Characterization of Biopores Resulting from Mole Crickets (*Scapteriscus* spp.)

by

David L. Bailey

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Approved by:

David W. Held, Chair, Associate Professor of Entomology
Francisco J. Arriaga, Affiliate Associate Professor Soil Science
Kathy L. Flanders, Extension Specialist and Professor

Abstract

Soil organisms, particularly arthropods, create biopores as they move or tunnel. The abundance and burrowing nature of mole crickets, a common soil-inhabiting pest in the southeastern United States, will likely influence the hydraulic conductivity of soils. The objectives of this research was to provide additional insight into the biology of soil-dwelling insects and the ability of biopores to influence surface-to-groundwater infiltration, and to characterize the way two species (*Scapteriscus vicinus* Scudder and *S. borellii* Giglio-Tos) of mole crickets tunnel. These trials were performed in PVC arenas. Computed Tomography (CT) scans were taken of the arenas at the College of Veterinary Medicine at Auburn University, using a GE highspeed CT/i model computed tomography instrument. The scans were used to acquire 3-dimensional models of the arenas to best determine mole cricket tunneling characteristics in the soil. It was found that the only characteristic that was significantly different between soil types was the ability of the mole cricket constructs longer tunnels in the loamy sand compared to the clay loam. None of the other characteristics between the two species were found significant although the southern mole cricket was found to branch twice as much in the upper 20 cm of the arena than the tawny mole cricket. When comparing the adult and immature southern mole crickets, adult mole crickets displaced on average three times the volume of soil that the immature mole crickets displaced. Southern mole crickets construct significantly longer tunnels when turfgrass was not present. Throughout the experiments comparing mole crickets tunnel characteristics the total volume was significantly correlated with total length of mole cricket tunnels. The ability that mole crickets have to change the hydraulic conductivity of the soils was examined in field conditions as well as greenhouse trials. Field trials found there were significantly higher infiltration rates and lower runoff rates in areas infested with mole crickets compared to uninfested areas of Bermudagrass.

In greenhouse experiments, the hydraulic conductivity of saturated soil was significantly greater in arenas with mole crickets or night crawlers compared to areas with no soil fauna. Also there were significantly lower saturation times in arenas when either mole crickets or earthworms were present compared to non-infested arenas. Field and greenhouse studies suggest that mole cricket tunneling activities may reduce runoff and erosion but, in turn, may facilitate movement of surface applied pesticides and fertilizers into groundwater.

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Chapter I

GENERAL INTRODUCTION

Soil and Soil Hydrology. Soils are comprised of a certain percentage of sand, silt, and clay particles. Sand particles are visible to the naked eye, sized from 0.05-2.0 mm, and have a very loose and gritty consistency. Silt particles, sized from 0.05 to 0.002 mm, have a smooth powdery texture and must be viewed through a microscope. Clay particles are the smallest (≤ 0.002 mm) and an electron microscope is required to view these particles. The consistency of clay particles is sticky and malleable (Brady and Weil 2002).

Three different soil types, Ultisols, Decatur silt loam, and Dothan sandy loam, are considered typical top soils for the southeast region (USDA-NRCS Soil Survey Division 2011). Ultisols and Dothan sandy loam (fine-loamy) are common coastal plain soils, and Decatur silt loam represents the Tennessee Valley area. Ultisols are weathered red or yellow acidic, soils that are located in warm humid areas. These soils have a base saturation less than 35 % (USDA-NRCS 2006). Decatur silt loam soils are formed from weathered cherty limestone and limestone rock. They are located on 2 to 6 % slopes and are well drained with high water capacity. Dothan sandy loam soils have more sand particles than Decatur silt loam, which means the soil has larger particles than less sandy soils. Sandy loam soils contain more than 60 % sand. Sand has large pores so it drains the fastest of all soil types, and is less likely to become waterlogged (USDA-NRCS, 2006).

Water travels through open pores between soil particles. Pores are different in each different type of soil. Silt loam soils have a smaller pore size than a sandy soil. Sandy soils have a larger pore size but, do not have as many pores as silty or clay soil. Water travels more freely through a sand layer due to its larger particle size and pore space, in silt or clay layers the water is restricted because the particle size is smaller. Sandy layers are resistant to the flow of water although the water will pass very slowly through this area and a water table will form (Gardner 1979).

Macropores are open spaces in soil (greater than 1000 µm in diameter) (Kim et al. 2010), and are created by many factors like erosion of soil, decaying roots, and burrowing insects. Earthworms, ants, and termites are the macroinvertebrates most commonly studied for their influence on biopores and soil hydrology. The architecture of tunnels of earthworms, (*Heteroporodrilus mediterreus* Fletcher), will not collapse in the presence of water (Friend and Chan 1995). Macropores created by these worms and possibly other macroinvertebrates have a significant effect on the movement of air, water, and solutes into the soil horizon. These biopores act as fluid pathways under wet soil conditions and can effectively conduct water (Friend and Chan 1995). Earthworms' tunnels are also found to withstand vehicle-induction compaction (Alakukku et al. 2002). Termite tunneling patterns are excavations where the soil that the termite is tunneling through is removed and placed outside the tunnels. This process can effectively change the bulk density of the soil in the area infested with termites (Tucker et al. 2004). While tunneling, ants bring nutrient rich soil to the surface. During a heavy rainfall, the nest becomes saturated and increases water infiltration (Cerda and Jurgensen 2008). There is little known about biopores generated by other macroinvertebrates such as soil-dwelling mole crickets (Orthoptera: Gryllotalpidae). The tunneling behavior of these insects likely has equal or greater impact on soil hydrology. The density of the soil may also change the architecture of the mole crickets' tunnels. When tunneling through sand, *Scapteriscus* mole crickets will change their tunnel direction when they come in contact with areas of higher density to continue in the areas of lower density (Villani et al. 2002).

Scapteriscus Mole Crickets. There are four species of mole crickets (Orthoptera: Gryllotalpidae) found in the southeast United States: the northern mole cricket (*Neocurtilla* hexadactyla Perty), the shortwinged mole cricket (*Scapteriscus* abbreviatus Scudder), tawny mole cricket (*Scapteriscus* vicinus Scudder) and the southern mole cricket (*Scapteriscus* borellii Giglio-Tos). *Scapteriscus* spp. are the south's most problematic pest of turf (Potter 1998) with the southern and tawny mole crickets causing the most severe damage in Alabama. The northern mole cricket is native, rarely damages turfgrass and is of low economic importance (Hudson 2007). The southern and tawny mole crickets were introduced into the United States at the port of Brunswick, Georgia, in the ballasts of merchant ships from South America in the early 1900s.

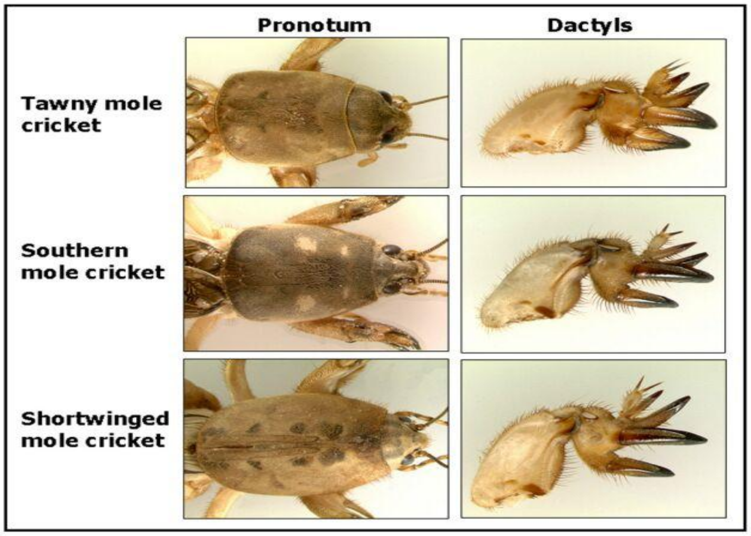

Figure 1.1 Mole Cricket Identification Chart (UFL, http://edis.ifas.ufl.edu/lh039)

Mole crickets now infest turfgrass throughout the southeastern Coastal Plain from Texas to North Carolina (Frank and Parkman 1999).

Mole crickets spend most of their life, (egg, nymph, and adult) underground and have one generation per year. Eggs are deposited into the ground around April to May in chambers that are constructed between 5 and 30 cm below the surface of the soil. The chamber is usually measured to be 2 to 4 cm in length, width, and height. The bean shaped eggs are deposited in a clutch averaging 35 eggs (Hayslip 1943). As the eggs absorb water they increase in size, eventually achieving the length of about 3.9 mm and a width of 2.8 mm. The color of the eggs varies from grey to brown. The egg life stage is between 10 to 40 d depending on soil temperature and species. Nymphs, or immature mole crickets, turn dark within 1d of hatching. They will eat their egg casing and even sometimes their siblings (Hayslip 1943). Nymphs molt eight to ten times before becoming adults. The last two nymphal stages have wing pads before molting to the adult stage (Hudson 1987, Braman 1993), and adults have well developed wings for flight. Tawny mole cricket nymphs move constantly during development and do not form the permanent burrow system of the adults (Hudson 2001).

Mole crickets have fossorial forelegs that enable them to dig through soil. The adults have large blade like projections off the forelegs called dactyls. When the soil is moist and warm, young mole crickets will tunnel right below the surface. As the soil gets cool and dry they will dig deeper in the soil profile. A significant relationship was found between soil moisture and mole cricket surface tunneling. Mole crickets are more active in soil with moisture of 4 to 23% (Hertl and Brandenburg 2002). The adults tunnel through the soil looking for food and the males produce sound chambers at the soil surface to call females at night when mole crickets are most active.

Figure 1.2 Males (left) can be identified by the dark sclerotized front margin on their wings Female (right)

Mole crickets have two flight periods. The first flight takes place in early March, usually overwintering adults. The second occurs in late April or May, which are new adults that developed from overwintered nymphs (Ulagaraj 1975). Mole crickets are caught easily by light and acoustic traps at night. The flights are usually short lasting about an hour right after dusk (Hayslip 1943, Ulagaraj 1975).

Southern and tawny mole cricket species cause significant damage to turf through their tunneling activity, which results in mechanical root damage and subsequent desiccation of infested turfgrass (Villani et al. 2002). Southern mole crickets are mostly carnivorous and tunnel through the soil searching for other arthropods or earthworms. The southern mole cricket can be identified by its “U” shaped dactyl. Also, the pronotum of the southern mole cricket is light brown and usually has four dots on the top. Tawny mole crickets usually are more damaging to turf than the southern mole crickets due to the fact that they also feed on the root system of the plant. Tawny mole crickets have a “V” shaped dactyl and have a central brown line on the pronotum.

The tunnel architecture of mole crickets varies depending on species and feeding behavior. *Scapteriscus vicinus* and *Gryllotalpa africana* Palis, which are predominantly herbivorous, tend to make deeper burrows, whereas the southern mole cricket, which is predominantly carnivorous, tends to make shallower burrows (Villani et al. 2002). Herbivorous mole crickets feed on plant roots and therefore cause more damage than southern mole crickets. The tawny mole crickets tend to have deeper more extensive tunnels than southern mole crickets (Villani et al. 2002). Tunnels are almost always created in a “Y” shape with two entrances. The tawny mole cricket usually has a tunnel length of 50 to 70 cm. The southern mole cricket tunnels are more like a reverse “Y” that has only one entrance at the soil surface which then branches within 10 cm of the surface. Southern mole crickets usually have shorter tunnels than the tawny (Brandenburg et al. 2002). Mole crickets prefer sandy soils, and the depth of the insect is related to soil moisture. When there is a higher percentage of moisture in the soil the mole crickets tunnel closer to the soil surface (Hertl and Brandenburg 2002). This causes major damage to turfgrass and sod farms around the United States.

Economic importance of Turfgrass. The turfgrass industry encompasses 20.2 million ha in the United States with an estimated annual value of $40 to 60 billion (Milesi et al. 2005). Plants, damaged by mole crickets, especially grasses, will turn brown and die. This is a common occurrence on golf courses around greens and tee boxes. To control mole crickets, treatments are made when nymphs are present in June, July, and sometimes early August (Cobb 1998). Insecticides for control of mole crickets average $70 to 140 per 0.4 ha (acre). There are many different insecticides used for mole cricket control including bifenthrin (Pyrethroid), acephate

(Organophosphate), carbaryl (Carbamate), fipronil (Phenyl pyrazol), and imidacloprid (Chloronicotinyl). Fipronil is still the industry standard (Reed 2012).

Biological controls have been introduced for the control of mole crickets in Florida and have spread to adjacent states (Frank and Walker 2006). These biocontrol agents are *Larra bicolor* Fabricius (Hymenoptera: Crabronidae) a parasitic wasp, an entomopathogenic nematode (*Steinernema scapterisci* Nguyen & Smart), and the Brazilian redeyed fly (*Ormia depleta* Wiede-mann)(Diptera: Tachinidae). Collectively, these biological controls have allegedly reduced mole cricket populations in Florida by 95 % since their release in the 1980's (Leppla et al. 2007).

Chapter II

Biotic and Abiotic Influences on Tunneling Behavior of *Scapteriscus* spp. of Mole Crickets

Abstract

Mole crickets (Orthoptera:Gryllotalpidae) spend most of their life history tunneling through soil. In turfgrass, this disrupts the root system causing wilting or death of infested grass. Due to the economic importance of mole crickets in the southeast, it is important to better understand mole cricket tunneling behaviors. These experiments were designed to determine the influence of soil type, mole cricket species, and age of tunnel architecture. Mole crickets were introduced to PVC arenas and allowed to construct their tunnels under controlled conditions in the greenhouse. Arenas and soil were imaged using the use of Computed Tomography (CT) then processed by converting pixels to voxels using MATLAB® (MathWorks, Natick, MA). There have been few previous studies using CT to learn about insects in the soil. Experiments compared a series of architectural differences in tunnels of adult and immature southern mole crickets; tunnels made by southern and tawny mole crickets; tunnels constructed in the presence and absence of turfgrass; and those constructed in different soil types. Generally mole crickets make tunnels that are 2.5-3 times their body width and immature mole crickets and adults produce tunnels similar in volume, length, average diameter, roundness, and tortuosity. Adult tawny and southern mole crickets, produce tunnels similar in length, diameter, volume, roundness, and tortuosity. Mole crickets that were placed in clay loam soils constructed significantly shorter tunnels than mole crickets that were placed in sand and loamy sand arenas. There were consistent correlations throughout the test that showed that total tunnel length was strongly correlated with total tunnel volume.

Introduction

Macroinvertebrates and the characteristics of soil habitat have reciprocal influences on one another. Insects such as mole crickets (Orthoptera: Gryllotalpidae) spend virtually of all their lives in the soil. Four species of mole crickets: northern mole cricket (*Neocurtilla hexadactyla*) which is native to the southeast United States, the shortwinged mole cricket (*Scapteriscus abbreviatus* Scudder), tawny mole cricket (*Scapteriscus vicinus*), and the southern mole cricket (*Scapteriscus borellii*) which were introduced to the southeast United States. The tawny and southern mole crickets are the most widespread geographically and the most economically important species to southeastern United States (Potter 1998). The tunnel architecture varies depending on species and feeding behavior. Adult *Scapteriscus vicinus* and *Gryllotalpa africana* Palis, which are predominantly herbivorous, tend to make shallow burrows; whereas *Scapteriscus borellii*, which is predominantly carnivorous, tends to make deeper burrows (Villani et al. 2002). Herbivorous mole crickets feed on plant roots and cause more damage than southern mole crickets. Adult tawny mole crickets tend to have deeper and more extensive tunneling systems (Villani et al. 2002). Tawny mole crickets tunnels are almost always created in a “Y” shape with two entrances. The tawny mole cricket usually has a tunnel length of 50 to70 cm. Adult southern mole cricket is more like a reverse “Y” that has only one entrance at the soil surface then branching within 10 cm of the surface. Southern mole cricket adults usually have shorter, less extensive, and shallower tunnels than the tawny (Brandenburg et al. 2002). Tunneling characteristics of these two species of mole crickets have not been extensively studied in relation to life stage, and abiotic factors.

The behavior of soil dwelling insects is influenced by soil compaction and soil moisture. The density of the soil may also change the architecture of the mole crickets’ tunnels. *Scapteriscus* mole crickets change the direction of tunnels away from higher density sand.

(Villani et al. 2002). Since insects are susceptible to desiccation, soil moisture can influence movement of insects in the soil (Villani and Wright 1988). A significant relationship was found between soil moisture and mole cricket surface activity. Mole crickets are more active in soil with moisture of 4 to 23 % (Hertl and Brandenburg 2002), but only have significant mortality when soil moisture is at or below 2 % (Hertl et al. 2001).

This study compared mole cricket tunneling characteristics in different soils and for various life stages and species. The first experiment compares tunnels of adult and immature southern mole crickets. Adult mole crickets were expected to construct tunnels that are more extensive and have a higher percentage of tortuosity and amount of curvature than immature mole crickets. Tunnels made by southern mole crickets were also compared with turfgrass and with bare soil, testing the hypothesis that the presence of turfgrass would increase tunneling and branching. Tunneling characteristics of adult southern and tawny mole crickets were also compared to confirm the previous work (Brandenburg et al. 2002) that tunnels constructed by tawny mole crickets would branch higher in the soil versus southern mole crickets' tunnels which should branch deeper. The final experiment tested the hypothesis that mole crickets would tunnel more through sand or loamy soils and would tunnel less through clay soil.

Methods and Materials

Source of Test Insects. Adult female *S. borellii* were field collected using a modified pool design acoustic trap (Thompson and Brandenburg 2004) from April through June 2011 at Grand National Golf Course in Opelika, AL. Adult *S. vicinus* were collected from Great Southern Golf Club in Gulfport, MS by soap flush on October 25, 2011. Once they surfaced, mole crickets were rinsed with fresh water then transferred directly into 473 ml plastic cups (Dart, Mason, MI) with ventilated lids containing autoclaved, moistened sand. In the lab, they were provided organic shredded carrots (Inter-American Products, Cincinnati, OH) and freeze-dried mealworms (Coleoptera: Tenebrionidae; Fluker Farms, Port Allen, LA) for food and held in a growth chamber (Percival Scientific, Perry, IA) at 27 °C with a 14:10 (L:D) photoperiod. The pronotal width was measured with a digimatic caliper (Digimatic Caliper Series 500, Mitutoyo, Japan) for insects used in all experiments.

Figure 2.1 Soap flush and acoustic trap for mole crickets

Test Arenas. The arenas were constructed from PVC pipe (25.4 cm diameter × 45.2 cm tall). A PVC cap was glued onto one end to hold the soil. Into each cap, 31 holes, 3.6 mm diameter each, were drilled in a circular pattern for drainage (Figure 2.2). A circular piece of landscape fabric (Greenscapes Home & Garden Products, Calhoun, GA) was placed inside the cap to prevent the loss of soil from drainage holes. Each arena was loosely filled with 40.7 cm of sifted autoclaved soil that was being tested.

Figure 2.2 PVC test arena showing height (45.2 cm), bottom cap, and drainage holes

Arena Trials. Experiments were conducted with one mole cricket per arena. Arenas were held in the greenhouse at Auburn University with the temperature set to 28°C and watered manually every other day. Arenas had mesh lids to keep the mole crickets from escaping.

Transport and Scanning of Arenas. At the end of each experiment, arenas were transported by vehicle to the Auburn University Veterinary School Small Animal Clinic for imaging. The arenas were loaded carefully into the bed of a truck and secured. At the clinic, the arenas were scanned with a CT machine (GE highspeed CT/i, GE, Cincinnati, OH) using a bone algorithm at 120 kV and 120 mA. Individual scans were taken every 5 mm in an axial program (Efilm Lite 3.1, Merg Healthcare, Milwaukee, WI) that scans every 2 sec with a 34 cm field of view. Individual scans were processed using imaging software to improve clarity (Capowiez et al. 1998) then rendered to determine 3-dimensional tunnel characteristics using MATLAB®

computer software. To characterize the structure of burrows developed by mole crickets in soils, we used a non-destructive imaging method known as X-ray Computed Tomography (CT). X-ray CT yields high-resolution 3-dimensional representation of burrow and other features in soil. X-ray CT is an advanced imaging technique that allows nondestructive and noninvasive imaging of specimens to depict cross-sectional and 3-dimensional internal structures. The 3-dimensional soil structures are divided into several cross sectional layers with each cross-sectional layer characterizing the burrow features in a gray-scale. Presences of burrows in any cross-sectional layer are represented by dark regions while the soil matrix is represented by gray/white region. In each layer, the burrow features are identified using image segmentation techniques. The goal of image segmentation is to convert each cross-sectional layer image in to a binary image with pixels that are either a part of a burrow or soil matrix. Burrows are identified using thresholding method where pixels with a gray-scale greater than a certain threshold value are classified as a burrow. Once the burrow features are identified in each layer, individual burrows are grouped in all the layers by alignment of binarized images from individual scans. Once the burrows were identified, then these tunnel characteristics; i.e. average diameter of the tunnels constructed, total linear length and depth of the entire tunnel systems, total volume of soil moved by the mole crickets, branching rate of the tunnels calculated by counting the amount of times the tunnels branched within the arenas, average roundness, and tortuosity or the curvature of the tunnel (Capowiez et al. 1998) were calculated.

Tortuosity was calculated with this equation:

Tortuosity = total tunnel length / distance between the ends

Comparison of Adult and Immature Mole Cricket Tunnels. For these experiments, arenas were filled with autoclaved sand (Butler Sand and Gravel, Butler, GA) from the Turfgrass Research Unit at Auburn University. Six arenas were prepared with adult S. *borellii* and six separate arenas with immature 4th instar *S. borellii*. Mole crickets had 1 wk to construct their tunnels. The arenas had no grass cover but were watered every other day. At the beginning of the trial, five freeze dried mealworms (Fluker Farms, Port Allen, LA) were spread randomly in each arena. The temperature in the greenhouse was set at 27 to 28 °C and monitored by a datalogger (HOBO Pro v2 2x External Temperature Data Logger, Onset Computer Corporation, Bourne, MA). Due to the number of arenas that could be scanned in one day, experiments were replicated in two separate trials, one week each, during a two week period in mid-September, 2011.

Figure 2.3 Adult and immature southern mole crickets (photo credit Yao Xu)

Effects of Soil Types on Tunnel Architecture. This experiment, conducted during November 2011, investigated the influence of soil types on tunnel architecture of southern mole crickets. A clay loam (45% sand, 17.5% loam, and 37.5% clay), sand only, and a loamy sand (82.5% sand, 10% silt, 7.5% clay) were used. The soil bulk densities were 1.18 g/cm^3, 1.13 g/cm^3, and 1.15 g/cm^3 for sand, loamy sand, and clay loam, respectively. Greenhouse temperature was set at 27 to 28 °C and monitored by a datalogger as previously described. Soils in the arenas were left barren but watered every other day to prevent desiccation of the mole crickets. Using a randomized block design where each soil type was in a block, five replications were used with one southern mole cricket introduced to each arena.

Tunnel Architecture in Turfgrass and Bare Soil. This experiment, conducted during August 2011, investigated if the presence of grass influenced tunneling behavior of mole crickets. Arenas were filled loosely with sand (approximant bulk density was 1.1g/cm^3). Ryegrass seeds were sown in the arenas and allowed to establish for four weeks at which time adult southern mole crickets were introduced. A separate experiment was conducted with tawny mole crickets during January and February 2012. Plugs of "Tifway 419" bermuda (*Cynodon dactylon* (Loppers.) × *Cynodon transvaalensis* (Burtt-Davy)) were collected from the turfgrass research unit at Auburn University and transplanted into the arenas. The roots were washed thoroughly with water to remove excess dirt from the roots and grass was allowed to grow for four weeks. The temperature in the greenhouse was set to 27 to 28 °C and was monitored as before. A single, adult tawny mole cricket was placed into each arena on February 6, 2012. Both experiments were replicated four times for each treatment. Ryegrass was used for the southern and was found to be difficult to grow without disease and pathogens, experimenting with the tawny mole cricket bermudagrass cores were used in hope less disease and pathogens would affect it.

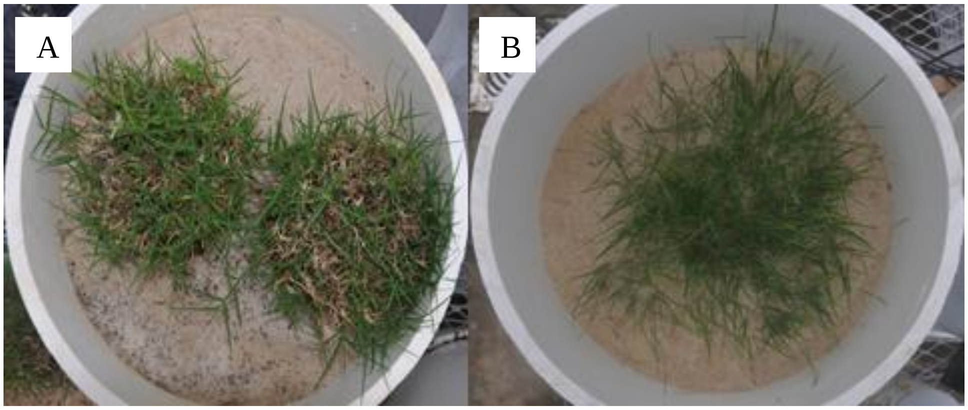

Figure 2.4 Experimental setup for the comparison of tunnel characteristics with turfgrass or bare soil. bermudagrass "Tifway 419" plugs (A) were used for comparison with tawny mole crickets and ryegrass grown from seeds (B) were used for southern mole crickets

Comparison of Tunnel Characteristics of Southern and Tawny Mole Crickets. In these experiments, arenas were filled with autoclaved sand collected from the Turfgrass research unit at Auburn University. Six arenas were prepared with adult southern mole crickets and six separate arenas were prepared for adult tawny mole crickets. On October 28, 2011, one mole cricket was introduced into each arena and allowed one week to construct its tunnel. The temperature in the greenhouse was set to 27 to 28 °C and monitored with a datalogger as before. The soil was left barren in all arenas. Arenas were watered every other day. Five freeze-dried mealworms (Fluker's Farm) were placed randomly in each arena at the start of the experiment. These experiments were conducted over a 2 wk period in late October to early November 2011.

Statistical Analyses. Within each experiment, Pearson product moment correlations among all five response variables were calculated using in SAS PROC CORR (vs. 9.2.1, SAS Institute, Cary NC). *P*-values were calculated for all correlation coefficients. For each experiment, all five measured response variables for tunnel architecture and pronotal width of mole crickets used in that experiment were analyzed using mixed models procedures as implemented in SAS® PROC

GLIMMIX (vs. 9.2.1, SAS Institute, Cary NC) with a normal distribution function. The experimental repeat (Set_N) was the sole random effect in addition to the residual variance term. Treatments means were calculated using the LSMEANS command within the above named PROC. For the experiment with soil types, simulation-adjusted *P*-values were calculated.

Treatments were subject to a joined analysis from three experiments (i) Joined Tunnel Architecture in Turfgrass and Bare Soil, Tunneling Behavior of Southern Mole Cricket Compare to the Tawny Mole Cricket, and (ii) Effect of Soil Texture on Tunneling Characteristics. Experiments with similar treatments (adult southern mole crickets in a sand medium) were combined providing more information on adult southern mole crickets. In the joint analysis, experiment and Set_N were random effects and the residual error term was the error term used to assess treatment effects. Least squares means, standard errors and *P*-values for pairwise comparisons were calculated as stated above.

Results

Comparison of Adult and Immature Mole Cricket Tunnels. Tunnels created in soil microcosms by adult and immature southern mole crickets were not significantly different in total tunnel length, tunnel average diameter, and tortuosity (Table 2.1). On average, adults displaced greater than 3 times the amount of soil during tunneling compared to immature (P=0.06). On average, immature mole crickets had a pronotal width of 3.25 mm and constructed tunnels with a diameter of 10.6 mm, about three times their body width. Similarly adult mole crickets had an average pronotal width of 5.76 mm and constructed tunnels about three times wider than their body width. Pronotal width was significantly correlated with tunnel volume (r=0.62).Tunnel volumes were significantly correlated with tunnel length, diameter and the number of branches. Other strong correlations were average diameter by average roundness (r=0.66) and number of branches by tortuosity (r=0.65).

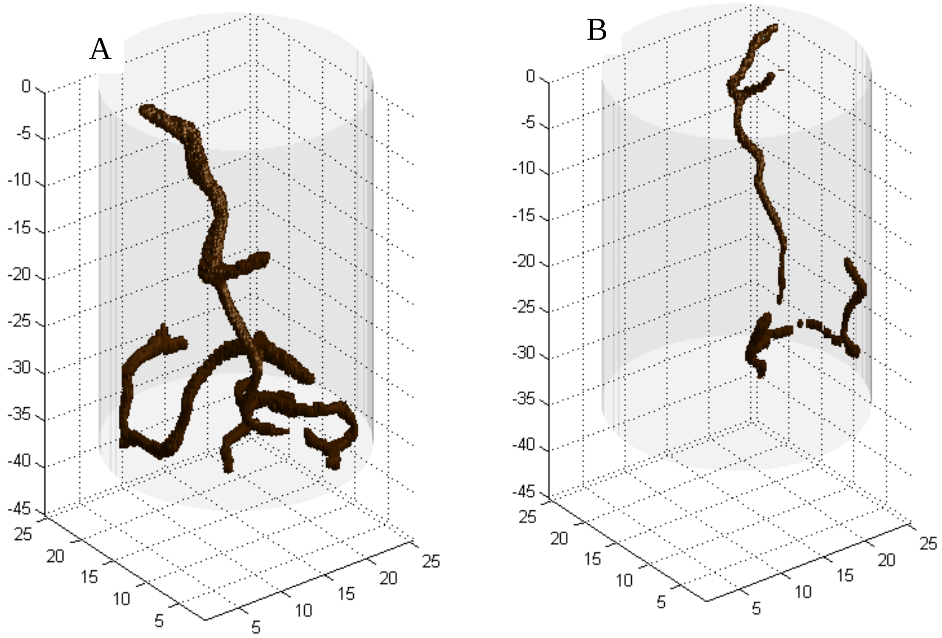

Figure 2.5 Examples of 3-dimensional renderings of adult (A) and immature (B) mole crickets

Table 2.1 Comparison of tunnel architecture for adult and immature southern mole crickets

	LS Means			
	Adult	Immature	SED[a]	*P*
Volume (cm^3)	150	46.7	48.85	0.067
Length (cm)	66.9	56.1	25.3	0.68
Diameter (cm)	1.5	1.0	0.29	0.15
Average roundness	0.4	0.4	0.05	0.88
Tortuosity(%)	2.0	1.7	0.33	0.49
No. of Branches	5.4	3.0	2.16	0.3
Pronotal width(mm)	5.7	3.1	0.54	0.001^*

[a] Standard Error of the Difference

Table 2.2 Pairwise correlations for tunnel characteristics and pronotal width for the experiment of adult and immature mole crickets

	Volume (cm^3)	Length (cm)	Diameter (cm)	Average roundness	Tortuosity (%)	No. of Branches	Pronotal width (mm)
Volume (cm^3)	1.0						
Length (cm)	0.73**	1.0					
Diameter (cm)	0.63*	0.14	1.0				
Average roundness	-0.32	-0.23	-0.66*	1.0			
Tortuosity (%)	0.56	0.54	0.47	-0.3	1.0		
No. of Branches	0.9**	0.86**	0.54	-0.4	0.65*	1.0	
Pronotal width (mm)	0.62*	0.23	0.38	0.098	0.34	0.46	1.0

* indicates significance at $P \leq 0.05$
** indicate significance at $P \leq 0.01$

Tunnel Architecture in Turfgrass and Bare Soil. Tunnels constructed by adult southern mole crickets in the presence of turfgrass were significantly longer than tunnels without turfgrass (Table 2.3, $P = 0.02$). Other tunnel characteristics were not significantly different in the presence or absence of turfgrass. Although not statistically significant, southern mole crickets displaced about two times the amount of soil volume and had three times the amount of branches when turfgrass was present. Southern mole crickets had an average pronotal width of 6.48 mm and created a tunnel with a diameter about 2.5 times their body width. Tunnel volume and length as well as average tunnel diameter and roundness were significantly correlated ($P \leq 0.05$).

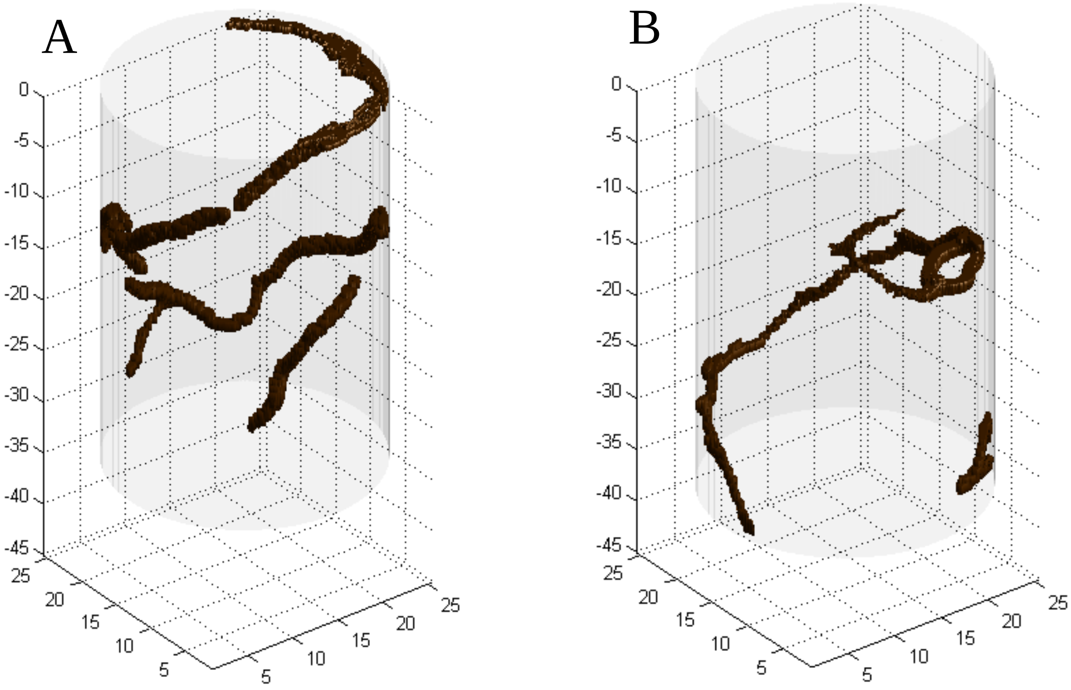

Figure 2.6 Examples of 3-dimensional renderings of southern mole cricket tunnels when turfgrass is present (A) or absent (B)

Table 2.3 Comparison of adult southern mole cricket tunnel characteristics when turfgrass is present or absent

	Mean			
	Turfgrass	Bare soil	SED[b]	*P*
Volume (cm^3)	144.1	69.9	31.81	0.1
Length (cm)	77.5	32.0	11.13	0.02
Diameter (cm)[a]	1.6	1.5	0.36	0.78
Average roundness	0.4	0.4	0.12	0.77
Tortuosity (%)	2.4	1.9	0.51	0.4
No. of Branches	3.5	1.0	1.34	0.16
Pronotal width (mm)	6.5	6.3	0.23	0.4

[a] Based on three replicates for bare soil and two for turfgrass

[b] Standard Error of the Difference

Table 2.4 Pairwise correlations for tunnel characteristics for adult southern mole crickets for the experiment when turfgrass is present and absent

	Volume (cm^3)	Length (cm)	Diameter (cm)	Average roundness	Tortuosity (%)	No. of Branches
Volume (cm^3)	1.0					
Length (cm)	0.95*	1.0				
Diameter (cm)	0.47	0.22	1.0			
Average roundness	0.27	0.11	0.91*	1.0		
Tortuosity (%)	0.87	0.71	0.72	0.49	1.0	
No. of Branches	0.83	0.76	0.43	0.23	0.58	1.0

* indicates significance at $P \leq 0.05$

For tawny mole crickets, tunnel architecture was not significantly different in the presence or absence of turfgrass (Table 2.5). Tawny mole crickets in this study had an average pronotal width of 7.42 mm, which is just about half the tunnel diameter (Table 2.5). Pronotal width was significantly correlated with tortuosity (the curvature of the tunnels) (Table 2.6). Tunnel volume and length were also significantly correlated (r=0.76).

From the joined analysis, tunnel length was the only response variable significantly different when turfgrass was present or absent (F= 8.87; df=1,23; *P*=0.007). In the absence of grass, tawny mole crickets have longer tunnels. When grass was present, however, southern mole crickets have significantly longer tunnels than tawny mole crickets (Species by treatment interaction, F=8.05; df=1,23; *P*=0.009).

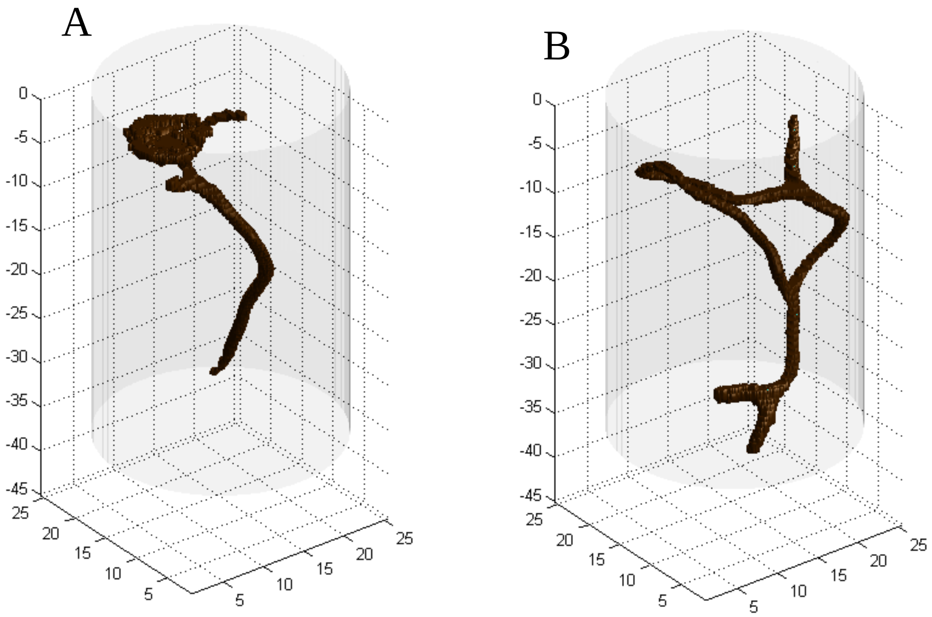

Figure 2.7 Examples of 3-dimensional renderings of tawny mole cricket tunnels when turfgrass is present (A) or absent (B)

Table 2.5 Comparison of architecture and tunnel characteristics of adult tawny mole crickets when turfgrass is present and or absent

	Mean			
	Turfgrass	Bare soil	SED[a]	*P*
Volume (cm^3)	119.8	83.1	42.42	0.42
Length (cm)	36.8	31.5	11.13	0.45
Diameter (cm)	1.8	1.8	0.36	0.98
Average roundness	0.5	0.5	0.12	0.27
Tortuosity (%)	1.5	1.6	0.51	0.66
No. of Branches	1.0	1.4	0.8	0.63
Pronotal width (mm)	7.1	7.7	0.23	0.19

[a] Standard Error of the Difference

Table 2.6 Pairwise correlations for tunnel characteristics and pronotal width for the adult tawny mole crickets for the experiment when turfgrass was present or absent

	Volume (cm^3)	Length (cm)	Diameter (cm)	Average roundness	Tortuosity (%)	No. of Branches	Pronotal width (mm)
Volume (cm^3)	1.0						
Length (cm)	0.76*	1.0					
Diameter (cm)	0.7	0.21	1.0				
Average roundness	-0.35	-0.13	-0.72	1.0			
Tortuosity (%)	-0.15	-0.44	0.49	-0.4	1.0		
No. of Branches	0.4	0.31	0.32	-0.62	-0.01	1.0	
Pronotal width (mm)	-0.34	0.59	-0.2	-0.13	0.8*	-0.08	1.0

* indicates significance at $P \leq 0.05$

Tunneling Behavior of Southern Mole Cricket Compared to the Tawny Mole Cricket. Tunnel architecture was not significantly different between adult tawny and southern mole crickets. Although not significant, tawny mole crickets displaced more soil volume and had greater tunnel length than southern mole crickets (Table 2.7). The total numbers of branches in the upper and lower 20 cm were also not significantly different between species. Interestingly, tunnels made by adult southern mole crickets branched twice as much in the upper 20 cm than the tawny (Figure 2.9). Tunnel volume was significantly correlated with both tunnel length and average diameter ($P \leq 0.05$).

From the joined analysis, tawny mole crickets make more rounded tunnels than southern mole crickets (0.4 versus 0.5; SED=0.04; P =0.03). Southern mole crickets have more curvature (tortuosity) to their tunnels than tawny mole crickets (means 2.4 versus 1.8; SED=0.2; P =0.008).

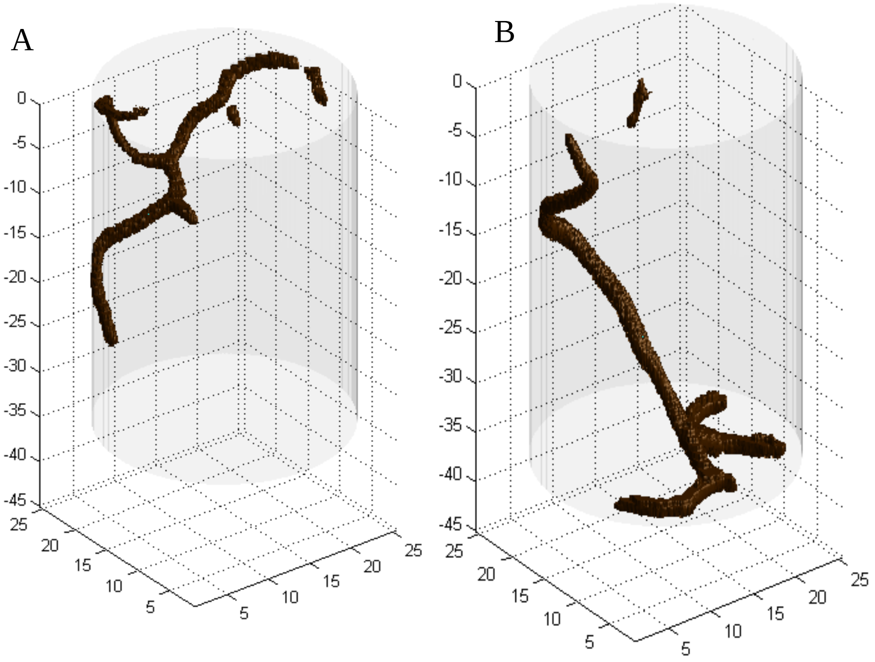

Figure 2.8 Examples of 3-dimensional renderings of southern mole cricket (A) tunnels and tawny mole cricket (B)

Table 2.7 Comparison of architecture and tunnel characteristics between southern and tawny mole crickets in sandy soil

	Mean			
	Tawny	Southern	SED[a]	*P*
Volume (cm^3)	103.7	80.4	17.95	0.23
Length (cm)	43.2	37.2	6.31	0.37
Diameter (cm)	1.8	1.7	0.14	0.66
Average roundness	0.5	0.4	0.04	0.07
Tortuosity (%)	1.6	1.9	0.17	0.18
No. of branches	2.0	2.8	0.92	0.41
Pronotal width (mm)	7.3	7.1	0.43	0.59

[a] Standard Error of the Difference

Table 2.8 Pairwise correlations for tunnel characteristics and pronotal width for the experiment of adult southern and tawny mole crickets

	Volume (cm^3)	Length (cm)	Diameter (cm)	Average roundness	Tortuosity (%)	No. of Branches	Pronotal width (mm)
Volume (cm^3)	1.0						
Length (cm)	0.68*	1.0					
Diameter (cm)	0.66*	0.04	1.0				
Average roundness	-0.06	0.07	-0.28	1.0			
Tortuosity (%)	-0.26	0.15	-0.13	-0.01	1.0		
No. of Branches	-0.29	-0.09	-0.09	0.04	0.45	1.0	
Pronotal width(mm)	0.05	0.04	-0.12	0.38	-0.3	-0.14	1.0

* indicates significance at $P \leq 0.05$

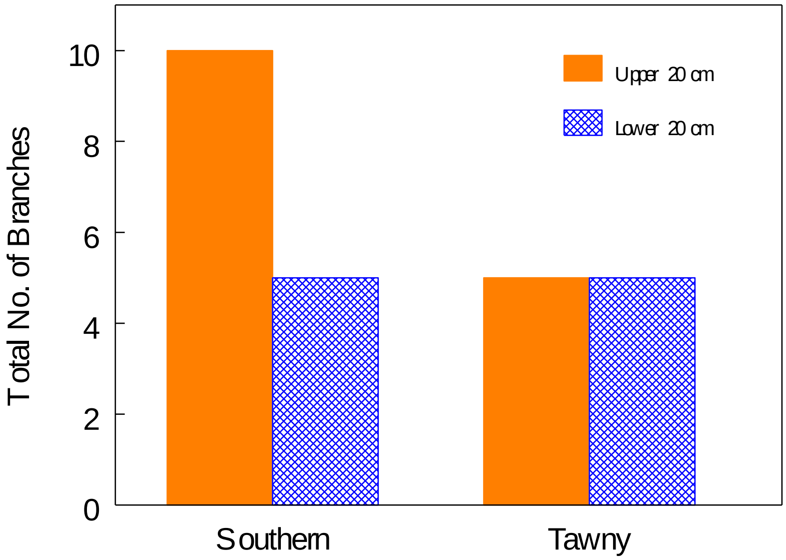

Figure 2.9 No difference between the upper 20 cm and lower for the southern mole cricket (Wilcoxon rank sum P=0.23) and tawny mole cricket (Wilcoxon rank sum P=0.89)

Effects of Soil Types on Tunneling Characteristics. Tunnel characteristics between loam and sand were not significantly different for southern mole crickets (Table 2.9). Tunnels in sand have more branches than those in clay (P=0.063). Tunnel length and volume were significantly greater in loam than in clay soils. Mole crickets had longer tunnels in loamy sand soils compared to clay loam soil. Tunnel volume was significantly correlated with tunnel length ($P \leq 0.05$) and the number of branches. Another strong correlation was average diameter by average roundness (Table 2.10).

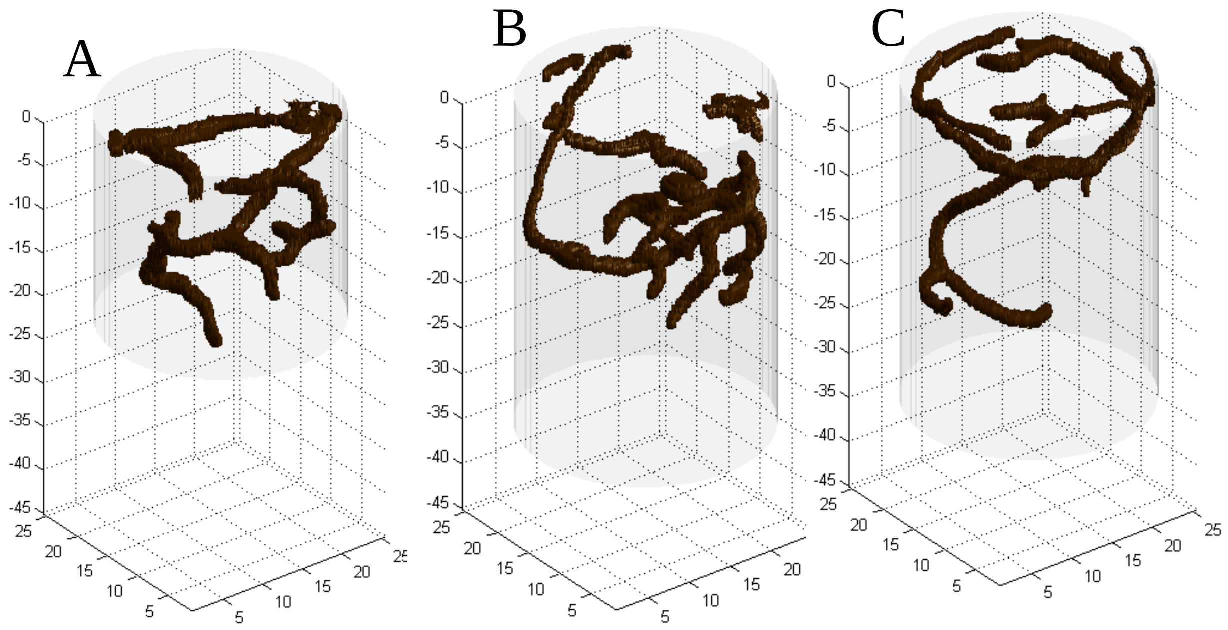

Figure 2.10 Examples of 3-dimensional renderings of mole cricket tunneling in different soil textures (Clay loam (A), Loamy sand (B), and Sand (C))

Table 2.9 Effects of soil types and texture of architecture of tunnels produced by adult southern mole crickets

	Means					Sim. Adj *P*-values[c]		
	Clay	Loam	Sand	SE_{max}[a]	SED_{max}[b]	Clay vs. Loam	Clay vs. Sand	Loam vs. Sand
Volume (cm^3)	88.9	208.8	122.6	38.55	54.52	0.046*	0.531	0.148
Length (cm)	23.3	64.1	46.5	10.62	15.03	0.019*	0.138	0.271
Diameter (cm)	2.2	2.1	2.0	0.17	0.13	0.539	0.110	0.309
Average roundness	0.3	0.3	0.3	0.03	0.04	0.334	0.073	0.365
Tortuosity (%)	2.7	2.6	2.9	0.37	0.52	0.899	0.701	0.692
No. of Branches	2.6	6.0	6.25	1.3	1.84	0.894	0.063	0.080

[a] Standard Error

[b] Standard Error of the Difference

[c] Simulated Adjusted *P*-values

Table 2.10 Pairwise correlations for tunnel characteristics for adult southern mole crickets in the experiment of different soil textures

	Volume (cm^3)	Length (cm)	Diameter (cm)	Average roundness	Tortuosity (%)	No. of Branches
Volume (cm^3)	1.0					
Length (cm)	0.91**	1.0				
Diameter (cm)	0.34	-0.03	1.0			
Average roundness	0.05	0.3	-0.57*	1.0		
Tortuosity (%)	-0.22	-0.17	-0.13	0.23	1.0	
No. of Branches	0.61*	0.71**	-0.03	0.41	0.27	1.0

* indicates significance at $P \leq 0.05$
** indicates significance at $P \leq 0.01$

Discussion

Three-dimensional (CT scans) imagery is still a relatively unused tool for studying the behavior of underground insects. The main areas that have been explored using 3-dimensional imagery are with earthworms, termites, ants, and soil-dwelling larvae (Capowiez et al. 1998, Villani and Gould 1986, Lee et al. 2007). This study was preceded by laboratory studies with mole crickets done in two-dimensional boxes and 3-dimensional castings of tunnels in the field (Villani et al. 2002, Brandenburg et al. 2002). Two-dimensional box studies were limited since the insect was only allowed to tunnels in one plane (*x* and *y* coordinate) which ignored a depth or *z*-coordinate. The *z*-coordinate allows the insect to burrow in a totally different plane, whereas, insects in the 2-dimensional experiments were confined to a smaller space. While casting can possibly provide a 3-dimensional perspective, there can be a gravitational limitation on the casting of mole crickets' tunnels. If the mole crickets were to tunnel deep in the soil branch and then have extensive tunnels, the cast material would not likely be able to travel against gravity, providing only a partial cast of the burrow system. This is why 3-dimensional imagery can provide better insight into the tunneling habits of mole crickets.

Adult southern mole crickets did not produce significantly longer tunnels with larger diameter, more branches or higher percent tortuosity than the immature mole crickets as we hypothesized. While constructing burrows the adult mole crickets displace three times the volume of soil that immature displace. Adult mole crickets have been observed to create extensive permanent burrows whereas immature are reported to not develop well-structured tunnels (Hudson 2001). Adult and immature mole crickets both construct a tunnel with a diameter that is typically 2 to 3 times the pronotal width of the insect. Worms with a diameter of 3.5 mm construct tunnels that are similar to or smaller than their body width (Joschko et al. 1991). Mole crickets have destructive ways of digging using the shoveling action of their dactyls which likely cause the tunnels to be considerably wider than their bodies, whereas earthworms tunnel by consuming the soil it is tunneling through (Edwards 2004). Adults have slightly larger diameter tunnels and longer tunnels which could explain the three fold difference in volume. Previous research has suggested that immature mole crickets do not construct permanent tunnels. Non-permanent tunnels, however, do not mean the tunnels are not extensive (Hudson 2001). Tunnel characteristics of immature mole crickets were similar to those of the adult southern mole crickets. Immature mole crickets (*Gryllotalpa gryllotalpa)* have been observed to construct longer, deeper tunnels to escape predators (Endo 2007).

Tunnel diameters were not significant in any experiment. This may be an artifact of the 3-D imagery. During image processing, pixels were converted to voxels, which are box shape objects that fill the image. Voxels may not be small enough to produce an exact enough measurement to detect significant difference at this scale. Both species of mole crickets construct tunnels that are statistically similar in many tunnel characteristics (Table 2.7) despite the reported differences in food habits (Hayslip 1943) and previously reported differences in tunnel architecture using 2-dimensional arenas or casts (Villani et al. 2002). A tunnel characteristic that was significantly different was average roundness (*P*=0.07). Test arenas are an artificial controlled environment; therefore, there were no other arthropods in the soil, but there was food (mealworms) placed on the surface of the arenas. Both species had to tunnel to the surface to feed, which may have resulted in similar tunneling characteristics. The tunnel length of the adult southern mole crickets was expected to be longer tunnels due to the carnivorous diet of southern mole cricket. *Scapteriscus* mole crickets were believed to tunnel deep in the soil before branching in search for food (Brandenburg et al. 2002). Endo (2007); however, suggests that mole crickets (*Gryllotalpa* spp.) use horizontal burrows escape routes from predators. Underground tunnels have multiple purposes such as moving the insect in the soil profile for food but also to prevent the insect from desiccation (Hertl et al. 2001).

The total length of the mole crickets' tunnels was likely influenced by the size restraints of the test arenas. Mole crickets are capable of tunneling 70 cm deep (Brandenburg et al. 2002) which is considerably deeper than the test arena. The arena size was the largest that could be processed on the available CT machine, which may have confounded difference between the adult and immature mole crickets. Tortuosity and branching rate of the mole crickets' tunnels were also not significant. These characteristics could change if studied under field conditions.

With a larger area to roam and larger populations of mole crickets, it is almost impossible to predict what tunnel characteristics would change with these variables.

Therefore, when comparing the differences in tunnel architecture when turfgrass was present or absent, southern mole crickets are known to be more carnivorous than herbivores so more branched and longer tunnels were expected for southern mole crickets (Villani et al. 2002). The diet of tawny mole crickets, consists of mainly roots and grasses (Hayslip 1943), so the tunnel characteristics were expected to be significantly different when turfgrass was present. Data suggests that there is no additional damage to the grass in the presence or absence of prey in turf cores (Xu et al. 2012). Even though tawny mole crickets are known to feed on turfgrass, they are also capable of feeding on arthropods. Dried mealworms were placed in the arenas, perhaps driving the mole crickets to the surface to feed.

In general, tunnels of adult southern mole crickets in clay soils had the shortest tunnel length, the lowest volume, and the fewest number of branches. Mole crickets would be expected to tunnel best through sand and loam which have larger particle size and larger pore space giving the mole cricket a path of least resistance (Gardner 1979). Mole crickets will deviate their tunnels when they come in contact with higher bulk density (Villani et al. 2002) which may explain these results. The approximant bulk density for sand, loam, and clay in this study was 1.2 g/cm^3. Mole crickets will choose not to tunnel through soil with higher bulk densities Villani et al. (2002). This could help understand why at golf courses you see most of the mole cricket damage on the greens and tee boxes. These areas are refined and the soil profile is changed to create a better area to grow certain varieties of turfgrass and for playability. These areas usually consist mainly of sand and loam through which mole crickets can tunnel more effectively (Table

2.9). These areas also are well watered which also increases surface activity (Hertl and Brandenburg 2002).

This study has provided additional insight into the tunneling characteristics of an important pest group in the southeastern United States. Future work could perhaps examine tunnel characteristics under field conditions similar to Capowiez et al. (1998) to determine if the tunnel characteristics reported here can be verified. Also, mole cricket tunneling may be influenced by other soil burrowing organisms. Xu et al. (2012) reported negative impact on turfgrass when mole crickets and earthworms are present. Similarly, Villani et al. (2002) suggested that two mole crickets in a confined area will construct separate tunnels and will not share tunnels. CT and 3-dimensional imagery could be used to better understand these soil interactions between mole crickets and other soil invertebrates.

Chapter III

Effect of Tunneling Behavior on Water Infiltration

Abstract

Soil organisms, particularly arthropods, create biopores in soils as they move or tunnel. The abundance and burrowing nature of mole crickets, a common soil-inhabiting pest in the southeastern United States, likely influences the hydraulic conductivity of soils. Using field and greenhouse experiments, this study evaluated the effects of mole cricket tunneling on formation of biopores and hydraulic conductivity of saturated soil. Hydraulic conductivity of saturated soil were compared in mole cricket infested and uninfested field sites using a sprinkle infiltrometer. Infiltration tests were also performed using arenas in the greenhouse. In the field, mole cricket damaged in the areas had higher the infiltration rate and lower runoff rate than undamaged areas. Areas with damage may allow solutes into the soil profile faster than if that solute was to just leach through the unaltered soil profile. In the greenhouse study, mole crickets and earthworms have similar runoff and hydraulic conductivity of saturated soil patterns and are significantly different from areas with no burrowing organisms. This suggests that the tunnels of soil-dwelling organisms can withstand collapse after the soil becomes saturated with water.

Introduction

Soil macroinvertebrates (e.g., earthworms and mole crickets) can influence soil hydrology by the formation of biopores. Earthworms, ants, and termites are the macroinvertebrates most commonly studied for their influence on biopores and soil hydrology. The architecture of the tunnels of earthworms (*Heteroporodrilus mediterreus* Fletcher) will not collapse in the presence of water. Biopores created by these worms and possibly other macroinvertebrates have a significant effect on the movement of air, water, and solutes into the soil horizon. These biopores act as fluid pathways under wet soil conditions and can effectively conduct water (Friend and Chan 1995). Earthworm tunnels are also found to withstand vehicle-induction compaction (Alakukku et al. 2002). Termites tend to excavate through soil rather than tunnel, which can significantly alter the bulk density of soil (Tucker et al. 2004). Ants also tunnel through the soil and can affect the bulk density of the soil as they tunnel to build their nest. While tunneling, ants bring nutrient rich soil to the surface. During a heavy rainfall, the nest becomes saturated and increases infiltration (Cerda and Jurgensen 2008). There is little known about biopores generated by mole cricket tunneling behavior and its impact on soil hydrology.

Mole crickets are one of the top economic pests of turfgrass in the southeast and most of their destructive behavior comes from mechanical damage during tunneling (Potter 1998). Studies on the effect of the water table on the characteristics of tunneling behavior have not been extensively researched but mole crickets have been known to be able to withstand being under water for a few minutes (Endo 2007). *Scapteriscus* spp. mole crickets were alive and actively tunneling following approximately 8 h of flooding during Hurricane Katrina on the Mississippi coast (D. Held, personal observation). Tunnels created by mole crickets may significantly impact soil hydrology. Mole crickets make extensive soil burrows as adults and immatures and can displace 145 cm^3 of soil in 7 d (Chapter 2). Furthermore, mole crickets make biopores that are 2 to 3 times their body width. Biopores created by earthworms are typically similar to, or smaller than, their body width (Chapter 2). So, mole crickets can potentially have a greater impact on hydraulic conductivity of soils than other soil invertebrates (i.e. earthworms). We hypothesize that mole cricket tunneling will increase soil hydraulic conductivity, accompanied by an increase in infiltration rates.

Materials and Methods

Source of Test Invertebrates. Adult female *S. borellii* were field collected using a modified pool design acoustic trap (Thompson and Brandenburg 2004) from April through June 2011 at Grand National Golf Course in Opelika, AL. *S. borellii* were also collected from Great Southern Golf Club in Gulfport, MS by soap flush on October 25 2011. Once they surfaced, mole crickets were rinsed with fresh water then transferred directly into 473 ml plastic cups (Dart, Mason, MI) with ventilated lids containing autoclaved, moistened sand. In the laboratory they were provided organic shredded carrots (Inter-American Products, Cincinnati, OH) and freeze-dried mealworms (Coleoptera: Tenebrionidae; Fluker Farms, Port Allen, LA) for food and held in a growth chamber (Percival Scientific, Perry, IA) at 27 °C with a 14:10 (L:D) photoperiod. The pronotal length and width were measured for all insects used in experiments. *Lumbricus terrestris* L. (approximately 10 to 12 cm long and 8 mm thick) were purchased (DMF Bait Company, Waterford, MI) for the experiments.

Test Arenas. The arenas were constructed from PVC pipe (25.4 cm diameter × 45.2 cm tall). A PVC cap was glued onto the end of the pipe to hold the soil, into each cap, 31 holes, 3.57 mm in diameter, were drilled in a circular pattern for drainage. A circular piece of landscape fabric (Greenscapes Home & Garden Products, Calhoun, GA) was placed at the bottom of each arena to prevent the loss of soil from drainage holes (31 holes, 3.57 mm diameter each, were drilled in a circular pattern). Each arena was filled to a depth of 40.7 cm with loamy sand soil collected from E.V. Smith Research Center (Macon County, AL). Soil was autoclaved and tamped to a bulk density of 1.1 to 1.2 g/cm^3.

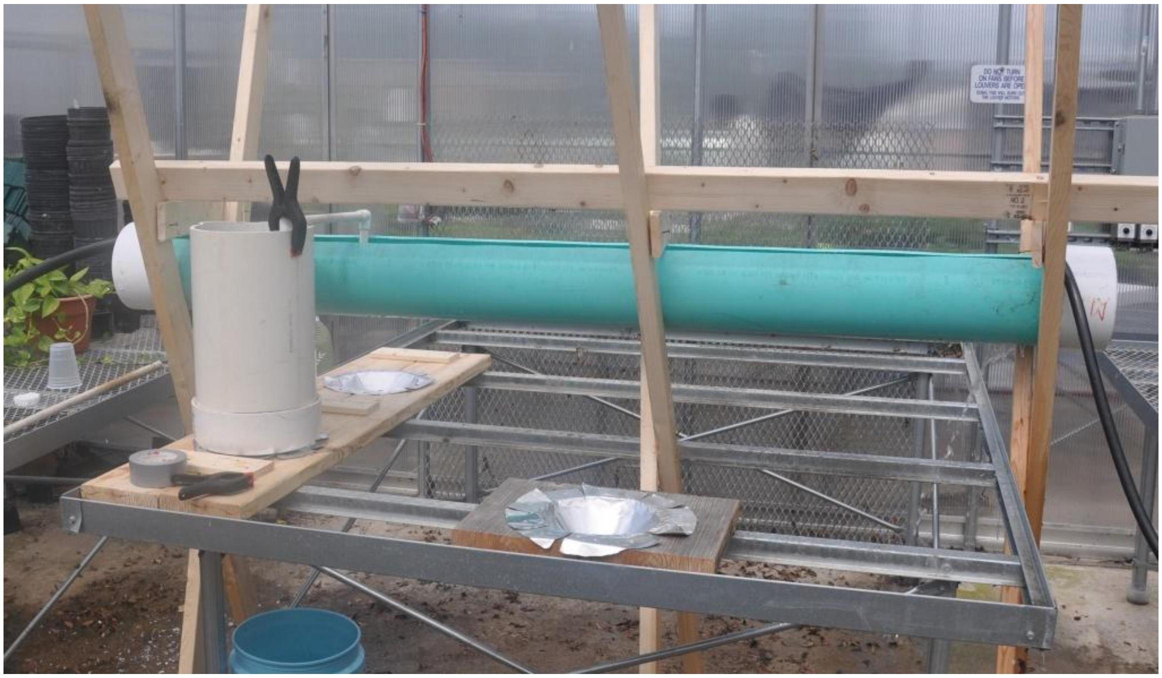

Figure 3.1 Infiltration flume design for constant head experiment

Measurement of Constant Head Hydraulic Conductivity. Greenhouse experiments were conducted in May 2012 on the Auburn University campus. Temperatures were monitored in the greenhouse using a datalogger (HOBO Pro v2 2x External Temperature Data Logger, Onset Computer Corporation, Bourne, MA). The temperature in the greenhouse during this experiment ranged from 22 to 30°C. Due to the limited space on the flume, this experiment was replicated over time with a total of eight replications of each treatment (control, earthworm, and mole cricket). One southern mole cricket or one night crawler was introduced per arena. Eight arenas with only soil were used as control treatments. Arenas were watered every other day. Five grams of ryegrass clippings were sprinkled over the surface of the earthworm arenas for food (Bastardie et al. 2003), and five freeze-dried mealworms were sprinkled randomly on the surface of the arenas with mole crickets for feed. Once the soil organisms had constructed their tunnels for 7 d, two arenas of each treatment were transported to the Small Animal Clinic at Auburn University where the same protocol as in Chapter 2 was used to verify the tunneling in the arenas.

The hydraulic conductivity of saturated soil was estimated using a constant head procedure (Lal and Shukla 2004). For this purpose, a flume was constructed from polyvinyl chloride (PVC) pipe with a 20.3 cm diameter and 213 cm length. A 12.5 cm wide slit was cut lengthwise on top of the pipe to provide access for the siphon tubes that fed water to each individual soil column. A wooden frame was constructed to hold the water flume at the proper height (Figure 3.1). Siphon tubes were constructed from 1.91 cm PVC pipe to feed water from the flume to each individual soil arena. The water on top of the soil inside the arena was kept at a constant ponding depth of 15 cm. Water was captured in a graduated cylinder. Measurements of outflow volume were taken every 10 minutes until the outflow volume of water was approximately equal for three consecutive measurements. Time to saturation was calculated by starting a timer as soon as water started to flood the arenas and stopping the time when water started to flow out the bottom of the arenas. Saturated hydraulic conductivity is the ability of soil to conduct water after all its pore space is saturated or full of water (Lal and Shukla 2004). Saturated hydraulic conductivity (K_{sat}) was calculated using Darcy's law for saturated water flow through porous media.

The saturated hydraulic conductivity equation was used:

Equation 3.1 $$K_{sat} = -Q/A(H_1-H_2)$$

where Q is the volume of water permeating through the soil, divided by the time interval between measurements, A is the cross sectional area of the arena, H_1 is the height of the soil and H_2 is the height to the top of the water.

Soil Infiltration under Field Conditions. A field experiment was conducted on 8 November 2011 at the Great Southern Golf Course in Gulfport MS. The air temperature during this test ranged from 15.56–26.4°C with a median of 20°C. The experiments were conducted on the fairways where the most mole cricket damage was found.

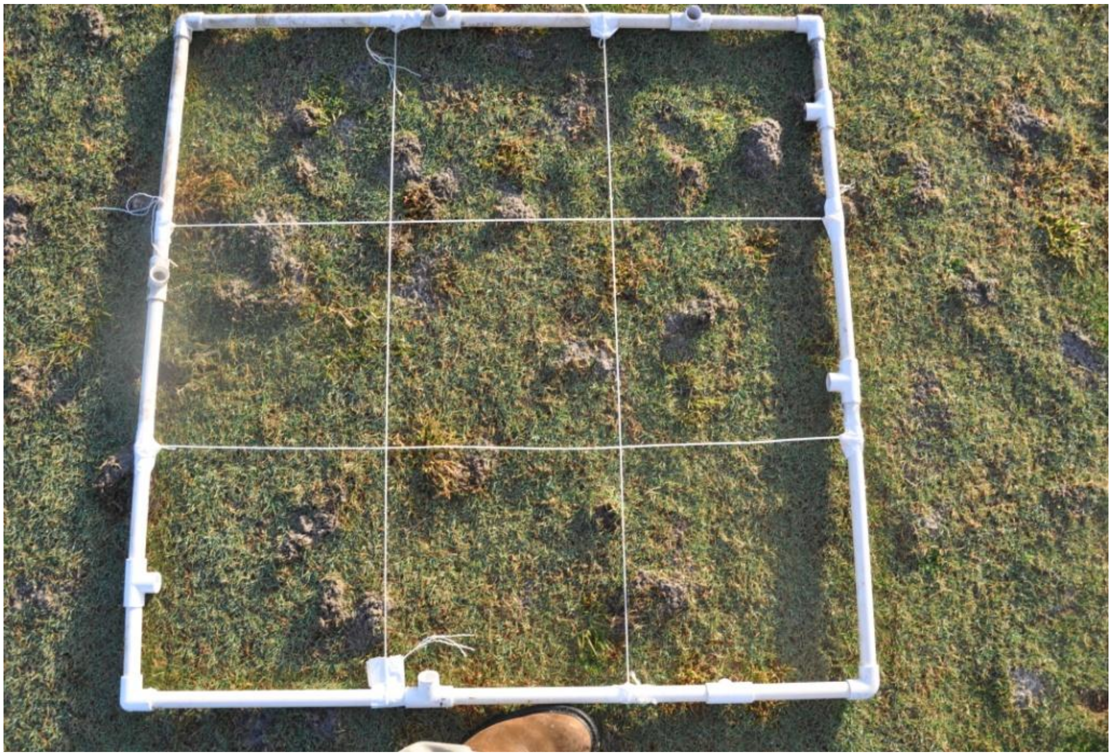

Figure 3.2 A frame with a 90 × 90 cm divided into nine equal grids was utilized to estimate the amount of mole cricket damage by surface area (Cobb and Mack 1989)

These sites had hybrid bermudagrass (*Cynodon dactylon* (Loppers.) × *Cynodon transvaalenis* (Burtt-Davy)) maintained at approximately 5 cm height. Soil analysis for texture, particle size, percent organic matter, and pH were recorded at each location where data were collected. The severity of the mole cricket infestation in each plot was determined using a damage rating (Cobb and Mack 1989), which assigns a rank of 0 to 9 to a 1 m^2 area with 9 being the most extensive damage. Measurements of thatch height were also taken at each site where infiltrations were measured. Six areas with visible damage and six adjacent areas without damage were used to compare water infiltration and runoff. A Cornell Sprinkle Infiltrometer (Ogden et al. 1997) was used to determine runoff and infiltration rate.

The Cornell Infiltrometer was placed over a metal ring inserted into the soil 15 cm (Figure 3.3) and water dripped through capillary tubing to simulate a constant rainfall flow. Infiltration rate was determined by subtracting the runoff rate from the total amount of water released by the reservoir. Runoff was measured by time to ponding and the volume of runoff over three minutes intervals until three consecutive measurements of equal volume (within 2 ml) were recorded.

Simulated rainfall was calculated by

Equation 3.2 $$r = (H_1 - H_2)/T_f$$

Where H_1 is the initial water height in the Cornell infiltrometer, H_2 is the water level at the end of the time period and T_f is the time in which it takes for the measurement to take place.

Figure 3.3 Cornell Sprinkle Infiltrometer

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Runoff rate (cm min^{-1}) was calculated by

Equation 3.2 $$runoff\ (ro_t) = (V_t - 457.3*t)$$

Where V_t is the measurement of runoff volume (ml), t is the time interval when the runoff water was collected (every three minutes) and 457.30 cm^2 is the ring area.

Infiltration rate (i_t) is the difference between the simulated rainfall rate and the runoff rate (Ogden et al. 1997).

Equation 3.4 $i_t = r - ro_t$

The results were analyzed using a two sample *t* test (Statistix v. 8.1).

Results

Soil Infiltration under Field Conditions. Average damage rating was 9 and 0 for mole cricket infested and uninfested areas, respectively. Areas with little to no damage were more likely to have higher amounts of runoff that the areas of high damage rates (Fig 3.4, $P<0.001$). There was a significant difference between the amount of water that was calculated to infiltrate the soil column when there was a greater amount of mole cricket damage in the area (Fig 3.4, $P<0.001$). Similarly, areas with a high amount of damage had a greater infiltration rate compared to areas with less or no damage.

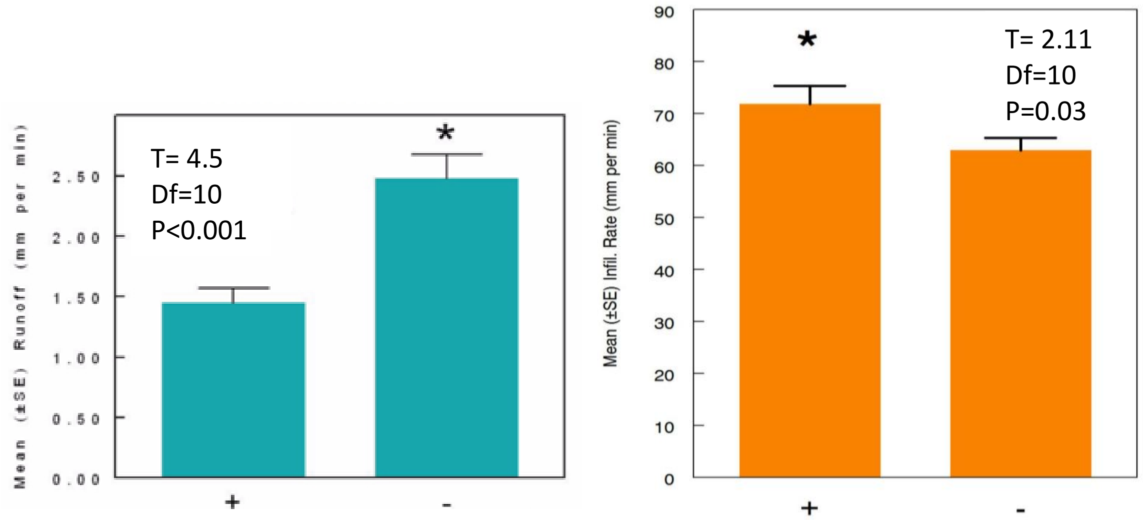

Figure 3.4 Runoff rates for Great Southern Golf Course areas with and without mole cricket damage and a sandy loam soil type. The error bars denote the standard error of the means.

Comparison of Soil Hydraulic Conductivity between Mole Crickets and Earthworms. Arenas with mole crickets and night crawlers had a significantly higher saturated hydraulic conductivity than arenas that were left with no soil organisms (Table 3.1, $P<0.01$). The arenas that had the soil dwelling organisms in them had tunnels that allowed for preferential flow of water through the soil whereas the water had to saturate the soil in the arenas with no soil organisms. Mole crickets and night crawlers had similar runoff and K_{sat} values and were both significantly different from the rates.

Table 3.1 Effects of soil organisms on the time to saturation and infiltration rate in greenhouse trials

			Mean			
	Scapteriscus	*Lumbricus*	Control	P-value[*]	F-value	DF[a]
Time to saturation	1.950a	2.10a	2.16b	$<0.0001^*$	19.3	2,21
K_{sat} (cm min^{-1})	0.063×10^{-4}a	0.067×10^{-4}a	0.032×10^{-4}b	0.0007^*	12.3	2,20

Means within row follow by same letters are not significant (Tukey's HSD test, $P<0.05$).

[a] Degrees of Freedom

Discussion

The results in the field trial showed that tunneling from *Scapteriscus* mole crickets allow more water to infiltrate the soil column and is less apt for water to runoff. When water floods an area it penetrates the soil using preferential flow that allows solutes to move through the soil faster and sometimes even reaching groundwater (Dekker and Ritsema 1994). Natural cracks and crevices as well as earthworm and other soil dwelling organisms' burrows can aid in the soils' ability to take in water (Bastardie et al. 2003). Field data using the Cornell Infiltrometer showed the water likely used the mole cricket tunnels to move into the soil more rapidly than in the areas that didn't have mole cricket damage. Earthworm's tunnels will withstand heavy compaction and not collapse (Alakukku et al. 2002). Mole cricket tunnels may be similarly reinforced which enables infiltration rates to be greater areas with mole crickets and less in areas without mole crickets.

Mole crickets on average can displace over 100 cm^3 of soil in a tunnel system (Chapter 2). These highly damaged areas will have high groundwater infiltration enabling solutes (i.e. fertilizers and pesticides) to move from the surface into the soil faster than if the solute leached through an intact soil profile. Mole crickets and night crawlers have comparable infiltration rates of water into soil. Therefore, the presence of either soil organisms may hasten movement of pesticides and fertilizers to groundwater. It is commonly recommended to apply pesticides for mole crickets soon after they hatch for their eggs. These results show that if the mole crickets are old enough to tunnel extensively through the soil profile, insecticide applied to control them may pass beneath the mole crickets in the soil and not be effective in controlling them.

In greenhouse studies, saturation times were not significantly different between the night crawler and mole cricket; however, the two soil organisms were significantly different than the control. The tunnels that were constructed by the mole crickets and night crawlers were used as pathways for the water to move into the soil. CT scans of each arena were conducted to make sure the organisms were tunneling through the soil. These pathways allowed the water to saturate the soil from the middle and bottom instead of just the surface like in the control. This leads to a shorter saturation time and a larger infiltration rate. Saturated hydraulic conductivity is higher with length of worm burrows and number of independent pathways throughout the tunnel system (Bastardie et al. 2002). This could be a result from the tunnels that the mole cricket and night crawler construct allowing water to filter deep into the soil. This can also be one of the reasons that there was a significantly lower time to saturation in the arenas that had night crawlers or mole crickets. Another cause for the saturation time to be lower may be that the water is using the tunnels as pathways into the soil. This allows faster preferential flow through the soil. When comparing mole cricket and night crawlers the runoff rates and infiltration rates are very similar and both were significantly different as if there were no organisms in the arenas. Mole crickets' tunnel's diameter is 2 to 3 times larger than their pronotal width (5.76 mm) whereas earth worms' tunnel's diameter is the same diameter and in some areas narrower (Joschko et al. 1991).

These experiments show that the presence of soil burrowing organisms will change the infiltration and runoff of the soil that is inhabited by them. This is insightful in many ways, as it can help water to stay in the soil and minimize erosion. The data can also help clarify that when applying insecticides it is important to apply the recommended amount of water with the insecticide, if applicable. Doing so will enhance the likelihood that the insecticide comes in contact with the insect or can move into the soil profile with the insect. Further studies need to be in the areas of examining the differences between tunneling characteristic of mole crickets and night crawlers to help further identify why these organisms have similar runoff rates and saturated hydraulic conductivities.

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