A crop growth-insect model used in field experimental design

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Abstract

A crop growth insect model can simulate the growing of a crop under different climate, water, nutrient, and insect stress conditions. Modeling crop and insect growth has application in the planning of field experiments. An object- orientated model has real world objects with software counterparts and each object consists of encapsulated data (attributes) and methods (behavior, and interactions). In this study, a cucumber spider mite model was developed to evaluate a proposed field research project. The crop insect growth model consisted of seven objects smaller models, which included a growth, water balance, and spider mite population model. Results of the model runs showed that the water irrigation levels of 75% and 50% of none stress Et had statistical difference in yield, but when low and high spider mite infestation were included in the calculation, only the 100% irrigation treatment had statistically lower yields due to spider mite damage. The model runs indicated that the spider mite infestation levels originally proposed for the field based experiments should be increased and the 0.75Et treatment removed.

Introduction

Combined crop growth and insect models can simulate the growing of a crop under different climate, water, nutrient and insect stress conditions to predict crop yield under different management practices. Consequently, models can help predict fundamental causal relationships in physical and chemical processes related to agricultural production on both small and large farms. Because field experiments are expensive and encounter unexpected abiotic and biotic variables, models can be used to refine experimental design and methodology, improving the results obtained from field based experiments. Once model predictions are field tested and proved correct, model results can be expanded, facilitating field management techniques for specific crops, pests and locations. Thus using the model to test proposed field experiments, reduces the number of experiments necessary to test each important variable. This is a more efficient approach to conducting agriculture research and rapidly applying the results.

A simple process orientated model that simulates a proposed field experiment is a tool that can reduce uncertainty of field experiments. Models can determine whether proposed experimental treatments, such as levels of irrigation, will produce sufficient change in a response variable, for example crop yield.

Model results can guide researchers during the design and planning phase of experiments by suggesting where experimental treatments may produce statically different results.

Cucumber are a short season specialty crop that grows anywhere in the United States. While large scale production of cucumbers is present in states such a Wisconsin, Michigan and Florida (WIFSS, 2017), cucumber are also grown in most backyard gardens and small diversified farms. Cucumbers are a vine crop that can be grown on the ground (bush varieties) or trellises in both fields and greenhouses depending on the variety planted and are hand-picked. The value of cucumber production across the United States was 204 million dollars in 2015 (USDA, 2017). The most common pests on cucumbers are cucumber beetles, spider mites, aphids, squash bugs pickleworms, and squash beetles (Clemson cooperative extension, 2017)

The two-spotted spider mites occur under hot dry weather conditions feeding on the contents of individual cells of the leaves with hundreds of mites per leaf. The damage can develop quickly and appears as pale yellow or reddish brown spots on the upper side of the leaf. The two-spotted spider mite has been reported infesting over 200 species of plants (Perry *et al.,* 1998) causing large economic loss when not controlled by IPM methods. To date, no economic IPM threshold has been developed for when to start spraying field grown cucumbers to control spider mite infestations using either inorganic or organic spraying protocols. Consequently, research is needed to evaluate the interaction of cucumber growth, water stress, and spider mite stress on cucumber yield.

Objective

A plant growth insect model was developed to assist in the design of an agricultural field experiment. The objective of developing the model is to use the model to estimate the impact of two spotted spider mites infestation levels , *Tetranychus urticae* Koch (Acari: Tetranychidae) on cucumber yield, growth and plant characteristics grown under different irrigation levels. The results of the model simulations will be used to refine the experimental methodology of the field experiment, increasing the probability of a successful experimental design.

Modeling Considerations

An effective simulation model must predict both abiotic and biotic system variables. Abiotic variables include climate, weather, rainfall, irrigation, while biotic variables may encompass insect, disease, or weed populations

A simulation model is expected to be a user-friendly decision support tool for irrigated or dry land crops and should include all programming “objects” necessary to grow the crop, using either mechanistic or empirical functional relationships (Acock and Reynolds, 1989). The model must contain objects of external stresses caused by lack of rainfall or irrigation, insects, or soil borne diseases. (Reynolds and Acock, 1997). An object orientated model has software counterparts to real world processes. Each model object consists of data (attributes) and methods (behavior, and interactions). Objects and the described variables in the object interact with each other as well as the environment. A benefit of simulation models are users can easily make changes in variables i.e. levels of insect infestation on a crop.

The best known group of plant growth models was developed by IBSNAT (International Benchmarks Sites Network for Agrotechnology Transfer). The model structure is a top down design, modularity, high cohesiveness, loose coupling (Hodges 1991). It was written initially using the FORTRAN language. These initial models developed into a group of sixteen crop growth models with one user interface called DSSAT (Decision Support System for Agrotechnology Transfer) crop models (Jones, et al., 2003).

However, a major problem with DSSAT models is the time and money necessary to develop a new crop and insect module. Consequently, crop modules were developed for the major crop but additional modules may never be available for specialty crops because of the cost and time of development. A second problem with the DSSAT model is the use of a large number of program languages including Python and Fortran, which restrict development of new crop models.

To overcome the need to learn DSSAT modeling languages and facilitate development of crop insect models for specialty crops, we used Excel. Excel is not a programming language; but a spreadsheet program written in C++. It is especially suited for quickly developing object- orientated plant growth models. Object oriented concepts should be separated from implementation in Object oriented languages. Consequently, even though excel is not considered an Object oriented Language the spreadsheet can be structured in the object oriented concept (Schroder, 2017) Each spreadsheet in a excel workbook can be set up in an object programming structure with the transfer of that objects output quickly and easily made to other objects. Graphical display of parameters and output can be made in the object or interfaced with a graphical display object resulting in the developer easily seeing the results of the methods programed in the object.

To use a crop growth- insect model to evaluate proposed agricultural field experiments, the process of designing field experiments must be compatible with the development of the model to simulate the proposed experimental design. The steps in a field design that must be simulated by the crop model are presented by Ganio (1997). They include a specific objective, a plan of action, field operation of the experimental design, and drawing conclusions from the field measurements. Finally, field observations are still needed to verify the management decisions made by the model.

Description of plant growth water balance spider mite model

The cucumber plant growth water balance spider mite model (flow chart figure 1) was developed to evaluate the plot design and measurements for the proposed research experiment described in the objective. The model was modified from a Pecan tree growth nitrogen model (Andales et al., 2006, Sammis et al., 2013) having a one dimension flood irrigated water balance model replaced with a two dimensional water balance drip irrigation module (Sammis et al., 2012) because the proposed cucumber experiment was to be drip irrigated. The alternating bearing and pruning, growth and nitrogen balance objects in the Pecan nitrogen model were turned off with a switch in the module. The model retained the soil temperature object from the Pecan model (Sammis, et al., 2013, Sharma et al., 2010) and soil water potential object added from a plant growth phytophthora disease model(Sammis et al., 2012b). The phytophthora disease object was turned off also with a switch because although phytophthora does attack cucumbers, in the proposed experiment phytophthora diseases was assumed to be not present in the soil. After conducting the experiment, if phytophthora disease is observed to be present then this object will be turn on when comparing experimental results to modeled results. A reference Et object described below was develop because the original models acquired the reference Et data from the internet at the location of the experiment. The spider miter growth model described below only needs weather data and calculates the spider mite stress function from that data based on two regression models of low and high spider mite infestation from experiments conducted in the field (Atanassov, 2014), and a population spider mite object that predicts spider mite infestation levels which are higher than field experiments in the literature described by Rabbinge, and Hoy (1980).

The attributes or inputs of each object are part of the parameterization of the object and move with the object when the object becomes part of another plant growth disease model

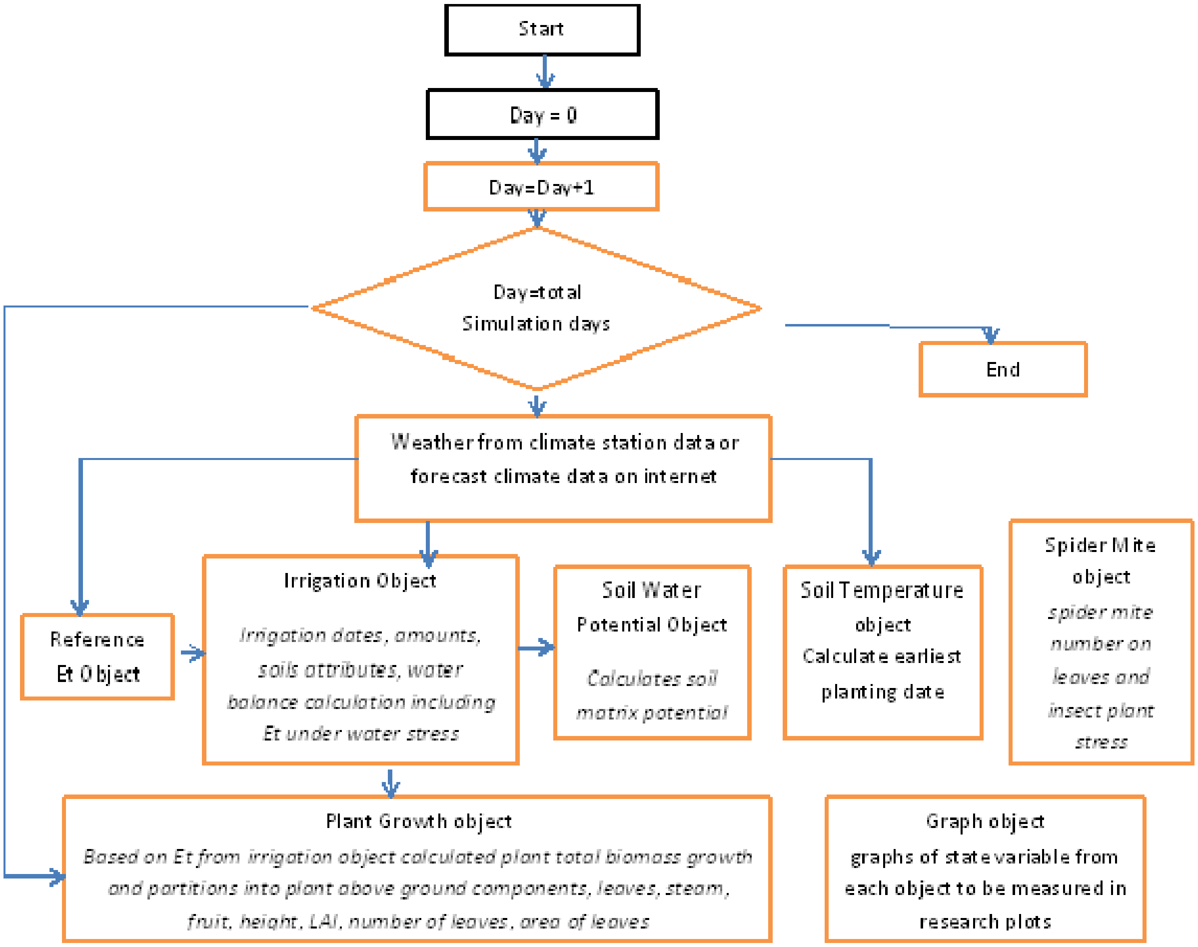

Figure 1 Flow chart for cucumber plant growth spider mite model.

Weather Data

Measured weather data at the proposed research site in Albuquerque NM for the year 2015 was acquired from the internet (Albuquerque Weather Data. 2017). The weather data is needed by the reference Et (Etr), the soil temperature, the irrigation and the spider mite objects. The weather data on the internet was in English units and was converted to metric units for calculation in the Etr object requiring those units. The other objects used metric units in the calculations.

Reference Et (ETr) object

The object was developed by equations described in (Allen et al., 2005) with the required climate input of maximum and minimum temperature and humidity, average wind speed, and solar radiation acquired from automated climate station data on the internet. The output of the object is ETr referenced to a tall crop (alfalfa) for use in calculating Et in the irrigation object. The output is in units of mm/ day but is converted to inch/ day for use by the Irrigation object.

Irrigation Object

The full description of the two dimensional water balance equations in the irrigation object are presented by Sammis (et al., 2012) but several parameters are unique to the experimental design of cucumbers and are listed in Table 1. The third order polynomial describing the crop coefficient (Kc) for non- stress cucumber plants in units of growing degree days (GDD) over the growing season is described equation 1.

$$\text{Kc} = 7.6\text{ E-3} + 3.30\text{E-3}*\text{GDD} - 1.00\text{E-.6}*\text{GDD}^{\wedge}2 - 2.00\text{E-10}*\text{GDD}^{\wedge}3 \qquad (1)$$

The coefficient of determination is 0.99 and the GDD with a base of 50 degree F was from Perry (et al., 2016) and the Kc values for specified GDD values came from FAO 24 (Doorenbos and Pruitt, 1977)

In the irrigation object the units of input and calculations are in English units because the original object was developed for use by farmers. Consequently, the GDD and kc has units of F. The Kc equation was derived by Allen (et al, 2017) which gave the kc values for different growing season periods and GDD days for those periods was given by Perry and Wehner (2016)

Object parameters	Parameter Description	Units	Reference
Maximum rooting depth	24	Inches	Veggie harvest 2016
Root growth rate	0.04	Inches/GDD	
Water holding capacity	2.5	Inches/ft	Spectrum Technologies 2016
Saturated water holding capacity	3	Inches/ft	Spectrum Technologies 2016
Beginning root depth	4	Inches	
Slope of water stress function	2		Allen et al 1988
Intercept of water stress function	0		Allen et al 1988
Row spacing	39	Inches	
Management allowed depletion %	50	For computer scheduling irrigation	Allen et al 1988
Irrigation depth for scheduled irrigations	1	Inch	
Management allowed	99	For specified	

depletion (MAD)		irrigation dates and amounts	

Table 1 Input parameters in irrigation object specified at top of excel spreadsheet in cucumber growth model workbook.

Plant Growth object

The plant growth object was simplified from plant growth object in the pecan nitrogen model and only includes the plant components listed in Table 2.

Object parameters	Parameter description	Units	Reference
Date	Days during the growing season	m/day/year	
Plant Growth (PG)	PG= ET(irrigation object) * Water use efficiency (input in object)	Kg/ha/day	
Growth per individual plant (GP)	GP= PG/Plant number/ha(input in object)	Kg/plant/day	
Leaf growth per plant (LG)	LG=PG* Leaf allocation (input in object) set to 0 after crop coefficient from irrigation object reaches 1.08	Kg/Plant/day	
Plant stem and branches(PSB)	PSB= PG* stem-branch allocation (input in object)	Kg/plant/day	
Plant stem and branch diameter accumulative	Calculated from PSB accumulative and wood density (input in object)	m/day	
Plant Height accumulative	Calculated from PSB accumulative and height to radius(input to object)	m/day	
Leaf area per plant (LA)	LA= ∑LG* specific leaf area(input to Object)	m^2/plant	
Leaf area index (LAI)	LAI= LA/plant spacing	None	
Accumulative yield when leaf growth equals 0 (AY)	Ay= ∑PG if LG=0	Kg/ha	
Leaf number (LN)	LN=LA/ leaf size (input to object)	Number	
Water Use Efficiency	15	Kg/ha/mm (input)	Yaghi et al., 2013
Wood density of stem (cotton)	185	Kg/m^3	Gagandeep Kaur Sidhu and Sandhya. 2015
Initial plant radius	0.0002	M	

Initial plant height	0.001	M	
growth to leaves or fruit (cv. Modumoti)	0.75	Decimal	Haque et al., 2009
Crop coefficient when allocation of growth goes 100% to yield	1.08		
Fruit dry weight (cv. Modumoti)	0.1	Kg	Haque et al., 2009
Specific leaf area (22 leaf types)	21	m^2/kg	Baret, Frederic and T Fourty. 1997
Harvest Date	7/27/2015		
Leaf area size (cv. Modumoti)	0.037	m^2	Haque et al., 2009
Number of plants/ha	33333		
Row spacing specified in irrigation object	1	M	
Height to stem ratio (variety dependent)	100		Haifa 2017

Table 2. Description of plant growth parameters and inputs constants in the Object plant growth calculations.

Spider mite object.

Spider mite (Acari: Tetranychidae)) infestations on cucumbers cause reductions in biomass, transpiration, photosynthesis ion, dry matter partitioning, chlorophyll reduction, and increases shedding of immature flowers (Park and Lee, 2002). These effects are simulated in the model by the interaction between spider mite number per leaf and the impact on evapotranspiration in the irrigation object which in turn reduces the components of the growth object. To develop the spider mite object, empirical stress function were developed from an experiment reported in the literature (Park and Lee, 2005**)** on the effect of spider mite numbers per leaf on cucumber yield. Figure 2 shows the spider mite population increase over time for different initial infestation levels on Chun-Gwang Baekdadagi cucumbers (Park and Lee 2005**).** The time day based data by Park and Lee et al. (2007) was converted to a growing degree time base using a base of 50 degree F (NC extension 2016). Two regression functions based on growing degree were developed for a low and high infestation level at fifth leaf (Figure 3 and 4). A spider mite population model (figure 4) was also develop to generate spider mite counts (Rabbinge, and Hoy. 1980) that were higher than the high infestation level for the field experiment after the initial runs of the model showed that the field experiment spider mite infestation was too low to separate water stress from spider mite stress under large water stress conditions (Et equal to 0.5 Etns). Spider mite infestation levels are reported in the literature as both spider mites per leaf and spider mites per plant, and the spider mite object calculates both spider mites per plant and per leaf.

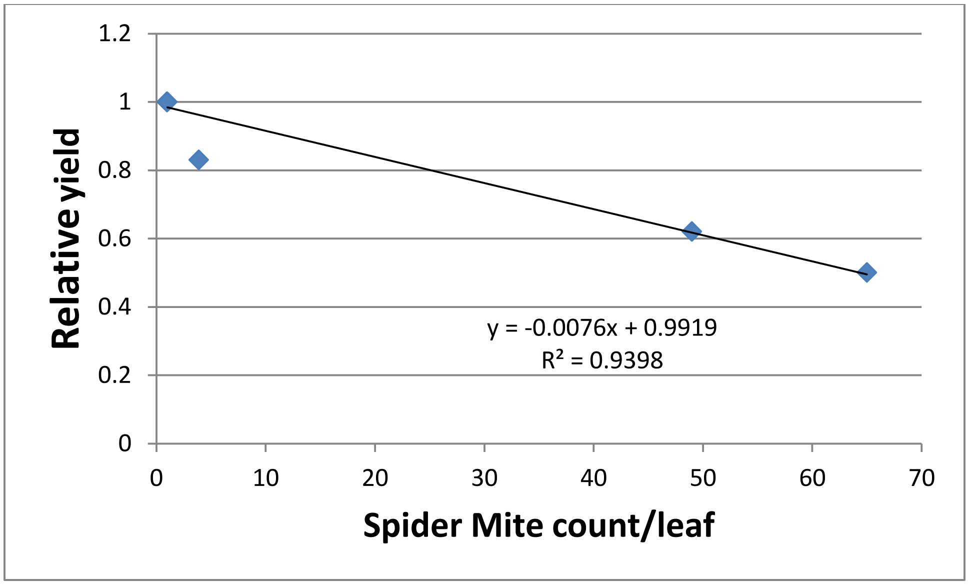

Figure 2. Spider mite count impact on plant evapotranspiration rates and plant growth

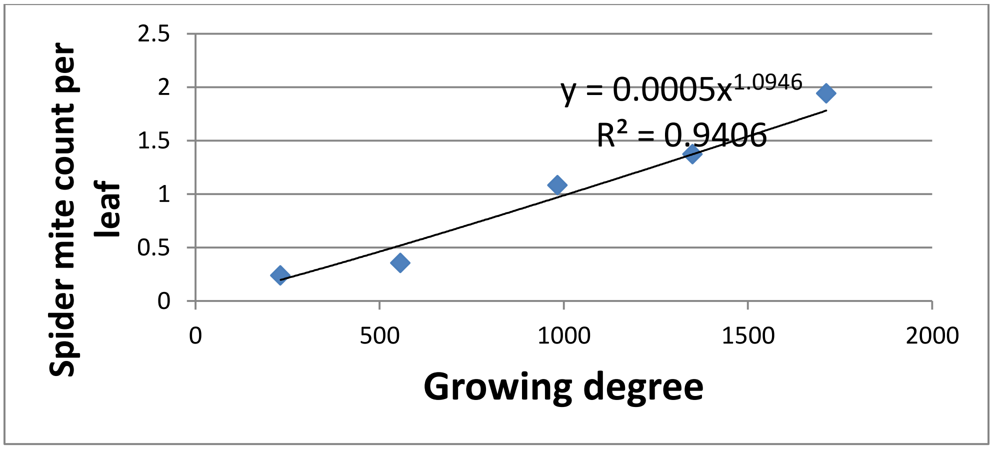

Figure 3 Spider mite count increase with growing degree days with a low initial infestation rate of 98 spider mites per plant at 5 leaf or 20 mites on one leaf at 5 leaf stage

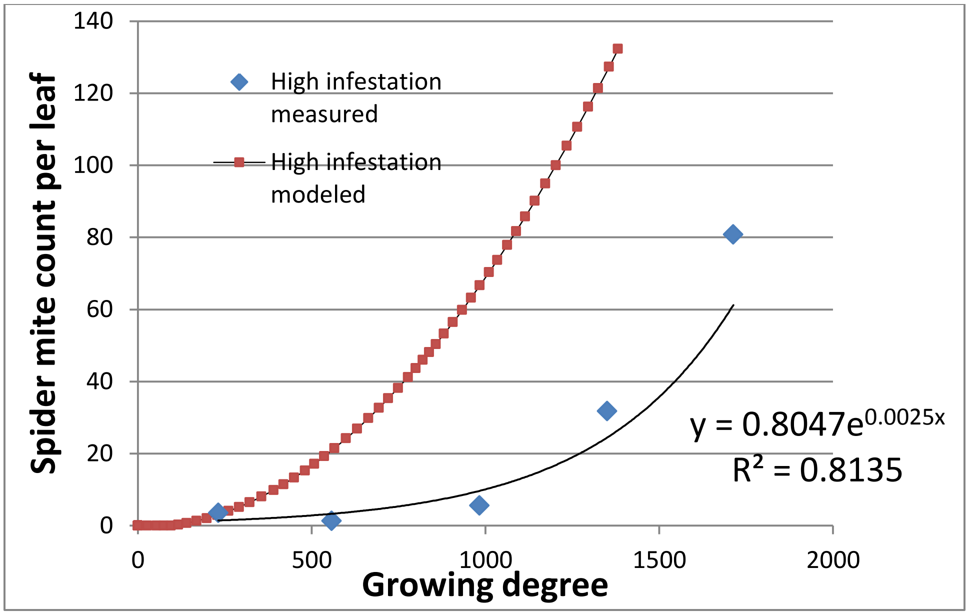

Figure 4. Measured and modeled using a regression equation of spider mite counts increase with growing degree days with a high initial infestation rate of 390 spider mites per plant at the 5 leaf stage and the population spider mite model with an initial high infestation.

The problem with spider mite infestation when a single leaf or two is infested with spider mites is that the population increase rate of the spider mites depends on the survival rate of the infestation. In the greenhouse experiment in the low infestation level the spider mite number per leaf never reached the initial infestation level and for the high infestation level it took the entire growing season to reach the initial infestation level on all leaves.

The literature indicates that with these infestation levels the spider mite number should have been a lot higher than measured because the report spider concentration after one to two generations (15 to 30 days or 250-500 GDD after infestation) on all leaf on a plant should be between 1 to 1.7 time the initial infestation level when two leaves are infested at 5 leaf (Nyoike, and Liburd. 2013, Reisigi and Godfrey, 2007)

An assumptive was made that Et and growth of the cucumbers were affected identical to the reported yield reduction in the field experiment. As second assumption was that evapotranspiration is reduced in a multiplicative model of soil moisture and spider mite stress (equation 2) similar to the pecan nitrogen stress model where Et is reduced as a multiplicative function of soil moisture and nitrogen stress (Sammis et al., 2013). This assumption needs to be verified by comparing the model results to measurements in the proposed experiment.

$$Et = Etns * Ks * Kspider \qquad (2)$$

Where: Etns=is the evapotranspiration under non stress conditions
Ks= soil waster stress function (varies between 0 and 1)
Kspider= spider mite stress function (varies between 0 and 1)

$$Etns = Etr * Kc \qquad (3)$$

Where : Etr= reference Et for a tall crop (alfalfa) (Allen et al., 2017)
Kc= crop coefficient based on growing degree days (Allen et al, 2017)

The spider mite object calculates the impact of spider mites. It uses a specified coefficient of variation for 0, 1, and 2 standard deviations from the mean spider count predicted by the regression model for high spider mite infestation and the spider mite population model to simulate the spider mite variation expected in the proposed experiment. The model user selects the different coefficient of variations and the model calculates the different spider mite counts. The object input data also has a switch, selected by the user, selecting zero, high regression model or high population spider mite infestation levels in the experiment. If the standard deviation is set to 0 no variation in the spider miter count from the predicted regression and population model will occur.

Materials and methods

Initial Plot design

The model was used to evaluate an experimental design to determine the interaction of cucumber growth, water, and spider mite stress on cucumber yield. For the proposed experiment, the variety selected was Green Finger cucumber, which is a 60 day maturing slicing variety. The experimental design after modification by use of the model will be a split plot design with irrigation as the main plot and infestation levels of spider mites as the subplot. Three irrigation levels will be tested including full irrigation or the control and 2 levels of deficit irrigation 25% and 50% of the control. Spider mites will be infested at 3 levels including 0, 100 and 400 mites / plant. The research plots will be located in Los Lunas NM, 25 km south of Albuquerque NM on a clay loam soil.

Weekly plant measurements will be collected on plant height, flower number, overall plant area cucumber fruit number, and weight. Mite counts, soil moisture, and canopy temperature will also be recorded on a weekly basis across treatment levels. Plant measurements and mite counts will be made on the three center plants of each plot.

Each plot will be 1 m wide and 2 m long with 4 m between each plot. The distance between blocks (n=4) will be 10 m. The cucumber plants will be planted in the center of the plot on 30 cm spacing containing 5 cucumber plants / plot. Plots will be seeded in mid-May.

The plots will be drip irrigated with an above ground drip system. The irrigation system will be operated every Monday, Wednesday and Friday. The amount of water applied will be determined from the previous week's calculated non-water stress Et applied over the three irrigations times. Irrigation amounts will be 1.0 ET ns for the control, 0.75 Et of the control, and 0.50 Et of the control. Drip irrigation emitters will not be installed in the space between plots.

Calibration procedure

The model parameters for cucumber growth were calibrated by using results from the literature (Tables 1 and 2). The cucumber model was run for the control, no water stress or spider mites, from May 18 to harvest July 20 2015. A frost could still occur after May 18 but the probability would be low (Farmer's Almanac 2016). Cucumber should not be planted until the soil temperature is above 65 degrees F (Veggieharves, 2016) and the soil temperature object predicted that on May 18 2015 the soil temperature would be 77 degrees F. With this planting data, the model predicted a 73 day growing season from planting or transplanting to harvest before the plant started to senesce. Accumulative GDD of 1084 corresponds to an early season maturing slicing cucumber cultivars that require 1,154 GDD. (NC extension 2016)

Results and discussion

The model predicted a cucumber yield of 2338 kg/ ha of dry matter. Divide the yield by 1.12 to calculate lb/ac. Converting this to wet weight assuming a cucumber moisture content of 96% (HealthyEating, 2017), the yield would be 58400 kg/ha. Commercial drip irrigated cucumber yield in California range from 56000 -89600 kg/ha after unmarketable cucumbers are pulled off the plants and left in the field (Schrader et al, 2017), which is within the range predicted by the model under no water or insect stress conditions.

Plant height was measured for fully irrigated cucumbers (cv. Hoshinokagayaki) in the field at Yamaguchi University, Japan (latitude 34.809 N, longitude 131.827 E and altitude 17 m above sea level) by Yuan (et al., 2016) and compared to the model growth height of cucumbers at Albuquerque, nm (Figure 5). The average air temperature during the spring growing season in Japan was 21 degree C in Japan compared to 23 degree in Albuquerque, NM.

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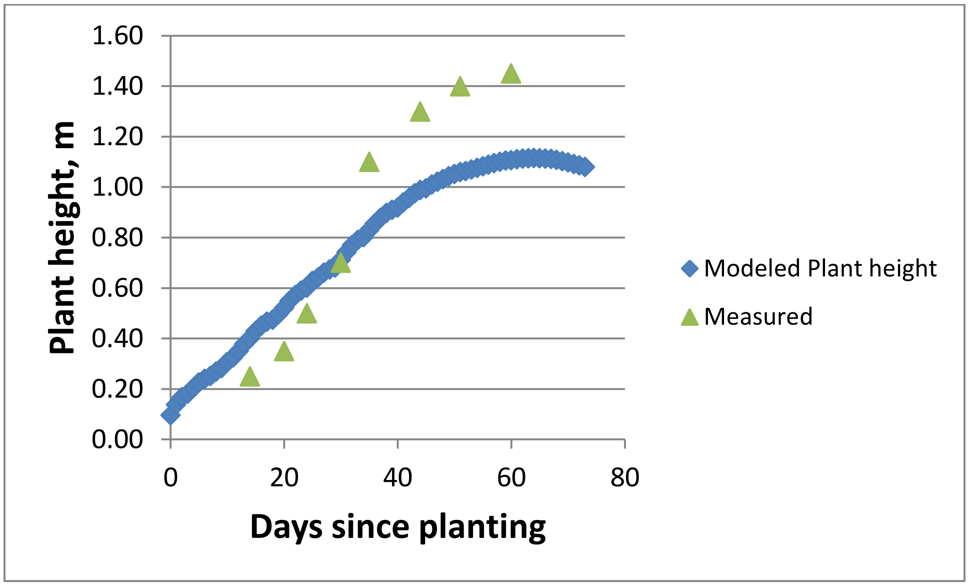

Figure 5. Measured cucumber growth height in the spring by Yuan (et al., 2016) and modeled height under no water or insect stress.

Albuquerque NM is at 35.1 N Longitude, Latitude 106.6 W and at 1614 m elevation, which positions Albuquerque at a higher longitude and elevation compared to Japan. . Despite the difference in longitude and elevation, the modeled and measure heights are very similar indicating that the growth and irrigation objects predicted reasonable results compared to measured cucumber growth data. However, the height to stem ratio is variety dependent (Table 2), meaning the results would have been different with a different height to stem ratio input parameter in the growth object.

The total biomass per plant was modeled as 160 g and the measured value was 100 g (Yuan et al., 2016).The 95% confidence interval was on the high side of the measurement at 140 g. Again different parameterization of the growth object could result in this amount of variability.

The model was run to simulate the application of an irrigation of 1 inch whenever the management allowed depletion in the soil water reservoir reached 50%, for the 1.0 Et treatment. This resulted in irrigation every other or every 3 days. When the 1 inch was applied when the 0.75 Et plots were irrigated at a management allowed depletion level 80% with one inch of irrigation, the time between irrigation increased to one every six days. The amount of water applied for the 1.0Et treatment was 25 inches compared to the 10 inches of irrigation applied to the 0.75 Et simulation treatment.

The relative total biomass for the 0.75 Et simulation produced by the model was 0.74 compared to relative total biomass of 0.65 measured in Japan when the irrigation amount in the field experiment was reduced to 74% of the non-moisture stress plots (ETns).

Yuan (et al., 2016) did not specify the irrigation dates or amounts; therefore the model run is only an approximation of the experiment conducted by Yuan (et al., 2016). However, if the irrigation object interacting with the growth object were not close to conditions for the experiment in Japan, the difference of the total plant growth under full and 75% irrigation would not differ by only 9%.

The difference in literature and model values for cucumber growth response also demonstrates the need to parameterize a cucumber model for the variety that is to be grown in the future field experiment. The need to model the correct variety has been demonstrated by the DSSAT group of models compared to measured value in the field Tsuji (et al., 2017). The plant parameters in the growth DSSAT model are unique for different varieties. The model proposed here will improve the methodology and experimental design for a field trial. The cucumber model as demonstrated by the above comparison does satisfactory predict cucumber growth under different water stress conditions. Verification of the model under spider might stress is needed because only one experiment was available from the literature to develop the spider mite functions in the model.

The literature did not have growth and insect parameters for the selected cultivar to modeled in Albuquerque NM but Table 1 and two used the values derived for varieties grown in those field experiment reported in the literature. Most of the cucumber varieties used in the parametrization of the model were vine types and a vining variety will be was selected for the field experiment that it is adapted to the climate in Albuquerque, NM but the variety will be different that those reported in the literature. Consequently, the model may not predict the same results that will be observed in the proposed future experiment because the model parameters may not be correct for the selected variety. The model simulation represents the average response of vine cucumbers varieties to water stress and spider mite infestation levels.

The model was run for different levels of moisture stress and spider mite infestation with the standard deviation of the spider mite count set to 0,+- 1 and +- 2 to generate the results of the split plot experiment (Table 3). The model simulations represent the expected effect on yield and total plant biomass under different levels of spider mite infestation and irrigation at the end of the growing season. The model was run for three levels of spider mite infestation and a control. However, the lowest level of spider mite infestation (4 spider mites per leaf at 5 leaf) showed no difference for different irrigation treatments. Consequently the model results are reported for only the high infection level of 390 spider mites per plant at fifth leaf resulting in a final infection level of 60 spider mites per leaf using the regression model in figure 4 and the high infestation level modeled by a population model resulting in a final infestation level of 135 spider mites per leaf (Figure 4). The field experiment spider mite population at the final measurement was 80 spider mites per leaf (Figure 4). However, there is a large standard deviation associated with the measurement.

To model a higher level of infestation because no field experimental results were in the literature for a high level of spider mites population, a spider mite population was generated where the spider mite level at the end of the growing season was double (135 spider mites / plant) the highest field experiment (Figure 4). We used a spider mite population model parameterized and described by Reisig, and Godfrey (2007) to model the effects of spider mite stress at this higher level of infestation. The initial model spider mite concentration was 1 spider mite per leaf or 0.64 females per leaf. However, the survival rate is 100 % in the model with no spider mite predators resulting in the high final spider mite count at the end of the growing season.

Consequently, based on the model runs, the field experimental design should have two treatment levels of spider mite infestation: 1. a high 390 spider mites per plant inoculated again at the 5 leaf stage resulting in a final spider mite count at harvest of 60 spider mites per leaf; also 2. a doubled spider mite inculcation level in the field (780 spider mites per plant) which should result in a spider mite count of 135 spider mites per leaf at harvest (Figure 4). The final spider mite counts in the field experiments in the literature were often less than the initial inoculation level. This is due to the problem of determining the sex of the number of spider mite infestations levels. Male's due not produce the next generation. Also, survival of the initial spider mite infestation level is not 100% due to predators.

Because of the poor relationship between initial inoculation levels and final spider mite count at harvest, the spider mite count in any field experiment must be measured after the second generation to determine what final level of infestation will be achieved in the experiment. If the second generation spider mite counts are two low compared to previous field experiments then the experiment predicted by the model will fail.

The model simulation was run for yield and biomass for the high and modeled infestation level at the end of the growing season (Table 3). The model was run for an irrigation water level of 100% of seasonal evapotranspiration (1.0 ET) representing non water stress conditions and for runs where the seasonal Et was 0.75 and 0.5 ET with uniform stress throughout the growing season with no spider mite infestation. The model was then run for a high spider mite infestation level using the regression model) and a spider mite population model set to initial conditions that generate a final spider mite count of 135 spider mites per leaf at harvest.

The model predicted that yield differences would be detectable from the control (no spider mites) at the non-water stress Et level (95 % confidence level based on a Duncan multiple range test) (Table 3) if the two levels of spider mite infestation followed the empirical high infestation level (60 spider mites/leaf) and the population model infestation levels (135 spider mites per leaf (Figure 4). The irrigation treatments of 0 0.75 Et level were statistically the same at the 90 % confidence level with final spider mite counts at 60 and 135 spider mites per leaf. When the irrigation stress was increased to 0.5 Et and the spider mite numbers increased to a final count of 135 spider mites per leaf at the end of the growing season, the yields decreased to 456 kg/ha (Table 3). The results in the model depend on the spider mite stress function presented in Figure 2. If this function is different for different cucumbers varieties then modeled yield would be different if a field experiment was not planted to Chun-Gwang Baekdadagi cucumbers

The cucumber biomass in Kg/ha was the same at the 100 % and 75% Et irrigation treatment for final spider mite counts of 60 and 135 spider mites when comparing biomass yield between the two spider mite levels but the biomass was lower for the two spider mite infestation levels for the 50% irrigation treatment. The model predicted that the spider mites had more impact on cucumber yield than cucumber total biomass. Consequently, it would be more important to measure yield at the end of the field experiment than total biomass given limited manpower resources.

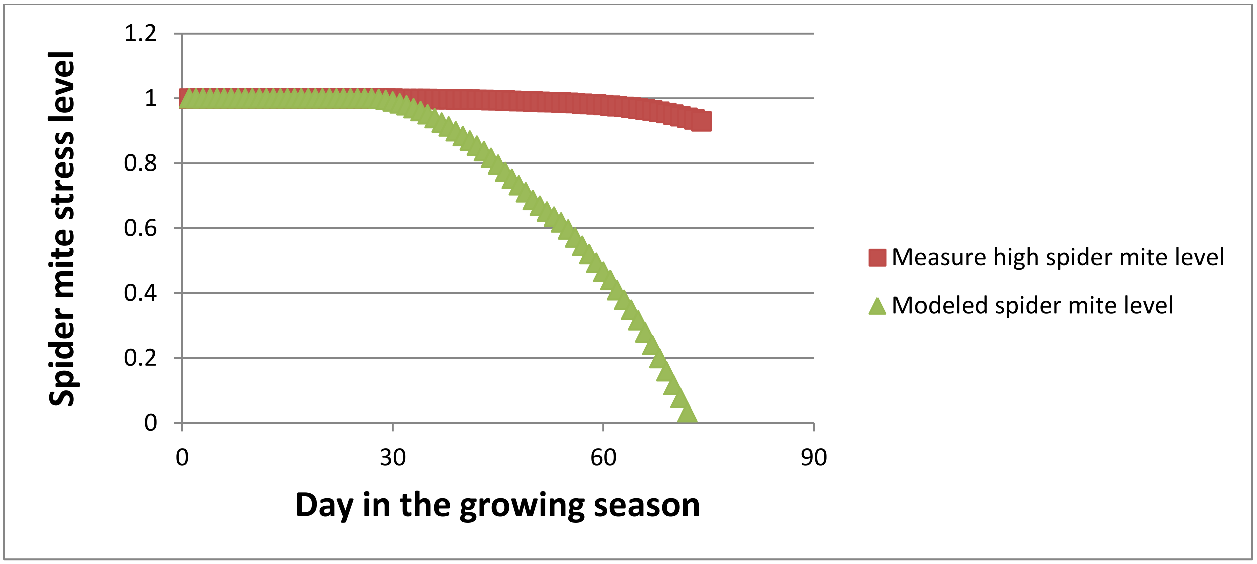

Figure 7 Spider mite stress reduction level in growth and yield for measured and simulated spider mite concentration using the measured and simulated spider mite counts in figure 4.

Spider mite infestation level	Model prediction of Cucumber Yield kg/ha			Model prediction of cucumber biomass kg/ha		
	Irrigation treatment 100% Et 360mm	Irrigation treatment75% Et 269 mm	Irrigation treatment 50% Et 183 mm	Irrigation treatment 100% Et	Irrigation treatment75 % Et	Irrigation treatment 50% Et
None						
Mean	2346 a	1727 abc	1017 abc	7772 a	5773 ab	3704 ab
High infestation 60 spider mite/leaf at harvest						
Mean	2266 ab	1708 abc	1004 abc	7556 a	5595 ab	3678 ab
Standard Deviation	25	7	4	53	100	8
Coefficient of variation %	1.1	0.38	0.41	0.7	1.75	0.22
Modeled infestation						

135 spider mites/leaf at harvest						
mean	744 b c	719 bc	456 c	4721 ab	3679 ab	2580 b
Standard deviation	507	479	329	1852	992	652
Coefficient of variation %	68	67	72	39	27	25

Table 3 . Modeled cucumber yield and biomass under three irrigation levels and two spider mite infestation levels, one measured (high infestation) and one modeled infestation.

Given limited time and financial resources, the ground truth measurements that should be collected are ranked in Table 4 based on the output of the cucumber growth insect model and the most easily measured parameters based on the simplicity of the measurements, time involved in taking the measurements, and need of the measurements to verify the cucumber growth insect model.

To verify the plant growth insect model, a number of plant growth and mite population measurement would be needed. The frequency of how often field variables should be collected is suggested (Table 4). In addition, the data from field collected variables that are needed to verify the plant growth insect model are ranked in term of their importance: high, medium and low priority (Table 4)

Object	Value predicted by Model	Original experimental measurements frequency	Proposed experiment measurements based on model output.	Priority of change, high medium , low
growth	Plant height (m)	none	Weekly measured by hand or hr by data logger	High, easy to measure
Growth	Plant biomass	none	End of the growing season	medium destructive sampling cannot be done during the growing season
Growth	Cucumber fruit yield	Weekly	Same as first design	
Growth	Cucumber fruit number	weekly	Same as first design	
Growth	Leaf number	none	weekly	High, count leaf number
Growth	Leaf Area Index	None	End of growing season	Medium time consuming to measure but only one measurement
Growth	Plant wood density	none	End of Growing season	Low, but easy to measure
Growth	Percent plant	None	End of the	Medium, time

	material as leaves fruit and stems		growing season	consuming to measure but only one measurement
Growth	Specific leaf area	none	Middle of growing season	High, need leaf area meter but only one subsample from plots
Growth/irrigation/ spider mite	Leaf damage index due to spider mite	Weekly	Same as first design	High, visual, pictures and hand held spectrophotometer
Growth /Irrigation	Plant Spacing	At planting	Same as first design	High
Irrigation				
Irrigation	Soil texture with depth	none	Before Planting	High, take soil samples to lab
Irrigation	Climate data	None	Hourly	High, automated climate station
Irrigation	Evapotranspiration	None	Daily	Low, costly and time consuming
Irrigation	Soil moisture	weekly	Daily	High ,use soil moisture sensor different depths and data logger
Irrigation /spider mite	Crop water Stress Index. stress caused by water and spider mite damage	Weekly, from canopy temperature	Every 1 minutes	High Infrared sensors connected to data logger to measure canopy temperature
Spider mite				
Spider mite	Spider mite count on leaves	Weekly	Same as first design	High , take pictures and count number using pictures
Spider mite	Plant Stress	weekly	Same as first design	High, Derived from leaf damage index
Soil Temperature	Soil temperature with depth	None	Hourly	Low, soil temperature sensors connected to data logger.

Table 4. Comparison of proposed field measurements in original experimental design compared to additional metrics that could be collected to improve final data set.

Conclusion

The simulated experiment results shows that the water stress overrides any impact that spider mites might have and that it requires a high spider mite infestation level to detect a change in cucumber yield compared to the non-water stress treatments. The experimental design should drop the 0.75 Et treatment and increase the spider mite infestation levels from the initial design based on previous maximum high infestation level experiments. Based on the simulation model the final infestation level needs to be 2 time the high field infestation level reported in the literature to have an impact on detectable yield at the end of the growing season.

A model has a large number of simulated output measurements that cannot be duplicated in the field experiment because of a limitation of man power, money and time. But as many measurements as is possible should be conducted in the experiment to validate a growth insect model and provide experiment data for future model development and field crop management decisions.

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