Spatial Ecology and Remote Sensing in the Precision Management of *Tetranychus urticae* (Acari: Tetranychidae) in Peanut

Erin L. Holden

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Advisory Committee:

Dr. Carlyle Brewster, Chair
Dr. D. Ames Herbert, Jr.
Dr. Edwin E. Lewis
Dr. Roger R. Youngman

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(ABSTRACT)

The twospotted spider mite (TSSM), *Tetranychus urticae* Koch, is a common polyphagous pest in peanut agroecosystems. The mite has caused serious economic losses to peanut farmers in the Virginia-Carolina area, where approximately 20% of the peanuts are produced annually in the United States. Peanut farmers depend on pesticides to control mite populations. Because TSSM has developed resistance to many acaricides and there are restrictions on the use of pesticides, an alternative approach, such as precision pest management, is needed that would reduce the amount of pesticides that must be applied. This study was initiated to determine whether precision pest management is a feasible management strategy for use against TSSM populations in peanut. Two requirements of the precision management approach are that maps of the spatial distribution of TSSM populations can be developed and the pattern of distribution changes little over time to allow management strategies to be implemented.

To this end, a study of four commercial peanut fields located in two counties of southeastern Virginia was conducted to characterize the spatial distribution of TSSM populations. Intensive sampling of TSSM populations was conducted within each of the fields. The results showed that there was a general increase in TSSM populations during the early phases of sampling. Fields with low densities of TSSM populations had a spatial distribution that was either uniform or random; in fields with relatively higher densities, TSSM populations usually were aggregated. Little or no change in the spatial distribution of TSSM occurred from week to week in all fields that were sampled. Where changes in the distribution were observed, these were apparently caused by the application of a pesticide by the grower.

The study also looked at remote sensing technology as an alternative to intensive sampling within peanut fields. Research was conducted under laboratory conditions to determine whether damage caused by feeding TSSM could be detected spectrally before symptoms become visible. The study showed that after eight days leaves of peanut plants subjected to low soil moisture levels had significantly lower reflectance ratios (mean = 9.4766; $\alpha = 0.05$) than plants given medium (mean = 10.0186) or high (mean = 10.5413) soil moisture levels. After 10 days, there were significant differences ($P < 0.05$) in the mean reflectance ratios of peanut leaves exposed to four levels of spider mite densities (0, 5, 10, 20 mites/leaf) and the three levels of soil moisture. However, no significant interaction was observed between soil moisture and spider mite density ($P = 0.8710$). The mean reflectance ratio for 20 TSSM per leaf was found to be significantly lower than 0, 5, and 10 TSSM per leaf at all levels of moisture (low, medium, and high). The results suggested that remote sensing could be used to detect and map plant damage caused by feeding of spider mites before visual symptoms of damage are observed.

The study also attempted to develop a platform for using remote sensing technology in the field. An Unmanned Air Vehicle (UAV) was evaluated that carried a remote sensing system. The UAV remote sensing system was flown over peanut fields where it captured images, which were analyzed to show the spatial distribution of plant stress. Further studies are needed to relate the distribution of plant stress or damage observed by the UAV with the distribution of TSSM densities within peanut fields. Once this has been accomplished, low-altitude remote sensing could be used as an alternative to sampling for building maps of the spatial distribution of TSSM populations for precision pest management.

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Chapter 1

Introduction and Review of Literature

INTRODUCTION

Mites have only been important pests of agriculture since World War II. In the 1940's and 50's a worldwide epidemic of spider mites occurred that involved several different species including the twospotted spider mite (TSSM), *Tetranychus urticae* Koch (Mitchell 1973). The introduction of synthetic organic pesticides was thought to be a major contributing factor in the new role of mites as pests. The TSSM has over 150 host plant species and is one of the most widely studied organisms (Jones 1990). Some of its more important host plants include cotton (Wilson et al. 1983), corn (Pickett and Gilstrap 1986), soybean (Klubertanz et al. 1990), raspberry (Roy et al. 1999), apple (Pratt et al. 1998), hop (Strong et al. 1997), almond (Youngman et al. 1986), and peanut (Brandenburg and Kennedy 1982).

Peanut production in the Carolina-Virginia area has often been affected adversely by the TSSM. Most of the damage occurs during periods of hot, dry weather, which is usually from July to September (Margolies and Kennedy 1985). The mite injures peanut plants by feeding on the cells of leaves, which compromises the photosynthetic process. In many cases, pesticides are applied too late and the ensuing yield and economic losses are significant (Herbert pers. comm.). Pickett and Gilstrap (1986) believed that the timing of pesticide application could be improved with accurate estimates of spider mite population densities and knowledge of their dispersion and invasion patterns. This type of information and information on the within field spatial distribution of TSSM also are needed for developing precision management programs for this pest in peanut.

The practice of precision pest management (PPM) falls into a new area of agriculture known as precision agriculture (precision farming or site-specific farming) (National Research Council 1997). At the core of precision agriculture are many technological advances, which are used to optimize a crop's potential and decrease the level of management inputs, such as pesticides, in the environment. Maps that characterize the spatial distribution of within-field variables such as pest populations are the most important components in the precision approach to agriculture. Technologies like the Global Positioning System (GPS) enable farmers to develop and use these maps with their map-sensitive farm equipment so that they can target only those areas within the field where problems have been detected. Within-field variables such as soil nutrient levels, weeds, and crop yields that are spatially static are relatively easy to map. However, constructing maps of within-field variables such as insect and mite populations is more difficult (Weisz et al. 1995). This is because existing methods for mapping the distribution of these spatially dynamic variables are complicated, labor intensive, and uneconomical. Therefore, for precision arthropod pest management a practical, efficient, and cost-effective way of mapping these within field variables is needed, which perhaps requires a more technological approach than previous management methods.

This research project was undertaken to develop an understanding of the spatiotemporal population dynamics of the TSSM for the precision management of this pest in peanut fields in the southeastern region of Virginia. The project integrates entomological science and spatial ecology with remote sensing and precision agriculture technologies to understand the changes that occur in the spatial distribution of TSSM populations within peanut fields. Our goal is to develop a method for detecting and mapping the distribution of this pest. The study begins with a review of the literature on the TSSM and of the technologies that will be used to study the spatial and temporal dynamics of the mite in peanut.

REVIEW OF LITERATURE

Origin, Distribution, and Taxonomic History of TSSM

Man has been aware of animals in the order Acari since 1550 B.C. Greek writings, for example, contained several references to mites and ticks (Jeppson et al. 1975). Of the mite species that attack plants, spider mites are probably the most common. One of the most widely known spider mite species is the TSSM (Helle and Sabelis 1985a).

The TSSM, like all spider mites, belongs to acarine group III, the Acarifórmes, suborder Prostigmàta, and family Tetranychidae (Borror et al. 1989). The tetranychids are different from other groups of mites in that they possess long needle-like chelicerae and palpal thumb claws. The chelicerae of most other mite species are forceps-like (Jeppson et al. 1975). Morphologically, the TSSM is about 0.5mm long with an oval shaped body which varies in color from greenish-yellow, to virtually transparent, brown, or red-orange (Fasulo and Denmark 2000). The characteristic two spots seen through the body wall are formed in areas of waste build up (Fasulo and Denmark 2000).

Although the TSSM has been widely studied, several aspects of its taxonomy are unclear and are compounded by the fact that there are about 60 synonyms of this species (Fasulo and Denmark 2000). What is known is that the TSSM was first described by Koch in 1836 (Pritchard and Baker 1955) from European samples and so is thought to originate from temperate climates (Fasulo and Denmark 2000). The exact origin of TSSM, however, is still unknown due mainly to the cosmopolitan distribution of this species.

Biology and Reproductive Behavior of TSSM

The life cycle of the TSSM consists of egg, larva, protonymph, deutonymph, and adult stages. Egg development tends to be relatively slow at cooler temperatures and can take as long as seven days. Larval, protonymph and deutonymph development are completed in a little over two weeks at the average temperature of 20.3° C (Laing 1969, Donahue 1985). However at 30°C the cycle of egg to adult can be completed in as few as seven days (Thomas 2001). Each nymphal stage feeds for only a short time before entering a quiescent period where the transformation to the next stage occurs. Individuals usually spend more time in the quiescent phase than the active phases (Mitchell 1973). Adult mites emerge about 17 days after eggs are laid and females can begin producing eggs within the third week of development (Mitchell 1973). The duration of phases and egg production is also temperature dependent and can also vary with geographic location. TSSM is an arrhenotokous species; unmated females produce only males and mated females produce either males or females (Potter et al. 1976).

Spider mite males usually develop faster than females. While in the adult stage males do not feed, but actively search for female deutonymphs and wait for them to emerge (Mitchell 1973). This behavior, known as 'guarding', is induced partly by the production of a pheromone released from the mid dorsal region of the female (Cone et al. 1971). Potter et al. (1976) reported that during the guarding behavioral phase males might also make contact with the mid dorsal region of females and sporadically stroke and tap the region using their palps. In addition to the ‘guarding’ behavior, two other behaviors of males were observed by Cone et al. (1971). These were a ‘hovering’ behavior where the male sits over the female and twitches his appendages and a ‘mating’ behavior where he positions himself partially under the abdomen of the female. Males also are known to engage in aggressive behavior. Four levels of this behavior between males have been observed by Potter et al. (1976) in studies where one male was already guarding a female when other males approached: 1) the approaching male retreats from the encounter without aggression; 2) the guarding male gives an aggressive response to approaching male who leaves without a show of aggression; 3) moderate aggressive behavior observed by both males, which caused one male to leave; 4) intense fight resulting in injury or the death of one male.

Female spider mites generally mate soon after emergence. Sperm precedence is given to the first male if multiple mating occurs, so her eggs are fertilized by sperm from the first male (Potter et al. 1976). After her eggs have been fertilized, the female disperses and enters an activity period of about one day, after which she settles down to feed. At this time she usually deposits silk webbing close to the vein of the leaf to mark her territory (Mitchell 1973) in which she oviposits (Hazan et al. 1974, Donahue 1985). The silk is a proteinaceous material that is thought to be to hydrophilic. The combination of silk and the deposition of fecal pellets is hypothesized to be a mechanism to regulate humidity during dry conditions (Hazan et al. 1974, Donahue 1985). Therefore, under conditions of low humidity females usually produce large amounts of silk to maintain a relative humidity adequate for egg development.

Economic Importance

The TSSM is recognized as one of the most important pests of agricultural crops. The ability of the TSSM to become a pest is due to its biology, polyphagous habit, and the damage it causes. The arrhenotokous nature of the females predisposes the mite to develop resistance to acaricides, and the haploidy of males allows for rapid selection for mutations (Huffaker et al. 1969). The production of large numbers of young by females seems to be an important adaptation for which there are some major modifications. Increases in mite population require that females mate and disperse. When mites become crowded the body size of females is reduced by 30-60% (Mitchell 1973). This growth reduction allows for a high level of dispersing females during low growth and food conditions. During these times a colony of mites also would severely restrict the living area ensuring that females are mated before dispersing. By confining the quiescent females to small areas marked off by webbing a small number of males are capable of finding and mating with the females (Mitchell 1973). Therefore, as Mitchell (1973) noted that by “putting significantly more than half the eggs into females and budgeting the growth of the males and females to minimize their demands until after dispersal to new resources, the spider mites have a vast potential for generating outbreaks.”

The damage to host plants caused by the TSSM is characteristic of the damage caused by most spider mite species. Mites can feed on both sides of the leaf, but during the day they usually are found on the underside of the leaf (Jeppson et al. 1975). Individuals use their stylets to penetrate the plant tissue and ingest the cellular material. Feeding leads to chlorosis, which results in yellow spots around the feeding area (Helle and Sabelis 1985b). Widespread chlorosis decreases the yield potential of the crop.

For example, one of the most economically important host plants attacked by the TSSM is peanut, *Arachis hypogaea* L. (Johnson et al. 1980, Margolies et al. 1984). Although certain species of domestic and wild peanuts are resistant to spider mite attack, large populations of TSSM can cause severe injury and reduced yields in this crop (Johnson et al. 1980). Small late occurring populations of TSSM also are known to affect peanut yields and the value of the crop (Smith and Mozingo 1983).

Population Dynamics of TSSM

Factors Affecting TSSM Dynamics

Management strategies that rely solely on chemical means rarely provide acceptable results to the problem of the TSSM in peanut and other agricultural crops. This is because the use of acaricides and some insecticides affect the population dynamics of this pest (Schoenig and Wilson 1992) and increase the probability of outbreak especially after long periods of dry weather (Johnson et al. 1982). A major factor in the rise of the tetranychid mites, for example, has been the use of broad spectrum insecticides, which cause mortality of predators that feed on mites (Jeppson et al. 1975).

The population dynamics of spider mites also are affected by environmental factors such as drought conditions of low moisture and high temperatures. The developmental rate of mite populations is usually accelerated under drought conditions especially when higher temperatures accompany drought. Youngman and Barnes (1986) found that significantly more spider mite eggs and motile stages of mites developed on almonds that were under water stress than those plants that were not stressed. Under drought conditions also there are lower populations of fungal pathogens and the reduced direct mortality of mites from the force of the rainfall (Klubertanz et al. 1990).

Dispersion and Temporal Distribution of TSSM

The spatial distribution of spider mites must be discussed with reference to their distribution on leaves, plants, and within whole fields. Spider mites tend to aggregate more than other mite species, although they usually do so less in the older life stages (Slone and Croft 1998). Highly aggregated egg distribution, for example, is thought to be caused by more sedentary TSSM females that lay their eggs within the silk webbing (Slone and Croft 1998). In addition, immature stages of TSSM tend to stay within the boundaries of the web thereby making mate finding easier and reducing dispersal under favorable conditions (Mitchell 1973).

Changes in the within-plant distribution of TSSM populations throughout the growing season of a crop usually occur because of changes in plant height and in the density of natural enemy populations (Strong et al. 1997). TSSM are negatively geotactic (Hussey and Parr 1963) so individuals tend to move upward as the season progresses (Braun et al. 1989). Populations of TSSM, therefore, usually will become more unevenly distributed vertically on plants as the population increases (Nachman 1981).

On the scale of a greenhouse or agricultural field there is some discrepancy as to the exact pattern of dispersion of mite populations. Nachman (1981) found that low density populations of TSSM tended toward a random distribution, but at higher densities their distribution was aggregated. Others have found that there was a trend toward aggregation early in the infestation phase (low densities) of mites (Wilson et al. 1983, Hollingsworth and Berry 1982, Slone and Croft 1998). This pattern, however, appeared to change to a more widely dispersed and random dispersal pattern as competition and crowding increased (Wilson et al. 1983, Hollingsworth and Berry 1982, Slone and Croft 1998). The trend toward a random pattern in the spatial distribution of TSSM populations over time within fields was thought to be indicative of aerial dispersal (Pickett and Gilstrap 1986).

Monitoring TSSM Population

Several techniques and tools are used to sample and monitor mite populations. Sampling and monitoring are essential components in the development and implementation of action thresholds and other pest management strategies (Margolies et al. 1984). Two important considerations in any sampling program are the precision and efficiency with which samples are taken. These components are particularly important when sampling small arthropods with high population densities (Margolies et al. 1984).

Monitoring mite populations with conventional counting methods, for example, was difficult and costly due mainly to the small size and very high numbers of mites that needed to be counted on foliage (Wilson et al. 1983). These researchers and others (e.g., Pickett and Gilstrap 1986), suggested using a presence-absence (binomial) sampling technique, which they found to be more effective. In another study, Perring et al. (1987) determined the intraplant distribution of TSSM and found that management of TSSM could be simplified by sampling adult females from three leaves on the primary branch of cantaloupe plants. This provided an effective evaluation of spider mite density and reduced the amount of time and energy required for sampling. Another approach suggested by Jones (1990) for use in pest management projects involved using generic Taylor coefficients developed from bootstrap estimates of coefficients from two different spider mite species using thirteen literature sources. The method required that a relatively small validation data set (about 20-40 samples) be taken and checked against the generic coefficients to determine whether the coefficients accurately predicted the mean population levels. Although this method is somewhat complicated, accurate estimates of the generic coefficients tended to reduce the time, money, and energy required for sampling mite populations (Jones 1990). For monitoring TSSM populations in peanut, Margolies et al. (1984) used a less complicated method based on action thresholds that involved taking three leaves per row-meter. The procedure was devised so that no more than five adult mites had to be counted.

No protocols describe how sampling would proceed to develop maps of the spatial distribution of TSSM within whole agricultural fields. In general, however, for many arthropods, samples collected on a grid provide a good representation of the spatial distribution of these organisms in a study area, with more intense sampling providing more information (Roberts et al. 1993).

Dispersal and Migration

Spider mites disperse in three ways: phoresy, whereby mites “hitchhike” on other organisms, passive aerial dispersal by drifting on air currents, and walking (Weeks et al.

2000). Long distance dispersal appears to be the most significant in the population dynamics of TSSM (Margolies 1995). Adult spider mites initiate this activity by climbing to the tops of the plant and forming large clumps of mites that are carried away by the wind or a passing animal (Slone and Croft 1998).

Plant stress due to drought usually is one of the main factors responsible for the dispersal of mites within fields (Klubertanz et al. 1990). Wilson et al. (1993) reported that mites are active in their search for new habitats especially when the original food source becomes undesirable due to leaf and crop aging, decline in nitrogen levels, general nutrient depletion due to crowding and loss of food quality due to feeding. The rate of dispersal also may be affected by spatial and temporal distribution of natural enemies, competitors and suitable hosts (Margolies 1995). Donahue (1985) and McEnroe and Dronka (1971) reported that shifts in photobehavioral response might also influence dispersal. Dispersing mites usually relocate far enough away from their original location to reduce intraspecific competition for nutrients and avoid predation by natural enemies (Donahue 1985).

Dispersal on Peanuts

TSSM infestations can sometimes be a gradual population increase, which would suggest that the spider mites walked in, or it could be a rapid population increase, which would suggest aerial dispersal (Boykin and Campbell 1984). Aerial dispersal, however, plays a considerable role in the infestation of the TSSM on peanut (Boykin and Campbell 1984). All stages of the mites including eggs have been shown to disperse aerially. Laboratory tests indicated that spider mites could disperse in winds of 8, 16, and 24 km/h at all levels of infestation (i.e., low, moderate, high, and severe). However, on severely infested plants spider mites tended to disperse in greater numbers at higher wind speeds (Boykin and Campbell 1984). In field tests, Boykin and Campbell (1984) captured mites on sticky slides at heights up to 2.1 meters, although the majority of the aerially dispersing mites were found at 0.6 meters (at about the height of the peanut plant). In general, there was an inversely proportional relationship between number of mites captured and the height of the traps (Boykin and Campbell 1984).

The application of pesticides does not increase the wind dispersal of mites directly, although some chemical combinations such as carbaryl, mancozeb+carbaryl, and benomyl+mancozeb+carbaryl caused population increases, which in turn increases the aerial dispersal (Boykin and Campbell 1984). Weed borders and barren field borders are also thought to play a role in delaying the infestation of spider mites into a field. Boykin et al. (1984) found that mowing the weed borders or treating the borders with herbicide next to peanut fields significantly increased the dispersal of TSSM into the peanut fields. Barren field borders of 4.5 to 6.0 meters could delay the infestation of mites that walked into fields (Boykin et al. 1984). Margolies and Kennedy (1984) observed that there was a swift increase in mite number when peanut plants were at peak bloom. This indicates that spider mites respond to the difference between the vegetative stage and the reproductive stage of the peanut. Boykin et al. (1984), therefore, suggested treating weed borders early in the season to reduce mite populations so that when individuals disperse they do so in lesser numbers and when peanut plants are less susceptible to invasion.

Management of TSSM Populations

Chemical Control

In 1985, it was reported that the TSSM had developed resistance to many of the acaricides used worldwide (Helle and Sabelis 1985a). Earlier, Campbell (1978) reported that most of the fungicides used on peanuts grown in North Carolina caused increases in spider mite populations. He also observed similar increases in populations when these fungicides were mixed with insecticides. Smith and Mozingo (1983) found that monocrotophos, dicofol, and carbophenothion prevented mite population increases when they were sprayed before infestations. However, they also found that carbofuran and disulfoton and the fungicides triphenyltin hydroxide, benomyl + mancozeb, and captafol caused increases in mite populations. Three other chemical insecticides, triphenyltin hydroxide, chlordimeform, and carbophenothion were shown to have an ovicidal effect on mites when used on peanuts in the laboratory (Campbell et al. 1974).

The three chemicals plus carzol and propargite and monocrotophos also provided good suppression of mite populations in the field (Campbell et al. 1974).

Biological Control

Natural enemies of spider mites can be found in several orders of arthropods including Aranea, Acarina, Coleoptera, Hemiptera, Thysanoptera, Diptera, and Neuroptera (Huffaker et al. 1969). Mites in the family Phytoseiidae, for example, are well known predators of spider mites. The most important of the Phytoseiids is *Phytoseiulus persimilis*, which is a specialized predator of the tetranychids (Huffaker et al. 1969). Phytoseiids have a lower food requirement than insect predators, but have a relatively fast development rate (Huffaker et al. 1969). In greenhouses infested with TSSM, *P. persimilis* proved to be a good biocontrol agent due to its short development time, high reproductive rate and prey searching efficiency (Walde and Nachman 1999). This predatory mite also has a lower oviposition rate, albeit longer oviposition period compared to tetranychids (Huffaker et al. 1969). The family Stigmaeidae also contains two genera, *Zetzellia* and *Agistemus* that have also been observed feeding on spider mite (Huffaker et al. 1969). These organisms, however, are generalists and their effectiveness as biological control agents is thought to be weak.

Fungal pathogens such as *Neozygites tetranychi* also can reduce populations of TSSM especially when the humidity is high (Jeppson et al. 1975). Other Neozygites spp. such *N. floridana*, two other species that are near *N. floridana*, and a fungus near *N. adjarica* are also known to attack spider mites (Helle and Sabelis 1985b). *Hirsutella thompsonii* Fisher and *Cephalosporium diversiphialidum* (Verticillium lecanii (Zimmermann)) Viegas have also been found to infect several species of spider mites (Helle and Sabelis 1985b).

Some beetles also prey on mites. All the species in the genus *Stethorus* in the family Coccinellidae are predators of mites. These small beetles thrive on high densities of mites, but do not appear in great enough number to have a meaningful impact on TSSM populations until after the economic level of mites is exceeded (Huffaker et al. 1969, Putman 1955, Clancy and Pollard 1952). There are several species in the genus *Oligota* in the family Staphylinidae that prey on tetranychids. The use of these species for biological control is questionable due to their inconsistent abundance (Huffaker et al. 1969).

The family Anthocoridae has several species that are known to feed on mites although most are mainly generalists. Several *Orius* species have been found to prey on spider mites, aphids and thrips (Huffaker et al. 1969). A few other families in the order Hemiptera such as the Miridae, Nabidae and Lygaeidae are also known to prey on mites (Huffaker et al. 1969).

A few species of Thysanoptera are specialized predators of tetranychids. *Scolothrips sexmaculatus* has been is an important predator of mites in cotton (Huffaker et al. 1969, Lincoln et al. 1953) and *Haplothrips faurei* was found to be an important predator of mites in fruit trees in Canada (Huffaker et al. 1969, Putman 1965).

Cultural and Other Control Strategies

Johnson et al. (1980) found that certain species of wild peanut were fairly resistant to spider mite infestation as indicated by the low fecundity and feeding damage. The use of barren soil borders also delayed the entrance of spider mites into a field (Boykin et al. 1984). In marked contrast, Boykin et al. (1984) found that mowing the weed borders surrounding fields increased the number of spider mites entering a field by aerial dispersal.

Precision Agriculture

Precision agriculture can be seen as a developing technology that modifies existing techniques and incorporates new ones to produce a new set of tools for management (National Research Council 1997). Understanding spatial variation is at the backbone of this new technology. The modern concept of precision agriculture, therefore, involves optimizing the potential of the crop by dividing the field into subunits and treating each unit separately instead of assuming that the field is uniform (Usery et al. 1995).

One of the first modern accounts of the use of precision agriculture practices was in the 1929 test of the within field condition of soils, which was conducted by measuring the spatial variation in soil acidity (Usery et al. 1995). Since then, much of the effort in precision agriculture has been focused on areas such as yield monitoring and mapping, weed management, and soil condition management (Goddard 1997). Very little has been done with respect to the precision management of arthropod populations or precision pest management (PPM). Early studies of the population dynamics of arthropods (mainly insects), for example, ignored information on the spatial variability in their densities. The population density of arthropods was assumed to be invariant over space, and, therefore, all spatial variation was ignored. Stern et al. (1959), for example, recognized that the population density of insects and their distribution changed through time and this change could be conceptualized as a series of density maps. In the end, however, the density maps were simplified to an average over space at each time point. The technologies and data analysis procedures used for developing integrated pest management (IPM) programs also did not consider the spatial variability in arthropod density. Economic thresholds, sampling technologies, and simulation modeling all ignored the tremendous capacity of these organisms for dispersal and movement.

It was the realization, that spatial variation in agricultural systems was common, which led to a new and emerging technology, Precision Agriculture (Site-Specific Farming or precision farming). By recognizing and reacting to this variability, farmers are now able to assess and respond to various parts of the field accordingly and where necessary apply different (or appropriate) management methods (Berry 1998). With the advances in technology, they are better able to monitor their fields and the spatial variability therein.

Like other management areas in precision agriculture, PPM relies on three key elements: information, technology, and management. Specifically for the PPM of spider mite populations, methods for assessing and analyzing the spatial and temporal distribution of the mites within the management unit (e.g., field) are needed. Technology also is needed for gathering information on the mites and for using this information effectively. Finally, management input is needed to integrate the information and the technology for the end-user (the farmer). PPM of mite populations, therefore, like other applications of precision agriculture will not only reduce the effort needed for management, but also will reduce pesticide load on the environment (Weisz et al. 1995), and preserve natural enemies while minimizing the development of resistance (Midgarden et al. 1997).

Technologies Relevant to PPM

A key component of any precision management operation is the Global Positioning System (GPS). This system was initiated in 1973 and consists of 24 satellites with ground support (Encarta® Online Encyclopedia 2001). The GPS system can be used to determine the location of specific entities in space using geographic coordinate reference systems such as Latitude/Longitude, which measure position in degrees or Universal Transverse Mercator (UTM), which measures location in meters.

Another technology useful to precision agriculture is remote sensing. The definition of remote sensing is very broad, but includes any method of gathering information about an object or objects through the analysis of data gathered by instruments that are not in physical contact with the object(s) of study (Avery and Berlin 1992). Historically, remote sensing has been used in the government and academic institutions for global monitoring and research, respectively. With advances in technology and greater access to this technology by the public, these systems are no longer limited resources. Anyone from large corporations to individual farmers has access to and can use remote sensing techniques to improve their product.

Remote sensing can be long range, using aerial photography and satellite imagery or short range, using electromagnetic induction and ground-penetrating radar (GPR) (Usery et al. 1995). Allen et al. (1999) also discussed the possibility of using medium range remote sensing for precision agriculture. These authors discussed the use of an Unmanned Air Vehicle (UAV) remote sensing system to capture low-altitude high resolution imagery of crop fields that could be analyzed to create maps of the spatial variation of plant stress conditions.

Remote sensing has been used in entomology and related fields. Three areas of remote sensing applications in entomology have been the monitoring of environmental factors that influence insect behavior, direct observations of insects, and the detection of the effects that insects produce (Riley 1989). It was in this last application that entomologists first used remote sensing. In the 1930's forest entomologists used airborne observers to make sketch maps of the areas of defoliation caused by the hemlock looper (Riley 1989). Hall et al. (1983) also found that it was possible to detect Douglas fir trees being attacked by beetles before any visual foliar damage occurred (Riley 1989). Low-altitude color infrared photographs have been used to detect European red mite infestations in peach orchards (Payne et al. 1971). By comparing treated and untreated areas, the aerial studies gave researchers a method for early detection of potentially damaging infestations and for evaluating the efficacy of control measures (Riley 1989).

In direct observations of insects using remote sensing, Schaefer (1976) used radar to investigate the nighttime flight of moths, grasshoppers, and locusts. This experiment helped to advance the knowledge on the subject of migratory fights in insects. Similar studies were done on moth flights from Australia to Tasmania, and to track the northerly movement from Mexico to the U.S. of corn earworm and tobacco budworm moths (Riley 1989).

Host-plant distribution, air temperature, and rainfall are important in the regional distribution of insect populations (Riley 1989). Aerial photography was used to examine the host-plant distribution of tropical fruitflies in Hawaii, El Salvador and Mexico (Riley 1989). Because some insects are very sensitive to variations in air temperature and migrate according to the changes that occur, their populations could be monitored using thermal remote sensing. One such study done by the National Aeronautics and Space Administration (NASA) involved monitoring the screwworm, *Cochliomyia hominivorax*, in the sterile-male release program (Riley 1989). Remote sensing of rainstorms has also been used to identify areas of potential outbreaks for insects that have been known to be concentrated by winds associated with storms. This approach was used to monitor populations of the African armyworm, *Spodoptera exempta* (Riley 1989).

The focus on the use of near infrared (NIR) technology began about 30 years ago in the laboratory of Karl Norris at the USDA (Williams 1996). Near infrared spectroscopy (NIRS) is used widely because it is quick, nondestructive, and it provides an extensive range for quantitative analysis for organic compounds of plant and animal tissue. In addition, NIRS does not require chemicals and the cost of analysis is low (Foley et al. 1998, Ghaedian and Wehling 1997).

Water, or more accurately the hydrogen bonds of water, absorbs a large amount of NIR radiation (Foley et al. 1998). It has been shown that both red and infrared spectral reflectance are strongly correlated with actively photosynthesizing crop covers. Healthy plants strongly reflect and absorb light energy in the near infrared and red wavelengths, respectively (Mahey et al. 1991). The spectral signature of plants is also determined by chlorophyll and other pigments (Mahey et al. 1991). Wiegand and Richardson (1984) found that the spectrum obtained from plant canopy could be used to show how the plant is responding to stress, its developmental process, and its potential yield capability. Red absorption and normalized difference vegetation index (NDVI), which is affected by both red and NIR reflectance, increase in early stages of crop growth and decrease as the crop begins to senesce. It was shown also that irrigated crops have a higher red and NDVI than non-irrigated crops (Mahey et al. 1991). Red absorption decreases as leaves senesce and so is sensitive to photosynthetic activity (Tucker 1979). NIR reflectance usually decreases because of degeneration of the cell (Mahey et al. 1991). Because of the relationship between red and NIR reflectance in green and non active (dead) vegetation, indices such as NDVI and NIR/red or reflectance ratio have become useful for monitoring plant health (Tucker 1979).

NIRS has been used to measure the nutritional makeup (moisture, amino acids, nitrogen, sugars, and starch) of animal feed (Foley et al. 1998, Kawamura et al. 1997) and to detect changes in the composition of samples of vegetation over time and space (Foley et al. 1998). NIRS also has proven to be an acceptable screening tool for predicting NDSF (Neutral Detergent-soluble Fiber) concentrations quickly for large numbers of forage samples in alfalfa (Fonseca et al. 1999). Finally, visible/NIR spectroscopy has been used to classify rice into qualitative groups (poor taste, better taste, and best taste) (Kawamura et al. 1997).

Recent studies have examined the use of NIRS for detecting insect larvae in stored grain. The current methods were noted to be time consuming, expensive, and require a trained radiography technician (Ghaedian and Wehling 1997). Using NIRS, Dowell et al. (1999) detected the presence of insect larvae or adults hidden in wheat samples. Cuticular molecules vibrate at unique frequencies and absorb NIR energy (Dowell et al. 1998). Therefore, by looking at the difference between absorbance characteristics based on the cuticle of the insect, it is possible to distinguish between life stages and species (Dowell et al. 1999).

Currently a majority of the wheat and barley in Canada are tested for protein content using NIR technology (Williams 1996). NIRS can potentially be used in the field of ecological modeling to develop whole-system models. By using NIRS, time and effort can be saved by looking at systems from a holistic viewpoint and seeing if they are capable of being modeled (Foley et al. 1998). Anything that is suspected of influencing the plant or animal material being studied could be modeled to predict its function on the performance of the test subject (Foley et al. 1998). With the increase in portable machinery, better fiber optics, and more powerful computers, Foley et al. (1998) predict that there will be more of a connection between scientific groups interested in airborne remote sensing and those interested in what goes on at finer resolutions.

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Chapter Two

Spatiotemporal Distribution of *Tetranychus urticae* (Acari: Tetranychidae) in Peanut Fields

INTRODUCTION

The twospotted spider mite (TSSM), *Tetranychus urticae* Koch, is a common polyphagous pest in field and greenhouse agroecosystems (Huffaker et al. 1969, Helle and Sabelis 1985a, b). Field and orchard crops such as almond, cotton, corn, soybean, raspberry, apple, hop, and peanut (Brandenburg and Kennedy 1982, Wilson et al. 1983, Pickett and Gilstrap 1986, Youngman et al. 1986, Oi et al. 1989, Klubertanz et al. 1990, Strong et al. 1997, Pratt et al. 1998, Roy et al. 1999) are particularly prone to infestations by the mite. The damage caused by feeding of TSSM, their biology, polyphagous habit, and dispersal behavior have caused this pest to become a severe economic problem in peanut, *Arachis hypogaea* L. (Johnson et al. 1980, Brandenburg and Kennedy 1982, Johnson et al. 1982, Margolies and Kennedy 1984).

In the Virginia-Carolina area, which produces 20% of the nation's peanuts annually, the TSSM has become a very difficult pest to manage (Herbert 1998, Owens 2001). Most of the damage to peanut fields usually occurs during periods of hot, dry weather conditions from July to September when mite populations tend to increase (Chandler et al. 1979, Hollingsworth and Berry 1982, Margolies and Kennedy 1984, Margolies and Kennedy 1985). Infestations of the spider mite in peanut usually are evident by the chlorosis or yellow stippling around the feeding areas on leaves. The damage to leaf tissues and the stress caused by feeding lead to a decline in photosynthesis and an overall reduction in yield (Johnson et al. 1980). For example, in a study in Virginia on the effects of TSSM on peanut, Herbert (1998) found that mite feeding reduced yields by about 1,450 lb/acre, or a 32% reduction compared with peanut protected with acaricide treatments.

The application of acaricides has been the main strategy to manage populations of TSSM in field crops such as peanut. Not surprisingly, TSSM has developed resistance to many acaricides (Helle and Sabelis 1985a). Although attempts have been made to use alternative management strategies such as the introduction of natural enemies (Huffaker et al. 1969, Jeppson et al. 1975) and cultural practices (Johnson et al. 1980, Boykin et al. 1984) against TSSM in peanut, little has been done to develop integrated pest management (IPM) or newer approaches such as precision pest management (PPM).

Precision management of pest populations requires knowledge of the within-field spatial distribution of the pest and the speed at which the distribution changes (National Research Council 1997). The development of maps depicting the spatial distribution of arthropod pests presents a challenge because the spatial arrangement of their populations within the management unit usually changes rapidly making it difficult to characterize them in a timely and economic manner (National Research Council, 1997). Several studies have used dispersion indices based on variance and mean relationships of counts (Taylor 1984, Kuno 1991) to characterize the spatial distribution of TSSM populations (e.g., Nachman 1981, Slone and Croft 1998). What these studied actually measured, however, was the frequency or probability distribution of counts of TSSM and not the spatial distribution, which refers to the spatial arrangement (or pattern) of the pest within sampling space (Young and Young 1998, p3). For the TSSM, it is important that we understand how the spatial distribution of the population changes both in time and space in peanut fields if precision management strategies are to be successfully implemented.

The goal of this study was to develop an understanding of the spatiotemporal distribution of TSSM populations in commercial peanut fields in southeastern Virginia. I, therefore, studied the typical pattern of distribution of TSSM populations within peanut fields to determine the rate at which the distribution changes. An understanding of the changes in the spatial distribution of TSSM is essential for developing methods for detecting and mapping its distribution and for timely implementation of precision management strategies within peanut fields.

MATERIALS AND METHOD

Study Area and Peanut Fields

The study was conducted during the summer months of 2001 and 2002 in commercial peanut fields located in Dinwiddie County (36° 52.3’ – 37° 16.9’ N and 77° 23.6’ – 77° 54.6’ W) and Isle of Wight County (36° 38.1’ – 37° 08.3’ N and 76° 29.0’ – 77° 55.5’ W) in southeastern Virginia (Fig. 2.1). Two commercial peanut fields were located each summer with the help of Virginia Cooperative Extension (VCE) agents in areas with a history of infestations by TSSM. Before sampling was initiated, I obtained permission from the growers to conduct the surveys in their fields. Also, I made no attempts to persuade the growers to alter their standard management practices, but asked only that I be informed when they treated their field with an acaricide. Therefore, throughout this paper the term “acaricide” will be used whenever the farmers reported that they treated specifically for spider mites and the term “pesticide” will be used when the substance applied to the field was unknown or was not an acaricide.

The first field (Field 1) sampled in 2001 was located in Dinwiddie County (Fig. 2.1). This field was ≈ 1.9 ha and was located adjacent to a corn field and a soybean field to the east, grassy areas to the west and south, and a wooded area to the north. I established 262 sampling points within this field using the sampling design outlined below (see Sampling Protocol). Field 2 sampled in 2001 was located in Isle of Wight County (Fig. 2.1) and was ≈ 9.6 ha.

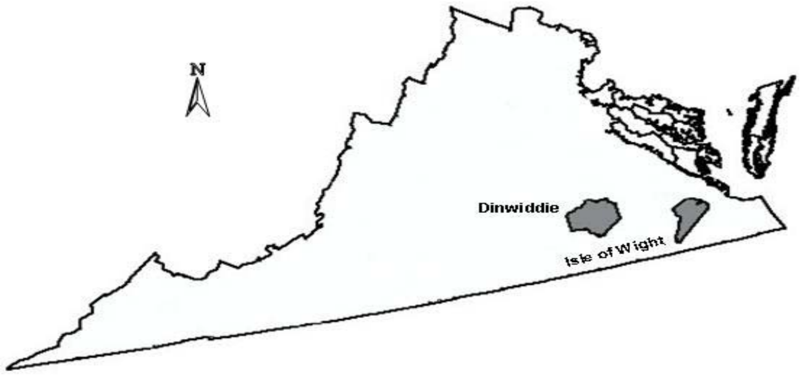

Fig.2.1. Map of Virginia showing the location of the counties (Dinwiddie and Isle of Wight) where the peanut fields were located.

This field was located along a busy highway to the east, was bordered by woods to the north, rye grass to the west, and an open area to the south. In Field 2, I established 344 sampling points. Both of the fields sampled in 2002 were located in Isle of Wight County.

Sampling Protocol

In 2001, I conducted weekly sampling of TSSM populations in Field 1 for five weeks (July 19–August 16), and in Field 2 for four weeks (July 24–August 14). In 2002 both fields (Fields 3 and 4) were sampled weekly for four weeks. Field 3 was sampled from July 10–July 31, and Field 4 was sampled from July 8–July 29.

For each of the four peanut fields, I superimposed a sampling grid over the entire field, but adjusted the sampling resolution of the grid based on the size of the field so that I could sample the entire field during a single session. In Field 1, which was a relatively small field (<2 ha), I used a sampling grid with a resolution of 10 × 10 m. In the largest field, Field 2 (9.6 ha), I increased the sampling resolution of the grid to 20 × 20 m. In Fields 3 and 4, which were slightly larger than Field 1, the sampling resolution was adjusted to 20 × 10 m.

In each of the fields, I started at one corner and used a handheld Garmin GPS III receiver (Garmin International, Inc., Olathe, KS) to lay out the sampling grid at the resolution that was predefined for the size of the field. The geographic coordinates of the sampling points on the grid were recorded in the Universal Transverse Mercator (UTM) system. I used flags in all but one of the fields to mark the position of each sampling point so that the same locations could be sampled weekly.

I used a 10X hand held lens to count the number of immature and adult TSSM on a quadrofoliate leaf that was arbitrarily selected from a peanut plant at each sampling point on the grid. TSSM usually are found on the underside of peanut leaves. Therefore, to ensure consistency in sampling, I assigned a number (1 to 4) to each of the leaflets of the peanut leaf that was selected starting from left to right when the leaf was turned over, and counted all of the mites on each leaflet.

Statistical Analysis

I used a two-sample Cramér-von Mises test (Syrjala 1996) to test the null hypothesis of no difference between any two spatial distributions of TSSM populations within each of the fields. The alternate hypothesis was that there was some unspecified difference between pair-wise distributions of spider mite populations within a field. I also used the Cramér-von Mises test to determine whether the spatial distribution of TSSM within each of the fields changed from week to week.

The main requirement for the Cramér-von Mises test is that the data for each of the two spatial distributions are collected at the same locations. The test was carried out using the following procedure:

1. A Cartesian coordinate (X, Y) system was superimposed on the spatial data of each population data set to create a rectangular grid similar to the one used for sampling.
2. The observed data for each population were normalized by dividing each observation on the grid by the sum of all of the observations.
3. Starting at each corner on the grid, four cumulative distribution functions were constructed from the normalized data of each population.

4. A separate test statistic was calculated for each of the four cumulative distribution functions by taking the squared difference between the respective distribution functions for the two populations.
5. An overall test statistic (Ψ) was calculated as the average of the four test statistics.
6. 999 pseudo-random permutations of the data for the two populations were examined and a test statistic was calculated after each permutation. Each permutation was done by randomly assigning one of the observations from corresponding locations to the first population and the other to the second population. The test statistic was calculated after each permutation following steps 1–5.
7. The *P-value* of the test was estimated as the proportion of the 1000 test statistics (999 from step 6 plus the test statistic for the observed data) that were greater than or equal to the observed test statistic (Ψ).

An algorithm for carrying out the stepwise process on the TSSM data was programmed using the mathematical and simulation software, MATLAB (Mathworks, Natwick, MA).

The Cramér-von Mises test can be used to determine whether there is a statistically significant difference between the distributions of two populations, but the test does not characterize the pattern of the distribution or the difference between the two distributions if one exists (Syrjala 1996). Therefore, I used geostatistical semivariogram analysis (Isaaks and Srivatava 1989, Rossi et al. 1992) to characterize the within-field distribution patterns of TSSM based on the shape of the semivariogram curve (Schotzko and O'Keeffe 1989, Midgarden et al. 1993). For this analysis, I used data collected in Field 1 and Field 2 as examples to show the kinds of spatial distribution patterns that can be expected for TSSM in peanut. The semivariogram, which is represented mathematically by

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2, \qquad (2.1)$$

was used to summarize the spatial dependence of all possible pairings of TSSM sampling data, where $\hat{\gamma}(h)$ is the estimated semivariance of TSSM samples (z) at all points (x_i) separated by lag distance *h*, and *N(h)* is the number of pairs of samples separated by lag distance *h*. The semivariogram analyses of the TSSM data were performed in the GS+ 3.11 (Gamma Design Software, Plainwell, MI) geostatistical software.

I also attempted to understand how the spatial distribution of TSSM in each of the fields was related to the frequency distribution of samples or dispersion of the population collected in the fields. The TSSM data from each sampling-week were used to derive dispersion indices for the mites in each field based on the variance/mean ratio and the inverse of the clumping index (*k*) in the negative binomial distribution (Taylor 1984, Kuno 1991). The clumping index, *k*, was estimated by

$$k = \frac{\bar{x}^2}{s^2 - \bar{x}} \quad , \qquad (2.2)$$

where $\bar{x}$ represents the mean and s^2, the variance, of the sampling data on the TSSM.

RESULTS

The density of TSSM in the four fields ranged from a mean (± SE) of 0.06 ± 0.02 (Field 4) to 16.9 ±1.99 (Field 1) mites/leaf. Field 1 had the highest mean density of TSSM among the four fields during most of the sampling weeks. The densities of TSSM in Fields 2, 3, and 4 were relatively low during all sampling weeks and ranged from 0.06 ± 0.02 (Field 4) to 2.59 ± 0.65 (Field 2) mites/leaf. Also, the mean densities of TSSM in Field 1, 2, and 4 increased initially, but decreased by end of the sampling periods (Table 2.1; e.g., Fig. 2.2). The mean density of TSSM in Field 3 decreased steadily during the study.

The results of the two-sample Cramér-von Mises test showed that, for most of the comparisons, there were no statistical differences ($P > 0.05$) in the spatial distributions of TSSM populations between sampling weeks in each of the fields. The analysis showed that there were a few cases where the spatial distributions of TSSM populations within a field changed between successive sampling weeks (Table 2.1). In Field 1, for example, the spatial distribution of mites observed in week 5 was significantly different from the previous week. This was also the case in Field 2 where mite distribution for week 4 differed significantly from the distribution observed in week 3. In Field 3, the distribution in week 3 was significantly different from those observed in the two previous weeks, but was not significantly different from the distribution observed in week 4. The spatial distribution of mites in week 4 also was statistically the same as those observed in weeks 1 and 2 (Table 2.1; $P > 0.05$). The comparison of sampling weeks in Field 4 showed that there were no significant differences in the spatial distributions of TSSM between any two weeks during the study.

Semivariogram analysis of TSSM data collected on 9 August 2001 in Field 1 showed that the population had an omnidirectonal distribution that could be described as aggregated or clumped (Fig. 2.4A). An exponential model of the form,

$$\hat{\gamma}(h) = Co + C[1 - \exp(-h / Ao)], \qquad (2.2)$$

provided the best fit ($r^2 = 0.5$) to the variogram points. In the model, $Co = 0.2630$ represents the nugget variance, $C = 1.0870$ is the structural or sample variance, and $Ao = 18.5$ m is the range parameter. For the exponential model, the effective range of the data actually is defined as that distance at which the semivariogram value is 95% of the sill (Young and Young 1998) and can be estimated as $3Ao$, which is ≈ 56 m. Therefore, the TSSM samples taken on 9 August within Field 1 tended to be correlated spatially up to an average distance of about 56 m. Figure 2.3B shows that the highest densities of the spider mite on that date were aggregated in the middle and near the western part (grassy area) of the field. Semivariogram analysis of the TSSM data collected on 16 August in Field 1 suggests that based on the good fit of a linear model to the data (Fig. 2.4B) that there was overall spatial autocorrelation in mite population at all lag distances throughout the field on that date (Fig. 2.3C, Fig. 2.4B). The geostatistical analysis of the sampling data collected in Fields 2, 3, and 4 showed that the spatial distribution patterns of mite population within those fields generally were either random or uniform (e.g., Fig. 2.5).

The dispersion indices based on variance-mean relationships showed that in general the frequency distributions of TSSM population in each of the field were predicted to be aggregated ($VM > 1$ and $1/k > 0$; Table 2.1). The exceptions occurred with the frequency distributions of sample counts in week 5 in Field 1 and week 4 in

Field 4, which suggested uniform ($VM < 1$; $1/k < 0$) and random ($VM = 1$; $1/k = 0$) dispersion patterns, respectively.

Table 2.1. Summary data and Cramér-von Mises test of the spatial distribution of TSSM populations in peanut fields in southeastern Virginia.

Sampling Week (Date)[1]	Mean (± S.E.) mites per leaf[2]	VM[3]	1/k[4]	Weeks compared	Test Statistic (Ψ)[5]	P- value
Field 1						
1 (19 July)	7.32 (1.14, n = 262)	46.5	0.16			
2 (26 July)	13.89 (1.52)	43.6	0.33	1 and 2	0.594	0.234
3 (2 August)	11.54 (1.79)	72.7	0.16	2 and 3	0.563	0.425
4 (9 August)	16.90 (1.99)	61.4	0.28	3 and 4	0.631	0.236
5 (16 August)	0.08 (0.03)	0.3	-0.11	4 and 5	1.111	0.018*
				1 and 4	0.580	0.467
				1 and 5	2.165	0.012*
Field 2						
1 (24 July)	1.01 (0.32, n = 344)	34.9	0.03			
2 (31 July)	1.43 (0.29)	20.2	0.07	1 and 2	3.088	0.686
3 (7 August)	2.59 (0.65)	56.1	0.05	2 and 3	5.960	0.239
4 (14 August)	1.76 (0.38)	28.2	0.06	3 and 4	49.717	0.001*
Field 3						
1 (10 July)	2.52 (1.06, n = 180)	80.3	0.03			
2 (17 July)	1.02 (0.46)	37.3	0.03	1 and 2	0.597	0.521
3 (24 July)	0.86 (0.17)	6.0	0.17	2 and 3	4.916	0.005*
4 (31 July)	0.62 (0.21)	12.8	0.06	3 and 4	0.414	0.414
				1 and 3	6.393	0.002*
				1 and 4	6.689	0.095
				2 and 4	5.052	0.091
Field 4						
1 (8 July)	1.31 (0.35, n = 146)	13.7	0.10			
2 (15 July)	2.00 (0.53)	20.5	0.10	1 and 2	1.066	0.445
3 (22 July)	0.29 (0.10)	5.0	0.07	2 and 3	1.481	0.158
4 (29 July)	0.06 (0.02)	1.0	0.00	3 and 4	0.368	0.111

[1] Field 1 and Field 2 were sampled in 2001; Field 3 and Field 4 were sampled in 2002.

[2] *n* is the number of locations in each field where samples were taken

[3] VM is variance/mean ratio or coefficient of dispersion

[4] *k* is the aggregation or clumping parameter in the negative binomial distribution

[5] Cramér-von Mises statistics

* The test statistics from pseudo-random permutations were significantly smaller than the test statistic (Ψ) for the observed data ($\alpha = 0.05$)

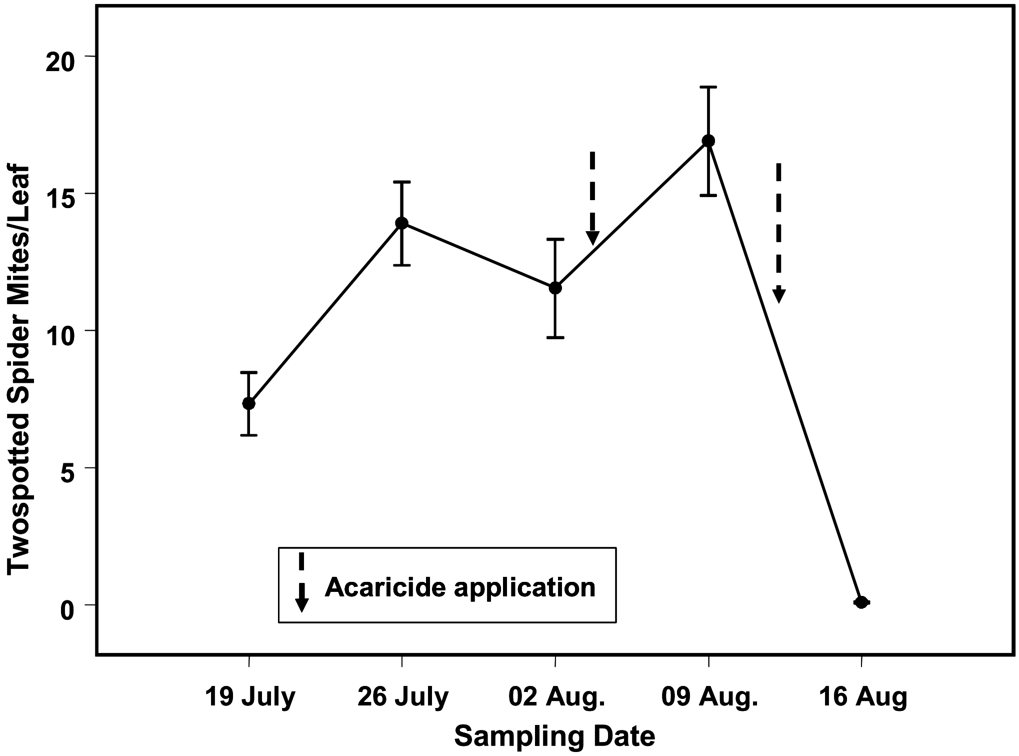

Fig. 2.2: Mean density of TSSM in a peanut field (Field 1). The broken arrows show the timing of pesticide applications.

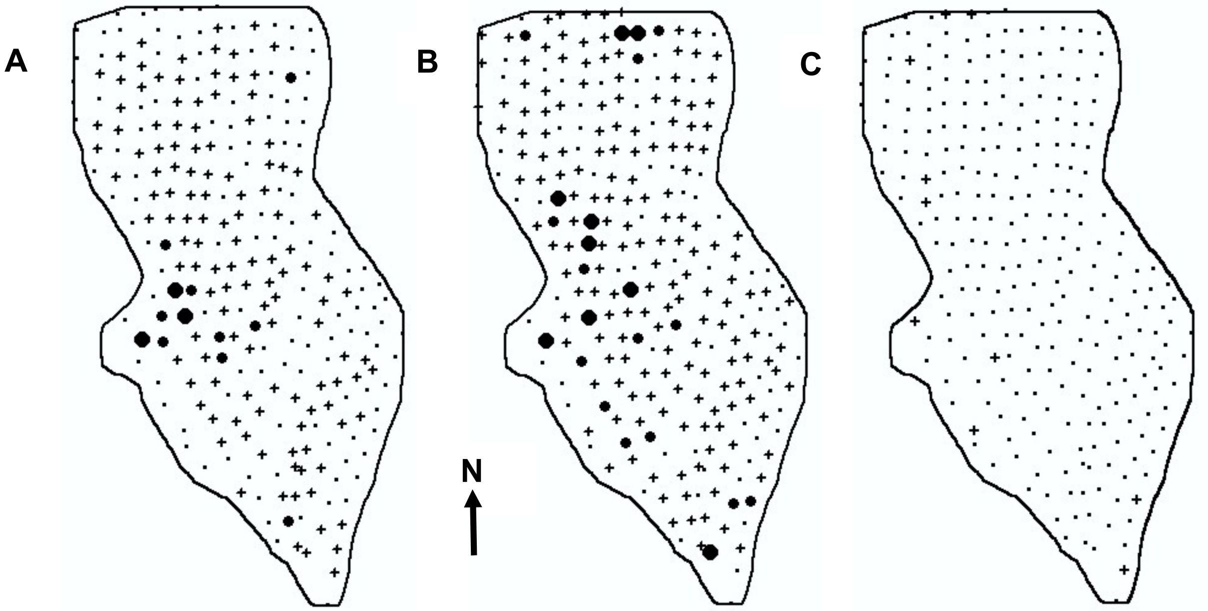

Fig. 2.3: **Distribution of TSSM on peanut in Field 1 on (A) 19 July (B) 9 August, and (C) 16 August 2001. A ▪ indicates a zero count, + indicates a count of <50, • indicates a count of <100, and ● indicates a count >100 mites per leaf.**

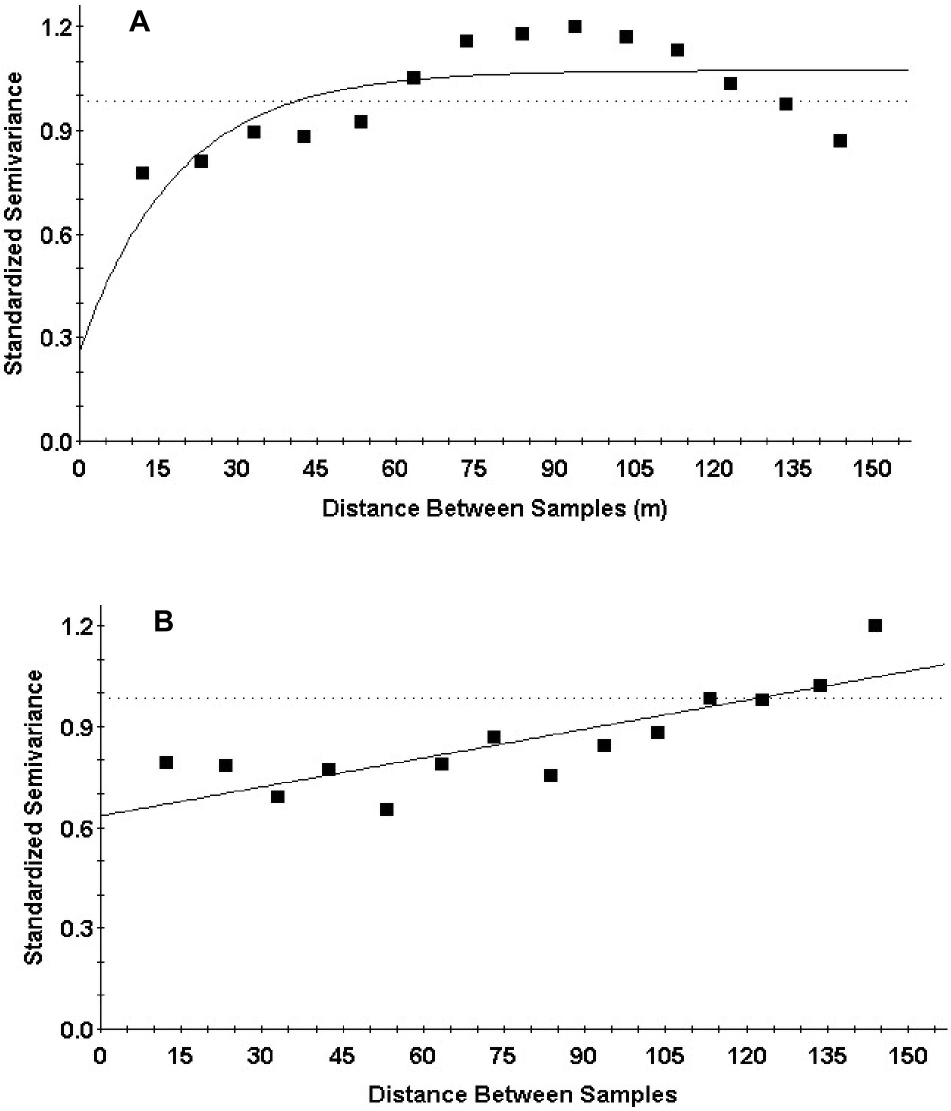

Fig. 2.4: Semivariogram analysis of sampling data on TSSM collected in Field 1 on (A) August 9 2001 and on (B) August 16 2002. The variograms are standardized by the sample variance.

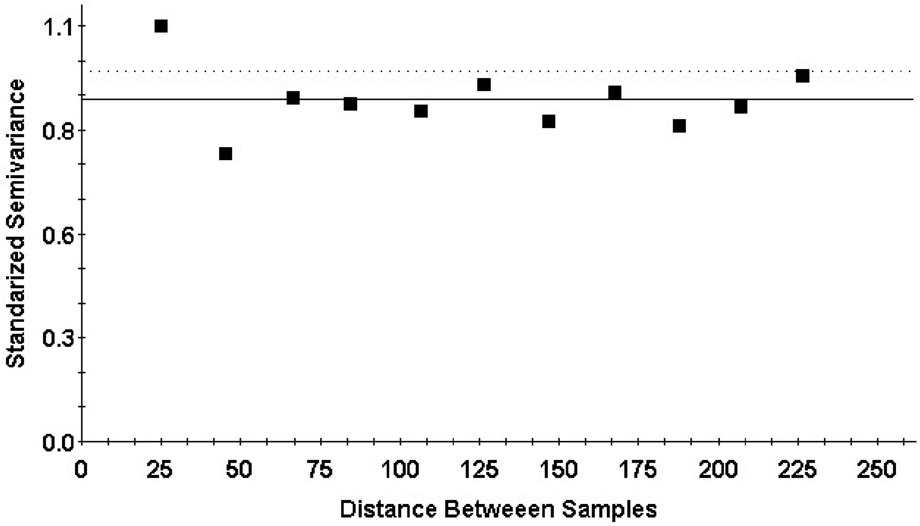

Fig. 2.5: Semivariogram analysis of sampling data on TSSM collected in Field 2 on 7 August 2001. The variogram was standardized by the sample variance.

DISCUSSION

The spatial distribution of TSSM within peanut fields in southeastern Virginia remained relatively constant from week to week in each of the fields that were studied. An advantage that the Cramér-von Mises test has over other similar tests (e.g., Kolmogorov-Smirnov) for examining the relationship between the spatial distributions of two populations is that the Cramér-von Mises test is sensitive to differences in the distributions of the populations, but is insensitive to differences in the population sizes (Syrjala 1996). Therefore, although the density of TSSM changed weekly in each field that was sampled, the changes did not appear to affect the spatial distribution patterns of TSSM between successive weeks. For example, the mean density of TSSM in the fourth week of sampling in Field 1 was more than twice the mean density in week 1, yet, there was no statistically significant difference in the spatial distribution patterns between week 1 and week 4 (Table 2.1, Fig. 2.3 A and B). The same was also observed for Field 4 where the spatial distributions of TSSM in weeks 2 and 3 were similar even though the mean density in week 2 was approximately seven times that of week 3.

In those cases where significant differences in the spatial distributions of TSSM were found between sampling weeks, the growers reported that they had applied a pesticide to their fields. In Field 1, for example, the grower applied an acaricide to the field between the third and fourth weeks of sampling and again a week later (Fig. 2.2). The use of pesticides also was responsible for changes in the spatial distribution of the spider mites that were observed in Field 2 and Field 3 (Table 2.1). The results for Field 3 suggest that the spatial distribution of TSSM population in that field changed between the second and third week, but by the fourth week the distribution had reverted to the one that was observed before the application of the pesticide. Although the evidence is not extremely overwhelming (based on *P*-values of only 0.09) and the overall mite density was very low, the results show that the distribution of mites in week 4 was statistically similar to the distributions observed in weeks 1 and 2 in Field 3. This might suggests that although the application of a pesticide can change the spatial distribution of mites within the field, the distribution may return to what it was previously. It is surprising that the spatial distribution would return so quickly to a previously observed distribution, but this could have been because of the low densities of TSSM within that field. Further studies are needed to verify this finding.

Studies have shown that arthropod populations have the tendency to reorganize in a predictable manner after being disrupted (e.g., by pesticides). Young and Young (1998) compared arthropod populations to particles (in statistical mechanics) that attempt to maximize their entropy by moving toward the most probable distribution regardless of their initial distribution. They noted that for most arthropods the most probable distribution was the geometric distribution. As an example, they observed that after applications of insecticides disrupted the distribution of cotton fleahoppers, the insect quickly returned to the initial distribution after the effects of the pesticide had diminished (Young and Young 1989). It must be pointed out, however, that the distribution that Young and Young (1989) were referring to was the frequency distribution of counts (dispersion) and not the spatial distribution. Young and Young (1998, Chapter 7) cautioned against associating the two types of distributions and presented examples to illustrate the inability of measures of aggregation based on frequency data to assess spatial distributions. This is supported by the results for Field

3 (Table 2.1) which show that although the spatial distribution of the TSSM changed during the sampling period, the dispersion indices suggest that the densities of TSSM were aggregated during all weeks.

The TSSM population in Field 1 initially had a spatial distribution that was aggregated or clumped (Fig. 2.4A). However, in week 5, after the second application of the acaricide, the spatial distribution changed and densities became more autocorrelated as suggested by the linear semivariogram model (Fig. 2.4B). The dispersion indices also support the claim that indicated that the densities of TSSM were distributed uniformly. It would appear, therefore, that at high densities TSSM populations in peanut tend to be aggregated spatially. The uniform distribution in mite density that was observed in Field 1 on 16 August was likely due to the extremely low number of mites found at all sampling locations within the field because of mortality of TSSM caused by the acaricide. The overall low numbers of mites in Fields 2, 3, and 4 also may account for the uniform and random spatial patterns that were observed for populations within those fields. Very little is known about the spatial distribution pattern of TSSM in peanuts and other field crops. However, studies of the frequency distribution of TSSM densities can be used (with caution) to help explain the spatial patterns of TSSM that were observed in this study. Nachman (1981) for example, found that low-density populations of TSSM populations generally were predisposed to a random distribution, but at higher densities their distribution was aggregated. This was the case in this study in Field 1 and is supported by the semivariogram analysis and indices of dispersion. It also has been shown that spider mites usually will have an aggregated distribution early in the infestation phase of a crop, but later on the pattern of aggregation changes to a more widely dispersed or random dispersal pattern as competition and crowding in the field increases (Wilson et al. 1983, Hollingsworth and Berry 1982, Slone and Croft 1998). The trend toward a random pattern in the spatial distribution of TSSM populations over time within fields also is thought to be indicative of aerial dispersal (Pickett and Gilstrap 1986). The patterns in the spatial distribution and the indices of dispersion for Field 4 would tend to support the view of TSSM population moving toward a random pattern over time.

Two requirements for precision pest management are that there exists some level of spatial variability in the density of the pest population within the field (i.e., the pest population has an aggregated spatial distribution) and that the spatial distribution changes very slowly over time. This study showed that TSSM populations in peanut fields tended to have an aggregated spatial distribution that changed very slowly. It may be possible that these two pieces of information may be used to develop precision management tactics for TSSM in peanut.

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Chapter Three

Spectral Reflectance of Peanut Foliage in Relation to Soil Moisture and Density of Twospotted Spider Mite (Acari: Tetranychidae)

INTRODUCTION

The twospotted spider mite (TSSM), *Tetranychus urticae* Koch, is a commonly occurring mite species in agroecosystems (Huffaker et al. 1969, Helle and Sabelis 1985a, b). The polyphagous habit of TSSM, its biology, and the plant injury it produces (Helle and Sabelis 1985a, b) make this mite a severe pest of high value field crops such as peanut, *Arachis hypogaea* L (Johnson et al. 1980, Brandenburg and Kennedy 1982, Johnson et al. 1982, Smith and Mozingo 1983, Margolies and Kennedy 1984). TSSM populations often increase during hot, dry weather (Chandler et al. 1979, Hollingsworth and Berry 1982, Oi et al. 1989). The injury to plant tissue and the stress that results from feeding often are exacerbated by lack of water or drought conditions (Johnson et al. 1982, Klubertanz et al. 1990, McNab et al. 1994) acting alone or in combination with the use of certain pesticides (Campbell 1978, Smith and Mozingo 1983, Boykin and Campbell 1984).

Feeding by spider mites can occur on both the upper and lower surfaces of plant leaves, but the underside of the leaf is preferred (Jeppson et al. 1975). The external symptoms of feeding injury by TSSM on plant foliage are characteristic of those caused by most spider mite species. The primary external symptom is a chlorosis or speckling of yellow spots around the feeding area (Helle and Sabelis 1985 b, Brandenburg and Kennedy 1987), which in acute cases can dramatically decrease the photosynthetic ability and yield potential of the crop (Johnson et al. 1980). Factors such as water stress, diseases, and insect-induced injuries that cause plant stress do so by promoting changes in the internal morphology and physiology of leaves through the removal of cell contents (Kielkiewicz 1985) and damage to the epidermal and spongy and palisade parenchyma (Huffaker et al. 1969, Campbell et al. 1990). Internal symptoms of damage usually can be observed before external symptoms (such as chlorosis) become visible.

Bounfour et al. (2002), for example, made this observation when TSSM were allowed to feed freely on red raspberry.

The appearance of chlorotic symptoms of mite feeding on plant leaves is often relied upon for making management decisions. Peanut farmers in Virginia, for example, usually will wait until they see mite-induced chlorotic areas in their fields before they intervene with pesticides. By this time, however, the TSSM infestation has already spread to most of the field, so that single or even double applications of acaricides offer limited control (Herbert pers. comm).

The internal changes in plant tissue that result from insect feeding cause changes in the way the leaves reflect and transmit radiant energy (Hsiao 1973). These spectral changes usually can be detected with the aid of remote sensing tools before visual symptoms become apparent (Myers et al. 1975). The ability to use remote sensing and the spectral signature of foliage to detect damage to plant tissue before visual symptoms appear could help improve the timing and placement of management inputs in IPM and PPM. Spectral reflectance data gathered by remote sensing systems have in the past been related to crop yield (e.g., Thomas and Gerbermann 1977, Tucker 1979), water stress (e.g., Mahey et al. 1991, Cohen 1991) and disease conditions (Hatfield 1990) in plants. Recently, there has been renewed interest in the application of remote sensing technologies for the management of arthropod pests (e.g., Dowell et al. 1999, Brewster et al. 2002).

The objective of this study was to use remote sensing technology in the form of a miniature fiber optic spectrometer to determine how soil moisture and mite density affected the spectral characteristics of peanut foliage under laboratory conditions. The idea was that this would serve as the basis for developing an Unmanned Air Vehicle (UAV) remote sensing system that could capture low-altitude high-resolution images of crop fields (Brewster et al. 2002). The images then could be used to develop maps of the spatial distribution of TSSM populations for precision management of this pest.

MATERIALS AND METHODS

Peanut plants were grown individually from seeds under laboratory conditions in 1-quart pots containing a mixture of 70% sand (Kiddies Fun Play Sand®) and 30%

potting soil (Sunshine Mix®). The pots were held under high intensity discharge (HID) mercury vapor lighting emitting 250fc with a 14:10 (L:D) photoperiod and without overhead watering. The soil moisture of all the plants was maintained within the range of the medium moisture level listed in Table 3.1. After six weeks, plants were selected randomly and each was assigned to one level combination of two treatments, soil moisture, and density of TSSM, in a 3 × 4 factorial design. This design was replicated five times during the study. The levels of moisture were low, medium, and high; the levels of TSSM density were 0, 5, 10, and 20 mites per leaf (Table 3.1).

Table 3.1: Factors and levels used in the study of light reflection from peanut foliage under laboratory conditions.

Mites per leaf (density)	Soil moisture [a]
0	High (8 –10)
5 (~0.3 mites/cm^2)	Medium (4 – 7)
10 (~0.6 mites/cm^2)	Low (0 – 3)
20 (~1.3 mites/cm^2)	

[a] Moisture levels were calibrated to 100% saturation (= 10 on the Lincoln soil moisture meter).

Each of the selected plants was placed in an individual battery jar, which was coated lightly with petroleum jelly on the inside lip to prevent the mites from escaping. The jars were then placed in plastic boxes that also had a light layer of petroleum jelly around the top two inches of the inside and double-sided sticky tape on the outside top of the box. The level of soil moisture for each plant was monitored using a Lincoln portable handheld soil moisture meter (Lincoln Irrigation, Inc., NE). The Lincoln moisture meter was standardized initially to a moisture level of 100% saturation for the soil mixture used in the study by adding water to a potted peanut plant until the soil was completely saturated. The three levels of soil moisture (low, medium, and high) were then calibrated based on the standard soil moisture.

A single peanut leaf, which is made up of four leaflets, was selected on each of the peanut plants to be infested with one of the density levels of TSSM (Table 3.1). Leaves that were selected were similar in size (~14–16 cm^2) and were generally ones that were not in close contact with other leaves on the plant. This was done to preserve the density of mites on the leaf by preventing them from moving on to other leaves. Small wooden coffee stirs were used to hold leaves apart and increase the distance between the mite-infested leaf and other leaves If the leaves on the plant were arranged closely. Each selected leaf was tagged by marking the petiole with a permanent marker at the base so it could be identified easily later for taking reflectance readings. A tiny layer of petroleum jelly also was applied to the petiole of tagged leaves to prevent the mites from crawling to other parts of the plant.

The mites used in the study came from a population that was raised initially on lima beans (*Phaseolus vulgaris*) held in rearing cages under laboratory conditions at 30°C and 14:10 (L:D) photoperiod. Mites were transferred to the tagged leaf on each plant using a camel's hair brush. No attempt was made to confine the mites to any particular leaflet of a leaf. As such, they were allowed to utilize all of the four leaflets of the tagged leaf. The moisture level of the soil for each of the plants was monitored twice daily to ensure it remained within the assigned moisture level range. Water was added when necessary to correct any deficiency. The number of mites on the tagged leaf of each plant also was monitored twice daily using 4X OptiVISOR magnifying glasses (Donegan Optical, KS). Mites were added or removed from the leaf as was required to maintain the initial density.

Reflectance readings were recorded daily from the tagged leaf of each peanut plant using USB 2000 Miniature Fiber Optic Spectrometer (Ocean Optics, Inc., FL) with version 1.1 OOIBase32 Spectrometer operating software running on a 300 MHz laptop PC with Microsoft Windows98 operating system. The unit used an R400-7-UV/VIS probe, that was illuminated with a halogen light source, to take reflectance readings at wavelengths between 0.200µm and 0.850µm. Before each set of readings was taken from a leaf, the spectrometer was calibrated to the dark and light reflectance ranges using a WS-1 Diffuse Reflectance Standard (Ocean Optics, Inc., FL). This standard is made of PTFE, a white plastic with a lambertian surface that reflects >95% of light in the range of wavelengths from 0.250–2.00 μm. The reading for the dark range was taken with the device set in scope mode, with overhead lights turned off, and with the probe covered so that no external light could be detected. The reading for the light range also was done with the unit in scope mode, but was taken with the overhead lights on. The percentage of reflection of light from the leaf surface was calculated relative to the reflection of light energy from the standard (WS-1) based on the following:

$$\% R_{\lambda} = \frac{S_{\lambda} - D_{\lambda}}{R_{\lambda} - D_{\lambda}} \times 100\% \qquad (3.1)$$

where *S* is the sample intensity at wavelength λ; *D* is the dark intensity at wavelength λ; and *R* is the reference or standard intensity at wavelength λ.

Reflectance readings were taken daily for a period of 10 days from the tagged leaf on each plant with the spectrometer set in transmission mode. Preliminary studies suggested that after 10 days the leaves on plants under the low soil moisture regime were unusable. Two readings were taken from each of the leaflets on the tagged leaf of each plant; a total of eight readings per leaf per day, therefore, were taken from each of the plants. To reduce the error caused by positioning of the spectrometer, readings were taken near the base of the petiole and at the top of the mid-vein on the upper side of the leaf to obtain spectral reflection from areas where mite feeding was known to be concentrated based on prior field work. The reflectance probe also was held at a 90º angle to the leaflet while readings were taken to ensure minimal light interference. In some cases the leaf had to be manipulated to achieve the required angle for taking the reflectance reading. The distance of the probe to the leaflet also was kept constant for each reading. The distance was determined at the time the reference spectrum was taken and, therefore, corresponded to the distance of the probe from the diffuse reflectance standard when the unit was calibrated. The distance was kept constant for each daily reading by taping an unfolded staple to the side of the probe to mark the distance from the sample to the instrument.

STATISTICAL/DATA ANALYSIS

The daily reflectance readings were stored in a text file, which could be imported into Microsoft Excel. The data for each tagged leaf on the plant were summarized using the average of the eight readings per leaf. The percentage of reflectance at wavelengths in the red region (0.630–0.690 μm) and the near infrared region (0.750–0.800 μm) of the electromagnetic spectrum (EMS) then were extracted. The average reflectance for the red (R) and near infrared (NIR) wavelength ranges for each plant was calculated to derive one metric for R and one for NIR. These values were used to derive the reflectance ratio (RR), which is (NIR ÷ R). Because of problems with the spectrometer, only data from three of the five replicates were found to be useful for analysis. These data were analyzed using a General Linear Model (GLM) ANOVA with a two-way interaction and Fisher's least significant difference (LSD) multiple comparison test for mean separation (SAS Analysis System, Cary, NC).

RESULTS

The percentage of light energy at wavelengths in the visible region of the electromagnetic spectrum (0.450–0.690 μm) that was reflected from peanut leaves was generally low (<10%), but increased to over 40% for light energy at some wavelengths in the near infrared (NIR) region (0.760–0.900 μm) (Fig. 3.1).

No significant differences in reflectance ratio (i.e., NIR/R) were found eight days after treatments started for leaves on peanut plants exposed to the combination of three levels of moisture and four levels of mite density outlined in Table 3.1. However, Fisher's LSD showed the mean reflectance ratio for plants receiving the low moisture treatment was significantly lower after eight days (mean = 9.4766; $\alpha = 0.05$) compared with plants exposed to medium (mean = 10.0186) and high moisture levels (mean = 10.5413).

Significant differences in the reflectance ratios were found for peanut leaves on plants exposed for 10 days to the four levels (0, 5, 10, and 20) of TSSM densities ($P = 0.0129$; Table 3.2) and three levels (high, medium, and low) of soil moisture ($P = 0.0028$; Table 3.2). However, no significant interaction was observed between soil moisture and spider mite density ($P = 0.8710$). The results of Fisher's LSD showed that plants with 20 spider mites per leaf had significantly lower mean reflectance ratios on day 10 compared with plants with 0, 5, and 10 spider mites per leaf at the three moisture levels (e.g. Fig. 3.2). The leaves of plants exposed to low moisture levels also had significantly lower mean reflectance ratios compared with those on plants under medium and high moisture levels (Table 3.2; e.g., Fig. 3.2)

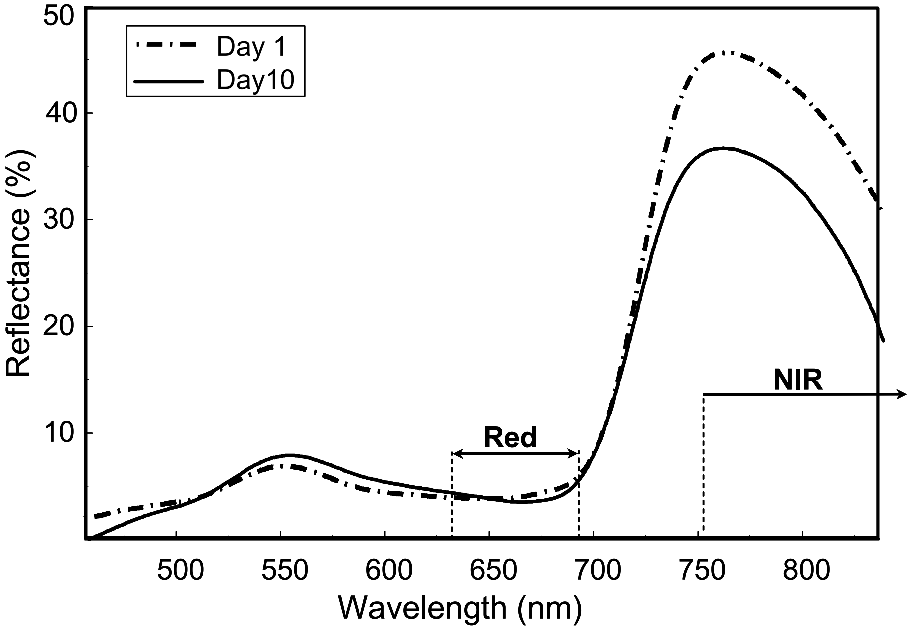

Fig. 3.1 Spectral reflectance curves from peanut plants used in the study showing the changes that typically occur as the plant ages.

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Table 3.2: Analysis of Variance and Fisher's LSD on the radiance ratios obtained from peanut plants after 10 days.

Source	df	*F*	*P*	Fisher's LSD (α = 0.05)	
				Factor Levels	Mean* RR[1]
Mite No.	3	4.43	0.0129	0	10.0631a
				5	9.7808a
				10	9.4817a
				20	7.9212b
Moisture	2	7.75	0.0028	Low	8.1200a
				Medium	9.5799b
				High	10.2352b
Mite No. × Moisture	6	0.40	0.8710		
Error	24				
Corrected Total	35				

* Means followed by same letter within each treatment are not statistically different (*P* > 0.05).

[1] RR = reflectance ratio.

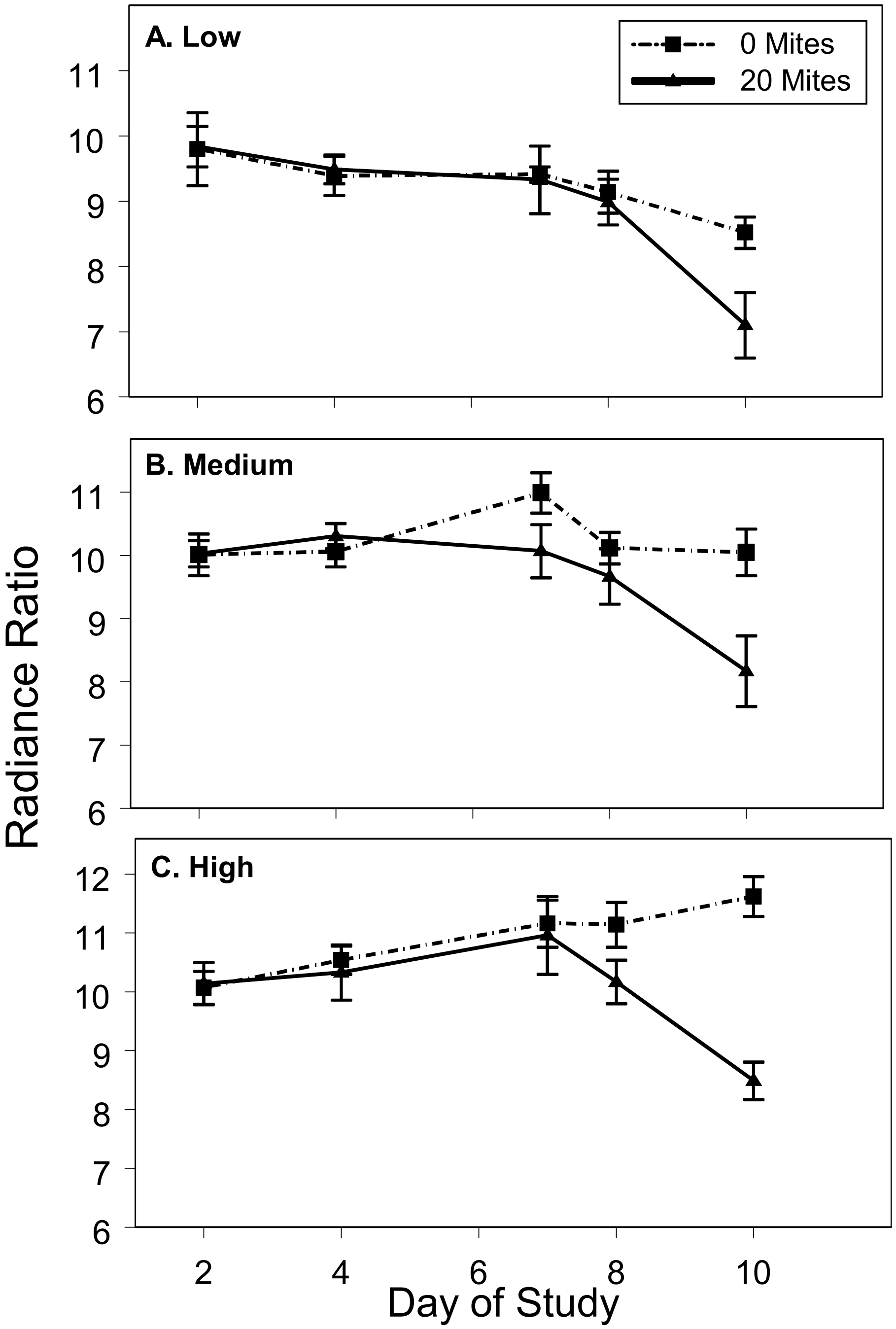

Fig. 3.2: Reflectance ratios for peanut foliage on plants with 0 and 20 TSSM per leaf and exposed to low (A), medium (B), and high (C) soil moisture levels.

DISCUSSION

Natural objects such as plants reflect (and transmit) electromagnetic energy in a manner that is characteristic of their physical and chemical (or biological) properties (Myers et al. 1975, Avery and Berlin 1985, Verbyla 1995). The spectral reflectance curves or spectral signatures observed from the foliage of peanut plants studied under laboratory conditions were typical for those observed for most vegetation types (Fig. 3.1). Vegetation usually has low reflectance of light energy in the visible region of the electromagnetic spectrum (EMS) because this energy is absorbed by plant pigments such as chlorophyll (Hoffer 1978, Richards and Jia 1999). The adsorption of light energy in the visible region of the EMS seems to be dominated by red radiance at wavelengths between 0.63 - 0.69 μm. Tucker (1977) showed that the wavelength of 0.675 μm was the point within the red region where maximum absorption of light by chlorophyll a and b occurred. He also inferred that the amount of red light absorbed by plant pigments could be used to determine the condition of the plant. For most vegetation, the amount of light reflected in the red region of the EMS usually is <10% (Tucker 1978, 1979, Richards and Jia 1999), as was observed in this study (Fig. 3.1).

There is usually a noticeable increase in the reflectance of light energy from vegetation at wavelengths in the NIR region of the EMS (0.76–1.30 μm). NIR radiance is not affected by the chloroplasts within the leaf, but by the internal structure of the leaf, primarily the presence of cell wall and air spaces of the spongy mesophyll layer (Hoffer 1978, Avery and Berlin 1985). Healthy leaves with many cell-wall interfaces, therefore, will reflect more light energy in the NIR region of the EMS. The percentage of reflectance of light energy in the NIR wavelengths varies with the plant species, but for most vegetation types it is typically between 40–50% (Hoffer 1978, Tucker 1978, Avery and Berlin 1985). The percentage of reflectance at NIR wavelengths for healthy leaves on the peanut plants used in the study was within this range (Fig. 3.1). Tucker (1977) found that the spectral point of 0.765 μm represented the region of enhanced spectral reflectance in the NIR range, and so recommended using the NIR wavelengths of 0.75–0.80 μm for studies of plant reflectance (Tucker 1979). The NIR wavelength range, therefore, was adopted in this study.

Indices such as the Normalized Difference Vegetation Index (NDVI) and the reflectance ratio have been used in reflectance studies to assess plant stress conditions (Tucker 1979, Mahey et al. 1991). Factors that cause plant stress such as drought, pathogens, and arthropod pests alter the form of the spectral signature (e.g., Fig. 3.1) in a way that would allow their effects to be detected before visual symptoms are observed. Peanut, for example, is a relatively drought tolerant species because of its extensive root system. However, peanut plants can become susceptible to lack of water during certain stages of growth, such as during the first two weeks of germination and near the eighth week of growth when nut development and fruiting is occurring (Ross 2002). The peanut plants used in this study were between six and seven weeks at the onset of the trial. Therefore, 10 days after the study was initiated the plants would have been approaching the physiological stage when their susceptibility to drought would be high. Usually at this stage, peanut plants require a level of soil moisture that provides about 50-60% of the available water (Ross 2002). The medium and high soil moisture levels used in the study were within the ranges of 40–70% and 80–100% of available water for the soil mixture. The low soil moisture level (0–30%), however, was well below the 50% range suggested by Ross (2002) for healthy growth and high yields. Many of the plants that were under the low soil moisture regime showed visual symptoms of drought stress (wilted or dying leaves) by day 10. However, it is evident based on the significantly lower reflectance ratios obtained from the leaves of these plants, that the remote sensing instrument was able to 'see' the effects of water stress at about the eighth day of the study (Fig. 3.2). Before visual symptoms of water stress were observed. The lower reflectance ratio of the water-stressed plants was a result of an increase in red reflectance and a simultaneous decrease in NIR reflectance (Mahey et al. 1991).

In addition to low soil moisture, the presence of twospotted spider mites also increased the stress to the peanut plants. A significant decrease in reflectance ratio occurred after 10 days for leaves that were infested with 20 mites compared with leaves infested with 0, 5, and 10 mites. The decrease occurred at all three levels of soil moisture (Fig. 3.2). Also, no interaction was found between mite density and soil moisture (Table 3.2). The lack of an interaction between TSSM and soil moisture is supported by the results found by Youngman and Barnes (1986). It was deduced that the lack of an interaction between the effects of mite feeding and water stress on gas-exchange parameters were probably due to the fact that the two stressors act independently of each other (Youngman and Barnes 1986). In studies where an interaction between soil moisture and mite density was observed under field conditions (Chandler et al. 1979, Hollingsworth and Berry 1982) it was suggested that it may be due to the ability of mite populations to increase freely in the absence of mortality caused by heavy rain or overhead irrigation. Both rain and overhead irrigation can physically remove individuals from the plant and at the same time create an environment that is favorable for fungal epizootics (Simpson and Connell 1973). In this study, the daily removal from or addition of individuals to infested leaves may have acted in a manner that was similar to the physical force of rainfall. However, it has been shown that in soybean, heavy rains did not significantly affect spider mite population density (Klubertanz et al. 1990). The different architecture and growth habits of soybean and peanut may be factors that determine how much of an impact heavy rain has on spider mite populations.

The study showed that under laboratory conditions the spectral reflectance of foliage could be used to detect stress to peanut plants caused by lack of water and mite infestation. The results also suggest that stress could be detected before the appearance of visual symptoms. Bounfour et al. (2002) used a nondestructive method of chlorophyll fluorescence induction to show that TSSM caused cellular injury to red raspberry leaves before visual symptoms were observed. Although the two studies were done under controlled conditions (laboratory or greenhouse) using individual plant leaves, they still provide information useful for managing TSSM populations in the field. A word of caution in applying the results, however, comes from Verbyla (1995) who warned that spectral relationships determined under laboratory conditions at the leaf level should not be used directly in making decisions under field conditions at the canopy level. One reason for this is that the magnitude of the reflectance in the red and NIR regions of the EMS usually will differ significantly between leaf and canopy level (Williams 1991). Therefore, studies need to be done in the field to validate the results of the laboratory study before spectral reflectance changes can be used effectively as an indicator of impending mite damage within peanut fields and to create maps of the spatial distribution of this pest for precision pest management.

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Chapter Four

An Unmanned Air Vehicle (UAV) Remote Sensing System for Use in the Precision Management of Twospotted Spider Mite in Peanut

INTRODUCTION

The goal of precision agriculture (or site-specific farming) is to optimize the potential of the crop by dividing the field into subunits and applying management inputs separately instead of assuming that the distribution of the within-field variable of interest is uniform (Usery et al. 1995). Like other aspects of precision farming, such as yield mapping (Pierce et al. 1997), soil conditioning, and weed management (Schueller and Wang 1994, Johnson et al. 1997), precision management of arthropod pests (precision pest management) is grounded in the principles of precision agriculture and, therefore, targets pest populations within individual crop fields.

Success in precision agriculture depends on our ability to combine information, technology, and management (National Research Council 1997). Technology is needed for gathering information on the spatial and temporal distribution of the variable of interest within the management unit (crop field) and management inputs (e.g., GPS-enabled equipment) are needed that can integrate the information and technology for the end-user (the farmer). Therefore, at the core of the precision management approach are many technologies, which help to optimize the potential of the crop and decrease the level of management inputs, such as pesticides, in the environment. Maps, for example, are needed to characterize the spatial distribution of the within-field variables of interest (National Research Council 1997). Technologies such as Global Position System (GPS), geographic information systems (GIS) and remote sensing enable farmers to develop and use these maps in their map-sensitive farm equipment so that they can target only those areas within the field where problems have been observed.

Maps of the within-field densities of arthropod populations currently are constructed with human labor. This method, however, is both inefficient and too expensive to be cost-effective at the farm level level. In addition, unlike other within-field variables such as soil nutrient levels, weeds, and product yields that are spatially static, at least on the time scale of one growing season, and, therefore, relatively easy to map, arthropod populations usually are spatially and temporally dynamic and so mapping their distribution is increasingly more difficult (Weisz et al. 1996). Thus, no efficient methods are available for making maps of arthropod density even though most arthropods, like weeds, tend to be spatially clustered (Taylor 1984, Southwood 1988) and vulnerable to spatially varying management strategies (Fleischer et al. 1997). Also, of the geo-information technologies available for precision agriculture (or management), remote sensing has been the most underutilized probably because of the lack of availability of cost-effective and time efficient methods for gathering remotely sensed data on crop fields.

As one possible solution to the problem of mapping arthropod densities for precision management, Allen et al. (1999) suggested using an Unmanned Air Vehicle (UAV) remote sensing system to capture low-altitude high resolution imagery of crop fields that could be analyzed to create maps of the spatial variation of plant stress conditions as a function of pest populations. The pattern of damage in the images, then, could be related to the spatial distribution of the pest population. In the specific case of the twospotted spider mite (TSSM), for example, it might be possible to detect spectrally the pattern of plant damage as a function of mite feeding in relation to the spatial distribution of mite densities within the field. The idea of using UAVs for surveillance is not new. Aerospace firms such as AeroVironment (http://www.aerovironment.com/area-aircraft/unmanned.html) have for some time been engaged in research and development programs on these systems for military use (http://www.darpa.mil/tto/programs/mav.html).

The goal of this study, therefore, was to evaluate the remote sensing system of an Unmanned Air Vehicle (UAV) for use in the precision management of arthropod pest populations in agricultural fields. The specific objectives were to develop a UAV aircraft with a remote sensing system, to test the flight and imaging capabilities of the UAV, and to relate spectral variations in the images captured with the system to the spatial distribution of densities of the TSSM in peanut fields.

MATERIALS AND METHODS

The study was designed to be carried out in three phases. Phase I, which involved the construction of a UAV with a remote imaging system, was completed by MLB Co. (Palo Alto, CA; http://www.spyplanes.com), a company that specializes in the development of Unmanned Air Vehicles and Micro Air Vehicles (MAV). Phase II involved testing the flight and imaging capabilities of the UAV. In summer 2001, I tested the UAV remote sensing system over an alfalfa field at the Virginia Tech Kentland Research Farm, and over peanut and cotton fields in Suffolk County, Virginia. In Phase III, I planned to test the utility of the UAV remote sensing system for mapping TSSM populations in peanut fields. The idea was to fly the UAV over a peanut field that was infested with TSSM to obtain visible color (Red, Green, Blue) and near infrared (NIR) images of the field. The images were to be used to generate a Normalized Difference Vegetation Index (NDVI) image of the field based on the relationship between the red and NIR images (Brewster et al. 1999),

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}} , \qquad (4.1)$$

The NDVI image would show spectrally the spatial distribution of plant stress or damage caused by TSSM feeding. At the same time, I planned to conduct a ground sampling of TSSM populations within the same field that was imaged to determine the spatial distribution of mite densities. Spatial correlation analyses, then, would be used to determine the relationship between the spatial distribution of plant damage (in the NDVI image) and TSSM population density (from the ground sampling) within the field.

RESULTS AND DISCUSSION

Phase I: Construct a UAV with a remote sensing system

This phase of the study was completed with the help of MLB Co. (http://www.spyplanes.com), which produces robotic UAVs and MAVs for imaging applications. The UAV measured 0.9 x 0.76 x 0.0762 m and was light enough (≈0.6 kg or 1.25 lbs) to be hand launched. The craft had altitude hold and wing leveling autopilot and a 1cc engine, which allowed it to fly for about 0.5 hr at altitudes up to 457 m and at speeds from 28.8–72 km/hr (18 to 45 mph). A radio control 8-channel PCM uplink on 72 MHz was used for flight control and imaging. Flight telemetry was limited to 1.44 km (0.9 mile) radius. The imaging sensors consisted of two downward facing video cameras. One of the cameras was capable of gathering spectral data on a crop field in the visible (red, green, blue) region of the electromagnetic spectrum (EMS) corresponding to wavelengths of 0.45–0.69 µm and the other camera gathered spectral data in the near infrared (NIR) region of the EMS, which corresponded to wavelengths of 0.76–0.90 µm. The UAV remote sensing system also had a forward facing color camera to aid in flight control. The cameras communicated with two ground video receiving and recording stations using a 72 MHz uplink and a 2.4 GHz downlink (Fig. 4.1).

Fig 4.1: (Left) the UAV, **(Middle)** the UAV with the remote control, video system, and antennae, and **(Right)** the UAV flying low over an alfalfa field at the Virginia Tech Kentland Research Farm, Montgomery Co., VA

Phase II: Test the flight and remote sensing systems of the UAV

The tests of the UAV remote sensing system showed that the unit could be operated and would capture video data on crop fields under harsh environmental conditions. For example, the UAV flew successfully at the Virginia Tech Kentland Research Farm in 37 km/hr (23 mph) winds and ambient temperature of 11°C. Although the craft was difficult to control under these conditions, I was still able to record video data of the agricultural area.

I also tested the UAV remote sensing system over peanut and cotton fields in Suffolk, VA. The video data that were recorded were uploaded to a desktop computer where I extracted images of the crop fields that corresponded to the red region of the EMS (0.63–0.69 µm). I also extracted the corresponding NIR images from the video data. The images were then used to derive the NDVI image, which provided a measure of plant condition (Fig. 4.2). In the NDVI images, areas of healthy vegetation are white, areas of unhealthy vegetation or the absence of vegetation are black, and shades of gray represent variations in the condition of the plants. Thus it may be possible that NDVI values can be related to pest population intensity to identify 'hot spots' within a field, which could be targeted for treatment by growers.

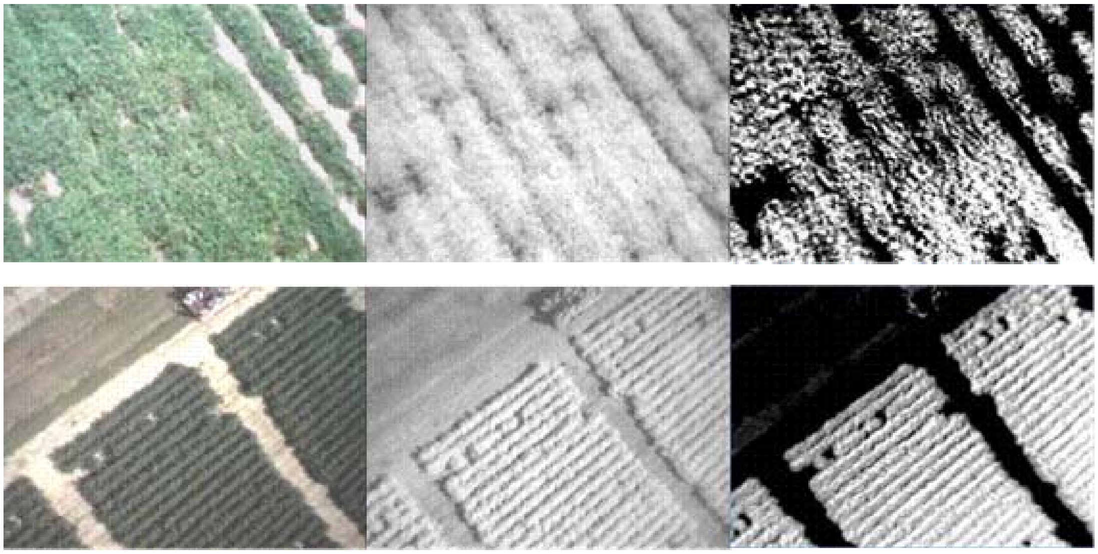

Fig 4.2: Images taken by the UAV remote sensing system over peanut and cotton fields in southeastern Virginia. **Left:** natural color images; **Middle:** near infrared (NIR) images; **Right:** NDVI images developed from the red and NIR images. Stressed and non-vegetated areas are black and areas of healthy vegetation are white.

It was evident from the tests that some modifications were needed in the flight control and imaging equipment that would greatly improve the efficiency of the system. For example, the analysis of the image data gathered by the UAV was a time consuming process that likely would reduce the effectiveness and use of the system for pest management. Both the color and NIR image data were recorded in analog format on Hi8 tapes. This meant that these data had to be viewed through a VCR and TV to select specific frames for analysis. These frames then had to be converted from analog to digital format so that they could be moved to the computer with the imaging software for spectral analysis, extraction of the red image from the visible color image, and generation of the NDVI image.

One improvement to the system that would help with the imaging and analysis problem would be to add an onboard GPS system, which would allow the UAV to operate autonomously to deliver high quality geo-referenced images. Another improvement either would be to replace the analog video recording system with a system that would record the video data in digital format or to replace the current ground console with a laptop computer to serve as the primary control console. The new console would have a moving map display showing the location, speed, and height of the aircraft in real time and also would allow the video data to be recorded directly in digital format on a computer that carried the image processing software. A final improvement would be to place the color and NIR cameras closer together on the aircraft so that the captured images would be better synchronized spatially during capture.

Phase III: Map pest populations with the UAV system

This phase of the study could not be completed because of unexpected equipment failure and loss of the UAV aircraft.

CONCLUSIONS

Although I was not able to complete all of the phases of this study, this initial work was encouraging as it showed that UAV remote sensing systems have the potential to become important tools in the precision management of arthropod pests in agricultural fields. Once a new UAV is constructed with the improvements that have been highlighted, all efforts should be directed toward understanding the relationship between the spatial distribution of spectral signatures from a crop field and the spatial distribution in the densities of the target pest within the field. In addition, the UAV system would need to be tested under different crop and pest conditions and other aircraft models could be considered and tested for use as UAV systems. Remotely controlled helicopters, for example, have the ability to hover and fly much slower over test plots than fixed-wing UAVs. This would make capturing, viewing and analysis of the image data a much simpler process. Finally, the experiences of this study suggest that the system should be equipped with an electronic homing device that would make the system easier to locate in the event of the loss of the aircraft caused by a loss of ground communication with the system as occurred during this study.

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Chapter Five

Summary

The twospotted spider mite (TSSM), *Tetranychus urticae* Koch, is a common polyphagous pest in agroecosystems (Huffaker et al. 1969, Helle and Sabelis 1985a, b). This mite is known to infest field and orchard crops (Wilson et al. 1983, Pickett and Gilstrap 1986, Klubertanz et al. 1990, Roy et al. 1999, Pratt et al. 1998, Strong et al. 1997, Youngman et al. 1986, Brandenburg and Kennedy 1982). The damage caused by feeding of the TSSM coupled with its biology and dispersal behavior has caused this pest to become a severe economic problem in peanut, *Arachis hypogaea* L (Johnson et al. 1980, Brandenburg and Kennedy 1982, Johnson et al. 1982, Margolies and Kennedy 1984).

The TSSM has been a very difficult pest to manage in the Virginia-Carolina area, which produces 20% of the nation's peanuts annually (Owens 2001). Most of the damage to peanut fields usually occurs during periods of hot, dry weather conditions from July to September in which spider mite populations are known to increase (Chandler et al. 1979, Hollingsworth and Berry 1982, Margolies and Kennedy 1984, Margolies and Kennedy 1985). Infestations of the spider mite in peanut usually are detected by the presence of chlorosis, a stippling of yellow spots around the feeding areas. The damage to tissues and the stress caused from feeding lead to a decline in photosynthesis, and overall reduction in yields (Johnson et al. 1980), and economic losses.

Although there have been some attempts to use biological control (Huffaker et al. 1969, Jeppson et al. 1975) and cultural practices (Johnson et al. 1980, Boykin et al. 1984) to manage populations of TSSM, peanut farmers usually have relied on applications of acaricides for mite control. Few attempts have been made to develop integrated pest management (IPM) or precision pest management (PPM) approaches for the mite in peanut.

Precision management of TSSM populations in peanuts would require information in the form of maps on the within-field spatial distribution of the pest and on the speed at which the distribution changes. The development of these maps, however, represents the main obstacle to the use of precision management approaches for arthropod pest populations because their spatiotemporal distribution usually changes rapidly making it difficult to characterize in a timely and economic manner (National Research Council, 1997). For the TSSM, it is important, therefore, to understand how the spatial distribution of the population changes both in time and space in peanut fields if we are to implement precision management strategies successfully. In addition, new tools and technologies are needed to help with the development of the maps that are required for precision management. One technology that can be explored is remote sensing. However, before remote sensing can be used in the precision management of mite populations, we would need to know if this technology can be used to detect plant damage caused by mite feeding and how this relates to the density of mites on the ground. Also, we would need a platform that would allow this technology to be used in a cost-effective and time-efficient manner in the precision management of TSSM populations in peanut.

The objectives of the study were: 1) to develop an understanding of the spatial and temporal dynamics and distribution of TSSM populations in peanut fields in southeastern Virginia, 2) to use remote sensing technology in the form of a miniature fiber optic spectrometer to determine how soil moisture and mite density affected the spectral characteristics of peanut foliage under laboratory conditions, and 3) to evaluate an Unmanned Air Vehicle as a remote sensing platform for use in the early detection of peanut stress due to TSSM infestations.

The first objective of the study was accomplished by conducting weekly sampling of TSSM populations in four commercial peanut fields in Dinwiddie County and Isle of Wright County, VA. The comparison of weeks of the spatial distribution of spider mite populations within each of the fields based on the two-sample Cramér -von Mises test showed that generally there was no change in the distribution of mites from week to week within any of the fields. Observed differences are thought to have occurred because of the application of a pesticide between the two sampling periods. For example, in Field 1 that was sampled in 2001, the spatial distributions of TSSM in week four and five were statistically different (*P* = 0.018) because of two applications of an acaricide. The application of a pesticide was also the cause of the change in distribution in the comparison of weeks three and four in Field 2 sampled in 2001 and in the comparison of weeks two and three in Field 3 that was sampled in 2002. No statistical differences in the spatial distribution of spider mites were found between any of the weeks in Field 4 sampled in 2002. This was probably because there was no external influence, such as the use of a pesticide, on the distribution of the population within that field. An interesting finding of the study was that when the within-field distribution of the spider mite had been altered (e.g., by the use of a pesticide), the distribution reverted to the pattern that was observed before the application of the pesticide. This was the case in Field 3 in which there was a significant difference between mite distributions in weeks two and three because of the application of a pesticide ($P = 0.005$), but there was no significant difference between the distributions in weeks one and four ($P = 0.095$). These findings are supported by other studies that studies the dispersion or frequency distribution of arthropods in which it was noted that their populations tend often to return to their initial (and most probable) distribution after disruption by some external factor (Young and Young 1989, 1998).

This understanding of the changes that can occur in TSSM distribution and of the speed with which these changes occur is crucial for developing a method for detecting and mapping the distribution of the pest and the implementation of precision management strategies within peanut fields. This study showed that even though the spider mite populations might be increasing, their spatial distribution remains fairly stable in the absence of external influences, such as pesticide application. Therefore, during the time when mites first begin to appear in peanut fields intensive sampling can be done to determine the spatial distribution of the mite. Density maps can be generated for the farmer that show those areas where populations are high. Pesticide applications, then, could focus only on these problem areas, reducing the cost of pesticides needed and the amount of chemicals that are released in the environment. If it can be shown that the population returns to its initial distribution, then follow-up applications of pesticide need only be applied to the ‘hot spots’ that were identified on the original distribution map.

The second objective was intended to determine whether remote sensing could be used to detect damage to peanut foliage caused by feeding of TSSM before visual symptoms are observed. Tests conducted under laboratory conditions using a spectrometer as the remote sensing device revealed that mite density and soil moisture level significantly affected the spectral reflectance signature obtained from peanut foliage before the appearance of visual symptoms (e.g., chlorosis). On day 10 of the study, the spectral signature from peanut foliage, as measured by the reflectance ratio (NIR/red), was significantly different on leaves with 20 mites than on leaves with 0, 5, and 10 mites ($P = 0.0129$). On day 8, the reflectance ratio was significantly lower for plants under the low soil moisture regime compared with those under the medium and high moisture regimes. However, there was no interaction between mite density and soil moisture level during the experiment.

This objective showed that under laboratory conditions the spectral reflectance of foliage could be used to detect stress to peanut plants caused by lack of water and mite infestation. The results also suggested that stress could be detected before the appearance of visual symptoms. Further, the study offered one possible explanation as to why spider mite populations tend to increase during periods of hot dry weather and in the absence of heavy rainfall. Both heavy rains and overhead irrigation can physically remove TSSM individuals from the plant and at the same time create an environment that is favorable for fungal epizootics (Simpson and Connell 1973). In this study, the daily manipulation of TSSM numbers on infested peanut leaves acted in a manner that was similar to the physical force of rainfall, which prevented that population from increasing.

The third objective was based on a suggestion that was made by Allen et al. (1999) to use an Unmanned Air Vehicle (UAV) remote sensing system to capture low-altitude high resolution imagery of crop fields, which then could be analyzed to create maps of the spatial variation of plant stress conditions in relation to pest populations. In the case of TSSM, a pattern of damage (based on chorotic foliage) would result from feeding.

In this objective, the goal was to build a UAV, test the flight capabilities of the aircraft and imaging system, and to relate spatial variation observed in images taken by the UAV system of peanut fields with spatial variations in twospotted spider mite densities. The overall system that was built was found to operate efficiently and was capable of capturing imagery of crop fields. However, I found the system needed many improvements and further testing before it could be used successfully as a tool for detecting infestations of TSSM and in precision pest management. The remote sensing cameras in the UAV needed to be placed closer together so that the red and near infrared images are aligned and their images corresponded spatially. There is also the need to convert the imaging system to one that could record digital data, which would make it easier to extract the information recorded during flight. Also, the UAV should have the ability to fly at slower speeds and needs to be equipped with GPS capability so that the coordinates of the field could be programmed into its flight pattern. Finally, the inclusion of the homing device on the craft is essential to ensure that in the event of loss of communication with the ground station the system could be found.

In conclusion, the present study demonstrated that precision pest management may be a feasible option for management of TSSM populations in peanut fields in southeastern Virginia. Two requirements for precision pest management of TSSM in peanut have been met. The pattern of the spatial distribution of the mite can be determined by sampling and this pattern remains fairly constant over time to allow for the implementation of the management strategy. The study also demonstrated that low-altitude remote sensing might be a feasible alternative to sampling for building maps of the spatial distribution of the mite for precision pest management.

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Vita

Erin Leigh Holden

Erin L. Holden was born November 17, 1977 in Columbus, Georgia. She lived in Miami, FL and Augusta, GA before moving to Charlotte, NC at the age of 5. She attended St. Patrick's Catholic school from kindergarten through eighth grade. She graduated from Charlotte Catholic High School in 1996 and moved to Daleville, VA a few weeks after graduation.

She attended Virginia Tech in Blacksburg, VA fall of 1996 as a freshman majoring in Biology. In order to fulfill a core requirement she took an Insects and Human Society class her sophomore year and became interested in the field of Entomology. She continued taking classes in the department and was able to earn a Bachelor of Science degree in Biology with a concentration in Entomology in May of 2000. That fall she entered into the department of Entomology as a graduate student. Her major advisor was Dr. Carlyle Brewster whose research and teaching centered on information technology in Integrated Pest Management (IPM). Her research with Dr. Brewster examined spatial ecology and remote sensing in the precision management of twospotted spider mites in peanut. She successfully defended her M.S. thesis at Virginia Tech in December 2002.