Impact of Climate Change on a Key Agricultural Pest: Thrips

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ABSTRACT

The world population is expected to exceed 9 billion by 2050 and most of this growth will occur in developing countries. As population increases more arable lands will be used to construct cities and these activities increase CO_2 in the atmosphere and contribute to climate change. Climate assessments have shown rising sea levels and increase in the frequency of droughts in many dry areas. Prolonged droughts can decrease the relative amounts of water available for human consumption and agriculture. In developing countries agriculture contributes to more than 15% of GD and when crops and livestock are deprived of water they become more susceptible to pests and diseases. As climate change continues of occur there is a need to develop strategies to manage key invasive pests and disease species that threaten agricultural production. Thrips are major agricultural pests with the majority of species in tropical regions. They are cosmopolitan in nature and damage crops when they feed and lay eggs in many parts of the plant. Thrips are also vectors for spreading plant diseases. They dispersed quickly into new areas where susceptible hosts exist. This chapter focuses on a few important thrips species that threatens agricultural production in the Americas including Central and South America and the Caribbean. The chapter discusses the ecology and pest management strategies for key invasive thrips species and examines the potential effects of climate change on these troublesome species.

Keywords: *Thrips tabaci*, Thysanoptera, *Thrips palmi*, *Frankliniella occidentalis*, *Frankliniella bispinosa*, *Frankliniella schultzei*, *Scirtothrips dorsalis*, *Chaetanothrips orchidii*, *Thelytoky*, *Arrhenotoky*, Dispersal,

INTRODUCTION

World Perspective of thrips as an agricultural pest

The world as we know it is an ever changing place, world population is expected to exceed 9 billion by 2050, significantly reducing the space of arable land for agriculture and food production. The vast majority of population growth over the next 4 decades is likely to occur in developing countries putting considerable strain on the resources that support human development (food, water and energy). This will significantly increase the use of fossil fuels for energy and the consumption of inorganic products including pesticides, fertilizers and growth hormones for crops and livestock production. Unless special efforts are made to combat the effects of human activities on the environment, the potential for environmental contamination will increase; and there will be an increase in the levels of carbon dioxide (CO_2) in the environment, resulting in an overall increase in global temperatures. Changes in our climatic conditions increase the potential for invasive pests and disease problems, which can threaten long-term human existence and can impact all terrestrial and aquatic forms of life.

Thrips are a key agricultural pest that affects the vast majority of our agricultural crops. They are distributed worldwide with the majority of the species in tropical regions. Some temperate species exist and a few species are also found in colder arctic areas. Most thrips species are of no economic consequence to man and usually go unnoticed unless they become pests causing direct feeding damage to crops, spreading viruses to agricultural crops or being a nuisance to humans. The incidence and impact of thrips as pests are highly variable worldwide and differs between geographical locations and the agricultural commodities they affect (Lewis, 1997; Stannard, 1968). There are many pest thrips species that are economically important worldwide, but for the scope of this chapter, we will focus on a select few species that are currently causing problems or will potentially be problems in the Americas including the islands of the Caribbean. The purpose of this chapter is to outline the important role that pestiferous thrips play in agricultural systems, and to discuss the potential impact of thrips and their crop hosts in response to climate change.

BACKGROUND

Influence of Climate Change Factors on Thrips Population

Climate in this context refers to the conditions of the environment that include temperature, precipitation, humidity, air pressure, solar radiation, cloud and wind movements in a particular area over an extended period of time, usually a decade or more. Weather, on the other hand, describes these phenomena over the short term such as hours, weeks or months. Climatic and weather factors are known to influence the distribution and abundance of insects such as thrips; insects are also known to be influenced by microclimates (Davidson et al.1948a; 1948b; Tscharntke et al. 2002). The influence of climatic factors can be observed in the annual fluctuations in insect populations, which come from the inter-annual variability in weather and climatic related events (Porter et al. 1991). Therefore, anthropogenically induced changes in these climatic factors will also have a substantial effect on insects and insect pests.

Climate change as defined by the Intergovernmental Panel on Climate Change (IPCC) is a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/ or the variability of its properties, and that persists for an extended period, typically decades or longer (Lenny et al. 2007). Climate change is now unequivocally proven by and supported by hundreds of scientific studies. One goal of the IPCC is to objectively assess on a comprehensive, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change. The IPCC also assesses potential impacts and options for adaptation and mitigation of climate change (IPCC, 2013). As such, the IPCC has been a leader in analyzing, compiling and publishing climate change research.

Climate change assessments have shown that there is a likelihood of an increase in the frequency of meteorological and agricultural droughts (less rainfall) in currently dry regions and will potentially decrease surface water and ground water availability (Jimenez Cisneros et al.

2014). A decrease in soil moisture will negatively affect agricultural production including plant growth and reproduction and is likely to positively affect the distribution and establishment of key agricultural pests including thrips. Since the 1960s, there has been a steady decrease in global and regional evapotranspiration and pan evaporation. These reductions in evapotranspiration have been attributed to changes in precipitation, diurnal temperature range, aerosol concentration, net solar radiation, vapor pressure deficit and wind speed (Jimenez Cisneros et al. 2014). Surface water can also be affected by climate change as there has also been a consistent decrease in the stream flow (the flow of water through the channel of a river or stream) in low and mid-latitudes regions that are consistent with drying and warming in these regions (Dai, 2013). Professor Martin Parry in 1990 suggested that changes in precipitation will possibly have a greater impact on agriculture than temperature changes, especially in regions where the lack of rainfall may be a limiting factor for crop production (as cited by Porter et al. 1991, p. 223). Moreover, a reduction in precipitation coupled with temperature increases can lead to devastating effects on agriculture in many regions of the world. In the Caribbean, a lot of the agriculture is carried out on low-lying coastal lands and there is high potential for damage to these areas with a projected rise in sea levels of at least 0.2 m by 2081 (Wong et al. 2014) leading to a subsequent threats to agriculture and the economy of this region. A reduction in available ground water, soil moisture and evapotranspiration can reduce the quality of agricultural crops and thus make them more susceptible to thrips infestations.

Description of thrips

Thrips are insects that belong to the order Thysanoptera; they are slender and minute, ranging in length from 0.5 mm-15 mm and characteristically have fringed or feathery wings (Mound & Marullo, 1996). There are a number of important agricultural pests in the family Thripidae that are worldwide in nature (Mound & Marullo, 1996). Pest thrips damage crops when they feed and lay eggs in plant parts resulting in injury and by acting as vectors for plant diseases increasing the spread of these diseases.

Thrips have rasping-sucking mouthparts which they use to rasp plant parts to suck the contents. A few thrips feed on fungi, some are predacious and others feed on mosses and detritus (Lewis, 1997). They possess only one developed mandible on the left side; the mandible on the right side is re-absorbed during embryogenesis resulting in the characteristic asymmetric mouthparts. Members of the Thysanoptera usually have two pairs of wings with marginal fringes of cilia giving it a fringed appearance, however, some members are apterygous; either lacking wings as adults or losing them sometime during their adult life (Mound, 2005).

Thrips reproduce both sexually and asexually; asexual reproduction is by parthenogenesis. Parthenogenesis occurs when an egg or ovum is able to develop without fertilization. Arrhenotoky and thelytoky are the main parthenogenic reproductive strategies of thrips. Arrhenotoky refers to unfertilized eggs developing into male offsprings and thelytoky refers to unfertilized eggs developing into females. Thelytoky negates mate finding and allows thrips to expend all their energy into reproduction and feeding. Some thrips can manipulate their sex-ratio by assessing the food quality to determine progeny sex-ratio composition. Sexual dimorphism is common in many thrips species often with the male being smaller in size or lacking wings (Ananthakrishnan, 1990) as shown in Figure 1. Females possess a characteristic ovipositor seen extending from the posterior right of the abdomen and are larger than males.

Figure 1. Frankliniella bispinosa male (on left) and female (on right) displaying sexual dimorphism observed in thrips species. Credit: Tamika Garrick

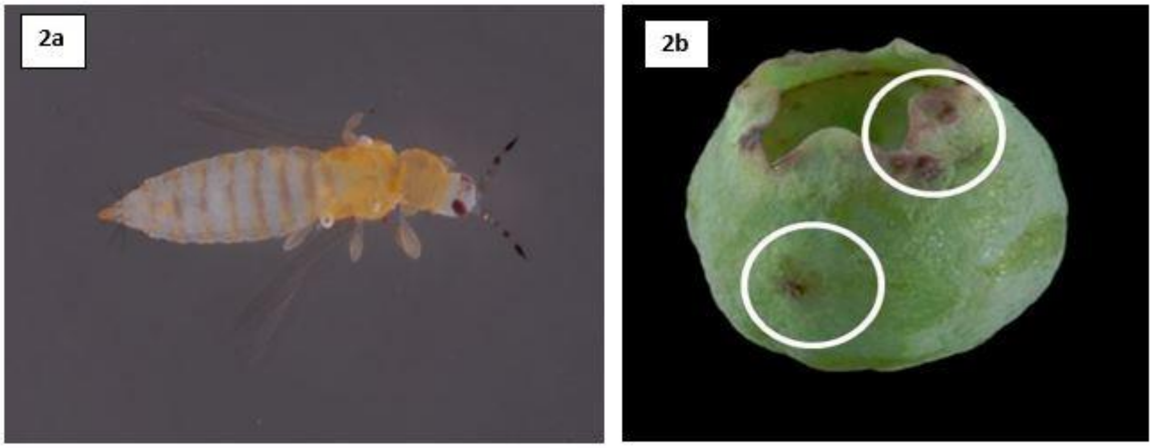
The insect order Thysanoptera is divided into two sub-orders: Terebrantia and Tubulifera. These sub-orders are usually easily distinguished by the tubular appearance of the posterior end in the Tubulifera (as its name suggests) with the analogous structure having a non-tubular shape in the Terebrantia. They can also be separated by the presence or absence of longitudinal veins or veinal setae on the forewings; the order Terebrantia possesses longitudinal veins or veinal setae while the Tubuliferans lack such structures on their forewings.

Thrips genus *Frankliniella*. There are many economically important pests in the genus *Frankliniella* including *Frankliniella schultzei*, *F. occidentalis* and *F. bispinosa*. Typically, *Frankliniella schultzei* (Trybom), the common blossom thrips, is a polyphagous species which is widespread in its distribution and host plants affecting over 500 plants in over 50 plant families (Mau & Kessing, 1993). In 1999, a census of the scientific literature conducted by the Centre for Agriculture and Biosciences International (CABI) revealed that *F. schultzei* was present worldwide in 71 countries with representative countries from all continents except Antarctica. Its range included Caribbean countries such as Barbados, British Virgin Islands, Cuba, Dominican Republic, Haiti, Jamaica and Puerto Rico (CABI 1999a). *Frankliniella schultzei* was reported to be the dominant species (98%) collected from commercially grown watermelons in the semi-arid region of Brazil in 2011 (Costa et al. 2015); on mangoes in India (Krishnamoorthy, 2012) and on vegetable crops such as cucumber, pepper, snap beans, squash in south Florida (Kakkar et al. 2012), and was found infesting strawberries in central Florida (unpublished data). *Frankliniella schultzei* is capable of transmitting: Tomato chlorotic spot virus (TCSV), Groundnut ringspot virus (GRSV), Chrysanthemum stem necrosis virus (CSNV) and Tomato spotted wilt virus (TSWV) (Nagata et al. 2004; Amin et al. 1981; Tamito, 2004).

Frankliniella occidentalis (Pergande), the western flower thrips, is among the world's most important insect pests due to its widespread occurrence and its efficient ability to spread tomato spotted wilt virus (TSWV). *Frankliniella occidentalis* is native to western North America including the countries of U.S.A, Canada and Mexico. Its extensive spread worldwide can be attributed primarily to the movement of agricultural products such as cuttings, seeds, and whole plants. It was commonly referred to as a greenhouse pest but has since become established outdoors especially in areas with milder winters. It is now established across the entire U.S.A., Australia, New Zealand, southern Europe, southeast Africa, South and Central America and parts of the Caribbean (Kirk & Terry 2003; CABI 1999b). The western flower thrips is known to reduce the aesthetics of ornamentals and vegetable crops even if they are marketable, leading to yield losses and reduced profits to farmers.

There are many other economically important thrips pest species in the genus *Frankliniella*; in Florida, the Florida flower thrips, *Frankliniella bispinosa* (Morgan) is common and can be found year round on a wide range of cultivated and uncultivated plants (Reitz, 2002) Figure 2a shows an adult female, a common species in Florida. This species predominates in the peninsular region of Florida and is a known economic pest of blueberries and citrus where it injures floral parts leading to damage of the resulting fruits as seen in damage to blueberry in Figure 2b showing that the aesthetics of the fruit is affected leading to economic damage. (Rhodes & Liburd, 2011; Childers & Bullock, 1999; Childers, 1991; Arévalo-Rodriquez, 2006). *Frankliniella bispinosa* is also found in Bermuda and the Bahamas Islands (Nakahara, 1992).

Figure 2.
2a: Adult female *Frankliniella bispinosa* (Florida flower thrips)
2b: Injury on blueberry in the green stage caused by *F. bispinosa* Credits: Oscar Liburd



Thrips palmi (Karny), most commonly referred to as the melon thrips, is also known as the oriental, palm or southern yellow thrips. It was originally described in Southeast Asia where it was first reported as a pest. In 1982-83, it was reported as a pest of cucurbits, eggplants, peppers and amaranth spinach in the western hemisphere in Hawaii (Sakimura et al. 1986). This species has spread and is now present in the mainland US, 10 countries in Africa (Algeria, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Mauritius, Nigeria, Reunion, Sudan and Togo) and in South and Central American countries. In the Caribbean, it has also been reported in Antigua and Barbuda, Barbados, Cuba, Dominica, Dominican Republic, French Guiana, St. Lucia, St. Kitts and Nevis, Netherland Antilles, Grenada, Guadeloupe, Haiti, Puerto Rico, Martinique, Trinidad and Tobago, Jamaica and St Vincent and The Grenadines. It is highly likely to be present in other countries as it continues to spread (EPPO Global Database, 2015b). *Thrips palmi* is known to attack plant parts such as flowers, buds, leaves and occasionally young fruits and silk (in baby corn). Leaves often exhibit bronzing or silvery patches which become more extensive and turns brown, eventually dying (Bernardo, 1991). Hence, *Thrips palmi* can be extremely damaging to vegetables in which the leaves are marketed.

The polyphagous onion thrips, *Thrips tabaci* Lindeman, is also known as the common cotton thrips, cotton seedling thrips or the potato thrips in other parts of the world (EPPO, 2015c). It is known to be widespread worldwide and is more damaging in temperate latitudes than in tropical regions and is rare in the wet tropics (Mound & Marullo, 1996). It is abundant on onions in Brazil and has been collected from Guatemala and Costa Rica (Mound & Marullo 1996). In the United States, *T. tabaci* can be a serious problem in onion producing regions. It also vectors Iris yellow spot virus (Kritzman et al. 2001).

Another polyphagous thrips species, *Scirtothrips dorsalis* (Hood), most commonly called the chilli thrips (Figure 3), is thought to originate from Southeast Asia or the Indian subcontinent. It is a new invasive species that has been moving throughout the Americas and Africa. It can now be found in the United States of America (Hawaii, Florida and Texas), Caribbean (Barbados, Guadeloupe, Jamaica, Puerto Rico, St. Lucia, St. Vincent and the Grenadines, Suriname and Trinidad and Tobago) and 4 African countries (Kenya, Cote d'Ivoire, South Africa and Uganda). It has also been reported in Oceana and is widespread in Asia. Chilli thrips are known to affect vegetable crops such as peppers, cucurbits and eggplants; as well as ornamental plants such as roses, causing serious damage and losses in yield (Kumar et al. 2014; EPPO, 2015a). In a 2004 risk assessment by Venette and Davis, (2004) it was determined that 28% of continental US extending from Florida up to the Canadian border had a suitable climate for the potential establishment of *S. dorsalis* and as many as 4-10 generations could be produced on the west coast of the U.S in places such as California, Nevada and Arizona (Brett et al. 2008) in a single growing season. Venette and Davis (2004) also determined that islands in the Caribbean such as Anguilla, Antigua and Barbuda, The Virgin Islands, St Kitts and Nevis, Montserrat, Dominica, Martinique and Grenada are at risk for the establishment of the chilli thrips due to the suitability of the climate.

Figure 3: Adult Chilli thrips (Scirtothrips dorsalis) a new invasive species in Florida that severely affects the ornamental industry. Credit: Lance Osborne

Chaetanaphothrips orchidii Moulton, commonly referred to as the red rust thrips or the orchid thrips is widespread in its distribution and can be found in the Oriental region, South America, Central America, the Caribbean, glasshouses in temperate latitudes such as Europe and parts of the United States including Florida, Hawaii, California, Washington DC, New York, Illinois, Louisiana and Kentucky (Mound and Marullo, 1996; Hara et al. 2002). In 1996, it was reported to be in Neotropical countries including Honduras, Costa Rica, Panama, Brazil, Dominica, Grenada, Guadeloupe and Trinidad, and may have since spread to other countries in the region (Mound & Marullo, 1996). In the Caribbean, it is found associated with banana growing in gardens and on the roadside. It is however, not considered a pest of banana because it is usually controlled by the practice of sleeving of bunches. It can become a serious pest in anthuriums, palms, *Begonia* spp., *Amaranthus* spp., *Commelina* spp., *Passiflora* spp., *Bougainvillea* sp., parsley, sweet potato, grass, *Cyclamen* spp., banana and citrus growing regions and can lead to economic losses (Childers and Stansley, 2005; Mound & Marullo, 1996; Hara et al. 2002; Jacot-Guillarmod 1974 [as cited by Gill et al. 1984]). This species has the potential to become important in the islands of the Caribbean and regions of Latin America.

EFFECT OF CLIMATE CHANGE ON THRIPS

Climate change factors can lead to both direct and indirect effects on key agricultural thrips species. Direct effects include the rate of thrips development, reproduction, distribution, migration/ dispersal and adaptation to the new environment. Alternatively, indirect effects include host plant interactions, natural enemies and insect relations (Porter, 1991).

Impact on dispersal and distribution

Movement and distribution of thrips species are influenced by their size and wing structure. A few thrips species lack wings (apterous), some have short/reduced wings (brachyapterous), while the majority have relatively long wings almost reaching the full length of their abdomen (macropterous). The wings are membranous and slender with long fringes of cilia which are straight or wavy, arising from wing edges or beneath the wings; short microtrichia or setae may also be present. Thrips are able to rearrange the conformation of the cilia to increase surface area before or during flight. The ability of thrips species to resist desiccation influences the length of time they can remain airborne and the distances to which they can be dispersed. Thrips are unable to feed and maintain body water concentration while flying in drier air environments (Lewis, 1997).

A key factor contributing to the importance of thrips as pests, is their ability to be dispersed by both natural and artificial means. Natural dispersal occurs both actively and passively; and such movements can be over short or long distances. Active and passive dispersal are not mutually exclusive, as thrips will oftentimes use them simultaneously to move around for short or long range travel. This phenomenon was reported very early by Carter in 1939, in which he observed a mass movement of thrips with many species flying freely and dispersing in great numbers in wind currents (Carter, 1939). Active dispersal involves the thrips using its wings with cilia as flying apparatus to propel its body through the air. Passive dispersal occurs when thrips are carried on air currents without the active involvement of their wings. Artificial dispersal usually involves the unintended movement of thrips such as via plant cuttings, flowers, fruits, soil and shipping containers in the international trade.

Thrips will disperse in response to declining food quality and quantity in search of new hosts. This was observed with *Thrips tabaci*, which is not normally migratory but, in response to a drastic interruption of its host plants, was forced into mass migration (Carter, 1939). So, as droughts become more widespread due to the effects of climate change, it is expected that mass migration of thrips populations may become more common.

Dispersal of thrips can be influenced by gender, as male thrips typically do not move as extensively as their female counterparts. Ananthakrishnan et al. (1981) observed that male *Chirothrips mexicanus* Crawford, did not disperse well but moved primarily within the grass inflorescences from which they emerged and mated with several females during their life span.

Females exhibited two modes of dispersal. The first involved mated alates emerging from eggs laid in floral parts of the plant and flying to new flowers where they feed on and oviposit in fresh ovaries. The second involved female pupae that develop from eggs deposited in old or senescing flowers; these females were mated as pupae by early emerging males, but failed to emerge as females before the flowers die and fall off. These females will be carried away inside the dried flowers by wind currents, and will emerge as adults in a new place (Ananthakrishnan, 1981).

Weather events can also facilitate thrips dispersal. Strong winds or wind currents derived from hurricanes or a storm can hasten dispersal by moving thrips infested plant materials far from the source of infestation. In addition, as previously discussed, thrips can take advantage of these wind currents by using their cilia and body orientation to glide long distances. This was speculated to have occurred in Trinidad in 1988, when *Thrips palmi* was moved by the winds of a tropical depression from nearby islands in the Caribbean and later became a pest in Trinidad (Cooper, 1990). As the frequency of hurricanes is expected to increase due to climate change factors, it is expected that distribution of thrips by natural disasters will increase.

Artificial dispersal is a key factor contributing to the spread of pests, and formerly unimportant thrips species to novel places, resulting in them being often found far from their original habitat and location, and even appearing in different climatic zones (Vierbergen, 1995). This is enhanced by increases in movement of goods and commodities by air, sea and land transportation. Between the years 1994-1999, *Thrips tabaci* was the most frequently intercepted species at U.S. ports, accounting for approximately 20% of all thrips interceptions (Nickle, 2008; 2009). The negative effects of climate change can cause extended dry seasons, droughts, floods, and devastating storms that will reduce the potential for some regions to adequately cultivate food crops to meet the needs of their people. As a result of this effect, increases in the movement of goods and commodities to such regions will increase the potential to spread pestiferous thrips species to new regions leading to the wider distribution of thrips species and new outbreaks with devastating consequences.
Climate change factors, primarily changes in temperature, can influence dispersal in thrips species. Insects are poikilotherms, in that their physiology is highly influenced by temperature. Insect flight has been shown to be influenced by increases in temperature with the flight muscles becoming more efficient and moving more rapidly (Machin et al. 1962). Coupled with the fact that temperature directly influences metabolic rates, insects will, therefore, be able to fly faster and further at higher temperatures which can influence their dispersal (capabilities and the extent to which they will be distributed) within a region.

Impacts on reproduction

Changes in temperature are predicted to exert the greatest influence on thrips' reproduction. However, other environmental factors such as humidity can influence the life parameters of thrips. Egg output (Fig. 4) and the time taken for larvae of *Frankliniella bispinosa* and *F. occidentalis* to emerge has been shown to be influenced by humidity (Garrick et al. in review). The number of progeny produced and the emergence period of a given thrips species can have a direct effect on thrips pest populations. Humidity changes can lead to an increase in the number of eggs laid by a species and larvae may emerge earlier than usual, generational time will be reduced and pest numbers can be increased.

Figure 4. The mean number of larvae hatched for F. bispinosa (Florida flower thrips [FFT]) and F. occidentalis (Western flower thrips [WFT]) females at a constant temperature of 25 ºC. Source (Garrick et al. in review)

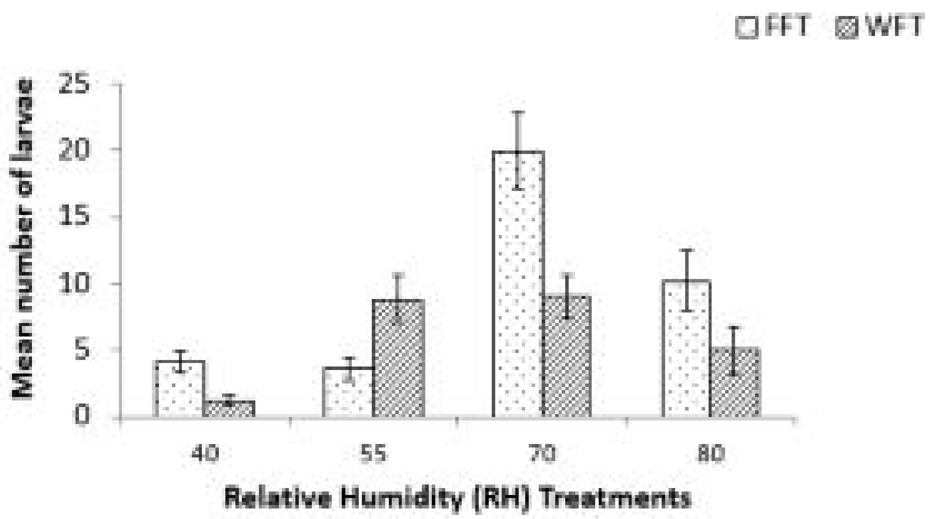


Figure 4 is a graphical representation of the effect of four relative humidity conditions of 40%, 55%, 70% and 80% on hatching of larvae of 2 *Frankliniella spp.* Error bars represent the standard error of the means (extracted from Garrick et al. *in Press*).

The response of insects to temperature changes are generally adaptive and specific and varies between species for different rate parameters. This is influenced by climatic adaptations inherent to that insect whether the temperature effects are long or short term (Rhainds et al. 2007). Rhainds et al. cited a compiled dataset from Robb 1989; van Rijn et al. 1995; Katayama 1997 and Gelinas 2000 which showed that the intrinsic rate of increase by the western flower thrips showed a negligible rate at 15°C to about 0.28 at 33°C but was close to zero at 35°C. However, thrips are known to be highly adaptable and exhibit a high degree of resistance to change. They can also adapt to host individuals over time with increased reproduction on plants from their native environment than on other genetically different plants or even on clones of their native plants (Karban 1989).

The mechanisms of reproduction employed by pest thrips are strategically adapted to their plant feeding habit. Ananthakrishnan et al. (1981) observed that male *Chirothrips mexicanus* Crawford mated with several females during their life span thus increasing the potential for sexually reproduced offspring in the population resulting in genetic diversity. This diversity is important to survival when the thrips population is subjected to population pressure.

It has been shown that the peak of male emergence in *Chirothrips mexicanus* is in the first few days of adult emergence after which, emergence declines rapidly. The females emerge over a longer period of time and survive longer than males (Ananthakrishnan, 1981). This influences the mode of reproduction employed by the species. Many thrips species can sexually reproduce which increases genetic variation within the progeny and enables the population to be more adaptive to environmental changes. Asexually reproducing thrips species are able to quickly increase population numbers and can thus bring about damaging effects to crops over very short time periods. Climate change effects that promote thrips' reproduction such as temperature increases and suitable humidity conditions will enable thrips to have a more devastating effect on cultivated crops.

Abundance

Thrips occurrence in an area usually appears in waves or cycles with a distinct peak in numbers and troughs where numbers are low or even imperceptible. There may be large and abrupt daily fluctuations in thrips populations as they move among host plants which may be related to the gregarious nature of thrips (Davidson and Andrewartha,. 1948a). In published work from a 14-year study that was conducted on *Thrips imaginis* Bagnall (apple blossom thrips) at the Waite Research Institute in Australia, it was concluded that *Thrip imaginis* exhibited a logistic rate of growth but this occurred at different rates over the course of the year (Davidson and Andrewartha 1948a; 1948b). Thus, thrips appear to be able to rapidly increase in numbers over a short period of time. They also concluded that among the environmental factors studied, temperature had the strongest influence on the population dynamics and abundance of this thrips species. These results have been observed with other thrips species worldwide.

A generalized Forrester diagram of thrips development is shown in Figure 5. Figure 5 shows the important role of temperature and the influence it has on the different processes associated with the thrips life cycle. Table 1 describes the processes outlined in Figure 5. Temperature is shown to exert an influence on developmental and mortality rates associated with each life stage of the insect's life. The influence of temperature on the crop or host plant is not shown in the Forrester diagram presented but is a known phenomenon and also has an impact on thrips abundance. Crop phenology also influences thrips abundance. Flower thrips are predominant in blueberries during the flowering season that lasts for approximately 3 weeks, after which thrips population numbers drastically fall when flowers senesce.

Because the development of thrips is highly influenced by environmental factors including temperature, monitoring degree-days or daily average temperatures has been helpful in predicting their abundance. In New Jersey, where the eastern flower thrips (*F. tritici* Fitch) is common, a degree day model to predict their abundance is used. It uses a base temperature of 10° C when 10%, 50% and 90% of thrips captures had been observed at 380, 650 and 1200 degree-day accumulation, respectively (Pavlis, 2010). This showed that thrips populations usually coincide with temperature increases or heat accumulation.

Temperature changes are expected to have their greatest effect on mid-high latitude regions (Lenny et al. 2007) thus expanding the natural geographic range over which many thrips species occur. Thus, temperature increases associated with climate change will: extend growing seasons, extend the availability of hosts, and serve to facilitate an increase in pest numbers. It has also been suggested based on global climate models that the greatest temperature changes in the future will be in the winter.

Figure 5. Relational diagram showing the major components and processes in the typical thrips life cycle, highlighting the great influence temperature has on all the processes involved.

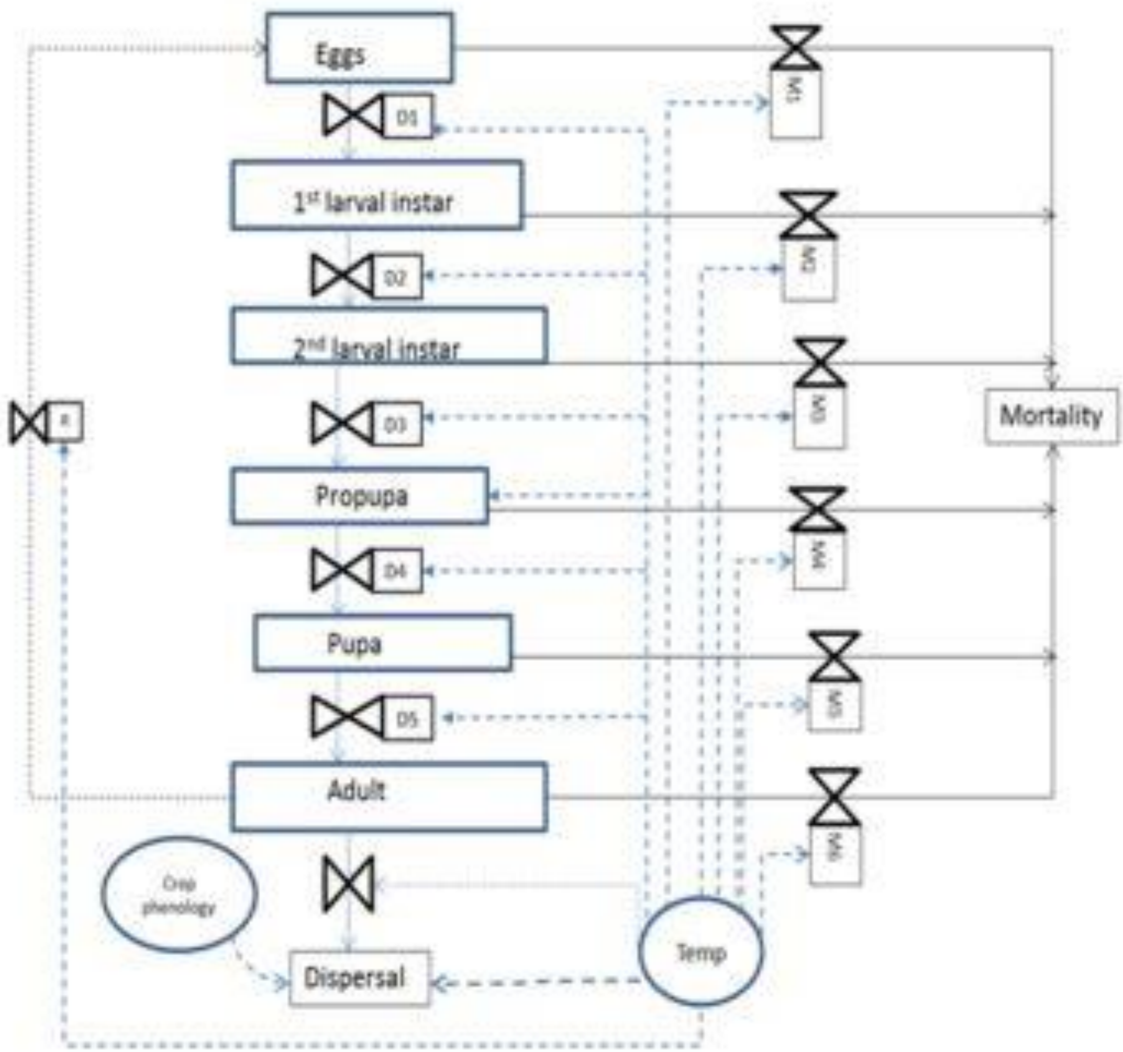


Table 1. Description of variables, processes and dimensions as outlined in the thrips Forrester (Relational) diagram in Figure 5.

Description of Forrester diagram

Variables	Description and dimensions
State variables	
Eggs	Proportion of eggs in the population at time t
1st instar	Proportion of 1st larval instar in the population at time t
2nd instar	Proportion of 2nd larval instar in the population at time t

Propupa	Proportion of propupa in the population at time t
Pupa	Proportion of pupa in the population at time t
Adult	Proportion of adults in the population at time t
Rate variables	
D1	Rate of development egg from time laid to hatched (per unit t)
D2	Development rate of 1st larval instar to molt into 2nd instar (per unit t)
D3	Development rate 2nd larval instar to molt to propupa (per unit t)
D4	Developmental rate of pupa into adult (per unit t)
M1	Mortality rate of eggs (per unit insect)
M2	Mortality rate of 1st larval instar (per unit insect)
M3	Mortality rate of 2nd larval instar (per unit insect)
M4	Mortality rate of propupa (per unit insect)
M5	Mortality rate of pupa (per unit insect)
M6	Mortality rate of Adult (per unit insect)
R	Rate of reproduction or replacement of progeny from adult population (per unit insect)
Dispersal rate	The rate at which thrips migrate from flower buds
Auxiliary variables	
Crop phenology	Crop stage influences abundance; no/low numbers of flowers influences migration
Thrips density	Carrying capacity influences rate of dispersal

Host range

Polyphagy in thrips is important in defining its host range and the number of plants on which they can feed, reproduce and survive. Oftentimes, pest thrips introduced into a new region on a single plant species, become established on native flora and later extend their host range by affecting new plant species in that area. Evidence of this can be seen with the Nearctic species, *Echinothrips americanus that* was introduced to Europe on *Syngonium* cuttings; within 4 years it had spread to other members of the family Araceae and 9 other plant families affecting 14 genera (Vierbergen, 1995; 1998).

A meta-analysis of terrestrial organisms conducted by Chen et al. (2011) showed that the distributions of organisms including insects have been shifting to higher elevations at an average rate of 11 meters per decade and at 16.9 kilometers per decade for higher latitudes. They also found that the highest increases in warming were associated with the greatest distance moved by species (Chen et al. 2011). Extended host range due to extended geographic distribution will allow thrips to utilize a wider range of plant hosts moving them into new regions where they were not able to survive previously. This also reduces the spatial distance between crops and pests.

The future climatic environment as influenced by climate change factors with an increase in CO_2 concentrations is projected to favor the proliferation of C3 weed species; C4 weeds could also benefit but with a slower response. However, studies have shown that a simultaneous increase in both CO_2 and temperature could favor C4 weeds (Porter et al. 2014). This could increase host availability for thrips as they are known to emigrate from earlier flowering crops and wild hosts including weeds, to a crop (Chellemi et al. 1994; Rhodes et al. 2011).

INTEGRATED PEST MANAGEMENT OF THRIPS

Climate change is likely to increase the distribution, reproduction and abundance of pest thrips. They have traditionally been managed primarily with chemical pesticides and an increase in their numbers as a result of climate change is likely to increase the rates and frequency of chemical applications. More frequent pesticide applications coupled with a shorter generation time increases the selection pressure for resistant thrips population to develop. Moreover, pesticides destroy beneficial insects, contaminate the environment and pollute groundwater sources, which pose risks to humans. Therefore, it is essential that an effective and highly developed Integrated Pest Management (IPM) program be implemented to effectively manage increasing pest thrips population that may be as a direct result of climate change factors.

Integrated Pest Management Strategies for Thrips

Integrated Pest Management (IPM) is an effective and environmentally sensitive approach to pest management that relies on a combination of strategies. IPM programs use current, comprehensive information on the life cycles of pests and their interaction with the environment. This information, in combination with available pest control methods, is used to manage pest populations by the most economical means, and with the least possible hazard to people, property, and the environment. IPM ranges from chemically-based systems that involve judicious use of reduced-risk pesticides, to biologically-intensive tactics that manage pests primarily through nonchemical means (EPA, 2015). IPM takes advantage of all appropriate pest management options and a good IPM program incorporates one or more of the 5 IPM strategies. These include monitoring, cultural control, biological control, establishing thresholds, and the use of reduced-risk pesticides, working synergistically to effectively manage a pest within its target crop. Some of the strategies that have so far been used by growers to control thrips are now presented.

Monitoring

The most important strategy of an IPM program is to monitor pest populations. Some common ways of monitoring thrips population is: i) the deploying sticky traps, ii) collecting parts of the plant tissues (flowers, leaves and stems) and placing into a container with alcohol and iii) floral / leaf tapping. Depending on plant species, white, blue or yellow sticky traps are typically deployed for monitoring thrips populations. White and blue traps are used in many fruit crops because thrips can be better seen on them, while yellow traps attract beneficial insects as well as thrips. Sticky cards can be left for any duration ranging from 2 days to one week depending on the thrips pressure,- the higher the pressure the more frequently traps are changed. The traps are then collected from the fields and thrips are counted directly on the traps. A few thrips are removed from the traps and slide mounted for further identification. In some instances, the count of the traps does not reflect the true value of thrips population in the field.

Collecting plant material usually provides a more accurate assessment of thrips population than the use of sticky traps. Typically, flowers are removed for flower thrips (*Franklinella* spp.) and leaves/stems are collected for other thrips species (*Scirtothrips* spp.). The plant material is usually collected and placed into a container with alcohol. The container is then brought back to a laboratory or an area for processing to determine thrips population. The shake and rinse technique developed by Liburd and Arevalo (2010) provides an effective way to assess the number of thrips collected on plant tissues.

Floral and leaf tapping are accomplished by placing a white paper or container below the flowers or leaves and tapping them lightly so that thrips are dislodged from the plant tissues unto the white background. This method of monitoring for thrips is convenient and provides a quick assessment to determine whether thrips are present or absent. The big disadvantage with this method of sampling is that it is not very reliable and does not provide a very accurate assessment of thrips population in the field.

Cultural management of thrips

The use of reflective mulches has been used successfully to reduce thrips numbers early in the season in vegetable crops. Reitz et al. (2003) were able to use UV reflective mulch to reduce the population of thrips early in the season in field-grown peppers. Furthermore, infection of pepper plants with tomato spotted wilt virus, a pathogen vectored by western flower thrips, was less in UV reflective mulch compared to the grower standard, black plastic mulch. Other cultural techniques involve removal of secondary hosts that support reproduction and development of thrips from production fields. Rhodes and Liburd (2011) recorded several reproductive hosts of *F. bispinosa*, including; Carolina geranium (*Geranium carolinianum* L.), white clover (*Trifolium repens* L.), and wild radish (*Raphanus raphanistum* L.). These plants grow adjacent to blueberry plantings and can influence the abundance of thrips in blueberry fields during the production season.

Biological Control

Some success has been accomplished with the use of the predatory mite *Amblyseius swirskii* (Athias-Henriot) to control the western flower thrips in greenhouse cucumbers (Messelink et al. 2007). *Amblyseius swirskii* was also a more effective predator against the invasive chilli thrips, *Scirtothrips dorsalis* compared with *Neoseiulus cucumeris* on pepper plants (Arthurs et al. 2009). Another biological control agent that has worked well in regulating thrips population is *Orius insidiosus* (Say). This predator was shown to suppress populations of three primary flower thrips (*F. occidentalis*, *F. tritici* and *F. bispinosa*) in pepper flowers (Funderburk et al. 2000).

Application of reduced-risk pesticides

Thrips infestations have historically been addressed with application of chemical insecticides. However, due to the increases in pesticide resistance of thrips to many pesticides the IRAC chemical classes, a new range of pesticides is now being used as part of an overall IPM program for thrips management. It is not uncommon for thrips species to become resistant to pesticides due to their life history strategy. Thrips as well as other agricultural pests are rapid colonizers and have short life spans. Arthropods with rapid generation times have the greatest potential to become resistant to pesticides (Mound et al. 1995) and this has been documented in thrips in numerous instances.

The reduced-risk pesticide, SpinTor® (group 5 insecticide; (active ingredient Spinosad) has been used since the mid-1990s to control key agricultural pests including thrips that feed on fruits and vegetables. This insecticide is the fermentation product of the bacterium *Saccharopolyspora spinosa*, a naturally occurring soil organism. SpinTor® is the formulation that was traditionally used in the US for the management of thrips in vegetables and fruit crops but other formulations such as Precise® and Conserve® have been recommended for thrips management in turf and ornamentals. Spinosad is very safe on beneficial insects, including *Orius* spp., a naturally occurring predator that regulates thrips population.

Approximately 10 years after the introduction SpinTor®, Dow AgroSciences introduced a new active ingredient Spinetoram that had better insecticidal properties and longer residual activity than SpinTor®. Spinetoram affects nicotinic acetylecholine receptors and γ-aminobutyric acid (GABA) receptors existing on postsynaptic membranes in insect nervous systems causing constant tremors (Shimokawatoko et al. 2012). The formulation used to manage thrips in vegetables is Radiant® whereas Delegate® is used in fruit production. Spinetoram like spinosad is derived from *Saccharopolyspora spinosa* and is a fermentation product. Spinetoram is more photostable (resistant to degradation by sunlight). In flowering crops, is best to spray spinetoram in the morning or late in the evening because it has a minimal effect on bees when dried; bees are less active during these times of the day and so it would not affect them adversely (England et al. 2007).

Spinetoram has essentially replaced the traditional SpinTor® and is used extensively for thrips management. It is also an excellent tool that can be integrated with other insecticides for resistance management. When scouting (monitoring) data indicates that thrips population has reached the established economic threshold (the level at which insect population must not exceed to prevent economic losses beyond the cost of control) pesticide application is initiated. To delay insecticide resistance in thrips population, it is advised that the applicator follows the label rate and avoid using the same active ingredient or insecticide with the same mode of action on successive generations even though multiple sprays on the same generation is allowed. The timing of the sprays is important and is most effective when targeted at the early developmental stages (larvae) of thrips. Using more or less than the recommended label rate can be just as harmful. Monitoring of the thrips population has to be carried out within the field to determine the effectiveness of the spray. If the thrips population is high, it is recommended that the spray is re-applied every 7-10 days because SpinTor does not exhibit long residual effects. SpinTor is not highly toxic and is best applied in the afternoon when bees are less active (Liburd, 2005).

SOLUTIONS AND RECOMMENDATIONS

The agricultural sector is faced with a complex situation as it relates to thrips as outlined previously in this chapter. As such, the measures required to control or curtail spread and in some cases eliminate pest thrips must be multifaceted and based on sound scientific research. Due to the small size of thrips, they often easily escape detection at quarantine facilities worldwide. Further complicating this is the arduous task of differentiating larval forms of pest thrips species from innocuous species. It is imperative that artificial means of dispersal be reduced in order to limit the spread of pest species. There is a great need for thoroughly trained Thysanopterists in addition to the development of reliable molecular identification tools in order to realize this goal.

Chemical control has become the most commonly used tactic when pest thrips species are encountered; however, this approach must be used discriminately and assessed on a case by case basis. The goal is to move towards more IPM tactics and in instances in which chemical control is necessary, to use reduced-risk pesticides which have less of an impact on the environment. IPM programs need to be developed on a systems basis which incorporates compatible or synergistic tools which require minimal chemical applications and are effective.

FUTURE RESEARCH DIRECTIONS

Numerous tools that have been investigated to manage thrips populations have failed due to the often cryptic nature, small size, and high reproductive potential of the species. The direction in which thrips research needs to be developed must include the use of technology. For instance, incorporating Geographic information system (GIS) as a tool in thrips research will serve to enhance spatial knowledge of thrips, which will aid in management operations, as research in this area is lacking. GIS could be used to understand thrips movement and dispersal and this information could be incorporated into its management programs. The spheres of modeling and forecasting may prove to be effective tools in the future to enhance management programs in the prediction and mitigation of economic thrips species and may become important in preventing establishment in some areas.

CONCLUSION

Climate change can cause a transformation in meteorological events that could increase CO_2 concentrations and global temperatures. The development of thrips is highly influenced by environmental factors including temperature. As temperature rises and becomes more conducive for thrips growth and development, the natural geographic range of many pest thrips species can potentially expand. As thrips population increases, traditional control programs that are focused primarily on conventional sprays will need to evolve into more integrated management plans. Management programs will have to be developed to mitigate the spread of pest thrips and the vector-borne diseases they transmit. Any comprehensive management program must involve the cooperation of state and local government agencies (plant quarantine units and extension services), private industry (pest control companies) and the general public to effectively tackle this problem. The use of technology and the role that beneficial insects play in regulating thrips population are important factors need to be fully understood. Wild hosts often serve as alternative hosts to thrips populations and act as sources of inoculum for many agricultural crops. Therefore, it will also be important to investigate the roles these hosts play in influencing thrips population in agricultural fields.

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DEFINITIONS

Alates: Insects having wings or wing-like appendages to aid in flight.

Arrhenotoky: Reproduction where unfertilized eggs develop into male offsprings and fertilized eggs into female offsprings.

Climate: The description of the atmospheric conditions such as temperature, precipitation, humidity, air pressure, solar radiation, cloud and wind movements in a geographic region over an extended period of time usually a decade or more.

Parthenogenesis: Occurs when an egg or ovum is able to develop without fertilization.

Population pressure: The sum of the forces exerted on the environment or the population itself as a result of increases in the population. Population pressure affects survival and often leads to dispersal or population decline.

Sexual dimorphism: Sexes of the same species exhibit differences in morphology or size.

Terebrantia: One of two sub-orders of the order Thysanoptera with their posterior end (10^{th} abdominal segment) split ventrally and rarely tube-like.

Thelotoky: Reproduction which results in unfertilized eggs developing into females.

Tubulifera: One of two sub-orders of the order Thysanoptera characterized by individuals possessing tubular posterior end (10^{th} abdominal segment).