Modeling Phytophthora disease development in chile and bell peppers under rain feed and irrigated conditions.

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Abstract

Different forms of phytophthora attack different plant species, but the abiotic and biotic factors that determine the virulence of disease are similar for all type of phytophthora blight. *Phytophthora capsici* is a major disease that leads to large financial loss on chile peppers, bell peppers, and cucurbit crops in the United States, including tomatoes, cucumber, watermelon, squash, and pumpkin. Oospores provide the initial source of inoculums in the field, and multiple life cycles in a growing season occur through improper irrigation management. The research objective was to develop a conceptual model of the life cycle of *phytophthora capsici* and the disease development on chile and bell peppers as affected by soil temperature and wet/dry soil moisture cycles caused by irrigation or rainfall events. A simple life cycle model, which describes the relationship between host and pathogen population density throughout the growing season and overwinter developed by Thrall, was combined with an irrigation scheduling model for one-dimensional and two-dimensional flow that predicted the incidence development of chile and bell peppers grown in New Mexico and North Carolina that were furrow or drip irrigated. The model and measured phytophthora disease incidence on chile peppers grown in Las Cruces, NM, under alternate-row furrow irrigation was 55% at the end of the growing season. The model predicted a disease incidence of 5% compared to a measured disease incidence of 1.5% for trickle-irrigated chile. The *phytophthora capsici* disease incidence of drip-irrigated bell peppers at Clayton, NC, in 1998 when only two irrigations were applied in addition to rainfall, was measured at 55% compared to the modeled 52% disease incidence. The model predicts accurately the disease development rate of *phytophthora capsici* under low rainfall in Las Cruces and high rainfall in Clayton for both trickle and furrow irrigation if the appropriate one- or two-dimension water flow model is used in the simulation.

Introduction

Phytophthora blight is caused by the oomycete pathogen. Different forms of phytophthora attack different plant species, but the abiotic and biotic factors that determine the disease virulence are similar for all types of phytophthora blight. *Phytophthora capsici* is a major disease that leads to large financial loss on crops of chile peppers, bell peppers, and cucurbit in the United States, including tomatoes, cucumber, watermelon, squash, and pumpkin (Hwang et al., 1995, Kreutzer et al., 1940, Ramsey et al., 1960, Yan Maa et al., 2008, & Babadoost, 2000). Sanogo and Carpenter (2006) have shown all the commercial chile pepper (Capsicum annuum) fields in New Mexico are infected to various degrees, mostly with *phytophthora capsici.* Chile pepper is grown on

approximately 1.3 million hectares in China, and *phytophthora capsici* has been reported to infect about 20% to 30% of the conventional farmed chile fields (Yan Maa et al., 2008).

Phytophthora capsici is a heterothallic organism in which two compatibility types designated A1 and A2 are needed for sexual reproduction. The sexual structure oospores are the main survival propagule and primary source of inoculums in the field (Bowers, 1983). Oospores provide the initial source of inoculums in the field, and multiple life cycles in a growing season occur through improper irrigation management (Bowers et al, 1990, Ristaino , 1990, Ristaino ,1991, Schlub, 1983). The virulence of the disease also is caused by the concentration of the pathogen in the soil at the beginning of the growing season. Because the pathogen is present in most soils, the overwintering survival rate also affects the virulence of the pathogen. In chile peppers, the phytophthora disease affects roots, crowns, stems, leaves, and fruit, causing seedling damping-off, stem lesion, stem and leaf blight, and fruit rot (Shannon, 1989, Biles et al., 1995). In spring, the oospores germinate into mycelium, which produces sporangia in water-saturated soil. Zoospores released from the sporangia swim through wet soil toward roots, where they encyst, germinate, and infect the root, causing it to rot. Secondary sporangia are produced on the infected root surface, and more zoospores are released. Oospores inside the rotting roots survive over winter. Zoospores and sporangia also may be splashed up onto plant leaves during rain or irrigation. Infected leaves produce additional sporangia, which release zoospores, which can be splashed onto adjacent plants or moved throughout the field on contaminated equipment. Consequently, during the growing season, the initial concentration of zoospores may be low and insufficient to kill a plant. The root and crown rot phase of the disease initially can appear on plants early in the growing season in areas of the field where soil remains saturated with water after an irrigation or rainfall. Subsequent periods of soil saturation encourage further disease development and plant death (Matheron and Porchas, 2002).

The life cycle of *phytophthora capsici* requires a wet/dry cycle, but the disease development also is affected by soil temperature. Rainfall and periodic furrow irrigation usually provide the needed wet/dry cycle in the soil, favoring sporangia formation during the drying period and zoospore release during flooding (Bowers and Mitchell, 1990).

Currently, best management practices (BMP) for control of the disease includes field preparation where fields are well drained with no low-lying areas that collect water (Larkin et al., 1995). Because phytophthora blight usually develops in fields in low-lying areas (Ristaino et al., 1993), laser leveling can be used before planting to minimize areas of standing water. The field also can be subsoiled or chisel-plowed to improve drainage in compacted areas (Garrison, 1999). Irrigation management should include reducing the number of wet/dry cycles though proper timing of irrigation both from flood, drip, and sprinkler irrigation. Disease incidence and severity are more severe and onset occurs earlier with more frequent than with less frequent irrigations (Café-Filho et al., 1995, Café-Filho et al., 1995, & Ristaino, 1991). A less frequent irrigation schedule on peppers of 21 days versus seven days resulted in less phytophthora blight without a reduction in yield (Café-Filho and Duniway, 1995). Drip irrigation on a daily basis prevents the occurrence of this wet/dry cycle and consequently controls the development of the disease (Xie et al., 1999). Alternate furrow irrigations are a BMP that can reduce the incidence of phytophthora root rot, reducing inoculum spread and disease in pepper (Biles et al., 1992, & Daniell and Falk, 1994).

The level of phytophthora in the soil can be determined only by taking a soil sample, culturing the sample and counting the number of propagules on the incubation plate per gram of oven-dried soil (McCain et al., 1967). If initial concentrations are low in a field at the beginning of a growing season, then proper irrigation management is not as critical as when the concentrations are high and can lead to 50% or more loss of crop yield. Control of phytophthora disease requires a multifaceted approach that integrates irrigation management, cultural practices, and non-chemical treatments

(Erwin and Ribeiro, 1996, Perez et al., 2003, & Mojica-Marín et al., 2011). Such a complicated system can be can be evaluated only through a modeling approach.

The objective of the research was to develop a conceptual model of the life cycle of *phytophthora capsici* and the disease development on chile and bell peppers as affected by soil temperature and wet/dry soil moisture cycles caused by irrigation or rainfall events. The second objective was to evaluate the model in different environmental conditions to determine the robustness of the model to predict the *phytophthora capsici* disease development rate for these two plant types.

Model description

Thrall et al. (1997) presented a simple life cycle model for phytophthora. The model describes the relationship between host and pathogen population density throughout the growing season, and over winter, for both natural and agricultural systems. Modeling of the life cycle of the host and pathogen provides insight and guidance on how to manage the pathogen to minimize yield loss. Soil water budgets and irrigation scheduling models (Sammis, et al., 2012, Ben-Asher et al., 1986) are available to model the remaining variables that affect the intensity and timing during the life cycles of phytophthora (Figure 1).

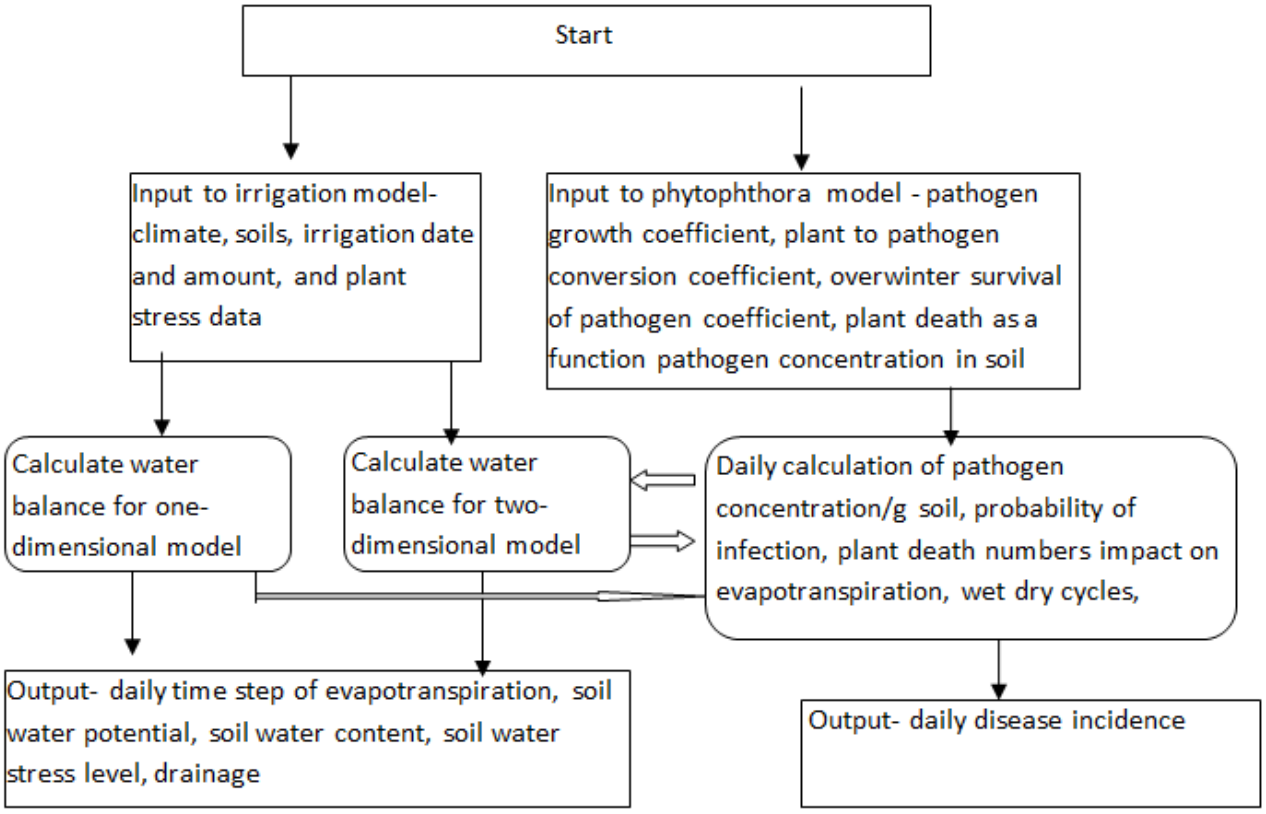

Figure 1. Block diagram of model

The model of Thrall et al. (1997) assumes that in temperate climates, population growth of soil-borne fungi occurs during summer months (through saprophytic growth and spore production, or through infection of new hosts), while during winter months, resting structures of chlamydospores can decay, but no new growth occurs. For the above species, oospores would be the resting structures considered. Consequently, the initial concentration of the pathogen population at the beginning of the growing season determines the initial virulence of the pathogen, along with the plant

density of the host. In the case of agriculture, the host population is constant from year to year, which is not the case in a natural system. Overwinter survival of the pathogen depends on soil temperature but is generally considered to be 10% of the fall concentration. In Thrall et al.'s (1997) model, the time step (t) of the model is dependent on the time step for the birth rate of the pathogen, which can be daily or seasonal or any time increment where the plant population change affects the concentration of the pathogen. If the time step is set to daily, then the time step for phytophthora can be determined from an agricultural water balance model set up for the specified host crop. The soil-water potential is calculated daily, and when an irrigation or rainfall event occurs that wets and then dries the soil past threshold values, a time step is implemented in the Thrall et al.'s model. This assumes that during the days when the soil is drying out but a wet/dry cycle does not occur, the concentration of phytophthora zoospores in the soil does not occur by the released of new zoospores by sporangia (Café-Filho et al., 1995, Ristaino, 1991, & Xie et al., 1999).

The Thrall et al. (1997) model is described by Equation 1 (labeled Equation 2 in paper):

$$Y(t+1) = Y(t)\alpha(1+\mathring{y}-\mathring{\int}Y(t)) + \alpha\,\varepsilon\,X(t)\,P \quad (1)$$

Where: P is the total probability of infection, $P = 1 - e^{-BY(t).}$

t = daily time step of model Y(t+1) changes only when a wet/dry cycle has occurred.
Y= concentration of pathogen in the soil.
α= overwinter survival rate of the pathogen in the soil.
$\mathring{y}$= host independent birth rate of soil pathogens that can live as sprophytes.
$\mathring{\int}$= strength of pathogen-dependent effects on the pathogen birth rate.
ε= rate at which infected plants are converted to the pathogen component in the soil.
X= plant population.
B= disease transmission coefficient.

The probability of infection (P) is described by an exponential function (Equation 2) or a linear function (Equation 3).

$$P = 1 - e^{-BY(t)} \quad (2)$$

$$P = B_1\,Y(t) \quad (3)$$

Where Y(t) is the infection concentration pathogens/g soil (pgs) from Equation 1.
B= exponential transmission parameter, which is a measure of transmission efficiency.
B_1 = linear transmission parameter, which is a measure of transmission efficiency.

In agriculture, the plant population (X) is described by Equation 4:

$$X(t+1) = X(t)\,(1 - \text{Loss}\,Y(t)\,P) \quad (4)$$

Where: X = the population of plant /area.
Loss= death of plant caused by concentration of disease organism.

A one-dimensional irrigation scheduling model for furrow and sprinkle irrigation and a two-dimensional model describing water movement under drip irrigation were combined with the Thrall model. The one-dimensional irrigation scheduling model is a simple volume-water budget model that solves the water balance equation on a daily time step after Sammis, et al. (2012).

The volume balance equation is:

$$\Delta Sm = R + I - Et - D \quad (5)$$

where R = rainfall (mm)
I = irrigation (mm)
D = drainage (mm)

Et = evapotranspiration (mm)
ΔSm = change in soil moisture (mm).

$$Et = Et_o \times Kc \times f \quad (6)$$

Et_o is calculated using penman's reference evapotranspiration equation described by Allen et al. (1998) when the full climate data is available and Et_o is calculated using Hargreaves and Samani (1985) equation when only temperature data is available.

The crop coefficient (Kc) is a fourth order polynomial where:

$$Kc = a + b*GDD + c*GDD^2 + d*GDD^3 + e*GDD^4 \quad (7)$$

Where: GDD is growing degree days.
Growing-degree days were calculated as:

$$GDD = \frac{(T_{max} + T_{min})}{2} - T_b \quad (8)$$

Where: T_{max} = daily maximum temperature (°C).

T_{min} = daily minimum temperature (°C).

T_b = base temperature (°C)

If T_{max} exceeds a cutoff temperature, then T_{max} is set to that cutoff temperature. The same occurs for the T_{min} minimum temperature. The cutoff temperatures are inputs to the model along with the base temperature, and the values depend on the crop being grown. The cutoff temperatures and crop coefficients for chile peppers, which also were used for bell peppers, are presented by Saddiq (1983).

The f factor is a soil water stress linear function (0-1) and usually is described as a step function where f is set to 1 when the soil water is at field capacity or larger and then decreases linearly when the soil water decreases below a threshold value (Allen et al., 1988).

The irrigation scheduling one-dimensional model has a single soil layer equal to the depth of the roots that changes throughout the growing season as a function of growing degree days (GDD). Consequently, it has no root extraction pattern. The two dimensional irrigation scheduling model is an ellipsoid layered model with a root extraction patter for each ellipsoid. Sammis et al. (2012) describes the comparison between the two models. Inputs to the model are climate, soil water hold characteristics, and irrigation data (Table 1). The model is run from planting date to harvest date. The climate data to calculate reference evapotranspiration (E_{to}) for grass was obtained from nearby weather station data. Irrigation or rainfall water is applied, increasing the available soil water in the root zone. The model automatically applies an irrigation when the soil water depletion reaches a input value in the model. Setting the value to 0.99 prevents the model from automatically irrigating and only the applied water on the specified data an input to the model simulated. Water application in excess of the soil water holding capacity of the root zone goes to deep drainage (Equation 5).

Table 1. Chile and bell peppers disease model parameters

Parameter	Values	
Soil water submodel	Chile Peppers	Bell Peppers
Beginning root depth, cm	10	10

Maximum root depth, cm	107	107
Root growth coefficient, cm/growing degree day	0.028	0.028
Irrigation amount for computer applied irrigation, cm	0.2	0.2
Soil water holding capacity between field capacity and permanent wilting point, cm/cm	0.12	0.12
Soil water management allowed depletion, %[1]	99	99
Row spacing (two-dimension model), cm	107	107
Water hold capacity of soil below permanent wilting point, cm/cm	0.1	0.1
Growing degree day coefficients for crop		
Coefficient calculation constant for GDD in degree C		
Equation 7 a=	0.098	0.098
Equation 7 b=	5.994 E-5	5.994 E-5
Equation 7 c=	6.188 E-7	6.188 E-7
Equation 7 d=	-1.895 E-10	-1.895 E-10
Cutoff temperature		
Tmax =	30	30
Tmin =	5	5
Tb =	5	5
Slope of water stress function ("f" in Equation 6)	2	2
Intercept of water stress function ("f" in Equation 6)	0	0
Disease submodel		
Initial pathogen, pgs one-dimensional model	45 two-dimensional model	10 on 6/13/1988
two-dimensional model	30 two-dimensional model	40 initial 1989
Cutoff temperature for zoospoor, degree C	35	35
Rate of growth of pathogen, pgs	0.03	0.03
Rate of plant converted to pathogen, pgs/plant	0.01	0.01
Strength of density on pathogen birth rate , pgr	-0.89	-0.89
Overwinter survival rate of pathogen in soil	0.1	0.1
Beta	0.0005	0.0005
Loss plant /pgs	0.05	0.05
Temperature submodel		
Soil albedo, decimal	0.15	0.15
Average annual air temp., C	16.2	15.5
Annual amplitude in mean monthly temp, C	22.2	16.6
Mean bulk density of soil, g/cm^3	1.4	1.4

A detailed description of both the one-dimensional and two dimensional model is presented by Sammis et al. 2012.

Because irrigation wet/dry cycles can be controlled by converting the irrigation from a furrow system to a drip irrigation system, it is necessary to combine the phytopathology model with a two-dimension volume balance trickle irrigation model that is based on the ellipsoid model described by Ben-Asher et al. (1986) and Sammis et al. (2012). The row distance between line sources and corresponding soil depth are divided into five halves of ellipsoids, and the ellipsoid shape is determined by the ratio of x/y (major/minor axis), an input to the model ranging from 0.5 to 1 (Figure 2). The x is in the root depth direction. This value is based on the soil type as defined by the soil water holding capacity of the soil, which is an input to the model. Rainfall is applied to the surface of each ellipsoid based on the surface of each ellipsoid containing 20% of the row spacing. All the rainfall stays within the ellipsoid that it enters except for that amount that exceeds the water required to bring the ellipsoid to field capacity. This water then is moved to the next ellipsoid and is distributed evenly throughout the ellipsoid. The extraction percentage of evapotranspiration (Et) taken from each ellipsoid depends on the root development depth. Root growth rate is calculated in the x direction, and when the roots reach the next ellipsoid, the Et extraction is distributed from the first to the rooting depth ellipsoid. Details about the two-dimensional model and a comparison between the one- and two-dimensional models for scheduling irrigation using a drip irrigation system is presented by Sammis et al. (2012).

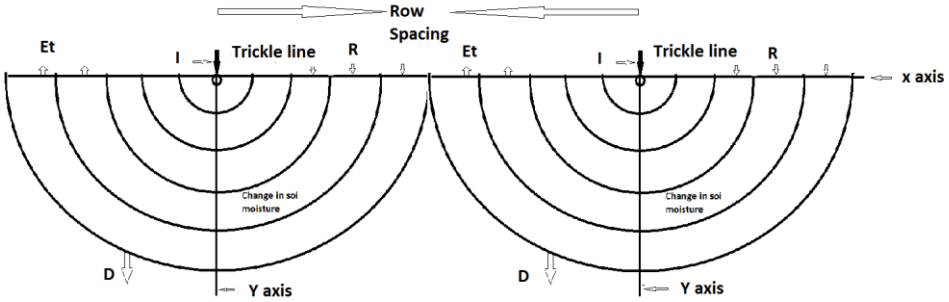

Figure 2. A two-dimensional volume balance water model.

Material and Methods.

Chile Pepper Experiment

The combined host-pathogen irrigation model for *phytophthora capsici* disease incidence on chile was tested against a *phytophthora capsici* disease development experiment conducted in 1995 on Brazito sandy loam soil (mixed, thermic typic torripsamments) located at the Fabian Garcia Agricultural Research Center in Las Cruces and on a bell peppers experiment conducted at Clayton reported by Ristaino (1991) and Ristaino and Hord (1992). The experimental design at Las Cruces was a randomized complete block design with three irrigation levels (daily trickle irrigation, three-day trickle irrigation, and alternate row furrow irrigation) and two phytophthora levels (non-infected [control] and infected). The daily trickle irrigation experiment was not used to evaluate the irrigation disease model because this high irrigation frequency is not used by growers. The experiment was

conducted in 1995. Every row was furrow-irrigated during transplant establishment and switched to alternate row furrow irrigation thereafter.

The 6143 strain, A1 compatibility type of *phytophthora capsici* isolated from diseased chile plants was used for this study. The inoculums were obtained by growing the isolate in vermiculite media amended with 350 ml of V8 broth and incubated at 24 C for four weeks (Ristaino et al., 1992). In April 1995, the inoculums, containing mycelium and sporangia, were placed on both sides of the bed, 15 cm from the center and 5 cm deep, at a rate of 360 ml m^{-1}.

Chile seedlings-- *capsicum annum* New Mexico 6-4, were transplanted on April 24, 1995, after eight weeks of growth in a greenhouse. The plants were placed on both sides of the bed in a staggered arrangement. Plants were placed 7.5 cm from the center with 60 cm spacing between two adjacent plants on the same side and 30.5 cm between two adjacent plants on opposite sides of the bed.

T-tape (T-tape: TSX-508-08-670, T-Systems, San Diego, CA) with emitters every 20 cm was buried 20 cm below the soil surface and in the center line between plant rows. The flow rate of the system was 5.0 l hr^{-1} m^{-1}. The drip system was operated by a computer-scheduling model that applied water to satisfy the calculated Et with 20% excess water applied based on an irrigation application efficiency of 80%. The water was applied to plots three times a week, and the amount was calculated from the accumulated Et since the previous irrigation. The water applied was measured with a flow meter. The experiment had an average 2.1 cm of water applied. The irrigation application depth varied from 0.15 cm, in the early part of the growing season, to a maximum application rate of 4.4 cm. The total number of irrigation applications was 56 in 1995. URAN® (32-0-0) was applied with the irrigation water for a total seasonal application of 397 kg ha^{-1} of NO_3-N. Before transplanting, phosphorus was applied at a rate of 67.3 kg ha^{-1}. Green yield was harvested on July 13, 1995, Aug. 2, 1995, on July 16, 1996, and Aug. 15, 1996, from three one-meter long subplots. Red chile yield was harvested on Oct. 15, 1995, and Oct. 31, 1996. Red chile and green chile yields were weighed and subsampled for moisture content. Combined yield (green chile yield plus red chile yield) was obtained by converting dry red chile yield to wet yield using a wet/dry ratio of eight (Gore and Wilken, 1995). Soil moisture was measured every two weeks with a neutron probe at depths of 30 cm, 60 cm, 90 cm, and 120 cm in the middle of the beds adjacent to the drip line.

Soil matric potential (ψ_m) was monitored weekly in three blocks at depths of 15 cm and 30 cm by tensiometers installed between two plants in the middle of the beds. Air temperature data was collected from a Campbell climate station at the site. Soil temperatures in 1996 were measured in three blocks using thermal couples located in the middle of the bed. The thermal couples were connected to a Campbell Cr10 datalogger, which recorded the temperature every 10 seconds and averaged the temperature hourly.

Disease incidence was collected weekly before June 14 i**n** 1995 and daily thereafter by visual examination. When the symptoms of disease progressed to the stem necrosis stage, the diseased plants were sampled for confirmation of the presence of *phytophthora capsici* by inoculating chile seedlings in the greenhouse. A complete description of the experimental design is given by Xie et al. (1999).

Bell Pepper Experiment.

An experiment on drip-irrigated bell peppers (variety Deystone Resistant Giant) artifically infested with *phytopthora capsic* was conducted by Ristaino (1991) and Ristaino and Hord (1992) in Clayton in 1988 and 1989. Plots were drip-irrigated two times during the 1988 growing season after being infected with three levels of inoculum and a control. The soil type was a Johns sand loam. The eight-week old pepper seedlings were transplanted in soil beds that had been treated with methyl

bromide-chlorpicrin. The experimental design was a split block design with irrigation as main plots and densities of inoculum as supplots. The treatments were replicated four times. The plots were either uninfested or infestested 43days in 1988 and for 31 days in 1989 after transplanting. Inoculum of *phytophthora* capsicis in V8 vermiculite mediums as applied to subplots. The incidence and severity of the disease on shoots was evaluated visually during the growing season. Soil samples to evaluate moisture conten an phythopthora were taken from the 0-20 depth. A complete description of the experimental design is givn by Ristaino (1991) and Ristaino and Hord (1992), along with the results of the experiment of the disease development rate over time.

Results

The disease incidence predicted by the one-dimensional model for the alternate row furrow irrigation followed the measured data except early in the growing season where disease incidence development occurred sooner than predicted by the model (Figure 3).

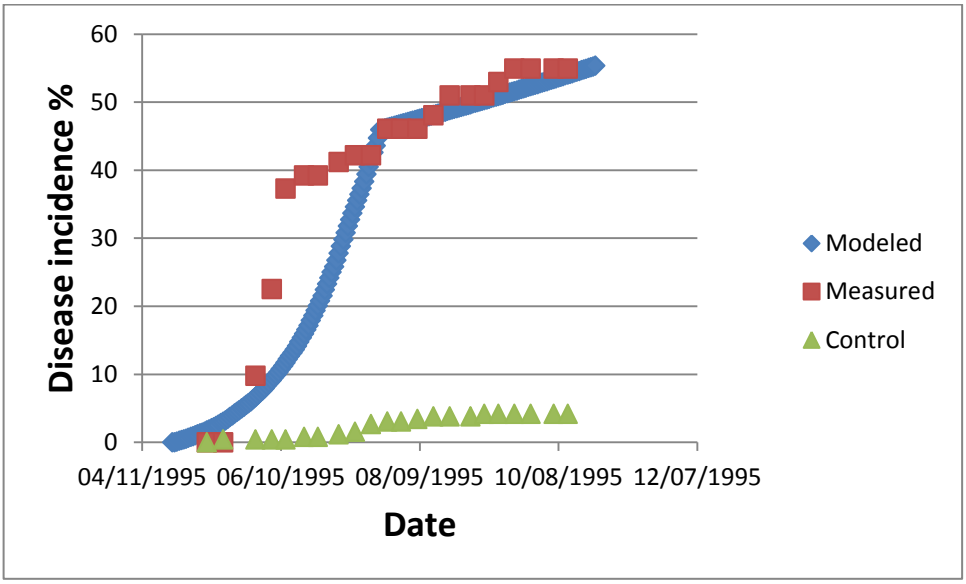

Figure 3. Measure and one-dimensional modeled disease incidence of phytophthora capsici for the furrow alternate row chile irrigation. The control was not infected with *Phytophthora capsici*.

The initial concentration in the soil was set in the model at 45 *phytophthora capsici* pathogen /g of soil. The level in the soil was not measured in the experiment after the application of inoculums, which is the case in most *phytophthora capsici* experiments. The model was modified to include the effect of high soil temperature on the life cycle of *phytophthora capsici*. If the soil temperature reached 30 C, then the disease incidence increase was described by a linear function that was a function of the *phytophthora capsici* levels in the soil at the time of the high temperature occurrence. The additional assumption added to the model is that the high soil temperature stopped the life cycle of the *phytophthora capsici,* and only those zoospores in the soil at that time continued to cause disease incidence. Without the additional constraint, the model predicted the disease incidence would continue in the power function shape that occurred in the beginning of the growing season. Because the data did not support this assumption, the additional temperature constraint was added to the model. The measured and modeled soil moisture content were similar indicating that the soil

moisture balance component of the model was tracking the impact of irrigations on the number of wet dry cycles correctly (Figure 4)

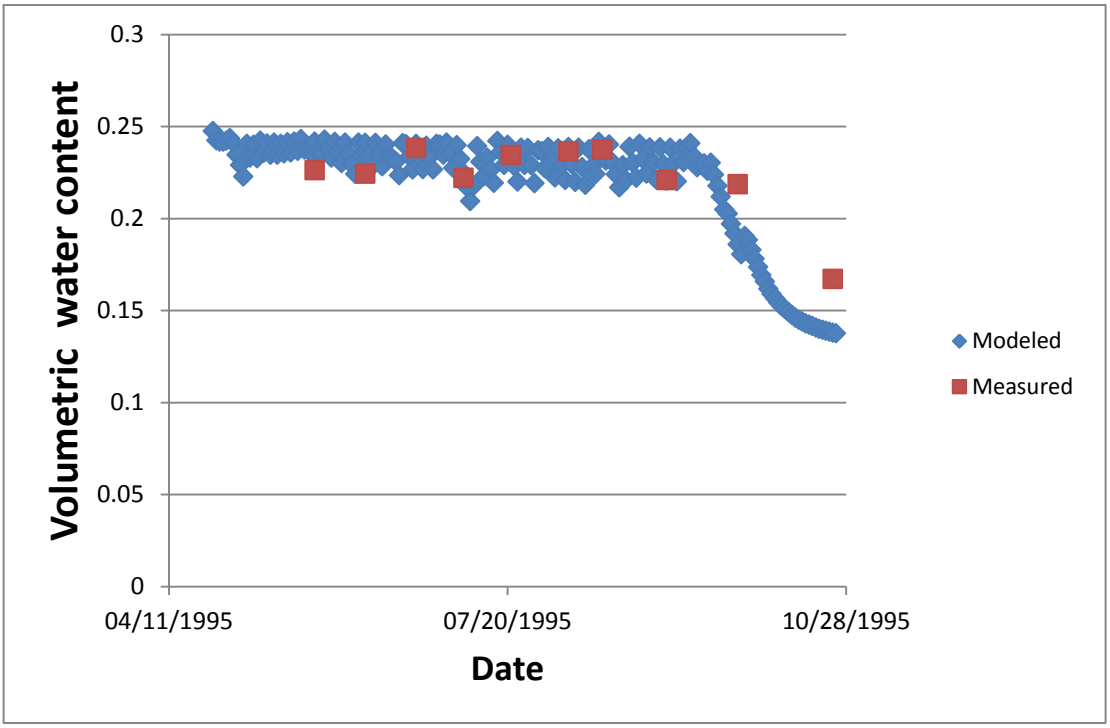

Figure 4. Measured and modeled (one-dimensional model) water content (30-90 cm) in a drip-irrigated chile field in Las Cruces, NM; 1995.

The model also was run using the two-dimension drip-irrigation model where the irrigation was applied every three days (Figure 5).

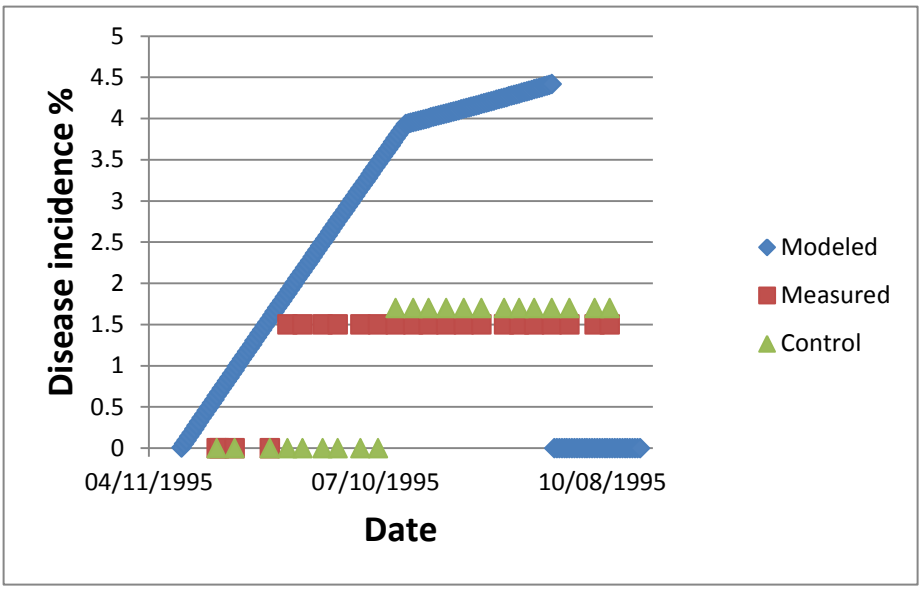

Figure 5. Measure and model disease incidence of phytophthora capsici for the 3 day trickle irrigation chile. The control was not infected with phytophthora capsici.

The two dimensional soil- water-disease- model overestimated the disease incidence final level for the three-day drip irrigation treatment. Something stopped the low rate of disease development after two months that is not explained by the model. However, the strength of the inoculums in the soil and the depth of infection are in question because no measurements were taken of soil inoculum levels.

The model parameters are estimates presented by Thrall et al. (1997) from a literature search with a wide range in values in the literature for the parameters. Addition experiments must be conducted before confidence in the model parameters is sufficient to determine if the difference between measured and modeled values is a function of the model structure or the model parameter values. Also, the model is a simple model that may not describe the biology of *phytophthora capsici* completely. Knowledge is lacking of the concentrations of *phytophthora capsici* in the soil under different environment conditions and of *phytophthora capsici* concentration over time and depth in the soil at location within the root volume. A better understanding of the relationship between soil water potential spatial distribution and disease propagation is critical. However, the model did simulate the interaction *of phytophthora capsici* with wet/dry cycles of soil moisture and the effect of soil temperature on *phytophthora capsici* disease development.

The model prediction of *phytophthora capsici* disease incidence was also compared to measurements of the disease incidence on bell pepper reported by Ristaino et al. (1991) where bell peppers in North Carolina were treated with *phytophthora capsici* at selected concentrations under a different drip-irrigation treatment, but where the majority of the water came from rainfall events. Two irrigations of 1.5 mm were applied 46 and 62 days after planting. The inoculum was applied 42 days after planting.

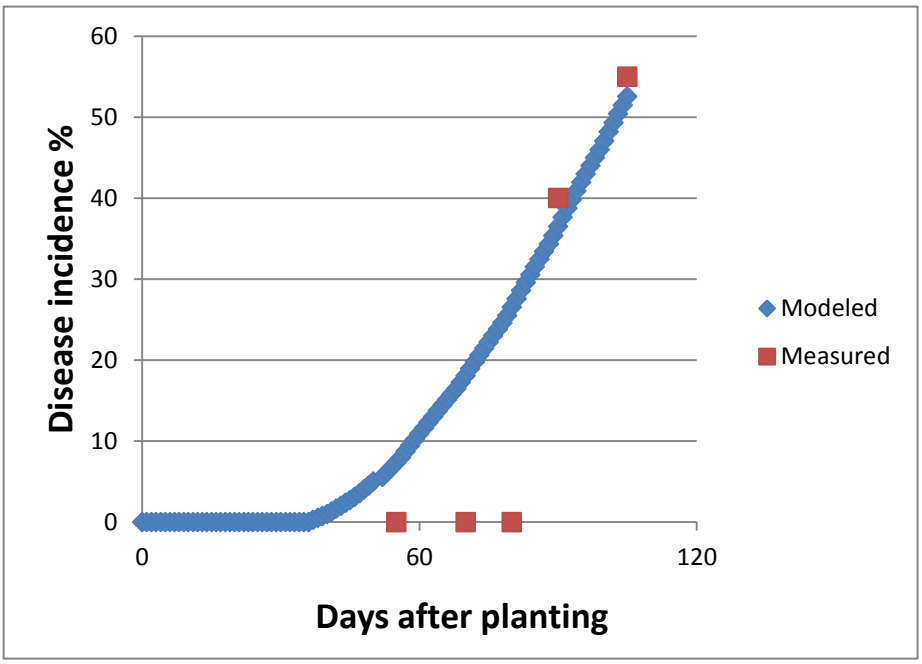

Figure 6. Comparison of model and measure *phytophthora capsici* disease incidence of drip-irrigated bell peppers at Clayton, NC, in 1988 when only two irrigations were applied in addition to rainfall and high disease inoculum.

The model disease incidence and model inoculum density (Figure 6 and 7) continued to rise as the growing season progressed. The disease incidence measurements along with inoculum density were steady during the growing season until the last measurements where both increased. The model predicted that the rainfall events would cause an increase in the disease which the measurements did not support. Consequently, soil microorganisms competition may have be suppressing the growth of the *phytophthora capsici.* This competition component is not in the model and may be more of a controlling factor in the higher rainfall area of NC. The organic matter in these soils is higher than in the soils in the west and higher organic matter soils have a higher diversity of microorganism (Linderman, et al., 1983).

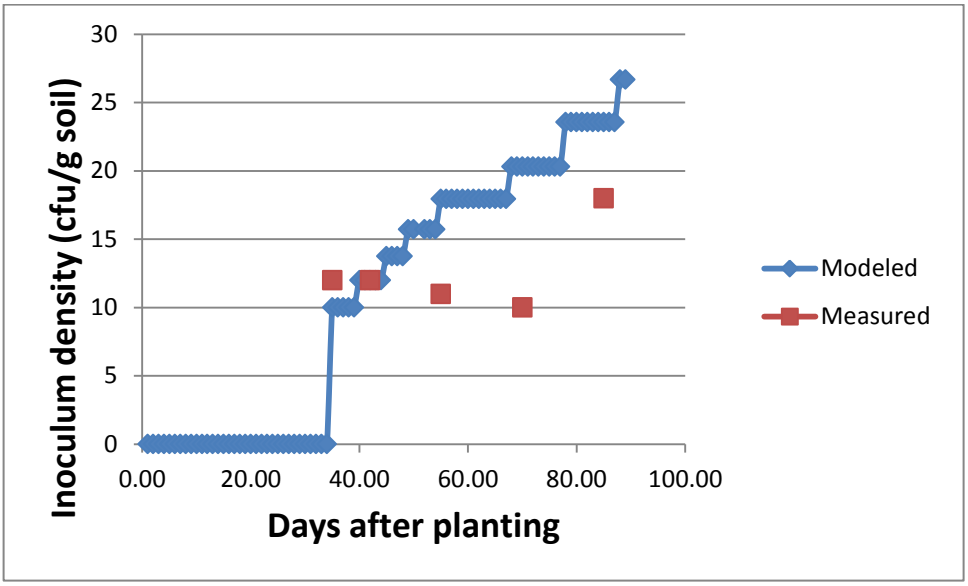

Figure 7. Measured and modeled inoculum density of phytophthora *capsici* the soil for drip irrigated bell peppers at Clayton, NC in 1988 with only two irrigations were applied in addition to rainfall and high disease inoculum.

In 1989 when the experiment was repeated but with a larger number of irrigations (six irrigations) the model followed the disease incidence measurements (Figure 8), but the measurements of the inoculum density of *phytophthora capsici* decreased over the growing season even though the disease incidence increased (Figure 9). The model predicted an increase in the inoculum density because in the model, the disease incidence is a direct function of the inoculum density. No error bars were given in the reported data but the variability of the inoculum density measurements determined by measuring the colonies of *phytophthora capsici* grown from a soil water agar extract on Masago's medium could be high. Also the inoculum density calculations did not include any measurements of chlamydospores in the root tissue which could have contributed to plant death.

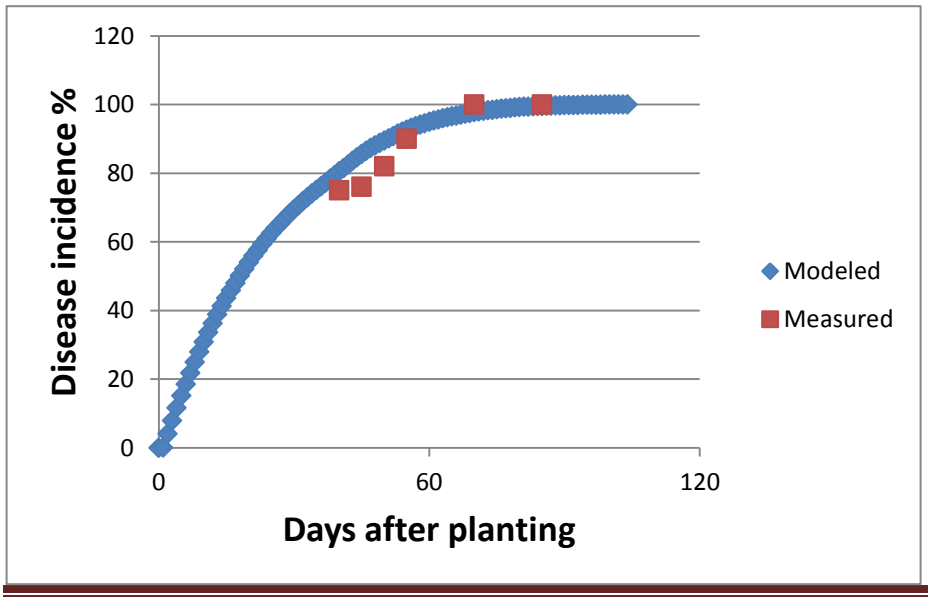

Figure 8. Comparison of model and measure *phytophthora capsici* disease incidence of drip-irrigated bell peppers at Clayton, NC, in 1989 when only six irrigations were applied in addition to rainfall and high disease inoculum.

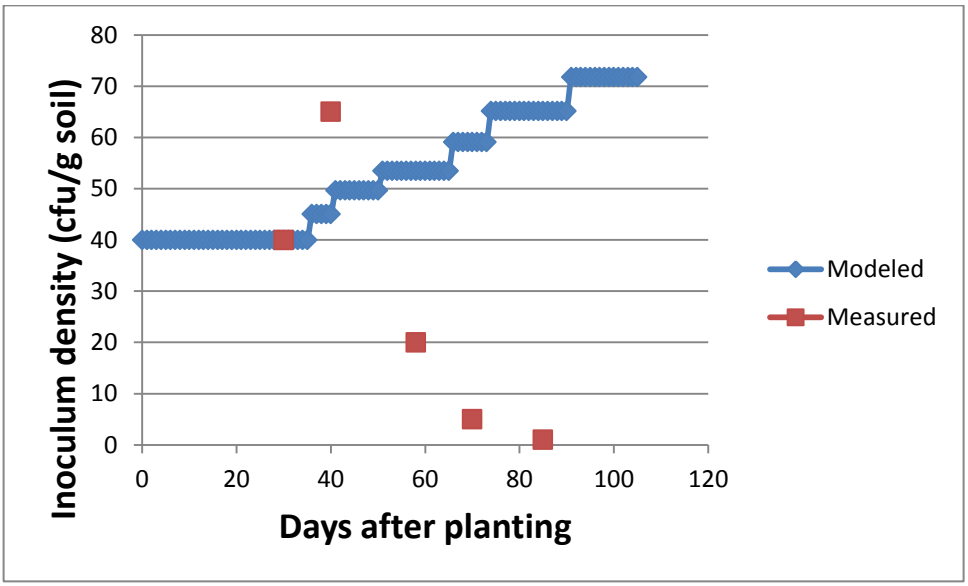

Figure 9. Measured and modeled inoculum density of *phytophthora capsici* the soil for drip irrigated bell peppers at Clayton, NC in 1989 with only six irrigations were applied in addition to rainfall and high disease inoculum.

The model and measured soil moisture for the two dimension soil water-plant-disease model had the same change in soil moisture throughout the growing season but the modeled over predicted the moisture content by 5 % compared to the measured values (Figure 10). This was similar to the results reported by Sammis et al. (2012) when comparing the modeled two dimension soil water content values averaged over an ellipsoid compared to point measurements from a soil core.

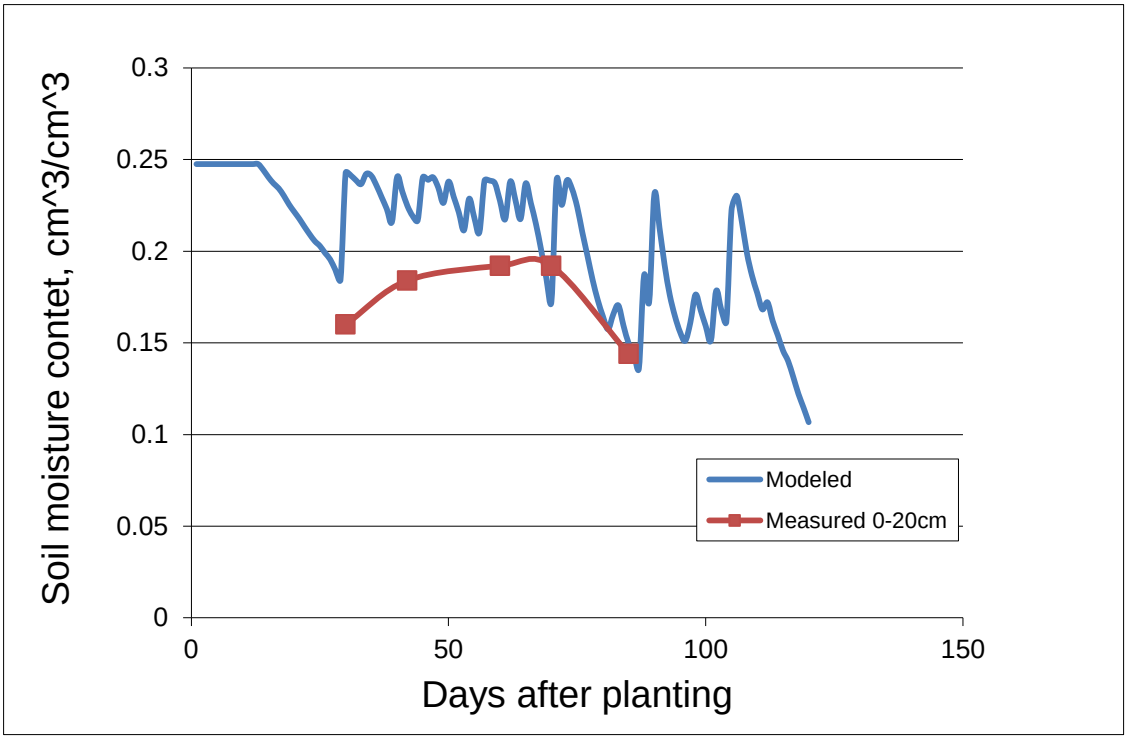

Figure 10. Measured and modeled two dimensional soil moisture content for drip irrigated bell peppers at Clayton, NC in 1989 with six irrigations in addition to rainfall and high disease inoculum. Model soil moisture is the second ellipsoid representing the soil moisture 21-42 cm location from the bell pepper row.

Conclusions

The chile pepper and bell pepper one-dimensional and two-dimensional irrigation scheduling models coupled to a *phytophthora capsici* disease model describe the progression of the disease under furrow irrigation, drip irrigation and drip irrigation, with rainfall supplying most of the water requirements of the crop. The model simulation of the *phytophthora capsici* disease progression points out the need for additional experiments where the *phytophthora capsici* concentration in the soil is measured along with the above-ground disease progression. Overwintering survival has a large impact on the model simulation and this was not measured. The values of the parameters in the model were estimates from the literature containing a large variation in numbers and these values need to be refined through additional field experiments because in some cases the parameter numbers were merely best guess values.

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