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Impact of Temperature and Rainfall Change on Epidemics caused by Plant viruses

Bayissa Regassa
Ethiopia Institute of Agricultural Research, Ambo Agricultural Research Center,
P. O. Box 37, Ambo, Ethiopia

Abstract

Plant virus diseases are one of the limiting factors to crop productivity by diminishing the quantity, quality and responsible for significant economic losses worldwide. The Epidemic of plant virus diseases is the result of interactions between virus, host plant, vector, and environmental factors. Changes in host plants and insect vector dynamics that result from temperature and rainfall change could have an influence on the spread of plant viruses. The rising of temperature and heat stress increase the susceptibility of host plants to virus infection and accelerates the fitness of viruses to cause disease. The increasing temperature also changes insect vector population dynamics by accelerating insect phenology, causing earlier and prolonged colonization because it makes appropriate environmental conditions for the insect vectors. Insect populations of most virus vectors build up more rapidly in areas with high temperatures and high relative humidity and decline at low temperature. In addition, the rising temperatures can increase the efficiency of virus transmission from infected to healthy plants by insect vectors. An increasing frequency of heavy rainfall events is likely to slow the virus prevalence and incidence by washing insect vectors, thus reducing vector density. Flooding within annual crop growing period enhances the subsequent growth of weed and volunteer crop plant which act as reservoirs of insect vectors and the viruses, and its occurrence outside growing seasons increases subsequent growth of such reservoirs.

Keywords: Host plant; Vectors; Virus epidemics
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1. Introduction

Plant virus diseases are among the major affecting agriculture productions worldwide and have estimated economic losses of greater than $30 billion per year (Sastry and Zitter, 2014). The challenge that the increasing rapidity of global warming and climate instability cause to mankind's ability to manage pests and diseases of cultivated plants. Since the start of the industrial period in 1750, the global average concentration of carbon dioxide (CO_2) in the atmosphere has increased by 41%, methane by 160%, and nitrous oxide by 20% (Jones, 2016). Climate change which composed of increased atmospheric CO_2, temperature and rainfall/water availability has important consequences on crop growth and quality as well as the interactions among plants, pests and diseases. Plant viruses are an important part of these interactions as they can have a devastating effect on food quality and yields. The major climatic drivers for changing the environmental fate and behaviour of plant protection products are rainfall seasonality and intensity, and increased temperatures (Bloomfield *et al*., 2006).

Viruses have diverse temperature optima that are a number of being adapted to warmer environmental areas and the others to a cooler temperature for multiplication within the host plants. These optimum temperatures are highest in plant viruses adapted to infect plant hosts growing in lowland tropical environmental conditions and lowest in viruses adapted to cold environmental areas, for example, those in cool temperate areas or at high altitude in mountainous regions. Different species of virus vectors and host plants also have varied temperature optima under which they flourish, some being adapted to warmer climates and others to cooler ones (Jones, 2016). These induced changes all affect the way viruses and vectors interact with their plant hosts and influence the spatial and temporal dynamics of virus epidemics.

2. Plant Virus Epidemics

The diseases caused by plant viruses are the most important menace to the productivity and profitability of a wide range of crops. Plant virus disease epidemic results from interactions between host plant, virus, vector and environmental factors (Geering and Randles, 2012). The artificial plant communities created for agriculture are less stable, and severe virus epidemics are common, especially where monoculture is practiced. The Extent of epidemics in crops and yield losses differ widely with geographical regions and year. The main driving factors are including the magnitude of primary virus source within the crop; vector first arrival time relative to crop emergence; abundance and activity of vectors in the crop; climatic factors, including influences of the temperature (Thackray *et al*., 2004). The losses and the resulting financial damage can be limited by managing plant virus epidemics using measures that reduce virus infection sources or suppress virus spread (Jones, 2004, Regassa *et al*., 2020).

Factors such as host plants, viruses, vector, environment, time, and people's activities (Agrios, 2005) regulate the intensity of epidemics. The ability of plant virus disease to spread and make a significant epidemic depends on each of these components remaining permissive, that is, none limiting. Rapidly-expanding global climatic change creates favorable conditions for development and increased spread of plant virus diseases due to direct or indirect impacts on population dynamics of virus-transmitting insect vectors (Pautasso *et al*., 2012; Geering and Randles, 2012).

Having epidemiological knowledge of plant virus disease is the most important for each virus pathosystem which involves collecting information on the nature of the primary virus infection sources, how the virus spreads into and within crops, how the virus spreads over distance to invade new sites and how it survives outside the main growing period. Then, a clear picture is required of the factors driving plant virus epidemics concerned, which are the most important that favoring the spread and which delay its epidemics (Jones, 2001).

Factors favoring epidemics include infection source within the crop and widely distributed, external infection source nearby, growing monocultures, extended growing periods, successive plantings of short-lived crops all-year-round, planting susceptible cultivars, planting cultivars with long growing periods, no crop rotation, poor control of weeds and 'volunteer' plants, old infected plantings left in a farm field, temperatures favor virus multiplication and vector (Jones, 2004).

3. Influence of Temperature Change

3.1. Host plant and viruses

The increasing of temperature alters host plant physiology, metabolic pathways, nutritional status, phenology and morphology (Canto *et al*., 2009; Jones and Barbetti, 2012). The heat stress and rising mean temperature increase the susceptibility of host plants to virus infection and decrease and rather provide the fitness of viruses to cause infection (Mitchell *et al*., 2005). Increased temperature in addition alters the rates of plant virus multiplication, systemic movement of individual viruses present in mixed infection (Jones, 2016). Additionally, it modifies virus evolution rates and selection pressures which can result in the development of virulent virus strains with broadened natural host ranges, higher virus multiplication rates in reservoir hosts, and increased vector transmission efficiencies. Extended heat waves are likely to cause remission of virus disease symptoms in infected plants by reducing their virus contents. In some instances, extended heat waves might destroy virus infections from growing plants where systemic invasion is already incomplete or the virus involved has unstable particles. Protracted heat waves might as well sometimes be sufficiently long to inactivate seed transmission of seed coat contaminants with viruses with unstable particles (Jones and Barbetti, 2012).

Jones (2014) reported the potential effects of high temperatures on potato virus epidemics. Potato-infecting viruses that are more common in warmer climates including *Potato leaf roll virus* and *Potato yellow vein virus* are likely to spread from their current habitats to areas of higher latitude previously too cool for them and to formerly cooler highlands in tropical and subtropical regions. On the other hand, the geographical distributions of viruses adapted to cooler regions such as *Andean potato latent virus* and *Potato mop-top virus* are expected to contract to areas of higher latitude or higher elevations in mountainous areas in tropical and subtropical areas, including ones previously very cold for the potato plant.

Nancarrow *et al*. (2014) studied the effects of elevated (10–21°C, night/ day) or (5–16°C, night/day) temperatures for the growth of wheat plants infected with *Barley yellow dwarf virus*. Infected plants grown below high temperatures were larger, developed virus symptoms earlier, and had higher virus titers than plants grown at ambient temperatures. Chung *et al*. (2015) investigated the effects of various temperature regimes on the speed of systemic invasion following inoculation of *Turnip mosaic virus* to Chinese cabbage. It took 48 days for the systemic infection to occur at 13°C but only for six days at 22–33°C. The rate of systemic infection increased linearly up to 23°C. The maximum temperatures for symptoms expression were 23–28°C. Aguilar *et al*. (2015) studied the effects of high temperatures upon the synergism interaction between *Potato virus X* and *Plum pox virus* infecting *Nicotiana benthamiana.* The result showed that the titers and virulence of both viruses decreased markedly with mixed infection at 30°C compared to 25°C.

Guerret *et al*. (2016) investigated the effects of temperature on the manifestation of symptoms in subterranean clover plants infected singly or in mixed infection with *Bean yellow mosaic virus* (BYMV) and the fungus *Kabatiella caulivora*. The plants were maintained at 18°C, 20°C, or 22.5°C after BYMV inoculation and inoculated with *K. caulivora* once systemic BYMV symptoms appear. Mixed infections have caused the symptoms of more serious diseases. In sole infections, BYMV symptoms were most pronounced at 18°C, but *K. caulivora* developed more severe symptoms at 20°C and 22.5°C. In mixed infections, the severity of the disease followed the pattern developed with BYMV alone as the temperature increased. Also, a synergistic increase in disease severity sometimes occurred at 18°C, but increases in severity were always additive at 20°C and 22.5°C, indicating the greater BYMV multiplication found in infected leaves at 18°C compared with 20°C or 22.5°C.

3.2. Insect vectors

Insect vectors are an important means for the transmitting and dispersal of the majority of plant viruses (BosquePérez and Eigenbrode, 2011). The viruses transmitted by insect vectors depend on the behavior and dispersal capacity of their vectors (Nault, 1997; Ng JCK and Falk, 2006). Sucking insects, such as aphids, thrips, whiteflies, and leafhoppers, are associated with virus transmission, which can lead to significant crop losses. Temperature is a major and predominant climatic parameter that influences vectors of viruses, occurrence, and herbivores that alter their growth, survival, fecundity, distribution, and abundance (Bale *et al*., 2002). Insect populations of most virus vectors build up more rapidly in areas with high temperatures and high relative humidity and decrease at low temperatures and high rainfalls (Islam *et al*., 2017).

Significant changes in the spread and distribution of insect vectors can result from small changes in moderate temperatures. Increasing temperatures alter the physiology of plants by influencing the secondary metabolite pathways, thereby altering the nutritious value of leaves to insect vectors. This alters the replication of the virus within the cells, thus influencing virus systemic movement and acquisition by vectors (Jones, 2016).

Rising temperatures, altering insect population dynamics by accelerating insect phenology, have created an earlier and prolonged colonization because it created the ideal conditions for the insect vectors and their host plants to capture several regions to be extended (Elad and Pertot, 2014; Jones, 2014; Jones and Naidu, 2019; Juroszek *et al*., 2019; Luck *et al*., 2011; Trębicki *et al*., 2016). In addition, rising temperatures can increase the effectiveness of virus transmission from infected to healthy plants by insect vectors. The improved efficiency of such transmission can allow the viruses they transmit to extend their ranges to areas formerly too cold for them to be transmitted successfully. However, distributions of some other viruses might contract from regions with increased temperatures due to reduced virus transmission efficiencies at higher temperatures. Also, long-term heat waves can reduce vector numbers thereby reducing virus epidemics (Canto *et al*., 2009; Jones and Barbetti, 2012).

Among insect vectors, aphids are the most common and cause for the transmission of 50% of insect-vectored viruses (Nault, 1997). Aphids respond strongly to small changes in temperatures due to their mobility, short generation times, high reproductive capacity, and the ability to make rapid life history and behavioral changes (Jones, 2016). Another five generations of aphids/year are predicted in warmer weather from a temperature of 2°C. As a result, the risk of severe epidemics of aphid-transmitted viruses increases as their populations and activities increase. In warmer climates, the survival of aphid vectors is likely to increase with milder winter temperatures, and higher summer temperatures are likely to increase their growth and reproductive rates. A few days with shorter cold spells raise their ability to overwinter, allowing them to enlarge their geographic ranges and enhance the period in which they are active each year. Rising winter temperatures make earlier starts to aphid annual life cycles, increase the number of winged aphids, and encourage their flight activity. Many aphid-borne viruses are most likely to spread in warmer climates under increasing winter and summer temperatures (Jones, 2009; Canto *et al*., 2009; Jones and Barbetti, 2012).

According to developed formulas to estimate the number of generations of insects under global warming, an increase in temperature of 3 ° C in warmer climates results in seven generations of aphids per year (Yamamura and Kiritani, 1998). The survival of the aphid can be suppressed when temperatures exceed 36°C during the summer months, thereby reducing the spread and persistence of the *Barley yellow dwarf virus* (Parry *et al*., 2012). The studies conducted by Gao *et al*. (2012) on the effects of rearing the vector species *Acyrthosiphon gossypii* (a cotton aphid) on cotton plants at 18°C, 21°C, 24°C, 27°C, and 30°C indicated that the average longevity of adult females was 16, 12, 8, 5, and 3 days, and the average number of offspring per female was 46, 38, 20, 14, and 0 at these temperatures, respectively. The optimal temperature range for its growth was 21–27°C, while 30°C was above the upper limit for reproduction.

Gillespie *et al*. (2012) found that the population growth of *Myzus persicae* (green peach aphid) was lower in temperatures (32°C and 40°C maxima) compared to areas with occasional hot days. Heatwaves also reduce the proportion of winged aphids in the population. Ryalls *et al*. (2013) investigated the ability of *Acyrthosiphon pisum* (the pea aphid) to colonize three alfalfa cultivars when temperatures increased from 26°C to 30°C.

Rising temperatures can increase thrips vector populations by accelerating their development rates leading to several generations per year. Since different thrips species have different tempreture limits, global warming is likely to change the composition of their species. For example, *Thrips palmi* is expected to expand into areas previously too cold for it, displacing vector thrips species adapted to cooler temperatures. This is expected to lead to an increase in new regions of several damaging tospoviruses it transmits. The same assumptions apply to viruses transmitted by leafhoppers, mealybugs, and eriophyid mites (Canto *et al*., 2009; Jones, 2009; Jones and Barbetti, 2012). Other studies by Yadav and Chang (2014) on *Thrips palmi* survival, development, fecundity, longevity, and population growth on eggplants at 16°C, 19°C, 22°C, 25°C, 28°C, and 31°C showed that its egg-to-adult developmental period declined from 36 to 10 days as the temperature rose from 16°C to 31°C. Fecundity was very high at 25°C and low at 16°C. Its population trend index was very high at 25°C and very low at 16°C, and the ideal development temperature was 25 ° C. Fecundity was very high at 25 ° C and low very high at 16 ° C. Its human population index was very high at 25 ° C and very low at 16 ° C, and the ideal development temperature was 25 ° C.

Whitefly vectors are also active in responding strongly to temperature changes due to their short generation times, high reproductive capacity, and the ability to generate rapid life history and behavioral changes (Jones, 2016). For example, due to the increase in winter temperatures in places formally too cold for it in winter, *Bemisia tabaci* is tending to displace *Trialeurodes vaporariorum* which increases its distribution in previously cooler areas. Also, this shift in vector distribution influences whitefly-transmitted virus distributions in various parts of the world, and the destructive epidemics of *B. tabaci*-transmitted begomoviruses are becoming more widespread (Jones and Barbetti, 2012).

4. Influence of Rainfall

Weather extremes result in excessive rainfall and flooding as well as severe drought (Anayamba *et al*., 2014). Such weather extremes can create exceptional conditions for extensive virus disease outbreaks in cultivated and natural vegetation. The study carried out in Ethiopia by Regassa et al. (2020) on the epidemic of maize lethal necrosis (MLN) which is caused by co-infection of *Maize chlorotic mottle virus* with *Sugarcane mosaic virus* indicated that high prevalence and disease incidence of MLN were highest at altitudinal ranges of and 1700–2000 m.a.s.l as compared to higher altitude of >2000 m.a.s.l. Maize grown at an altitude range of 1700 to 1200 m.a.s.l receives moderate rainfall (Abate *et al*., 2015), and characterized by warm and semi-humid weather conditions, which could be conducive environment for insect vectors development and spread that result in increased prevalence and disease incidence of MLN. While, higher altitude areas (>2000 m.a.s.l) of Ethiopia are characterized by high rainfall (Abate *et al*., 2015) and highland (cool temperature), which could hinder insect vector reproduction and ease of mobility to spread the viruses. Insect populations of most virus vectors build up faster in areas with high temperature and high relative humidity, and decline at low temperature and high rainfalls (Islam *et al*., 2017).

Epidemics of insect-transmitted plant viruses such as arthropods are likely to alter significantly as climate change alters the world's rainfall patterns, flood events and drought happen to more extreme and wet seasons become increasingly less predictable in many parts of the world. The increased repeated occurrence/frequency of heavy rainfall, extreme drought, or flood events expected to arise from climate change is possible to influence plant virus disease epidemics in various ways. An increasing frequency of heavy rainfall events is likely to slow the virus prevalence and incidence by washing insect vectors like thrips, whiteflies and aphids off foliage, thus reducing vector density. Water logging as a result of flooding kills pupal life stages of thrips vectors in the soil, consequently reducing epidemics of the viruses they transmit by reducing insect vector densities. Flooding within annual crop growing period enhances the subsequent growth of weed which acts as reservoirs of plant viruses and insect vectors, and its occurrence outside growing seasons increases following growth of such reservoirs. On the other hand, prolonged drought stress on crop plants can limit insect vector population size and also limit the size of reservoirs of viruses and vectors (weed and volunteer crop) (Jones, 2016).

With the spread of contact-transmitted viruses, the high frequency and intensity of summer storms linked with heavy rainfall or hail that increase rain splash and wounding of plants, and also provide moisture are expected to accelerate their spread leading to a severe virus epidemics. Additionally, both flood and drought can influence survival of unprotected virus particles in contaminated soil and their abilities to act as sources of inoculum for spread to susceptible crops. For example, the dry, compacted, or waterlogged soils typical of drought or flooding, respectively, favor survival of the stable, contact-transmitted virus *Tobacco mosaic virus* in plant debris in soil but well-aerated soils favor its inactivation. An increase in flooding from storms would speed up water-borne virus dispersion through irrigation and drainage channels, rivers and streams; however drought environment would have the opposite effect (Jones and Barbetti, 2012).

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