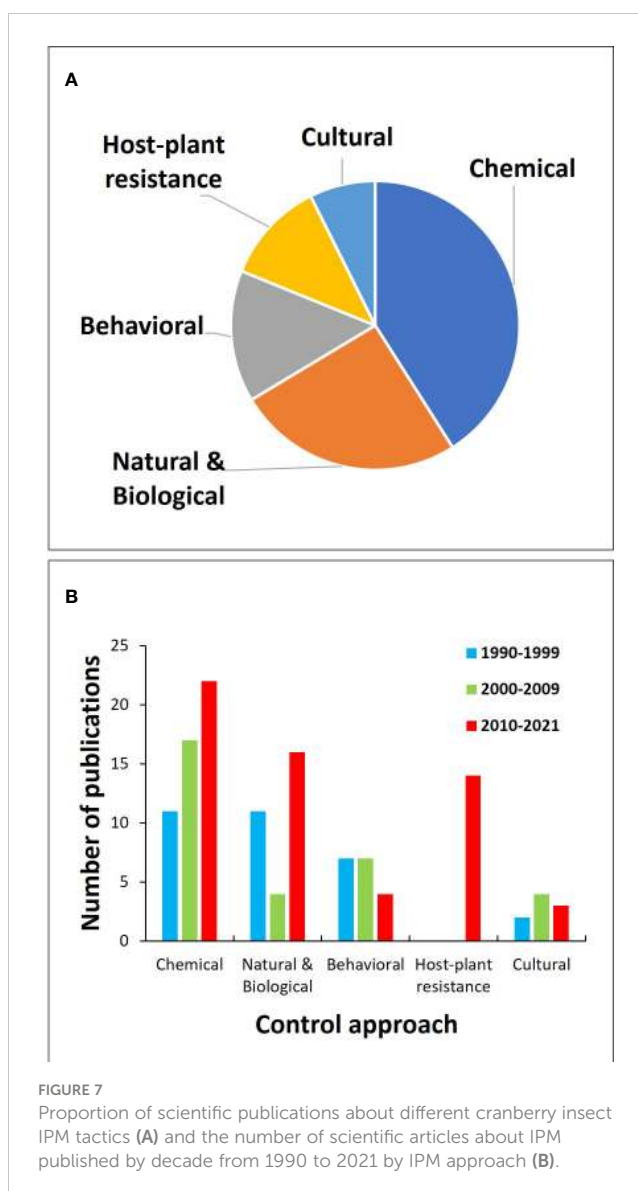
We divided the published papers into monitoring and decision-making, and five control tactics: chemical control, natural and biological control, behavioral control, host-plant resistance, and cultural control. If a paper mentioned multiple IPM approaches, then it would count for every tactic it discussed. Articles on



monitoring and decision-making were analyzed separately because they are IPM tactics used to assist in the pest management decision process but not for directly controlling pests as with the other tactics. Of the control tactics, chemical control has been researched the most, followed by natural and biological control and then behavioral control (Figure 7A). However, there have been slightly different trends in the focus of IPM research over the past three decades (Figure 7B), with natural and biological control being highly studied in the 1990s, then experiencing a drop in the 2000s, and increasing again in the 2010s. Chemical control has consistently been the most studied IPM approach every decade, continuously increasing with every decade. Behavioral control has also been consistently studied; however, in the 2010s, papers on behavioral control have almost halved. On the other hand, research on host-plant resistance received little attention until the 2010s, when it surpassed research on behavior and cultural control. Cultural control has received little research attention throughout the past three decades. These control tactics together with monitoring and decision-making are the foundation of an effective IPM program for cranberries (Figure 8).

Monitoring and decision-making

Knowledge of the presence of pestiferous and beneficial insects in the agroecosystem allows farmers and researchers to implement further pest control measures. Thus, there have been many studies in cranberries that focussed on specific techniques of monitoring or decision-making. The most common methods of monitoring for cranberry insect pests involve sweep netting and the use of traps baited with sex pheromones. Sweep netting is a scouting technique that uses a 12-inch diameter net swung along the canopy of the cranberry plant, with around 25 sweeps per sweep set being done for every one to two acres (Averill and Sylvia, 1998; Armstrong, 2016). As proficiency in chemical ecology techniques improved, new insect pheromones have been identified. The major sex pheromone components have been identified and used in Delta



traps for *R. naevana* (Fitzpatrick and Troubridge, 1992; Cockfield et al., 1994c; Dixon and Hillier, 2005; Steffan et al., 2017b), *A. vaccinii* (Marchand and McNeil, 2004b; Dixon and Hillier, 2005; Medina et al., 2013; Steffan et al., 2017b) (Figure 3), and *S. sulfureana* (Polavarapu et al., 2001; Deutsch et al., 2014; Steffan et al., 2017b; Pradit et al., 2019), which are important direct pests, widely distributed across cranberry-producing regions.

Other known insect pheromones, but not widely used, are those for *A. musculus* (Szendrei et al., 2011; Rodriguez-Saona et al., 2020a), *C. parallela* (Polavarapu and Loneragan, 1998), *C. topiaria* (Dixon and Hillier, 2005), *D. oxycoccana* (Fitzpatrick et al., 2000), the cranberry blossomworm, *Epiglaea apiata* Grote (Lepidoptera: Noctuidae) (Zhang and Polavarapu, 2003), *Hoplia equina* LeConte (Coleoptera: Scarabaeidae) (Zhang et al., 2003; Weber et al., 2005), the white grub *Phyllophaga georgiana* Horn (Coleoptera: Scarabaeidae) (Robbins et al., 2009), and the cranberry root grub, *Lichnanthe vulpina* Hentz (Coleoptera: Scarabaeidae) (Robbins et al., 2006). There are many potential reasons for their limited use, including their cost, lack of efficacy, and limited availability due to the narrow distribution of the pest. For example, the major components of the *A. musculus* aggregation pheromone have been identified and evaluated using yellow sticky cards in cranberries (Szendrei et al., 2011; Rodriguez-Saona et al., 2020a); yet, the pheromone blend remains inefficient and needs improvement, likely because additional components might be missing. Populations of *D. oxycoccana* that live on blueberries (*Vaccinium corymbosum* L.) are theorized to have a different sex pheromone than those that subsist on cranberries (Cook et al., 2011; Fitzpatrick et al., 2013), which might mean that the two populations are cryptic species (Cook et al., 2011; Cook et al., 2012); however, the high cost of pheromone production might challenge their use for monitoring *D. oxycoccana* populations (Fitzpatrick et al., 2013).

Traps and baits that are under evaluation for use in cranberry IPM include sticky traps of varying colors that can be baited with the plant volatile methyl salicylate to attract natural enemies of herbivores (Rodriguez-Saona et al., 2011a; Rodriguez-Saona et al., 2012; Salamanca et al., 2017; Salamanca et al., 2019; Rodriguez-Saona et al., 2020c). Sticky traps catch a wide variety of insects, making them good for monitoring local diversity, but a lack of specificity can make them ineffective when looking for one specific pest. Other types tested include bucket traps for *D. oxycoccana* and *H. equina* (Weber et al., 2005; Fitzpatrick et al., 2018) and cross vane traps for *P. georgiana* (Robbins et al., 2009). Visual inspection of cranberry plants and surrounding weeds can also be used as a monitoring tool. For instance, *A. vaccinii* tends to prefer larger cranberries (Marchand and McNeil, 2006) and can induce early fruit reddening (Marchand and McNeil, 2004a). Also, some cranberry pests, like *C. parallela* (Stuart and Polavarapu, 1998) and *C. topiaria* (Roland, 1990), show oviposition and feeding preferences for different weeds, with the latter sometimes preferring to feed on the weeds over the cranberries (Roland, 1990). Thus, assessment of oviposition and feeding damage on weeds in cranberry beds can be indicative of the presence of some insect pests. The two invasive pests *L. dispar* (Rodriguez-Saona et al., 2011b) and *O. sulcatus* (Miller et al., 2012) are highly

polyphagous and are thus likely to be present on, and sometimes even prefer, certain weed species.

In addition to monitoring for insect pests, decision-making and risk assessment are critical aspects of IPM. This is commonly achieved using degree-day models which set temperature-mediated thresholds based on insect phenology. Degree-day models have been developed to predict phenological events, such as the onset of adult activity, peak adult flight, and time of egg hatch, to better time insecticide applications for *S. sulfureana* (Deutsch et al., 2014; Deutsch et al., 2015), *A. vaccinii* (Medina et al., 2013; Chasen and Steffan, 2016), *C. topiaria* (Cockfield and Mahr, 1994), and *R. naevana* (Cockfield et al., 1994b). Studies have also been conducted to characterize the injury caused by insect pests like *D. oxycoccana* (Tewari et al., 2012; Tewari et al., 2013), *A. musculus* (Long and Averill, 2003), *S. frontalis* (Jaffe et al., 2021a), the toad bug *Phylloscelis rubra* Ball (Hemiptera: Dictyopharidae) (Rodriguez-Saona et al., 2020b), and the broad-winged bush katydid *Scudderella pistillata* Brunner von Wattenwyl (Orthoptera: Tettigoniidae) (Labarre et al., 2020). For example, plants that were infested with *D. oxycoccana* or mechanically girdled had more than a 55% decrease in fruit size relative to uninfested, ungirdled plants (Tewari et al., 2014), and simulated *A. musculus* damage led to a 30% decrease in fruit number and weight (Long and Averill, 2003). These studies can help with the establishment of economically-relevant damage levels and economic thresholds. For example, knowledge on the pest's phenology and life history with the use of economic thresholds can reduce crop damage caused by *A. musculus* (Long and Averill, 2003). Unfortunately, many important cranberry pests currently do not have economic thresholds, such as *L. vaccinii* (de Lange and Rodriguez-Saona, 2015a), *D. oxycoccana* (Mahr, 2005), and *C. topiaria* (Madore, 2010). Other pests have combined thresholds, such as all noctuid lepidopterans with *L. dispar* at 4.5 larvae per sweep set (Averill and Sylvia, 1998; Le Duc et al., 2004), or 4 larvae per sweep set for *C. parallela* (de Lange and Rodriguez-Saona, 2015b). There are also pests that have different thresholds depending on the location; for instance, *S. sulfureana* has an economic threshold of 5 larvae per sweep set in eastern Canada (Le Duc et al., 2004; Madore, 2010), but 2 larvae per sweep set in Massachusetts and Wisconsin (Sylvia and Averill, 2013; Guédot and McMahan, 2015). Establishing better and more up-to-date models on insects and their injury characterization can contribute to the economic threshold calculations, which is needed for several insect pests of cranberries.

Chemical control

There have been several changes in chemical control in cranberries in the last 30 years. In 1996, the EPA FQPA was passed in the USA, restricting certain broad-spectrum insecticides, such as the organophosphates azinphos-methyl (Guthion®) and chlorpyrifos (Lorsban®), ultimately leading to the implementation of newer reduced-risk insecticides (Figure 3). As such, chemical control has been the highest studied control approach, comprising 41% of all research on cranberry insect IPM

(Figure 7A). Decades before the EPA FQPA, cranberry growers had used DDT to control *R. naevana* and *L. vaccinii*. But these insects developed resistance to this insecticide, necessitating a switch to pyrethrum, malathion, dieldrin, and parathion (Brody et al., 2002). In the 1990s, parathion was utilized via chemigation, aerial, or boom sprays to control various insect pests (Clark et al., 1994), whereas azinphos-methyl, in conjunction with parathion, was also used to control *R. naevana* (Wan et al., 1995). Since then, these two organophosphates have been banned for use in cranberries because of environmental and human health concerns.

In 2021, the organophosphate chlorpyrifos was also banned for use in cranberries (Figure 3). This insecticide was widely used to control several cranberry insect pests, including *S. sulfureana*, *C. parallela* (Putnam et al., 2002; Rodriguez-Saona et al., 2016), *A. musculus* (Putnam et al., 2002), and *L. vaccinii* (Rodriguez-Saona et al., 2019). However, residues could be detected as long as 2 months after application (Putnam et al., 2002) and the insecticide has significant negative effects on beneficial insects (Rodriguez-Saona et al., 2016). *Sparganothis sulfureana* has already developed resistance to organophosphates in Massachusetts (Averill and Sylvia, 1998). As a response to the EPA FQPA, farmers soon began switching to newer insecticides with different modes of action, such as insect growth regulators (IGRs), spinosyns, and diamides, which are more environmentally friendly and have greater compatibility with biological control methods than organophosphates (Rodriguez-Saona et al., 2016). The past two decades saw the registration of IGRs like methoxyfenozide (Intrepid®), spinosyns like spinetoram (Delegate®), diamides like chlorantraniliprole (Altacor®), and pyrethroids like fenpropathrin (Danitol®) and bifenthrin (Fanfare®) (Figure 3). IGRs, spinosyns, and diamides are more selective than the broad-spectrum insecticides (i.e., organophosphates, carbamates, and pyrethroids) targeting mainly lepidopteran pests such as *S. sulfureana*, *A. vaccinii*, *R. naevana*, *C. parallela*, and *L. dispar* (Rodriguez-Saona et al., 2016). Due to the highly permeable sandy soils and connection to water in the regions where cranberries are grown, there are few registered insecticides, namely neonicotinoids like imidacloprid, to control root insect pests; however, neonicotinoids can have severe nontarget effects especially on pollinators (Lu et al., 2020). For organic farming, pyrethrins (like Pyganic®), the spinosad Entrust®, and neem oil products (like Trilogy®) are currently available for insect pest control (Armstrong, 2017).

Natural and biological control

A little more than one-fourth of the published research on insect IPM in cranberries dealt with natural and biological control (Figure 7A), which utilizes predators, parasitoids, and pathogens to reduce pest abundance. The most popular predators used in cranberry agriculture are entomopathogenic nematodes that can be sprayed to control root pests, such as *Steinernema carpocapsae* Weiser (Rhabditida: Steinernematidae) for the control of *O. sulcatus* (Hayes et al., 1999), *Heterorhabditis bacteriophora* Poinar (Rhabditida: Heterorhabditidae) for the cranberry rootworm, *Rhabdopterus picipes* Oliver (Coleoptera: Chrysomelidae)

(Polavarapu et al., 2000), and *Steinernema scarabaei* Stock and Koppenhöfer (Rhabditida: Steinernematidae) for *P. georgiana* (Koppenhöfer et al., 2008). The recently discovered nematode *Oscheius onirici* Torrini et al. (Rhabditida: Rhabditidae) can kill *S. sulfureana* (Ye et al., 2018; Foye and Steffan, 2019) and *A. vaccinii* (Ye et al., 2018), as well as suppress *S. frontalis* (Foye and Steffan, 2019). Other predators that are commonly present in cranberry ecosystems include spiders (Bardwell and Averill, 1996; van Zoeren et al., 2018; de Lange et al., 2019b), staphylinid beetles (Haase-Statz, 1997), coccinellid beetles (Rodriguez-Saona et al., 2011a; Salamanca et al., 2017; de Lange et al., 2019b; Salamanca et al., 2019), chrysopid lacewings (Rodriguez-Saona et al., 2011a; de Lange et al., 2019b; Salamanca et al., 2019), and syrphid flies (Rodriguez-Saona et al., 2011a; Salamanca et al., 2017; de Lange et al., 2019b; Rodriguez-Saona et al., 2020c).

Among parasitoids, native trichogrammatid wasps have been found to occur naturally, and shown effective on *R. naevana* (Li et al., 1993; McGregor and Henderson, 1998), *A. vaccinii* (Simser, 1995), and *C. parallela* (Stuart and Polavarapu, 2000). In addition, several naturally occurring braconid and ichneumonid wasps, as well as tachinid flies, were found to parasitize the lepidopterous pests *R. naevana*, *S. sulfureana*, the false armyworm *Xylena nupera* Lintner (Lepidoptera: Noctuidae), the green spanworm *Macaria sulphurea* Packard (Lepidoptera: Geometridae), and the Rannoch looper *Macaria brunneata* Thunberg (Lepidoptera: Geometridae) (Drolet et al., 2019). Native eulophid and platygastid wasps were found to attack *D. oxycoccana* (Peach et al., 2012).

In terms of pathogens, it has been demonstrated that a fungal formulation of indigenous *Metarhizium robertsii* Metchnikoff Sorokin (Hypocreales: Clavicipitaceae) (formerly known as *Metarhizium anisopliae*) can be used against *O. sulcatus* and *C. topiaria* (Booth and Shanks, 1998; Booth et al., 2000). There has also been a bacterium, *Chromobacterium subtsugae* MWU12-2387 (Neisseriales: Neisseriaceae), discovered in the rhizosphere of cranberry plants that has biocontrol potential (Vöing et al., 2017). Another strain of *C. subtsugae*, PRAA4-1T, is actually used as a bioinsecticide (Grandevo®), which can be useful to control *S. sulfureana*, *A. vaccinii*, *R. naevana*, the common eupithecia *Eupithecia miserulata* Grote (Lepidoptera: Geometridae), and occasionally *D. oxycoccana* (Guédot and Perry, 2015; Guédot and Perry, 2016a; Guédot and Perry, 2016b). *Burkholderia rinojensis* A396 (Burkholderiales: Burkholderiaceae) is also a bacterium that has been marketed (Venerate®) for pest control in cranberries, showing efficacy against *S. sulfureana*, *A. vaccinii*, *R. naevana*, and *E. miserulata* (Guédot and Perry, 2015a; Guédot and Perry, 2016b). Another bacterium that has been widely utilized as a biocontrol agent, particularly in organic farming, is *Bacillus thuringiensis* Berliner (Bacillales: Bacillaceae) (Dipel®, Biobit®, and Xentari®) in the form of aerial sprays and occasionally chemigation to target lepidopterous pests such as *L. dispar*, *E. apiata*, *X. nupera*, *M. sulphurea*, and the brown spanworm *Ematurga amitaria* Guenée (Lepidoptera: Geometridae) (Sandler and Mason, 1997; Armstrong, 2017). There has been an unnamed granulosis virus discovered that is associated with *R. naevana* mortality (Theilmann et al., 1995), although there have been few studies on this virus and its use as a biological control agent.

Behavioral control

Research on behavioral control comprises 14.8% of the published literature (Figure 7A). Mating disruption functions by releasing components of each pest's sex pheromone which can reduce mating and fecundity (Fitzpatrick, 2006), and is the main behavioral control tactic tested to manage cranberry insect pests like *S. sulfureana* (Cockfield et al., 1994a; Polavarapu et al., 2001) (Figure 3), *R. naevana* (Cockfield et al., 1994c; Fitzpatrick et al., 1995; Baker et al., 1997; Fadamiro et al., 1998; Fitzpatrick, 2006) (Figure 3), and *C. parallela* (Polavarapu and Lonergan, 1998). Mating disruption for *A. orientalis* has also been evaluated in cranberries (Wenninger and Averill, 2006), although it has yet to be implemented likely because other grub species are more important pests. However, the efficacy of mating disruption can be inconsistent, like in the case of *A. vaccinii* (Steffan et al., 2017a). Other times they have not even been attempted because of sufficient tolerance to the pest, as in the case of *H. equina*, which has an effective pheromone lure (Zhang et al., 2003; Weber et al., 2005). Various methods to deploy pheromones for mating disruption have been assessed including drones (Luck et al., 2021), flowable emulsions for *A. vaccinii* and *R. naevana* (Steffan et al., 2017b), a sprayable microencapsulated formulation of *S. sulfureana* pheromones (Polavarapu et al., 2001), as well as a meter semiochemical timed release system for *R. naevana* (Baker et al., 1997; Fadamiro et al., 1998). Mating disruption can be used in organic cranberry farms; however, there were no commercially available products at the time of the submission of this paper.

Host-plant resistance

Most of the insect pests of cranberries are native to North America and have probably co-evolved with the crop. Cranberries have a high phenolic content (Rodriguez-Saona et al., 2011b; Vorsa and Johnson-Cicalese, 2012), which may limit feeding by non-adapted insect herbivores. However, recent releases of high-yielding cranberry cultivars have led to an increase in research on host-plant resistance from 0 to 11.5% in the last decade (Figure 7A). Cranberry cultivars have been bred for different purposes. In the beginning of cultivation and during the 19th century, farmers grew cranberries that were propagated from wild plants, some of which are still actively cultivated varieties, such as 'Early Black,' 'Ben Lear,' 'Howes,' 'McFarlin,' and 'Potter' (Vorsa and Johnson-Cicalese, 2012). There have been two major breeding programs since the cultivation of cranberries, one starting in the 1920s and the other in the 1980s (Vorsa and Johnson-Cicalese, 2012). The first breeding program crossed wild cultivars and was directed at an ultimate goal of resistance to *L. vaccinii*, the vector of a phytoplasma that causes cranberry false blossom disease (Hancock et al., 2008; Vorsa and Johnson-Cicalese, 2012) (Figure 3). This resulted in the release of the popular cultivars 'Stevens' and 'Franklin' in the 1950s (Vorsa and Johnson-Cicalese, 2012). However, in the 1940s and 1950s,

reliable broad-spectrum insecticides, such as organophosphates, organochlorines, and carbamates, were increasingly utilized to control *L. vaccinii* (Wheeler, 2002), reducing the need for developing insect-resistant cultivars. Therefore, the second breeding program for cranberries was aimed at developing higher-yielding cultivars, with bigger fruit that ripens earlier and with more intense color, producing cultivars such as 'Crimson Queen,' 'Mullica Queen,' 'Demoranville,' 'GH1,' and 'HyRed' (Hancock et al., 2008; Vorsa and Johnson-Cicalese, 2012; McMahan et al., 2016).

Because of the history of breeding in cranberries, cultivars are expected to differ in resistance against insect herbivores. For instance, Franklin was bred for high productivity and resistance to *L. vaccinii*, whereas Demoranville and Crimson Queen were bred for large fruit size, high yield, and earlier ripening seasons (de Lange et al., 2019a; de Lange et al., 2019b). In terms of insects, Mullica Queen and Ben Lear suffered more *A. vaccinii* larval damage than did Stevens or GH1 (McMahan et al., 2016). On the other hand, *S. sulfureana* performance did not differ among Mullica Queen, Ben Lear, Stevens, GH1, and HyRed (McMahan and Guédot, 2018). Stevens appears to be more tolerant to *O. sulcatus* than McFarlin (Miller et al., 2012). Two high-yielding cultivars, Crimson Queen and its parent Ben Lear (Rodriguez-Saona et al., 2011b), along with Howes and Franklin (de Lange et al., 2019a), were shown to be more susceptible to *L. dispar* than McFarlin (Rodriguez-Saona et al., 2011b), Stevens (Rodriguez-Saona et al., 2011b; de Lange et al., 2019a), or the very resistant cultivar Potter (Rodriguez-Saona et al., 2011b; de Lange et al., 2019a). Stevens, Howes, Franklin, Crimson Queen, Early Black, and Potter all showed equal resistance to *S. sulfureana* and *C. parallela* (de Lange et al., 2019a). *Lymantria dispar* also showed a preference for Howes over Early Black, although *A. musculus* did not show any preference, and *S. frontalis* had an insignificant trend toward preferring Howes (Neto et al., 2010). *Lymantria dispar* damage on Stevens, Mullica Queen, and Howes did not affect the cranberry's induced response (Tjiurutue et al., 2017), despite the three cultivars having different phenolic and volatile profiles (Tjiurutue et al., 2017; de Lange et al., 2019b). In general, there seems to be an inverse relationship between growth and defense such that cranberry cultivars that were bred for high yield tend to be less defended against insect pests (de Lange et al., 2019a).

In some cases, plant diseases, such as cranberry false blossom, can interfere with the levels of nutrients and defenses in cranberry plants (Pradit et al., 2019; Pradit et al., 2020; Rodriguez-Saona et al., 2021), which can affect *L. vaccinii* development (Pradit et al., 2019), as well as benefit non-vector pests, like *S. sulfureana*, *C. parallela*, and *L. dispar* (Pradit et al., 2020). Moreover, commercial elicitors of plant defenses, such as activators of the salicylic acid (SA) and jasmonic acid (JA) defense pathways, failed to increase cranberry resistance against insect herbivores as well as the disease-causing phytoplasma (Rodriguez-Saona et al., 2021). However, the application of elicitors of the JA defense pathway can lead to higher volatile production that can potentially attract natural enemies of insect pests (de Lange et al., 2019b; Rodriguez-Saona et al., 2021) or repel pests, such as *S. sulfureana* (Rodriguez-Saona et al., 2013).

Cultural control

Cultural control tactics account for 7.4% of the published research on cranberry insect IPM (Figure 7A). These are methods in which the grower changes the environment of the cranberry bed to combat pests, such as flooding, sanding, and weeding. Flooding is normally implemented in the fall for harvest, with the crop remaining underwater for the duration of the winter for protection from frost (Averill et al., 1997), although the timing of fall flooding (Demoranville et al., 2005) or spring draining (Averill et al., 1997) can be altered for insect pest management. For example, *A. musculus* adults emerge from non-crop habitats around farms in early spring and start moving to the cranberry beds to lay eggs on the flower buds (Szendrei et al., 2011). In New Jersey, where spring draining of cranberry beds typically begins in mid to late April, a discontinuity between insect and plant phenology may serve as an agent to reduce *A. musculus* incidence; although *A. musculus* is not a top pest of cranberries in New Jersey (Mechaber, 1992; Szendrei et al., 2011). Flooding can be used to drown many insect pests but has been used particularly to control *R. naevana* (Cockfield and Mahr, 1992; Teixeira and Averill, 2006), *A. vaccinii* (Averill et al., 1997; Demoranville et al., 2005; Teixeira and Averill, 2006), and *C. topiaria* (Teixeira and Averill, 2006; Fitzpatrick, 2007), and it has the potential to work against *S. sulfureana* (Teixeira and Averill, 2006). Flooding also has been prescribed throughout the year to control *E. apiata*, *L. dispar*, *X. nupera*, the white grub, *Phyllophaga anxia* LeConte (Coleoptera: Scarabaeidae), and the southern red mite, *Oligonychus ilicis* McGregor (Trombidiformes: Tetranychidae) (Averill et al., 1997). Additionally, early season flooding has been shown to increase natural enemy abundance, such as spiders and parasitoids (van Zoeren et al., 2018). Flooding is also used in IPM against certain weeds (Demoranville et al., 2005) and fungi (Averill et al., 1997). It prevents the crop from being exposed to pests and low temperatures when not in production (Averill et al., 1997; Demoranville et al., 2005). However, since flooding requires a lot of water and also has the potential to lead to fungal rot, there has been a decrease in its usage for pest control with the increased popularity of insecticides (Cockfield and Mahr, 1992; Averill et al., 1997; Demoranville et al., 2005). Other than flooding, sanding has been shown to control *C. topiaria* and *C. parallela* without reducing cranberry yields (Davenport and Schiffhauer, 2000). Mowing, pruning, and burning of weeds are additional cultural control methods for some cranberry insect pests, like *C. parallela* (Stuart and Polavarapu, 1998) and *C. topiaria* (Roland, 1990). Still, flooding remains as the most effective cultural control practice that cranberry growers utilize against insect pests (Armstrong, 2016).

Conclusions and future perspectives

Figure 8 provides a summary of the advances in IPM strategies for cranberry insect pests. By looking at the research conducted over the past 30 years on cranberry insect IPM, there are some evident trends. Research on chemical control has consistently increased,

and research on host-plant resistance has gained increased attention in the past decade. This is likely due to the recent focus on testing the efficacy of new, reduced-risk insecticides and on breeding for high-yielding cultivars with no prior knowledge of their resistance to pests. Other control tactics, such as natural and biological, behavioral, and cultural control, have remained relatively stable across the decades, with the research focus ranked as follows: natural and biological control > behavioral control > cultural control (Figure 7B).

We expect future IPM research in cranberries to likely result in better monitoring techniques and thresholds for insect pests. As of now, there are economic thresholds for only a few key insect pests (Averill and Sylvia, 1998), and we lack thresholds for new emerging pests, such as *L. vaccinii*. Coordinating economic thresholds with degree-day models of insect growth can be an important next step in IPM, especially considering how insect populations may be affected by ongoing climate change. The discovery of new pheromones and other attractants is likely, and the subsequent development and employment of more efficacious traps and lures, either for monitoring or as a method of behavioral control. Furthermore, there is a need for more research on monitoring and conserving beneficial insects, such as the natural enemies of pests and pollinators (Blake et al., 2007).

As new high-yielding cranberry cultivars are developed, there will be an increased need to study their susceptibility to insect pests. For instance, cultivars with higher yields often have reduced resistance to pests (Rodriguez-Saona et al., 2011b), and will likely experience more pest pressure and require more insecticide applications. These newer high-yielding cultivars can be more susceptible to not only direct pests but also to vectors of diseases, such as *L. vaccinii*. Since the reduced insect resistance of the newer cultivars could result in increased pest pressure, we expect the future focus of breeding programs to shift to resistance against pests, as well as understanding the mechanisms of resistance in wild populations. An IPM tactic that has remained relatively unexplored is genetic control. With newer molecular technologies, it is possible to investigate the genetic modification of either the cranberry crop (to make it more protected against pests) or the insect pests, such as sterile male technologies. However, caution needs to be taken because of the risk of modified genes being transferred to wild cranberry populations in their native range.

More than two decades after the EPA FQPA, many broad-spectrum insecticides are still being banned or are limited in use. These broad-spectrum insecticides are being replaced by more selective, environmentally-friendly, and reduced-risk insecticides. However, the adoption of these reduced-risk insecticides can lead to a resurgence of old insect pests, such as has been the case for the blunt-nosed leafhopper, *L. vaccinii*, and the toad bug, *P. rubra*. As farmers adopted new reduced-risk insecticides against lepidoptera pests in the past two decades, such as IGRs, spinosyns, and diamides, populations of pests that are not affected by these insecticides, like *L. vaccinii*, have been on the rise (de Lange and Rodriguez-Saona, 2015a). This, in conjunction with a shift in cranberry breeding from insect resistance to fruit quality (Vorsa and Zalapa, 2020), has resulted in the increased incidence of false blossom disease in New Jersey, namely because the only effective

control of the disease is to target the vector (Rodriguez-Saona et al., 2021). This pest resurgence has been exacerbated by the recent banning of the organophosphate chlorpyrifos (Lorsban®) that was widely used to control *L. vaccinii*. Recently, however, two pyrethroids, a class of synthetic insecticides not previously available to farmers, were registered for use in cranberries, i.e., fenpropathrin (Danitol®) and bifenthrin (Fanfare®) (Figure 3), which are effective against the pest. As cranberry production continues to globalize, there is a rising threat of invasive insect pests, which will likely require adaptation of the existing pest management programs. Moreover, public concerns about pesticide use have in general increased the interest in organic farming; however, there are few effective tools currently available for organic pest control in cranberries (Armstrong, 2017; Rioux, 2018; Drolet et al., 2019). With the increase in organic cranberry production, we hope to see an increased registration of behavior-based strategies, such as mating disruption, that can provide an alternative tool for insect pest control.

As restrictions in insecticide use expand, research on nonchemical management tactics is expected to increase. Farmer adoption of these tactics could help conserve beneficial insects and thus improve biological control and pollination in cranberry agroecosystems (Rodriguez-Saona et al., 2011a). Moving forward, the role of non-crop habitats surrounding cranberry farms, i.e., landscape composition, as a potential source of insect pests and beneficial insects (natural enemies and pollinators) warrants more research.

In summary, this literature review provides a synthesis of cranberry insect IPM research over the past three decades, which aims at providing knowledge on recent trends and at existing knowledge gaps. With an increasing global production of cranberries and the threat of invasive pests, we expect changes in IPM tactics to be reflected in future research. Also, as more insecticides are being banned or their use restricted, we anticipate further research related to sustainable IPM tactics.

Author contributions

YB-Z wrote the manuscript. CR-S edited the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2023.1006106/full#supplementary-material>

SUPPLEMENTARY TABLE 1

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