



Chapter 1

Introduction

1.1 Aims

The aims of this study were to:

1. Determine the seasonal development and sex ratio of *G. africana* in the field.
2. Analyse the field stridulation characteristics and test for temperature dependence and temporal variation between recordings of the African mole cricket.
3. Investigate the phonotactic flight patterns (including sex ratios) of *G. africana*, and determine its dependence on environmental variables.
4. Quantify the efficacy of chemical control of *G. africana* on turfgrass.

1.2 Hypothesis

Null (H_0) and alternative (H_A) hypothesis included the following:

1. H_0 : *G. africana* has a univoltine life cycle in the study area.
 H_A : *G. africana* does not have a univoltine life cycle in the study area.
2. H_0 : The sex ratio of *G. africana* in the field is not significantly gender biased.
 H_A : The sex ratio of *G. africana* in the field is significantly gender biased.
3. H_0 : There is no significant relationship between soil temperature and the stridulation characteristics of field-recorded mole crickets.
 H_A : There is a significant relationship between soil temperature and the stridulation characteristics of field-recorded mole crickets.
4. H_0 : There is no significant temporal variation in the stridulation characteristics of field-recorded mole crickets.
 H_A : There is significant temporal variation in the stridulation characteristics of field-recorded mole crickets.
5. H_0 : There is no significant relationship between temperature and moon phase with flight patterns and flying gender ratios of *G. africana*.
 H_A : There is a significant relationship between temperature and moon phase with flight patterns and flying gender ratios of *G. africana*.

6. H_0 : The monthly sex ratio of flying individuals of *G. africana* is not significantly different from the field population.
 H_A : The monthly sex ratio of flying individuals of *G. africana* is significantly different from the field population.
7. H_0 : *G. africana* cannot be controlled effectively on turfgrass by chemical control.
 H_A : *G. africana* can be controlled effectively on turfgrass by chemical control.

1.3 Statistical analysis

The statistical analysis of all the data was conducted on the software program “Statistica” Version: 5 (Starsoft Inc. 1995). All data conformed to the assumptions of the specific statistic analysis applied (Sokal & Rohlf 1997). Where applicable, the specifics of the analysis are elaborated. Decimal places of means and standard deviations (including standard errors) are provided according to Sokal & Rohlf (1997). Significance level was set at the biological standard 5 % level.

1.4 Classification

The family Gryllotalpidae or mole crickets are closely related to the Gryllidae, the true crickets, diverging mainly by specialization in a subterranean existence (Tindale 1928 and Townsend 1983). The Gryllotalpidae is distributed throughout the tropical and temperate regions of the world and consists of five genera (Chopard 1968, Townsend 1983, Otte & Alexander 1983, Nickle & Castner 1984 and Otte 1994a), although Tindale (1928) reported six genera in Australasia. A species number of between 50 and 70 can be calculated from literature reports (Chopard 1968, Otte & Alexander 1983, De Villiers 1985, Frank *et al.* 1998 and Walker & Moore 2002), constant with the approximately 70 species listed by Otte (1994a) and Otte (1994b) in a worldwide catalogue. Some species have been described subsequently, evident that not all are yet known (Frank & Parkman 1999). Works of Tindale (1928) noted several subfamilies, three being Australasian. Townsend (1983), however, reported only two subfamilies, the Scapteriscinae and

Gryllotalpinae. The subfamily division is based on a difference in the origin of the basal spur of the fore leg, which arises from the trochanter in *Scapteriscus* and from the femur in the other four genera (Townsend 1983). In the Scapteriscinae the fore tibia has two dactyls (*Scapteriscus*), numbering three (*Triamescaptor*) or four (*Neocurtilla*, *Gryllotalpella* and *Gryllotalpa*) in the Gryllotalpinae (Townsend 1983).

The revision of Townsend (1983) is essentially based on interspecific male stridulatory file morphology. Species-specific male file morphology is supported in the literature (Walker & Carlyle 1975, Otte & Alexander 1983 and Hoffart *et al.* 2002). In this study the phenetic classification of Townsend (1983) will therefore be followed. Table I.1 précis the genera, subfamilies and general occurrence of mole crickets. Male song characteristics are useful in identifying winged species (Bennet-Clark 1970a, Bennet-Clark 1970b, Otte & Alexander 1983, Nickle & Castner 1984, Kavanagh & Young 1989, Walker & Figg 1990 and Broza *et al.* 1998).

This family is represented in South Africa by the genus *Gryllotalpa* and four species (Townsend 1983 and De Villiers 1985), *Gryllotalpa africana* Palisot de Beauvois, *Gryllotalpa devia* Saussure, *Gryllotalpa parva* Townsend and *Gryllotalpa robusta* Townsend (Townsend 1983). *Gryllotalpa africana* is the only known local pest species (also see Chapter 1.9: Gryllotalpidae as pests) and *G. devia* the only endemic species (known to occur in the Cape province and Lesotho) (Townsend 1983 and De Villiers 1985).

Gryllotalpa devia has previously been incorrectly named *Neocurtilla devia* (Saussure) (Townsend 1983) and most of the common African, Asian and Australian species have been lumped together under the name *G. africana* (Tindale 1928 and Townsend 1983) (Figs. 1.1, 1.2). Townsend (1983) reported that *G. africana* is the most common species in Africa, but does not occur outside the African continent. *Gryllotalpa fossor* Scudder, *G. confusa* Chopard and *G. colini* Rochebrune are synonyms of *G. africana* and *G. orientalis* Burmeister (previously thought to be a synonym of *G. africana*) occurs in Asia and Indonesia (Townsend 1983). Nickle & Castner (1984) reported, “there is growing evidence to suggest that *G. africana* may be a complex of several sibling species.” Otte & Alexander (1983) described a new

species, *Gryllotalpa monaka*, and regard all previous records in Australia of *G. africana* to be the former. Hence, studies conducted on *G. africana* not from the African continent may not represent the same species studied in this instance and may therefore depict information relating to other *Gryllotalpa* species. Where applicable, dates, results and locations of these studies (and specimen origins, when provided) were however included.

A review of *G. africana* is therefore needed to accurately determine areas of present occurrence. Song character homogeneity can be used as an additional criterion to confirm future accounts of species (also see Chapter 3: Stridulation of *G. africana*).

Table 1.1 The classification and general occurrence of mole crickets (Gryllotalpidae) (Townsend 1983).

Subfamily	Genus Author	Occurrence
Gryllotalpinae	<i>Gryllotalpa</i> Latreille	Old World
Gryllotalpinae	<i>Gryllotalpella</i> Rehn	New World
Gryllotalpinae	<i>Neocurtilla</i> Kirby	New World
Gryllotalpinae	<i>Triamescaptor</i> Tindale	New Zealand
Scapteriscinae	<i>Scapteriscus</i> Scudder	Mainly New World, also the Oriental region



Fig. 1.1 Adult *G. africana*.



Fig. 1.2 Lateral view of the right, front trochanter, femur, tibia and tarsus of *G. africana*, showing the four tibial dactyls.

1.5 Morphology and biology

Mole cricket species are grey-brown to black and may be covered with fine ochreous pubescence (Tindale 1928, Annecke & Moran 1982, Townsend 1983, De Villiers 1985, Cobb 1998 and Frank *et al.* 1998). The head is essentially prognathous (De Villiers 1985). These specialized burrowing insects have fossorial forelegs bearing two to four strongly sclerotised dactyls (Tindale 1928, Townsend 1983 and Nickle & Castner 1984). Tunnelling efficiency and power are accentuated by the fact that mole crickets can tunnel out of the neck of a chicken (which ingested them) (Smith 1893) and Japanese tunnelling machines marketed under the name “Mole-cricket” (Harding 1981). The saltatorial hind legs are relatively small (De Villiers 1985). Adults of the family vary interspecifically (on average length) from 18.8 mm to 52 mm (Townsend 1983, Fowler & De Vasconcelos 1989, Walker & Figg 1990, Broza *et al.* 1998, Cobb 1998 and Buss *et al.* 2002). Most species are macropterous, but brachypterous, micropterous and apterous species have also been identified (Tindale 1928, Townsend 1983, De Villiers 1985 and Frank *et al.* 1998). (In following discussions no distinction between brachypterous and micropterous will be made). Intraspecific wing length and subsequent flight ability may vary geographically (Tindale 1928, Semlitsch 1986 and Frank *et al.* 1998). Hind wings may also be vestigial in males but present in conspecific females (Kavanagh & Young 1989). The ovipositor is vestigial or absent (De Villiers 1985, Tindale 1928) and male mole crickets (of most winged species) differ morphologically from females by having a pair of large cells (anterior of which is the harp) on each forewing, known as the stridulatory area (Townsend 1983 and Frank *et al.* 1998 (also see Chapter 3: Stridulation of *G. africana*).

Mole crickets dig a complex of burrows within which they live, feed, sing, mate and breed (Townsend 1983). Soil cavity architecture shows some interspecific variation and may be influenced by behavioural ecological differences between species (Brandenburg *et al.* 2002). Frank *et al.* (1998) divided soil cavities in three categories: Firstly, tunnels, or deep mines made in the ground. Secondly, horizontal mines just below the soil surface, classified as galleries (see Chapter 1.9: Gryllotalpidae as pests Fig. 1.3) and thirdly, an egg chamber cavity made by

females. Nymphs (of one species) are more inclined to gallery tunnelling than adults, especially during autumn (Hudson 1985a and Hudson & Saw 1987). In dry soils and low temperatures mole crickets dig deeper in the soil (Frank & Parkman 1999) and burrows of 75 to 100 cm have been reported (De Villiers 1985 and Frank & Parkman 1999). Soil and moisture content preference vary (Bennet-Clark 1970b, Townsend 1983) and species occur in sandy to heavy clay soil (Ulagaraj 1975, Otte & Alexander 1983, Fowler & De Vasconcelos 1989, Broza *et al.* 1998 and Brandenburg *et al.* 2002), usually with high (Tindale 1928, Ulagaraj 1975, Otte & Alexander 1983, De Villiers 1985 and Broza *et al.* 1998), but also with relatively low moisture content (Townsend 1983 and Broza *et al.* 1998) (some species also occur in highly saline soils or prefer soils rich in organic matter (Broza *et al.* 1998)). Tindale (1928) reported mole crickets with glabrous pronota and other body parts are generally found in sand, while the strongly pubescent species may be found in light soils. Gryllotalpids may be mainly carnivorous, mainly herbivorous or omnivorous (Tindale 1928, Matheny 1981, Hudson 1985b and Frank *et al.* 1987) and cannibalistic behaviour has also been reported (Sithole 1986 and Brandenburg 1997). Mole crickets of most genera can secrete a fluid (which may be expelled) from their anal glands, serving as a defence and/or deterrence mechanism against predators (Baumgartner 1910, Tindale 1928 and Walker & Masaki 1989) (also see Chapter 2: Seasonal development of *G. africana*).

Some species aggregate in leks for mating (Hill 1999), while others form sprees (temporal lek) (Walker 1983). Mating takes approximately one minute in *Scapteriscus* and has been reported in *Gryllotalpa* by the female mounting the male and spermatophore transfer taking place in this position (Alexander & Otte 1967). *Neocurtilla* copulation has been described in the burrow by sexes facing in opposite directions, with the male laying on his back (or his side) and the tips of the two abdomens being end to end (Baumgartner 1905). Alexander & Otte (1967) hypothesised that mating orientation may not be interspecific, but depend on whether copulation takes place in or outside the burrow. The male spermatophore of *Neocurtilla* is characterised by a bulbous sperm containing ampulla and a short, thick spermatophore tube (Loher & Dambach 1989), being relatively similar in

Gryllotalpa, except for a long spermatophore tube (Alexander & Otte 1967). *Scapteriscus* males pass the spermatophore (< 1 mm diameter) to the female during mating, which she then consumes (Forrest 1986). *Scapteriscus* females have been reported to store viable sperm in their spermathecae for seven months (Walker & Nation 1982). Eggs are laid in egg chambers, 2.5-30.5 cm below the soil surface (dependant on soil moisture) (Hayslip 1943, Forrest 1986, Frank *et al.* 1998 and Potter 1998). Eggs per clutch are intraspecific and dependent on physiological condition (Frank *et al.* 1998), but may be independent of soil moisture (Hertl *et al.* 2001). Some females produce more than 450 eggs and as many as 10 clutches (the number of eggs per clutch is inversely correlated) (Forrest 1986). Other species may only produce one clutch, ovipositing 37-58 eggs (Semlitsch 1986). Oviposition for some species generally occurs during spring/early summer for different generation periods and distributions (Forrest 1986, Semlitsch 1986, Brandenburg 1997, Cobb 1998, Frank *et al.* 1998, Potter 1998 and Buss *et al.* 2002). Variation within this seasonal period occurs and may be dependent on soil moisture (Hertl *et al.* 2001) and to a lesser extent soil temperature (Brandenburg 1997), factors probably also influencing peak oviposition period for other species. Oviposition period is usually shorter and longer (relative to univoltinism) in species having semi- and bivoltine life cycles, respectively (Walker *et al.* 1983 and Semlitsch 1986). Some species may not show seasonal breeding in certain geographical areas and all ontogenic stages are present at all times (Brandenburg 1997, Frank & Parkman 1999 and Buss *et al.* 2002) (egg laying peak in late spring and winter (Frank & Parkman 1999)). Incubation time is generally three weeks, temperature dependant (Frank *et al.* 1998 and Potter 1998). Brood care has been reported for the genera of *Gryllotalpa* (Frank *et al.* 1998) (probably absent in some species (Hill 1999)) and *Neocurtilla* (Forrest 1983a and Semlitsch 1986), but is absent in *Scapteriscus* species (Forrest 1986). Nymphs develop through several instars, variable on an intra- and interspecific temporal and spatial scale. Values of between six and 12 instars (Hudson 1987, Braman 1993, Brandenburg 1997, Frank *et al.* 1998 and Potter 1998) have been reported. First instar nymphs may be the only active jumpers (Fowler 1988) and adults may only use their hind legs to propel their body in the air to initiate flight

(Ulagaraj 1975). First instars may have a banded appearing abdomen (Tindale 1928) or may be white, darkening after a day (Frank *et al.* 1998). Young nymphs are wingless (Sithole 1986 and Frank *et al.* 1998), wing buds are, however, present in late instar nymphs of winged species, where functional wings are limited to adults (Sithole 1986 and Cobb 1998). Alexander (1968) reported likely examples of adult diapause (during winter) in two semivoltine mole cricket species. Over wintering population constitution (life stage percentages) are interspecific (adult or nymph biased) (Forrest 1986) and may vary intraspecifically between seasons (Brandenburg 1997) (also see Chapter 2: Seasonal development of *G. africana*). A proportion of mole cricket individuals may be active throughout the winter (Brandenburg & Williams 1993). In semivoltine species, individuals are immatures during the first over wintering period and adults in the subsequent winter period (Semlitsch 1986), resulting in both ontogenic stages being present in winter. The adult sex ratio in the field may be skewed (three females: one male) (Semlitsch 1986) (also see Chapter 2: Seasonal development of *G. africana*). Usually after over wintering as adults, the life cycle is repeated.

Voltinism is variable on a geographic scale (not species specific), with one species being semi- or univoltine (Semlitsch 1986) and another uni- or bivoltine (Walker *et al.* 1983 and Forrest 1986), in a relatively cooler and warmer latitudinal range, respectively. Gryllotalpid generations range from two and a half years (Tindale 1928) to being bivoltine (De Villiers 1985, Forrest 1986, Fowler & De Vasconcelos 1989, Brandenburg 1997, Frank *et al.* 1998 and Vittum *et al.* 1999).

1.6 Stridulation (phonotactic signal)

The tegmina of winged male mole crickets are characterised by a serrated vein/file (*pars stridens*) on the ventral side, but lacking a mirror (Bennet-Clark 1970a, De Villiers 1985). The tegmina may be analogous (De Villiers 1985 and Kavanagh & Young 1989) or the file may be limited to the right tegmen (Bennet-Clark 1970a). The arrangements of the teeth on the stridulatory file are species specific, resulting in species-specific song (Bennet-Clark 1970a, Townsend 1983 and Bennet-Clark

1989). Well-developed files have been reported for females of some species (Tindale 1928 and Nickle & Carlisle 1975).

Gryllotalpid males produce calling songs by rubbing the file across a scraper (*plectrum*) on the other wing (Walker & Carlisle 1975, Bennet-Clarke 1987, 1989), producing sound as the wings close (Bennet-Clark 1970a). Stridulating males may be “ambidextrous” in the use of their tegmina (producing similar sound with the left-over-right tegmina and the visa versa arrangement) (Forrest 1987 and Kavanagh & Young 1989). Some Gryllotalpids produce an advertisement call of chirps (four known species and one unknown) (Nevo & Blondheim 1972, Otte & Alexander 1983, Walker & Figg 1990, Broza *et al.* 1998 and Hill 2000), whilst most species produce trills (Nickle & Castner 1984 and Hoffart *et al.* 2002) and others no advertisement call at all (two known species) (Tindale 1928 and Walker & Figg 1990). The morphology of the stridulatory apparatus does not segregate chirping and trilling species (Hoffart *et al.* 2002). The acoustic repertoire of mole crickets also includes a courtship and disturbance call, distinct from the advertisement call (in relation to carrier frequency and syllable rates) only in chirping species (Hill 2000). Females of the family are known to stridulate (Baumgartner 1905, 1910, Tindale 1928, Zhantiev & Korsunovskaya 1973, Ulagaraj 1976 and Townsend 1983), they do not, however, produce pure frequencies and the sounds they produce are probably not used for mate recognition (Townsend 1983). Baumgartner (1910) stated female stridulation is used for recognition, Zhantiev & Korsunovskaya (1973) reported it to be territorial and threatening, Ulagaraj (1976) also presumed it to be in the nature of aggressive behaviour and Otte & Alexander (1983) suggested it might be connected with aggressiveness during parental behaviour.

Most mole crickets construct specialized burrows (funnel or horn-shaped gallery endings), from which males call (tail orientated outward) to increase acoustic output (Bennet-Clark 1970a, Ulagaraj 1976, Forrest 1983b, Bennet-Clark 1987, Kavanagh 1987, Walker & Figg 1990 and Frank *et al.* 1998). Calling position (orientation is constant) and horn shape (terminates in one to four surface openings) may vary between genera or species (Bennet-Clark 1970a, Nickerson *et al.* 1979, Snyder & Oliver 1979, Bennet-Clarke 1989, Kavanagh & Young 1989 and Walker

& Figg 1990). The shape of the sound field around the burrow of a calling male may show some variation, potentially due to burrow design differences (Bennet-Clark 1970a, Bennet-Clarke 1987 and Kavanagh 1987). Male mole crickets of most species produce advertisement calls to attract conspecific females (Frank *et al.* 1998), although conspecific males are usually also attracted (phonotaxis) (Ulagaraj 1975 and Forrest 1983a), generally through flight. The advertisement call of one chirping species can be detected as low frequency seismic vibrations up to 3 m from the focal male (Hill & Shadley 1997). Sensitivity of mole crickets to ground vibrations (measured by influence on calling activity) may vary from high to relatively low. Trilling species may generally be less sensitive (exceptions have been reported (Bennet-Clarke 1970a) than chirping species (Bennet-Clarke 1970a, Forrest 1991, Hill & Shadley 2001 and Hoffart *et al.* 2002). Chirping species may detect and respond to substrate vibrations produced by neighbouring calling males (Forrest 1983b and Hill & Shadley 1997, 2001). The courtship song is produced in the presence of a conspecific female, as when a female enters a male calling burrow (Ulagaraj 1976, Forrest 1983a and Hill 2000), after which the burrow opening may or may not be closed by the male or female (Forrest 1983a). The courtship song may be recognised as rhythmic sequences of soft, short trills, produced intermittently (Alexander 1962 and Ulagaraj 1976). Disturbance calls in chirping and trilling species can be recognised by a sharp repeatable click (Hill 2000) and short intermittently produced trills (Ulagaraj 1976) following disturbance, respectively. In the chirping species, the disturbance call shows broad frequency coverage as most known disturbance calls produced with the typical Orthopteran file-scraper mechanism (Masters 1980). Advertisement calling of trilling species can continue after female attraction, when females may start fighting with the male, who may then stop calling (Forrest 1983a). Attracted males may wait outside burrows of callers, fight with resident males in their burrows or construct their own acoustic burrows (Forrest 1983a), usually thereby interrupting phonotactic calling only briefly.

Male singing (in a trilling *Gryllotalpa* species) may start at ambient temperatures of 8 °C, only becoming established, however, above 9 °C (Bennet-

Clark 1970a). Ulagaraj (1976) reported calling songs of trilling *Scapteriscus* not to have been witnessed below 18 °C (ambient and soil temperature). In a chirping species, males usually only call at temperatures above 12.5 °C, although some males can call at temperatures as low as 5 °C (Hill 2000). Male trilling songs usually start from dusk (Ulagaraj 1976 and Otte & Alexander 1983), ending after two hours (30-60 minutes in a chirping species (Walker & Figg 1990 and Hill 1998)) or may be produced till late in the night, correlated with moisture (Ulagaraj 1976) and/or flight activity (and therefore usually seasonal (see Chapter 1.7: Flight patterns (phonotactic response)) (Forrest 1983b and Walker 1983). Attracted individuals are choosing among males on the basis of their calls (Ulagaraj 1976 and Forrest 1983a). Phonotactic response is a positive function (sex ratio constant) of song intensity (Forrest 1983a), the latter positively correlated to male size and generally to temperature and rainfall (soil moisture) (Bennet-Clarke 1970a, Ulagaraj 1976, Forrest 1980, Forrest 1983a, Forrest 1991 and Hill 1998) (also see Chapter 1.7: Flight patterns of *G. africana*). This is consistent with Burk's (1988) contention that intensity indicates fitness (which can not be counterfeited) and keeping with the physics of competing sound fields (Walker 1988).

Sound pressure levels (measured just beyond the nearfield (15-20 cm in line with the burrow, re. 20 µPa) may vary from 65 to 97 dB between trilling (highest intraspecific sound pressure level variation of 67 to 91 dB) (Ulagaraj 1976, Forrest 1983a, Bennet-Clarke 1987, Kavanagh & Young 1989 and Walker & Forrest 1989) and 90 to 104 dB in a chirping species (Hill 1998). Bennet-Clark (1970a) reported mean sound power levels (at 1 m vertically above the insect, re. 10^{-12} W.m⁻²) for two trilling species of approximately 66 dB and 87 dB, respectively. Ulagaraj & Walker (1973) reported sound intensities varying from 42 to 92 dB (at 15 cm, no intensity reference level provided) for males of two trilling *Scapteriscus* species. Using a practical threshold of 40 dB for mole cricket hearing (Bennet-Clark 1989), the potential range of a call can be over 200 m (Bennet-Clark 1989 and Hill 1998), although mean ranges may be just over 100 m (Hill 1998) for trilling and chirping species. The song of a trilling *Gryllotalpa* species has been reported to be audible to the human ear up to 600 m from the call site (Bennet-Clarke 1970a). Specific song

characters may be related to temperature for an intermediate temperature range (Bennet-Clark 1970a, Kavanagh & Young 1989, Hill 1998 and Hill 2000), while others, like carrier frequency, may be temperature independent (Bennet-Clark 1989) and vary from 1.5-4.3 kHz in the family (Otte & Alexander 1983 and Nickle & Castner 1984).

1.7 Flight patterns (phonotactic response)

Mole crickets occupy temporary habitats and flights are therefore adaptive to individuals (Ulagaraj 1975). Mole crickets in flight are positive phototactic (Chao 1975, Ulagaraj 1975, Ulagaraj 1976 and Fowler & De Vasconcelos 1989) (see Chapter 1.8.2: Sampling methods: Flying individuals) and phonotactic (Ulagaraj 1976) (see Chapter 1.8.2: Sampling methods: Flying individuals). Mole crickets fly to conspecific stridulatory males (flight and sound production are temporally correlated (Ulagaraj 1975, Walker 1983, Forrest 1980, Forrest 1983a and Forrest 1983b)), but may occasionally be attracted in small numbers to heterospecific male calls (Forrest 1980 and Matheny *et al.* 1983). The tympanal organs are situated on the protibia (Frank *et al.* 1998 and Otte & Alexander 1983), but may be absent in apterous species (Tindale 1928). According to De Villiers (1985), however, the tympanal organs are absent on the fore legs and the prothoracic spiracles are large and similar in shape and position to that of the Tettigonids and might serve as acoustical openings. A protibial slit is present in *G. africana* (personal observation) and Bennet-Clark (1987) reported paired tympanal organs in mole crickets, having an acoustic input from the prothoracic spiracle and tibial slit. Auditory sensitivity can vary between flying and flightless species (Mason *et al.* 1998). Low frequency hearing is constant with intraspecific signals of conspecifics, but high frequency ultra sound hearing may be limited to flying species, suggesting a role for hearing in the avoidance of bat predation (Mason *et al.* 1998). The carrier frequency and syllable repetition rate are important sound characters in species-specific phonotaxis (in *S. borellii*) (Ulagaraj & Walker 1973, 1975). Flight may be gender specific within a species (hind wings absent in male *Gryllotalpa australis* Erichson) (Otte & Alexander 1983 and Kavanagh & Young 1989), latitudinal intraspecific or absent.

Neocurtilla hexadactyla (Perty) is usually macropterous in the Caribbean and Central and South America, but usually brachypterous in Florida and incapable of flight (Frank *et al.* 1998) (also see Chapter 1.8.2: Sampling methods: Field population). The sex ratios of most flying adult species are female biased (Ulagaraj 1975, Forrest 1983a, Matheny *et al.* 1983 and Fowler *et al.* 1987). Mean sex ratios between species vary from 3.7 to 5.5 (Forrest 1983a) or 3.3 to 7.5 females per male (Matheny *et al.* 1983) and a mean of 83 % of flying individuals has been reported as females over a two year period (Ulagaraj 1975). Females may use male song as a fitness indicator and/or to find moist soil (suitable oviposition sites) (Forrest 1980 and Forrest 1983a) (also see Chapter 1.6: Stridulation of *G. africana*), whilst male phonotaxis may involve dispersing to other favourable areas (suitable habitat), locating good calling sites (moist soil) and/or mating with attracted females (Ulagaraj 1975, Forrest 1980 and Forrest 1983a) (also see Chapter 1.6: Stridulation of *G. africana*). The latter speculation on the significance of male phonotaxis is supported by the fact that males are more dispersed than females in their landing sites relative to the sound source (Forrest 1981, Matheny *et al.* 1983 and Walker & Forrest 1989), irrespective of sound intensity (Walker & Forrest 1989). Females attracted to male advertisement calls may start fighting with the male, who may then stop calling (Forrest 1983a). Attracted males may wait outside burrows of callers, fight with resident males in their burrows or construct their own acoustic burrows (Forrest 1983a). Individuals may fly more than once (Ulagaraj 1975, Ngo & Beck 1982 and Forrest 1986) and some species may fly between egg clutches (Forrest 1986), a factor contributing to high dispersal rates (Walker & Nickle 1981).

Flight is endothermic and mole crickets have to warm-up thoracic muscles (which may involve raising and rapidly moving tegmina (Ulagaraj 1975)) to temperatures exceeding 25 °C before take-off is possible (Forrest 1983a). Flying attempts are generally not attempted below an ambient temperature of 17 °C (Ulagaraj 1975 and Forrest 1983a). Adults may use hind legs to propel them in the air to initiate flight, which can be preceded by small leaps of several centimetres and/or short flights of a few meters (Ulagaraj 1975). Light intensity may play a role as a cue in flight initiation and mole crickets may not fly at light intensities more

than 65 lux (Ulagaraj 1975). Mole crickets fly at approximately 7 – 11 km/h (Ulagaraj 1975), although wind velocity and direction affect flight and landing distribution (Beugnon 1981 and Matheny *et al.* 1983).

Insect flights may be classified as migratory (inter-habitat, relatively long range) or local (intra-habitat, relatively short range) (Walker & Fritz 1983). Migration may occur repeatedly in the genus *Scapteriscus* (Walker & Fritz 1983 and Walker & Masaki 1989) and is primarily concerned with dispersal. Local flights are concerned with reproduction and dispersal to other favourable areas (Ulagaraj & Walker 1973, Ulagaraj 1975, Forrest 1980, Forrest 1983a, Otte & Alexander 1983 and Potter 1998). In tropical climates, some species fly throughout the year (Fowler *et al.* 1987). In more temperate climatic areas, relatively warm night temperatures may cause mole crickets to fly late in the evening, although flight is usually concentrated just after sunset (Forrest 1983a) in most areas and of a seasonal nature (Ulagaraj 1975, Forrest 1986, Potter 1998 and Henne & Johnson 2001) (also see Chapter 4: Flight patterns of *G. africana*).

Flight periods generally peak in spring and autumn (Ulagaraj 1975), with some interspecific variation (peak flight may be separated by a few months) (Ulagaraj 1975) and intraspecific geographical variation (Henne & Johnson 2001). Dispersal flights (Forrest 1986) and mating generally occur during spring (Ulagaraj 1975 and Walker & Nation 1982). Autumn flight is usually less pronounced (Ulagaraj 1975), but mating may take place and sperm stored (in the female spermatheca) for egg fertilization in spring (Walker & Nation 1982). Autumn flight may also be used to obtain suitable overwintering sites or simply for dispersal (Ulagaraj & Walker 1973 and Potter 1998). Geographical variation may cause some species to become bivoltine (also see Chapter 1.5: Morphology and biology), when flights may occur in spring/summer and summer (Walker 1985 and Potter 1998). Peaks within a flight period vary from seven to 12 days (Henne & Johnson 2001). Forrest (1986) and Hertl *et al.* (2001) reported within seasonal flight peaks not to be due to oviposition cycles (mainly in spring), but caused by synchronized maturation or favourable environmental factors, such as rainfall (Hayslip 1943, Ulagaraj 1975, Walker 1982 and Hertl *et al.* 2001). Reproduction can be independent of flight and

mating may occur through subterranean tunnelling using phonotaxis (Walker 1983). Mating in a flightless species is independent of flight and phonotaxis (no song is produced) (Walker 1983 and Frank *et al.* 1998).

1.8 Sampling methods

A major component to any quantitative study of mole crickets is the sampling method. The sampling technique should be the most practical, reliable, economical and efficient for a specific species, spatial and temporal requirements and the purpose of the study (to collect live or dead specimens). Different techniques used to sample mole crickets in the field and in flight are discussed in the following respective subchapters in light of their fulfilment of the above requirements.

Field and flight sampling is not mutually exclusive and in certain studies, especially those aimed at collecting live specimens, sampling methods may be combined (Hertl *et al.* 2001).

1.8.1 Field population

Sampling techniques for Gryllotalpids in the field essentially include liquid formulations to flush crickets from the soil (irritating drenches or disclosing solutions (Potter 1998)) (Short & Koehler 1979 and Walker 1979), pitfall trapping (Lawrence 1982), estimation of surface burrowing (Walker *et al.* 1982 and Cobb & Mack 1989) and soil core extraction (Williams & Shaw 1982).

Evaluated disclosing solutions include synergized pyrethrins (pyrethrins and piperonyl butoxide), dishwashing soap, dishwashing soap and vinegar, vinegar and ammonia (Short & Koehler 1979), all dissolved in water. Of these, synergized pyrethrins (pyrethroid) are the most effective, flushing 30 % more mole crickets (*Scapteriscus*), but at an equal rate (emergence within 30 s of application), than dishwashing soap on bermudagrass (*Cynodon dactylon* L.) (Short & Koehler 1979). Vinegar shows no synergistic effect when combined with dishwashing soap (although lemon scented detergent may be more effective and is currently recommended (Brandenburg & Williams 1993, Brandenburg 1997, Cobb 1998, Potter 1998 and Buss *et al.* 2002)) and vinegar and ammonia flush significantly less

mole crickets than pyrethrins and dishwashing soap (Short & Koehler 1979). Availability and price can make pyrethrins uneconomical and an impractical, whilst these factors make dishwashing soap the optimal surveillance material (Short & Koehler 1979), which is most commonly used (Hudson 1989). The soap acts as an irritant (Brandenburg 1997) (may also dissolve the cuticular wax of the mole cricket), causing the crickets to burrow to the surface, where they may die of desiccation. Early instar nymphs may stop moving after surfacing (Potter 1998). compelling intense visual scouting. Several different dishwashing liquid brands provide similar results (Short & Koehler 1979), but some may vary in concentration and ingredients. Soap flush sampling may also be preferably used, as insecticide flush sampling may have a higher reliability variance (caused by crickets dying before emergence (Hudson 1988)) and soap being more environmentally acceptable. (Insecticide bait formulations have also been used for sampling, but proved inadequate (Williams & Shaw 1982)). Flushing studies demonstrated soil flushes to be highly variable and not very efficient (Walker 1979). Walker (1979), however, speculated that confining mole crickets to buckets (in his experiments) affected their behaviour and may have biased the results obtained. Hudson (1988) supported this hypothesis and reported that even a relatively large cage; especially at high mole cricket densities, appear to have some effect on behaviour. During cold or dry periods, mole crickets may move deeper into the soil profile (Potter 1998), which may be responsible for temporal variance in flushing results. Efficiency and accuracy of irritating drenches may therefore be influenced by soil temperature and soil moisture (including other factors influencing mole cricket activity and solution penetration). Dishwashing soap applications at concentrations of 30 ml/5 litres H₂O/m² on bermudagrass is not phytotoxic (Short & Koehler 1979), whilst the equivalent concentration on kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov.) is 50 ml/5 litres H₂O/m². Higher volume application (at comparable but usually lower concentrations to that reported by Short & Koehler 1979)) per unit area are also recommended as a guide for unspecified turfgrass (Brandenburg & Williams 1993, Brandenburg 1997, Cobb 1998 and Buss *et al.* 2002). Potter (1998) recommends post watering of soap-flushed areas, which minimizes sun scalding of

the turf (Cobb 1998). Some detergents vary in concentration and ingredients, restricting the use of dilution recommendations as a guide only. Soap flushing efficiency (studied on *S. vicinus* nymphs) is a function of soil moisture (over a small range of low moisture levels) and can be related to absolute nymph population size (Hudson 1989). Soap flushing may be more effective in bringing nymphs to the surface (Hudson 1989) and is not very suitable for collecting live mole crickets, as there is usually some level of mortality (Frank *et al.* 1998) (probably due to desiccation) involved. Mortality, however, can be minimized if crickets are submerged for a few seconds in tap water immediately upon emergence and kept out of direct sunlight. Soap flushing is time-consuming and labour intensive (Brandenburg 1995).

Pitfall traps can also be used to sample mole crickets. Basic pitfall traps are containers sunken into the ground flush with the soil surface. A linear pitfall trap (Lawrence 1982) may be more effective in collecting mole crickets, having the added feature of a gutter (with rims flush with the soil surface). These traps may be cumbersome, difficult to install and not very portable (Frank & Parkman 1999). Pitfall traps may be used to collect live surface burrowing and feeding adults and nymphs (Lawrence 1982), but have been reported to be inefficient in low-density areas (Hudson 1985a) and are not highly specific (Lawrence 1982). Non-uniform infestations over large areas may also cause pitfall traps to be impractical (Short & Koehler 1979). The number of mole crickets caught in pitfall traps depends on mole crickets in the vicinity of traps and activity, which varies upon physiological status, which is influenced by age, time of year, time of day, temperature, moisture, nutritional status and other factors (Frank *et al.* 1998). These sample values should therefore not be used for determining or estimating absolute field or flight population sizes or economic thresholds and are therefore generally used for collecting mole crickets for research needs (Vittum *et al.* 1999).

Surface burrowing damage may also be used to assess abundance, developed by Walker *et al.* (1982). Hudson (1988) reported this method (like all other sampling methods), may show variability in results. Cobb & Mack (1989) reported a damage grid method (for *S. vicinus* on hybrid bermudagrass), dividing a

0.6 m² grid in nine subsections. A damage rating is then given, based on the number of subsections with fresh damage (on a scale of one to nine). The method assumes mole cricket damage is distinguishable from damage by other pests (Cobb & Mack 1989). There are several limitations to this approach, including only periodical usage capabilities restricted to times when mole crickets are large enough to produce visible damage but with low relative mobility (mid-season nymphs) (Cobb & Mack 1989). Accurate estimates will also not be obtained if high mole cricket densities consistently damage all nine sections of a 0.6 m² sample (Cobb & Mack 1989). Optimal temporal and spatial damage rating sampling can, however, be accurately ($r^2 = 0.92$, $p < 0.0001$) linearly ($y = 0.57x - 0.78$, where y = number of mole crickets per 0.6 m² and x = damage rating) related to densities obtained with soap flushing (Cobb & Mack 1989). This method may be effective in assessing management practises with low labour intensity, but is apparently little used by turf and pasture managers (Frank & Parkman 1999). In a preliminary study, relating damage (as the percentage surface area without kikuyu grass per 0.25 m²) to *G. africana* infestation (as quantified by emerging crickets after soap flushing (at the concentration stated in § 2) in 0.25 m²) provided variable results between and within adults and three different nymphal size classes.

Otte & Alexander (1983) reported a shovel to be almost indispensable in collecting mole crickets. Digging may be used to collect live specimens and may be the most effective technique in low-density areas (Fowler & Justi 1987), but can be impractical (digging on sensitive golf course areas defeats the purpose!), labour intensive and may not provide reliable estimates due to the extreme mobility of mole crickets (Short & Koehler 1979 and Hudson 1989). The latter also causes manual coring devices to be ineffective, which led to the development of a tractor mounted coring device (Williams & Shaw 1982) (which mole crickets may well also escape (Hudson 1988)). The most accurate absolute sample may presumably be obtained with such a large soil corer. Hudson (1988), however, found no difference in efficiency between this method and soap and pyrethrin flushes (in relation to density of *S. vicinus* per unit area sampled). A tractor mounted coring method may be uneconomical (relatively expensive) and impractical, especially in sensitive

areas and areas with small spatial dimensions. There is also a problem in transporting samples to the lab and sifting through samples may be labour intensive (see Fritz (1993) for a discussion on sorting techniques) (Hudson 1988). This method may however be effective in determining activity in the soil profile (by tunnel presence) and for collecting live specimens. A hydraulic tree spade has also been used for density sampling. The cost of a tree spade is however prohibitive for most projects and such a device also provides some quantification problems due to the cone-shaped sample it extracts (Williams & Shaw 1982).

Between and within sampling methods, efficiency may vary significantly between and within species, emphasizing interspecific behavioural and/or habitat differences (Fowler & Justi 1987 and Hudson 1988). Geography may also influence choice of an optimal sampling technique, as some species may show intraspecific morphological and behavioural differences. (*N. hexadactyla* usually is brachypterous in Florida and cannot fly, whilst in the Caribbean, Central and South America the species is macropterous and capable of flight (Frank *et al.* 1998) (see Chapter 1.8.2: Flying individuals)).

An optimal field sampling method is therefore dependant on various factors, including specific study aims, funding, manpower, species and geography.

1.8.2 Flying individuals

Sampling techniques for flying adult Gryllotalpids essentially include sound - (Ulagaraj & Walker (1973, 1975), Ulagaraj (1975), Walker 1982 and Walker 1988) and light traps (Chao 1975 and Ulagaraj 1975), which may be combined (Ulagaraj 1975 and Beugnon 1981).

Sound traps can be classified as natural or artificial. Song of males calling from soil filled buckets surrounded by a trapping device may be regarded as natural sound traps (Forrest 1980 and Forrest 1983a), whilst artificial sound traps (developed by Ulagaraj & Walker (1973, 1975), Ulagaraj (1975) and Walker 1982) broadcast recorded natural (see Chapter 1.7: Flight patterns (phonotactic response)) or electronically synthesized sounds (set to the carrier frequency, syllable repetition rate and duty cycle of the natural song) (see Chapter 5: Development of an

electronic acoustic caller for mole crickets in South Africa) above a trapping device (designs reported by Walker 1982). Artificial sound traps are the most effective sound traps, as synthetically produced mole cricket song is produced at higher sound pressure levels than natural calls (Ulagaraj & Walker 1975 and Walker & Forrest 1989) (also see Chapter 1.6: Stridulation (phonotactic signal) and Chapter 5: Development of an Electronic Acoustic Caller for Mole Crickets in South Africa). Values (intraspecifically variable) as high as 3297 individuals per night have been reported (Walker 1982). Females are mainly collected in sound traps (see Chapter 1.7: Flight patterns (phonotactic response)). Sound traps are highly specific and attract conspecifics and host specific parasitoids and predators (Walker 1988) (also see Chapter 1.6: Stridulation (phonotactic signal)). Sound traps are however costly, may be damaged by vertebrate cricket predators, stolen and/or disturb local residents (Walker 1982). A large proportion of attracted individuals may also land around the trapping funnel of sound traps (Frank *et al.* 1998). A power function has, however, been determined to estimate total numbers attracted (Matheny *et al.* 1983).

Light traps may also be used to attract mole crickets (Chao 1975 and Ulagaraj 1975). Mole crickets are attracted to incandescent, fluorescent (Ulagaraj 1976 and Frank *et al.* 1998), mercury (Ulagaraj 1975) and ultra-violet (Ulagaraj 1976) lights (Fowler & Justi 1987). Light traps usually make use of a ultra-violet or fluorescent “black light” tube (Potter 1998). Attractiveness is generally positively correlated with light brightness and may be influenced by wavelength (ultra-violet light is particularly attractive for numerous insects) (Frank *et al.* 1998). The wavelength most attractive for mole crickets, however, has not been investigated (Frank *et al.* 1998). A proportion of attracted individuals may also land around the trapping funnel of light traps (Frank *et al.* 1998). Significantly more mole crickets can be attracted to broadcast sound (at an intensity of 100 dB at 15 cm – no intensity reference level provided) than to ultra-violet or fluorescent light traps (Ulagaraj & Walker 1973 and Ulagaraj 1976). Mole crickets flying at incandescent lights 100 m from a sound broadcast (at an intensity of 100 dB at 15 cm – no intensity reference level provided) will alter direction and fly to the sound source

(Ulagaraj & Walker 1973). Sampling by only using light traps is therefore not recommended due to relative low attraction potential, relative low specificity and high potential purchase cost (Potter 1998). Light traps may, however, provide a sample not significantly gender biased (Ulagaraj 1975) and prove more successful when combined with sound (Beugnon 1981).

Flight activity depends on mole crickets in the vicinity of traps and activity, which varies upon physiological status, is influenced by age, time of year, time of day, temperature, moisture, nutritional status and other factors (Frank *et al.* 1998). Sound and light traps therefore capture an unknown fraction of flying, dispersing adults, which are also an unknown fraction of the total population (Fowler & Justi 1987). These sample values should therefore not be used for determining absolute field or flight population sizes or economic thresholds. Results of Ngo & Beck (1982) suggest, however, that flight trap catches can serve as a relative indicator of flight activity, but state, “there is no independent method of verifying that the trap catch is specifically related to the size of the flying population”. Acoustic traps (especially sound traps) are however imperative in behaviour and ecological studies, for live specimen collection in high numbers, for biological control agent identification and establishing these agents and monitoring their spread (Walker 1988).

Sampling efficiency, including methods of shovel excavation, linear pitfall traps, sound traps and black light traps vary significantly between and within species, emphasizing interspecific behavioural and/or habitat differences (Walker 1982 and Fowler & Justi 1987). Sampling efficiency may even vary on an intraspecific level. Effective sampling methods for *N. hexadactyla* may be dependant on latitude, as this species is usually macropterous in the Caribbean, Central and South America and attracted to ultraviolet light, but usually brachypterous in Florida and incapable of flight (Frank *et al.* 1998) (see Chapter 1.8.2: Field population). Flight traps may therefore appear to be “ineffective” in attracting *N. hexadactyla* (Cantrall 1943, Hayslip 1943 and Ulagaraj 1975) due to “ineffective” (no) flight ability.

1.9 Gryllotalpidae as pests

The minority of mole cricket species are pests, most are innocuous and some are rare (rare species include *Gryllotalpa gryllotalpa* (L.) in Britain and *Gryllotalpa major* Saussure in the U.S.A) (Frank & Parkman 1999). Mole crickets may be mainly carnivorous, mainly herbivorous or omnivorous (Tindale 1928, Matheny 1981, Hudson 1985b and Frank *et al.* 1987) and have been reported damaging cereal crops (wheat, maize, rice, sorghum, millets, barley and oats), beet, cabbage, cantaloupe, carrot, cauliflower, chufa, collard, flowers (coleus, chrysanthemum and gypsophila), weeds (pigweed), ginseng, yam, kale, lettuce, peanut, spinach, sweet potato, cotton, coffee, cacao, eggplant, onion, pawpaw, rhubarb, sweet pepper, groundnuts, cassava, turnips, seedling vegetables, tobacco, sugar cane, potatoes, beans (*Phaseolus*), strawberries, seedbeds (including that of *Cola* and sunflowers), seedling trees (eucalyptus and fig), tea, tomato, ornamental plants (gladiolus and tulip), turfgrasses and pasturegrasses (Tindale 1928, Ramlogun 1971, Daramola 1974, Broadley 1978, Annecke & Moran 1982, Townsend 1983, Matsuura *et al.* 1985, Sithole 1986, Potter 1998, Frank & Parkman 1999, Vittum *et al.* 1999, Kim 2000 and Buss *et al.* 2002). Mole crickets feed on the roots, tubers and bulbs of these plants and, like cutworms, sever the stems of seedlings at ground level (Frank & Parkman 1999). Carnivorous species can also cause extensive damage due to their burrowing activities (Matheny 1981).

Most mole crickets feed mainly on the roots of grass, but may also feed on the surface at night (Schoeman 1996), the latter being of no consequence to healthy grass (Frank & Parkman 1999). A weak turfgrass root system causes high susceptibility to damage by foot traffic, golf carts or recreational play (Potter 1998). Feeding activity also cause thinning of turf and appearance of patches devoid of living grass, which cause weed invasion and the subsequent need for weed control (Frank & Parkman 1999). Mechanical damage to turf is caused by the tunnelling activity of mole crickets (usually the only damage caused by mainly carnivorous species) (Frank *et al.* 1998), which may also increase the incidence of *Rhizoctonia* root rot (Schoeman 1996). Galleries (horizontal tunnels just below the surface, causing protuberance of soil onto the surface) (Frank *et al.* 1998) (Fig. 1.3), causes

root desiccation (Potter 1998), damage mowing equipment and interfere with play by deflecting puts. The feeding ecology of mole crickets therefore adversely affects sensitive turf areas (such as golf course greens, surrounds and tees), causing unsure footing, disrupting play and lowering the aesthetic appeal of these areas (Fig. 1.3). Mole crickets (even at relatively low densities) may also attract birds (and other vertebrates) that prey on them, which damage turf by their foraging actions (Schoeman 1996 and Frank & Parkman 1999).

Mole crickets reported as pests of turfgrass belong to three genera, are mostly immigrants and are listed in Table 1.2. The turfgrass pest status of *Gryllotalpa orientalis* in Hawaii needs to be clarified (Frank *et al.* 1998). *Gryllotalpa africana* has been reported as a pest of guinea grass in India (Dhaliwal 1998), although the culprit may more likely be *G. orientalis* (also see Chapter: 1.4: Classification). Otte & Alexander (1983) noted the habitat of *G. australis* to be lawns, moist pastures and moist roadside ditches. Turf grass pest status information of the species was not found in the literature. Tindale (1928) reported *Triamescaptor aotea* Tindale do a considerable amount of damage in the North Island of New Zealand. Specific crops were not mentioned, but the species, if introduced to turfgrass monocultures, may be damaging (native species can also be pests (Table 1.2)).

Most turfgrasses and pasture grasses in Florida are susceptible to mole crickets (Frank *et al.* 1998). Mole crickets are economical pests of warm season grasses in the southeastern United States (Hertl *et al.* 2001). In general, bahiagrass (*Paspalum* sp.) (the most important pasturegrass in Florida, U.S.A.), bermudagrass (*Cynodon* sp.) and hybrid bermudagrass (*Cynodon dactylon* (L.) × *C. transvaalensis* Burt-Davy) are highly susceptible (Frank *et al.* 1998 and Frank & Parkman 1999). Bermudagrass and hybrid bermudagrass are the most popular turfgrasses for golf course greens, tees and fairways in Florida, U.S.A. (Frank & Parkman 1999). St. augustinegrass (*Stenotaphrum* sp.), zoysiagrasses (*Zoysia* sp.) and centipedegrass (*Eremochloa* sp.) suffer less damage (Frank *et al.* 1998). Damage to bahiagrass is accentuated due to its open growth habit, resulting in a high rate of root desiccation when soil is disturbed (Potter 1998). Close mowing of bermudagrass reduces root

depth, increasing susceptibility to uprooting and desiccation from mole cricket tunnelling (Potter 1998). The response of st. augustinegrass is less severe, probably due to its canopy like growth habit and coarser root system (Frank *et al.* 1998).

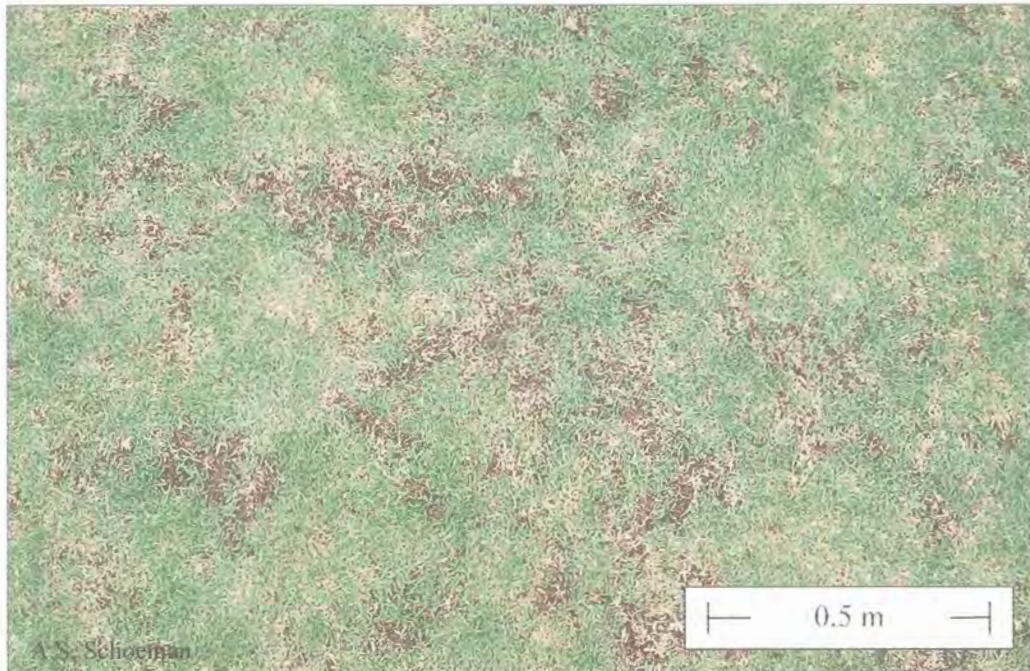


Fig. 1.3 Damage of *G. africana* to kikuyu grass (*Pennisetum clandestinum*).

G. africana was only studied on golf courses in the central northern part of South Africa, with associated limiting soil and turf types and conditions. This low system heterozygosity limits the deductive power of preference observations (which was also not empirically tested), although general tendencies in the range of conditions may be informative. Soil types on studied (and most South African) golf courses are moist and essentially sandy or clayey with associated bent grass (*Agrostis stolonifera* L.) or kikuyu grass, respectively. *Gryllotalpa africana* prefers clayey, moist soil and/or kikuyu grass (clayey soil is associated with this grass type, the causal preference factor is therefore obscure). Kikuyu grass (used for golf course fairways, tees and surrounds, as well as lawns, sport fields, parks and landscaping in South Africa) therefore appears to be susceptible and prone to *G. africana* infestation, whilst bent grass (usually used for golf course greens and

landscaping) appears to also be susceptible, but rarely infested in South Africa. Empirical studies should therefore be conducted to determine causal factors. If the different turf species and soil type contribute to preference, then the open growth habit and clayey soil planting areas of the kikuyu and the high root density and sandy soil planting areas of the latter, may contribute to their susceptibility and relative resistance, respectively. Soil preferences observed have been documented for *G. africana* (Brandenburg *et al.* 2002) and the genus *Gryllotalpa* (Tindale 1928, Otte & Alexander 1983).

Table 1.2 Mole cricket species reported as pests of turfgrass (Anneck & Moran 1982, Rentz 1996, Schoeman 1996, Brandenburg 1997, Frank *et al.* 1998 and Potter 1998).

Location	Species status	Common name	Genus species Author
South Africa	Native	African mole cricket	<i>Gryllotalpa africana</i> Palisot de Beauvois
Southeastern USA	Immigrant	Tawny mole cricket	<i>Scapteriscus vicinus</i> Scudder ¹
Southeastern USA	Immigrant	Southern mole cricket	<i>Scapteriscus borellii</i> Giglio-Tos ²
Southeastern USA	Immigrant	Short winged mole cricket	<i>Scapteriscus abbreviatus</i> Scudder ³
Puerto Rico, Virgin Islands and Australia	Immigrant	West Indian mole cricket or Changa	<i>Scapteriscus didactylus</i> (Latreille) ⁴
Northeastern USA	Immigrant	European mole cricket	<i>Gryllotalpa gryllotalpa</i> (L.)
Puerto Rico	Immigrant	Imitator mole cricket	<i>Scapteriscus imitatus</i> Nickle & Castner ⁵
Continental USA	Native	Northern mole cricket	<i>Neocurtilla hexadactyla</i> (Perty) ⁶

¹ Confused in the economic entomology literature with *S. didactylus* (Frank *et al.* 1998).

² The North American population of this species was known (until 1992) as *Scapteriscus aletus* Rehn & Hebard (Frank *et al.* 1998).

³ Only a restricted distribution in Florida (due to inability of flight) (Frank & Parkman 1999).

⁴ Confused in the economic entomology literature with *S. vicinus* (Frank *et al.* 1998).

⁵ The level of turfgrass damage still need to be clearly distinguished from damage caused by *S. didactylus* (Frank *et al.* 1998).

⁶ Rarely occurs at pest densities (Brandenburg 1997 and Frank *et al.* 1998).

1.10 Economic thresholds

On turfgrass, economic threshold values (management related density values) (Dent 1991) are mainly related to loss of aesthetic appeal, specific to site sensitivity (i.e. green, fairway or tee), turf condition (Potter 1998), grass species and sampling method. Mole cricket life stage will also influence turf aesthetic appeal, as tunnelling behaviour between life stages may differ (Hudson 1985a and Hudson & Saw 1987) (see Chapter 1.5: Morphology and biology). Damage may also be positively related to size, but therefore described by a function which is not necessarily linear. Mole crickets attracting different birds and other vertebrate predators cause extensive turf damage (Schoeman 1996 and Potter 1998). Economic threshold calculations may therefore be further biased as predatory attractive densities of mole crickets may show some variance between predatory species and on a spatial and temporal scale.

Economic thresholds can be divided in three categories. Firstly the threshold for economic damage, the amount of damage that justifies the cost of artificial control (Dent 1991). Secondly the economic injury level, the lowest population density that will cause economic damage (Dent 1991). Thirdly the action threshold, the population density level at which control methods should be implemented to prevent an increasing pest population from reaching the economic injury level (Dent 1991). Individual per surface area may be regarded as an adult, as this is the potential final, most damaging mole cricket ontogenic stage. Values will be highly specific, as variation will be reflected from different sources, including the sampling technique, aesthetic appeal quantification and income loss per surface area. It may be accepted that thresholds will have a relatively low value even in areas of moderate sensitivity (e.g. golf course fairways), as one adult can form a gallery of several metres per night (Brandenburg & Williams 1993 and Frank & Parkman 1999). The latter fact is responsible for zero tolerance on golf course greens and/or tees (Brandenburg & Williams 1993 and Frank & Parkman 1999).

Brandenburg & Williams (1993) and Brandenburg (1997) reported general yield loss values for *Scapteriscus* mole crickets on fairways of golf courses with a modest budget in the southeastern U.S.A. Four to five and six to seven mole

crickets per m^2 (emerging from a soapy water (at a concentration of 20 ml/6 litres H_2O/m^2) flush) can be regarded as the threshold for economic damage and the economic injury level on a fairway, respectively. The action threshold can be assumed to be equal to that of economic damage. Frank *et al.* (1998) and Buss *et al.* (2002) reported slightly higher economic threshold values per square meter. Economic thresholds for *G. africana* have not been determined, but the above-mentioned values are not considered as an accurate guide in South Africa (Schoeman pers. comm.). *Gryllotalpa africana* is usually only a pest in South Africa on highly tolerant kikuyu grass (relative to bermudagrass commonly used for fairways in the southeastern U.S.A. (Brandenburg 2000)). Guideline action threshold (equal to the economic threshold) and economic injury level values are set at 30 to 50 and more than 50 mole crickets per m^2 , respectively (Schoeman pers. comm.). At a higher detergent concentration (50 ml/5 litres H_2O/m^2), the middle to upper limits of the action and economic threshold range may be used. Using the sampling technique of estimating surface burrowing, action and economic damage ratings may be regarded as more than three areas of tunnelling per square meter (Brandenburg & Williams 1993).

1.11 Chemical control

The most important aspect of chemical management of mole crickets is the timing of insecticide application (Brandenburg 1997). Mole cricket populations should be targeted when nymphs are young (Schoeman 1996), as insecticide toxicity is a function of body weight. Mole crickets may have the ability to detect and avoid insecticides and pathogens in the soil (Brandenburg 1997 and Xia & Brandenburg 2000), with larger crickets having a greater capacity to tunnel and escape treated areas and staying deep in the soil until residual activity subsides (Brandenburg 1997). Spring monitoring may usually reveal adult tunnelling, feeding and mound production “hotspots”. These areas should be mapped and targeted for control later in the season (Potter 1998), avoiding costly large area applications that will potentially increase population resistance build up.

Flushing of infested turf areas with soapy water (50 ml liquid soap/5 litres $\text{H}_2\text{O}/\text{m}^3$) (higher concentrations may be phytotoxic to turfgrass (Brandenburg 1993)) will bring mole crickets to the surface (also see Chapter 1.8.1: Sampling methods: Field population), helping to determine optimal application time (Schoeman 1996). Weekly samples should be taken especially in “hotspot” areas identified in spring (Brandenburg 1997). Northern exposures with associated higher soil temperatures may have increased mole cricket activity (Brandenburg & Williams 1993). Ideal application time may vary in space and time and a turf-monitoring program should be implemented to determine site-specific optimal treatment times.

According to Potter (1998), the ideal time to control mole crickets of the *Neocurtilla* and *Scapteriscus* genera with short residual insecticides is after most of the eggs have hatched, but before nymph length exceeds 12.5 mm. In the southeastern U.S.A., this is usually during mid-summer, with high soil temperatures also conducive to high pesticide efficiency (Brandenburg & Williams 1993). A general rule-of-thumb is to initiate control strategies three weeks after first instars nymphs are sampled (Brandenburg 1997). Short residual insecticides are however not recommended for initial applications (Brandenburg 1997). Insecticides with a longer residual action are optimally applied during egg hatch (Potter 1998). Dissected females with oocytes covered by an egg shell (vitelline membrane and chorion) (feels like firm beads between fingers) will deposit them in approximately a week (Potter 1998). Two weeks after initial treatment, insecticide efficiency should be ascertained using an irritating drench (liquid flushing formulations) (Brandenburg 1997). If control levels are unsatisfactory (see Chapter 1.10 Economic thresholds) after three to four weeks, re-treatment should be considered (Brandenburg 1997), especially in highly managed areas. A re-treatment does not constitute treatment failure, but may reflect high initial mole cricket densities (Brandenburg 1997) and/or new introductions through flight. In some seasons, adult damage may be severe and justify adult control (Brandenburg 1997). Adults are difficult to control and conventional insecticides can be used with variable levels of success (Brandenburg 1997). Biological control agents are effective in controlling adults and have been

marketed in some countries (Brandenburg 1997) (see Chapter 1.12: Biological control).

Mole crickets can be controlled by different insecticidal formulations, including sprays, granules and baits (Frank *et al.* 1998). Chemicals (sprays and granules) should preferably be applied early morning or late afternoon (Brandenburg & Williams 1993) (to minimize photodecomposition risk) when overnight temperatures are expected to exceed 15.5 °C (Potter 1998). During dry conditions mole crickets are relatively low down in the soil profile, minimizing exposure to treatments (Brandenburg & Williams 1993). Pre-irrigation of dry areas will aid in insecticide penetration (sprays and granules), bringing the insects closer to the surface (Villani & Wright 1988) and may increase mole cricket feeding activity on baits (Brandenburg 1997 and Frank *et al.* 1998). Bait formulations are useful against larger nymphs (Buss *et al.* 2002) and should be applied late in the afternoon, with no subsequent irrigation or rain predicted for 24 hours (Potter 1998). After applying sprays or granules, turf should be irrigated with 6-12 mm of water (Brandenburg & Williams 1993 and Potter 1998) (Frank *et al.* (1998) reported 1.5 cm of water) to reduce potential adverse impacts on humans and the environment (Xia & Brandenburg 2000). Post irrigation also enhances insecticide efficiency by carrying a portion of the insecticide beneath the thatch layer (Xia & Brandenburg 2000) and bringing insects closer to the surface (Villani & Wright 1988). Irrigation regimen, timing and quantity, however, may not always significantly improve treatments and may be influenced by factors including mole cricket behaviour and insecticide properties. Over watering may be conducive to runoff or puddling and should be avoided (Brandenburg & Williams 1993).

Subsurface application of liquid or granular formulations may relatively improve control, but significant levels are not always obtained (Brandenburg & Williams 1993). Subsurface application may be expensive with relatively (compared to conventional methods) slow application rates, but may reduce surface residues and control at lower application rates (Potter 1998). Adjuvants do not significantly increase insecticide performance, but may lead to more mole crickets dying on the surface (Brandenburg & Williams 1993).

The control method of choice in the U.S.A. (up to the 1940's) for controlling mole crickets on vegetable crops and turf was baits containing calcium arsenate or calcium cyanide, which were not highly effective (Frank & Parkman 1999). Chlordane was the following chemical of choice (up to the early 1970's, when it was banned), followed by carbamate and organophosphorous chemicals, which are currently slowly losing their registration in the U.S.A. and replaced by insecticides with newer chemistry (Frank & Parkman 1999). Currently used insecticides generally have short residual activity and treated areas are soon subject to reinvasion (Frank & Parkman 1999). Different insecticides are registered in the U.S.A. for different turfgrass applications (e.g. golf courses, sod farms, home lawns and recreational areas) (Brandenburg & Williams 1993) and vary between states (Frank *et al.* 1998). Carbamate, synthetic pyrethroid and organophosphate insecticides are currently registered for crickets (Orthoptera: Ensifera) on home garden lawns in South Africa (Nel *et al.* 1999), with no insecticides registered specifically for mole crickets.

Chemical resistance can be managed. Applying different chemicals (of different classes if possible) (registered for the specific pest) at recommended dosages in a temporal and spatial mosaic may delay resistance by restricting the period of exposure to each selecting agent. Insecticide alteration is most effective if frequencies of resistance to each compound decline in absence of the selector, due to dilution of the population by immigration of susceptible homozygotes, which decreases fitness of resistant insects (Denholm & Rowland 1992). Further details of resistance management are beyond the scope of this study, but adhering to the basic principle described above, the potential rate of resistance build-up will be lowered.

Insecticides are non-specific; kill non-target and natural invertebrate enemies and may cause avian mortality (Frank & Parkman 1999), necessitating responsible chemical application and usage. Areas infested with mole crickets adjacent to water should not be chemically treated and transformed in an ornamental planting or treated with biopesticides (Brandenburg & Williams 1993). Play on golf courses may need to be suspended for a legally no-entry time after chemical treatment, which are usually applied at night to avoid exposure (Frank &

Parkman 1999). Hence, chemical control also has several associated negative aspects and should therefore not be used in isolation, but combined with biological and cultural control (including physical control) in an integrated pest management strategy.

1.12 Biological control

Biological control against mole crickets has generally been implemented in the form of classical biological control, biopesticides and generalist natural enemies, all being dependent. Classical biological control has been attempted in the U.S.A. against pest *Scapteriscus* and several native specialist natural enemies was introduced and distributed, including the parasitoid wasp, *Larra bicolor* F. (Sphecidae), parasitoid fly, *Ormia depleta* Wiedemann (Tachinidae) and the entomopathogenic nematode *Steinernema scapterisci* Nguyen & Smart (Frank & Parkman 1999). Predatory larvae of the South American beetle *Pheropsophus aequinoctialis* L. are also being researched (Frank *et al.* 1998). *Larra bicolor* attack adult and nymphal *Scapteriscus* mole crickets (Frank *et al.* 1998, Potter 1998), whilst the larvae of *O. depleta* or the red-eyed fly are also parasitoids of *Scapteriscus* and attracted to their calls (Walker 1988). Establishment of populations of these parasitoid wasps and flies may be dependant on the species geographical origin (Frank & Parkman 1999) and specific plants, as adults feed on plant nectars (Frank *et al.* 1998). Densities of wasps and flies may therefore be increased by introducing certain plants (Frank *et al.* 1998). Densities of *S. scapterisci* are not sufficient to control mole crickets in all American counties (Frank *et al.* 1998) and will be discussed further in § 3 of this subchapter. Adult *P. aequinoctialis* are generalist feeders (like those of *Stenaptinus*), but larvae appear only to develop on diet of mole cricket eggs (Frank *et al.* 1998). These beetles may provide several advantages over other classical biological control agents, as it targets *Scapteriscus* eggs (contrasted with nymphs and adults), has a preference for riverbanks and moist areas (may replace chemicals in these environmentally sensitive areas) and do not require nectar (adult beetles are predators and scavengers) and are potentially impervious to cold damage to plants (Frank *et al.* 1998). Classical biological control may be labour intensive and

expensive. This is however limited to the research and range establishment stage, after which control may be achieved with no recurrent cost (Frank *et al.* 1998). Ideally, classical biological control will provide area-wide control after supplementing general natural enemies already present (Frank & Parkman 1999). In the U.S.A., this control method may have reduced populations; but not to levels below economic thresholds (Frank *et al.* 1998) (see Chapter 1.10: Economic thresholds). Significant reduction by means of classical biological control is, however, potentially conceivable (Frank & Parkman 1999).

Biopesticides that have been marketed for control of pest mole crickets in the United States include the *Beauveria bassiana* (Balsamo) fungi (White muscardine), a natural enemy, and several nematodes (Rhabditida: Steinernematidae) (*Steinernema carpocapsae* Weiser, *Steinernema riobraviss* Cabanillas, Poinar and Raulston, and *Steinernema scapterisci*) (Cobb 1998 and Frank *et al.* 1998). Naturalis®-T (biopesticide containing *Beauveria bassiana*) has been marketed in the U.S.A. against mole crickets and other turf insect pests (Potter 1998). There is however limited information on the level of suppression the product may provide (Potter 1998). Different strains of this fungus show variable results and are not host specific (Frank *et al.* 1998). Native North American *Beauveria bassiana* and *Metarhizium anisopliae* (Metchnikoff) (Green muscardine) fungi may, however, be more virulent to *Scapteriscus*. An effective application method of fungi in the field, has however not been developed, but may include soil injection or baits (Frank & Parkman 1999). Fungi may show efficiency against mole cricket nymphs (Frank *et al.* 1998) and research has shown that nymphs (of *Scapteriscus tenuis* Scudder) respond to *Metarhizium* after contact by dispersing (transporting the fungus between areas) (Fowler 1988). Fungal applications may be less effective if combined with insecticides.

Several nematode products have been registered and tested as control agents (Brandenburg 1997, Frank *et al.* 1998 and Potter 1998). *Steinernema scapterisci* is the only soil persistent nematode from marketed entomopathogenic nematodes against mole crickets and specific to the genus *Scapteriscus* (Frank *et al.* 1998). Efficiency statistics are intraspecifically variable; *S. scapterisci* is however effective

against adults and large nymphs (not against small nymphs) of the major pest species of the genus *Scapteriscus* (southern and tawny mole cricket) (Frank *et al.* 1998). *Steinernema scapterisci* may also spread by flight of infected mole crickets (Frank & Parkman 1999). Biopesticides may not be host specific and specificity is increased by bait formulations that are attractive to the target species (Frank *et al.* 1998).

Nematodes are generally not compatible with insecticides, although *S. carpocapsae* is generally less influenced by most chemicals (Grewal 2002). For best results, nematode products should be applied one to two weeks before or after chemical application (Grewal 2002). Biopesticides may have a shelf life of a few months, be susceptible to temperature extremes, highly sensitive to ultra violet radiation and may be slower acting (Frank *et al.* 1998) and not as reliable as chemical insecticides (Potter 1998) (50% adult control has been reported for Vector MC (*S. riobravis*) (Brandenburg 1997)). Nematode efficiency depends on the complement of bacteria occurring in their guts (once nematodes penetrated their hosts, the bacteria causes death) (Frank & Parkman 1999) and host presence (nematodes die without infection of mole crickets) (Cobb 1998). Pre - and post treatment irrigation and late afternoon (low light intensity) application (with over night minimum temperatures expected to exceed of 15.5 °C) are prerequisites for current optimal nematode application (Potter 1998 and Frank & Parkman 1999). Alternative methods to improve nematode application include soil injection or baits (Frank & Parkman 1999). Nematodes (being more specific than fungi) may be an alternative treatment near waterways or environmentally sensitive areas and golf course fairways and roughs with relatively low sensitivity (Frank & Parkman 1999). Biopesticides also have no effect on vertebrate animals and there is no withholding period after use, making them ideal for use in pastures, lawns and playing fields (Cobb 1998 and Frank & Parkman 1999). Biopesticides may compete in price to other recently developed turf chemicals but highly exceeds chemical prices used for pastures (Frank & Parkman 1999). Applications of a nematode biopesticide may establish populations for more than eight years (Frank & Parkman 1999) and can be

used to augment nematode densities (augmentative biological control) (Frank *et al.* 1998).

Some other reported natural enemies of mole crickets include the generalist *Aspergillus*, *Beauveria*, *Isaria*, *Metarhizium anisopliae* Metchnikoff (Green muscardines) and *Sorospora* fungi (Frank & Parkman 1999 and Vittum *et al.* 1999). Specific natural enemies of *Neocurtilla* have been identified and include the entomopathogenic nematode *Steinernema neocurtillae* Nguyen & Smart (Rhabditida: Steinernematidae) and the wasp, *Larra analis* (F.) (Frank *et al.* 1998). *Larra polita* (Smith) is specific on *G. orientalis* in Hawaii (Frank & Parkman 1999). Cannibalistic behaviour of mole crickets does not notably suppress high-density populations. Fowler (1988) studied *Scapteriscus* in Brazil and reported: “predators, especially Cicindelid beetles and earwigs, concentrate in areas of nymphal aggregations”. In Florida, U.S.A., *Sirthenea carinata* (F.) assassin bugs (Frank *et al.* 1998), Cicindelid beetles (Fowler 1988), *Solenopsis invicta* (Buren) fire ants (Henne & Johnson 2001), earwigs, *Megacephala* tiger beetles, *Pasimachus* Carabid beetles and spiders, especially in the families of Lycosidae (wolf spiders) and Salticidae (jumping spiders) have also been identified as natural enemies of Gryllotalpids (Frank & Parkman 1999 and Vittum *et al.* 1999). *Ormia ochracea* and an Anthomyiid fly from the *Acridomyia* genus have also been identified as parasitizing different *Scapteriscus* species, although these are not their natural hosts (Henne & Johnson 2001). Otte & Alexander (1983) reported Australian birds (Northern Queensland nightjars) and the anuran, *Bufo marinus* to mimic mole cricket songs. The *Bufo* genus has also been reported as natural enemies of *Scapteriscus* (Buss *et al.* 2002).

Classic biological control has not been attempted in South Africa and general and specialist biological control agents are currently being identified. No biopesticides for *G. africana* are currently registered. Two entomogenous fungi, *Paecilomyces carneus* and *Scopulariopsis* sp. acted as naturally occurring entomopathogens of *G. africana* in India. The former caused 37 % mortality. The latter was an opportunistic fungus causing 40 % mortality in combination with *P. carneus* (Hazarika *et al.* 1994). *Beauveria bassiana* was found to attack 38.6-66.7 %

of the nymphs and adults of *G. africana* in field surveys in China. The rate of parasitism was significantly affected by precipitation and irrigation. Parasitism was 1.6 and 32 % before and after rainfall, respectively (Hu 1985). Larvae of *Neothrombium medium* (Acari: Neothrombiidae) act as ectoparasites of *Gryllotalpa africana* in Ningxia, China (Zhang 1994). The nematodes *Psilocephala nisari* (Thelastomatidae) (Parveen & Jairajpuri 1985a) and *Gryllocola thapari* (Thelastomatidae) (Tewarson & Gupta 1978) were identified as parasites of *G. africana* in India. *Cruznama brevicaudatum* (Nematoda: Rhabditidae) (Latheef & Seshadri 1972), *Indiana coimbatorensis* (Nematoda: Travassosinematidae) (Latheef & Seshadri 1972), *Binema striatum* (Nematoda: Travassosinematidae) (Rizvi & Jairajpuri 2000a), *B. parva* (Parveen & Jairajpuri 1985b), *Chitwoodiella tridentata* (Nematoda: Travassosinematidae) (Rizvi *et al.* 1998), *C. neoformis* (Parveen & Jairajpuri 1984a), *Gryllophila basiri* (Nematoda: Thelastomatidae) (Parveen & Jairajpuri 1981), *Isobinema dimorphicauda* (Nematoda: Travassosinematidae) (Parveen & Jairajpuri 1982), *Cameronia klossi* (Nematoda: Thelastomatidae) (Parveen & Jairajpuri 1984b), *Mirzaiella indica* (Nematoda: Travassosinematidae) (Singh & Singh 1990) and *M. asiatica* (Rizvi & Jairajpuri 2000b) have been found in the intestine of *G. africana* from India. *Indiana roselyneae* (Adamson & Van Waerebeke 1987), *I. gryllotalpae*, *Gryllophila skrjabini*, *Pteronemella macropapillata*, *B. korsakowi*, *B. ornata* and *B. mirzaia* (Bain 1965) have been identified in *G. africana* from Madagascar and *Gryllonema bispiculata* (Nematoda: Travassosinematidae) from Russian specimens (Belogurov & Shvetsova 1980). No suppression statistics or soil persistence characteristics that these nematodes may provide are available.

Frank & Parkman (1999) reported nematodes from the *Steinernema* genus might prove useful as biopesticides against pest *Gryllotalpa* species. Specifically, *Steinernema neocurtillae* could be potentially effective against *Gryllotalpa*, as the natural host (*Neocurtilla*) are closely related to that genus (Frank & Parkman 1999). Establishment of *Larra polita* on *G. orientalis* in Hawaii (Frank & Parkman 1999) increases the possibility that a *Larra* species may be specific to *G. africana*. No flies have been identified to be parasitoids of *G. africana*. According to Frank *et al.*

(1998), all *Larra* species are parasitoids of Gryllotalpids. No species have however been identified as a parasitoid of *G. africana*. Bombardier beetle larvae of the genus *Stenaptinus* have been known for some decades as specialized predators of *Gryllotalpa* eggs (Frank *et al.* 1998). In Japan, *Stenaptinus jessoensis* (Morawitz) larvae have been reported to attack *Gryllotalpa africana* eggs and undergo hypermetamorphosis within the egg chamber (Habu & Sadanaga 1965, 1969). The larvae of the Carabid *Pheropsophus jessoensis* (Morawitz) also prey on eggs of *Gryllotalpa africana* in Japan (Habu 1986). Predation of *G. africana* by the earwig, *Labidura* (Labiduridae) sp. was also documented in China, with 1 adult of *Labidura* sp. consuming 1 adult or 1-3 nymphs/day. The population of the predator was positively correlated with that of the prey (Hu 1985).

None of the reports (relevant to biological control) documented in this subchapter refer to *G. africana* from Africa and may therefore not be relevant to the “true” *G. africana* (also see Chapter 1.4: Classification).

During this study, two different fungi (resembling White - and Green muscardine), earwigs, spiders and wasps were identified as potential invertebrate biological control agents. The two different fungi were only observed in the laboratory populations and never witnessed in the field. Relatively high earwig and spider numbers were associated with mole cricket infestation in the field. A predatory relationship was not investigated, but mole cricket infestations were very high even at high densities of these two species. Only two specimens of one wasp species were observed in the field during the duration of the study (two years) and a parasitic relationship needs to be investigated. Bats (Mammalia: Chiroptera) were observed actively preying on flying mole crickets and may form part of an integrated pest management program. The efficacy of bat predation, however, needs to be determined, as high frequency ultra sound hearing in mole crickets has been identified in a flying species (Mason *et al.* 1998). No host specific anurans of *G. africana* were identified in the study. Other vertebrate predators (including raccoons, armadillos, moles and birds) however, are usually not feasible biological control agents, as their foraging actions may damage the turf (Schoeman 1996 and Potter 1998).

The potential ecological impact and risk of biological control introductions, including host specificity and host shift likelihood (short and long term) should to be assessed and used in a cost benefit analysis before any action is taken.

Biological control methods in isolation are currently insufficient to keep mole cricket densities under economic thresholds. The latter and the fact that biological control strategies are generally effective against adults (Brandenburg 1997) and have little effect against small nymphs (Potter 1998) (life stage where high efficacy is obtained with insecticides), emphasizes the current optimal strategy to be that of integrated pest management (also see Chapter: 1.11: Chemical control and Chapter 1.13: Cultural control).

1.13 Cultural control

Cultural control may include several practices, including host resistance, physical control and promoting healthy turfgrass. Host resistance may take the form of antibiosis, antixenosis or tolerance (Gullan & Cranston 1994 and Potter 1998). Limited research in the U.S.A. focussed on turf resistance to mole crickets (Potter & Braman 1991). (No such research has been conducted in South Africa). In the U.S.A., mole crickets may not prefer coarsely textured (over finer texture) grasses, but these grasses may suffer heavy damage if they are the only grasses available (Hudson 1986, Brandenburg & Williams 1993 and Braman *et al.* 1994). Braman *et al.* (1994) evaluated different zoysiagrass cultivars against the tawny mole cricket and found characteristics in addition to non-preference in some cultivars that may reduce the risk of mole cricket injury. A genetically resistant bermudagrass (a fine textured cultivar), Tift 94 (TifSport) (*C. transvaalensis* × *C. dactylon*), shows almost no mole cricket (*S. vicinus*) activity (Hanna & Hudson 1997). TifSport not only shows non-preference, but also resistance or a superior tolerance to feeding (Hanna *et al.* 2001). TifSport has excellent colour, quality and cold resistance and may be used for golf course fairways, sport fields, parks, lawns and landscaping in the U.S.A. (Hanna & Hudson 1997). Braman *et al.* (2000) evaluated bermudagrass and bahiagrass (*Paspalum vaginatum*) genotypes and concluded “TifSport” bermudagrass and bahiagrass “561-79 (Argentine)” maintain the highest percentage

of normal growth after four weeks of tawny mole cricket feeding (relative to the other varieties tested). No information is however available to determine whether these cultivars may also deter infestation by *G. africana* (even though there may be similarities in the feeding ecology of *S. vicinus* and *G. africana* (Brandenburg *et al.* 2002)) and it may not be suitable for local conditions. No genetically resistant turfgrass cultivars are currently known for *G. africana*.

Cultural control may also include pest free propagating material (to avoid spread of a pest) and physical control methods, including soapy water flush (irritating drench) (also see Chapter 1.8.1: Sampling methods – field population). High detergent solution concentrations may however be phytotoxic (Brandenburg 1993); the method is labour intensive and not economically viable as a control method and should be reserved as a monitoring tool to predict outbreaks. Gadallah *et al.* (1998) found pitfall traps to be the most effective way to control *G. africana* in a field study with pepper (*Capsicum*) in Egypt. Pitfall traps (also see Chapter 1.8.1: Sampling methods – field population) may be part of an IPM strategy for *G. africana* on turfgrass, but have several drawbacks: These traps are not pest specific, mainly targets surface feeding mole crickets and can only be used in certain areas of managed turf. Pitfall traps are therefore generally used mainly for collecting mole crickets for research needs (Vittum *et al.* 1999). Flight and light traps are used to collect winged, adult mole crickets for experimental purposes (also see Chapter 1.8.1: Sampling methods – flying individuals). They were not designed as methods of controlling mole crickets and there is no evidence that they reduce Gryllotalpid populations even when operated constantly for years (Frank *et al.* 1998 and Potter 1998). These traps may however be used to infect mole crickets with highly specific pathogens and to attract mole crickets away from managed turf areas (see Chapter 5: Development of an electronic acoustic caller for mole crickets in South Africa). Flooding (Frank & Parkman 1999), tillage (at appropriate times to desiccate eggs and small nymphs (after exposure to solar radiation)) and burning dry leaves and grass on infested soil appear to be effective measures for controlling mole crickets (Denisenko 1986 and Sithole 1986). These methods may be effective for organic vegetable growers, but will not be feasible on turfgrass (unless severe damage

necessitates replanting and tillage can be employed).

Cultural management also aims to encourage a deep, healthy root system, more tolerant to mole crickets (Frank *et al.* 1998). Mowing, irrigation and fertility practises are especially important. Improper mowing and excessive water or fertilization can cause turfgrass to develop a thick, spongy mat of runners (Frank *et al.* 1998). This spongy mat, referred to as thatch, is an excellent habitat for turf insects and prevents insecticide penetration, thereby reducing control efforts (Frank *et al.* 1998). Earthworms and microorganisms decompose thatch (Potter 1998) and coring, topdressing and vertical cutting are employed to reduce thatch build-up (Ernmons 1995 and Christians 1998). Turf should not be allowed to dry out excessively and when irrigation is required, 19 mm of water should be applied to encourage deep root growth (Frank *et al.* 1998). Turf should be fertilized to maintain optimum levels of potassium and other macro- and micro-nutrient levels (Frank *et al.* 1998). Water-soluble inorganic nitrogen fertilizer usage should be minimized, as it results in rapid succulent growth, which acts as an insect attractant (Frank *et al.* 1998). The suitability of the discussed methods to promote a deep, healthy grass root system have not been tested for kikuyu grass in South Africa.

1.14 References

- ADAMSON, M.L. & VAN WAEREBEKE, D. 1987. *Indiana roselyneae* n. sp. (Oxyurida; Nematoda) from Madagascan Gryllotalpoidea (Orthoptera; Insecta) with comments on the structure of the cephalic extremity of *Indiana*. *Canadian Journal of Zoology* 65: 2755-2759.
- ALEXANDER, R.D. 1962. Evolutionary change in cricket acoustic communication. *Evolution* 16: 443-467.
- ALEXANDER, R.D. 1968. Life cycle origins, speciation, and related phenomena in crickets. *The Quarterly Review of Biology* 43: 1-43.
- ALEXANDER, R.D. & OTTE, D. 1967. The evolution of genitalia and mating behavior in crickets (Gryllidae) and other Orthoptera. *Miscellaneous Publications of the University of Michigan Museum of Zoology* 133: 1-62.
- ANNECKE, D.P. & MORAN, V.C. 1982. *Insects and mites of cultivated plants in South Africa*. Butterworths, Durban.
- BAIN, O. 1965. Parasitic oxyurids of the intestine of the mole cricket, *Gryllotalpa africana*, Beauvois, in Madagascar. *Annales de Parasitologie Humaine et Compar e. (Paris)*. 40: 659-676 (In French).
- BAUMGARTNER, W.J. 1905. Observations on some peculiar habits of the mole crickets. *Science N. S.* 21: 855.
- BAUMGARTNER, W.J. 1910. Observations on the Gryllidae: III Notes on the classification and on some habits of certain crickets. *Kansas University Scientific Bulletin* 5: 309-319.
- BELOGUROV, O.I. & SHVETSOVA, L.S. 1980. The oligomerization of spicules in oxyurids and its taxonomic significance, exemplified by *Gryllonema bispiculata*. *Gel'minty Nasekomykh* 8-12 (Abstract cited).
- BENNET-CLARK, H.C. 1970a. The mechanism and efficiency of sound production in mole crickets. *Journal of Experimental Biology* 52: 619-652.
- BENNET-CLARK, H.C. 1970b. A new French mole cricket, differing in song and morphology from *Gryllotalpa gryllotalpa* L. (Orthoptera: Gryllotalpidae). *Proceedings of the Royal Entomological Society of London (B)* 39: 125-132.

- BENNET-CLARK, H.C. 1987. The tuned singing burrow of mole crickets. *Journal of Experimental Biology* 128: 383-410.
- BENNET-CLARK, H.C. 1989. Songs and physics of sound production. In: Huber, F., Moore, T.E. & Loher, W. (Eds.) *Cricket Behavior and Neurobiology*. 227-261. Cornell University Press, Ithaca.
- BEUGNON, G. 1981. Orientation of southern mole cricket, *Scapteriscus acletus*, landing at a sound source. *Florida Entomologist* 64: 463-468.
- BRAMAN, S.K. 1993. Progeny production, number of instars, and duration and development of Tawny and Southern mole crickets (Orthoptera: Gryllotalpidae). *Journal of Entomological Science* 28: 327-330.
- BRAMAN, S.K., DUNCAN, R.R., HANNA, W.W. & HUDSON, W.G. 2000. Evaluation of turfgrasses for resistance to mole crickets (Orthoptera: Gryllotalpidae). *HortScience* 35: 665-668.
- BRAMAN, S.K., PENDLEY, A.F., CARROW, R.N. & ENGELKE, M.C. 1994. Potential resistance in zoysiagrasses to tawny mole crickets (Orthoptera: Gryllotalpidae). *Florida Entomologist* 77: 301-305.
- BRANDENBURG, R.L. 1995. Intuitive forecasting of turfgrass insect pests. *Turfgrass Trends* 4: 1-8.
- BRANDENBURG, R.L. 1997. Managing mole crickets: Developing a strategy for success. *Turfgrass Trends* 6: 1-8.
- BRANDENBURG, R.L. 2000. Golf in South Africa: Practicing IPM in the dark. *Golf Course Management* August.
- BRANDENBURG, R.L. & WILLIAMS, C.B. 1993. *A complete guide to mole cricket management in North Carolina*. North Carolina State University, Raleigh, NC.
- BRANDENBURG, R.L., XIA, Y. & SCHOEMAN, A.S. 2002. Tunnel architectures of three species of mole crickets (Orthoptera: Gryllotalpidae). *Florida Entomologist* 85: 383-385.
- BROADLEY, R.H. 1978. Insect pests of sunflower. *Queensland Agricultural Journal* July-August 307-314.

- BROZA, M., BLONDHEIM, S. & NEVO, E. 1998. New species of mole crickets of the *Gryllotalpa gryllotalpa* group (Orthoptera: Gryllotalpidae) from Israel, based on morphology, song recordings, chromosomes and cuticular hydrocarbons, with comments of the distribution of the group in Europe and the Mediterranean region. *Systematic Entomology* 23: 125-135.
- BURK, T.E. 1988. Acoustic signals, arm races, and the costs of honest signalling. *Florida Entomologist* 71: 400-409.
- BUSS, E.A., CAPINERA, J.L. & LEPPLA, N.C. 2002. Pest mole cricket management. University of Florida, Gainesville. *World Wide Web*: http://edis.ifas.ufl.edu/BODY_LH039.
- CANTRALL, I.J. 1943. The ecology of the Orthoptera and Dermaptera of the George Reserve, Michigan. *Miscellaneous Publications of the University of Michigan Museum of Zoology* No. 54.
- CHAO, Y.L. 1975. Mole cricket – it's behavior and control. *Scientia Sinica* 18: 88-105.
- CHOPARD, L. 1968. Gryllides. Family Gryllidae: subfamily Mogoplistinae, Myrmecophilinae, Scleropterinae, Cachoplistinae, Pteroplistinae, Pentacentrinae, Phalangopsinae, Trigonidiinae, Eneopterinae. Family Oecanthidae, Gryllotalpidae. In: Junk, W. (Ed.) *Orthoptera Catalogus* 12: 215-500. Gravenhage.
- COBB, P.P. 1998. Controlling mole crickets on lawns and turf. Auburn University, Auburn. *World Wide Web*: <http://www.aces.edu/department/extcomm/publications/anr/anr-176/anr176.htm>.
- COBB, P.P. & MACK, T.P. 1989. A rating system for evaluating tawny mole cricket, *Scapteriscus vicinus* Scudder, damage (Orthoptera: Gryllotalpidae). *Journal of Entomological Science* 24:142-144.
- CHRISTIANS, N.E. 1998. *Fundamentals of turfgrass management*. Ann Arbor Press, Michigan.
- DARAMOLA, A.M. 1974. A review on the pests of *Cola* species in West Africa. *Nigerian Journal of Entomology* 1: 21-29.

- DE VILLIERS, W.M. 1985. Orthoptera: Ensifera. In: Scholtz, C.H. & Holm, E. (Eds.) *Insects of Southern Africa*. 86. Butterworths, Durban.
- DENHOLM, I. & ROWLAND, M.W. 1992. Tactics for managing pesticide resistance in arthropods: theory and practice. *Annual Review of Entomology* 37: 91-112.
- DENISENKO, M.K. 1986. An effective method of controlling mole crickets. *Zaschchita Rastenii* 10: 51 (In Russian).
- DENT, D. 1991. *Insect pest management*. CAB International, Wallingford.
- DHALIWAL, J.S. 1998. Record of some new pests of forage crops. *Journal of Insect Science* 11: 180 (Abstract cited).
- EMMONS, R.D. 1995. *Turfgrass science and management*. Delmar Publishers, United States of America.
- FORREST, T.G. 1980. Phonotaxis in mole crickets: It's reproductive significance. *Florida Entomologist* 63: 45-53.
- FORREST, T.G. 1981. Acoustic behavior, phonotaxis, and mate choice in two species of mole crickets (Gryllotalpidae: *Scapteriscus*). M.S. thesis, University of Florida, Gainesville.
- FORREST, T.G. 1983a. Calling songs and mate choice in mole crickets In: Gwynne, D.T. & Morris, G.K. (Eds.) *Orthopteran Mating Systems: Sexual Selection in a Diverse Group of Insects*. 185-204. Westview Press, Boulder, CO.
- FORREST, T.G. 1983b. Phonotaxis and calling in Puerto Rican mole crickets (Orthoptera: Gryllotalpidae) *Annals of the Entomological Society of America* 76: 797-799.
- FORREST, T.G. 1986. Oviposition and maternal investment in mole crickets (Orthoptera: Gryllotalpidae): effects of season, size, and senescence. *Annals of the Entomological Society of America* 79: 918-924.
- FORREST, T.G. 1987. Sinistrality in the Southern and Tawny mole crickets (Gryllotalpidae: *Scapteriscus*). *Florida Entomologist* 70: 284-286.
- FORREST, T.G. 1991. Power output and efficiency of sound production by crickets. *Behavioral Ecology* 2: 327-338.

- FOWLER, H.G. 1988. Dispersal of early instar of the mole cricket, *Scapteriscus tenuis*, as a function of density, food, and pathogens (Orthoptera: Gryllotalpidae) *Entomologia Generalis* 13: 15-20.
- FOWLER, H.G. & JUSTI, J. 1987. Field collection techniques for genera *Neocurtilla* and *Scapteriscus* mole crickets and their effect upon the evaluation of their natural pathogens in Brazil. *Journal of Applied Entomology* 104: 204-208.
- FOWLER, H.G., ORTEGA, V.R. & TEIXEIRA, L.L. 1987. Flying activity of *Neocurtilla hexadactyla* Perty (Orthoptera: Gryllotalpidae) asynchronous mobile populations. *Journal of the New York Entomological Society* 95: 469-473.
- FOWLER, H.G. & DE VASCONCELOS, H.L. 1989. Preliminary data on life cycles of some mole crickets (Orthoptera: Gryllotalpidae) of the Amazon Basin. *Revista Brasileira de Entomologia* 33: 139-141.
- FRANK, J.H., FASULO, T.R. & SHORT, D.E. 1998. *M cricket Knowledgebase*. CD-ROM. Institute of Food and Agricultural Sciences. University of Florida, Gainesville.
- FRANK, J.H. & PARKMAN, J.P. 1999. Integrated pest management of pest mole crickets with emphasis on the southeastern USA. *Integrated Pest Management Reviews* 4: 39-52.
- FRANK, J.H., WOODRUFF, R.E. & NUÑEZ, C.A. 1987. *Scapteriscus didactylus* (Orthoptera: Gryllotalpidae) in the Dominican Republic. *Florida Entomologist* 70: 478-483.
- FRITZ, G.N. 1983. A technique for separating mole crickets from the soil. *Florida Entomologist* 66: 360-362.
- GADALLAH, A.I., ZIDAN, Z.H., EL-MALKI, K.G., AMIN, A. & EISSA, M.A. 1998. Seasonal abundance of *Gryllotalpa africana* adults and efficacy of pitfall traps in reducing its population in qena governorate. *Annals of Agricultural Science (Cairo)* 3: 911-923 (Abstract cited).

- GREWAL, P. 2002. Insect parasitic nematodes for turfgrass pest management. Ohio State University, Wooster. *World Wide Web*: http://www.oardc.ohio-state.edu/nematodes/turfgrass_pest_management.htm.
- GULLAN, P.J. & CRANSTON, P.S. 1994. *The insects: An outline of entomology*. Chapman & Hall, London.
- HABU, A. 1986. Redescription of larvae of *Pheropsophus jessoensis* Morawitz (Coleoptera, Carabidae). *Entomological Review of Japan* 41: 113-122 (Abstract cited).
- HABU, A. & SADANAGA, K. 1965. Illustrations for the identification of larvae of the Carabidae found in cultivated fields and paddy-fields (3). *Bulletin of the National Institute of Agricultural Sciences (Japan) Series C, Plant pathology and Entomology* 19: 81-216. (In Japanese.)
- HABU, A. & SADANAGA, K. 1969. Illustrations for the identification of larvae of the Carabidae found in cultivated fields and paddy-fields (supplement 1). *Bulletin of the National Institute of Agricultural Sciences (Japan) Series C, Plant pathology and Entomology* 23: 113-143. (In Japanese.)
- HANNA, W.W., BRAMAN, S.K. & HUDSON, W.G. 2001. Bermudagrass hybrids just say "no" to mole crickets. *Golf Course Management* July.
- HANNA, W.W. & HUDSON, W.G. 1997. Genetic resistance to mole crickets in turf Bermudagrass. *Turfgrass Trends* 6: 17-18.
- HARDING, P.G. 1981. Introducing the Tele-Mole, an innovation from Japan. *Tunnels and Tunnelling* 13: 26-30.
- HAYSLIP, N.C. 1943. Notes on biological studies on mole crickets at Plant City, Florida. *Florida Entomologist*. 26: 33-46.
- HAZARIKA, L.K., PUZARI, K.C. & BARUAH, G. 1994. Fungi as microbial insecticides on mole cricket. *Two and a Bud* 41: 22-25 (Abstract cited).
- HENNE, D.C. & JOHNSON, S.J. 2001. Seasonal distribution and parasitism of *Scapteriscus* spp. (Orthoptera: Gryllotalpidae) in southeastern Louisiana. *Florida Entomologist* 84: 209-214.

- HERTL, P.T., BRANDENBURG, R.L. & BARBERCHECK, M.E. 2001. Effect of soil moisture on ovipositional behavior in the southern mole cricket (Orthoptera: Gryllotalpidae). *Environmental Entomology* 30: 466-473.
- HILL, P.S.M. 1998. Environmental and social influences on calling effort in the Prairie mole cricket (*Gryllotalpa major*). *Behavioral Ecology* 9: 101-108.
- HILL, P.S.M. 1999. Lekking in *Gryllotalpa major*, the Prairie mole cricket (Insecta: Gryllotalpidae). *Ethology* 105: 531-545.
- HILL, P.S.M. 2000. Elements of the acoustic repertoire of the Prairie mole cricket (Orthoptera: Gryllotalpidae: *Gryllotalpa major* Saussure). *Journal of the Kansas Entomological Society* 73: 95-102.
- HILL, P.S.M. & SHADLEY, J.R. 1997. Substrate vibration as a component of a calling song. *Naturwissenschaften* 84: 460-463.
- HILL, P.S.M. & SHADLEY, J.R. 2001. Talking back: Sending soil vibration signals to lekking prairie mole cricket males. *Integrative and Comparative Biology* 41: 1200-1214.
- HOFFART, C., JONES, K. & HILL, P.S.M. 2002. Comparative morphology of the stridulatory apparatus of the Gryllotalpidae (Orthoptera) of the continental United States. *Journal of the Kansas Entomological Society* 75: 123-131.
- HU, M. 1985. An investigation on the control of *Gryllotalpa africana* by *Beauveria bassiana* and *Labidura* sp. *Natural Enemies of Insects Kunchong Tiandi* 7: 110-112 (Abstract cited).
- HUDSON, W.G. 1985a. *Ecology of the tawny mole cricket, Scapteriscus vicinus (Orthoptera: Gryllotalpidae): population estimation, spatial distribution, movement, and host relationships*. Ph.D. thesis, University of Florida, Gainesville.
- HUDSON, W.G. 1985b. Other behavior, damage and sampling. In: Walker, T.J. (Ed.) *Mole crickets in Florida*. 3-10. *Bulletin – University of Florida, Agricultural Experiment Stations* 846 (1984).
- HUDSON, W.G. 1986. Mole cricket (Orthoptera: Gryllotalpidae) damage to *Hemarthria altissima*: resistance or non-preference? *Journal of Economic Entomology* 79: 961-963.

- HUDSON, W.G. 1987. Variability in development of *Scapteriscus acletus* (Orthoptera: Gryllotalpidae). *Florida Entomologist* 70: 403-404.
- HUDSON, W.G. 1988. Field sampling of mole crickets (Orthoptera: Gryllotalpidae: *Scapteriscus*): a comparison of techniques. *Florida Entomologist* 71: 214-216.
- HUDSON, W.G. 1989. Field sampling and population estimation of the tawny mole cricket (Orthoptera: Gryllotalpidae). *Florida Entomologist* 72: 337-343.
- HUDSON, W.G. & SAW, J.G. 1987. Spatial distribution of the tawny mole cricket, *Scapteriscus vicinus*. *Entomologia Experimentalis et Applicata* 45: 99-104.
- KAVANAGH, M.W. 1987. The efficiency of sound production in two cricket species, *Gryllotalpa australis* and *Teleogryllus commodus* (Orthoptera: Grylloidea). *Journal of Experimental Biology* 130: 107-119.
- KAVANAGH, M.W. & YOUNG, D. 1989. Bilateral symmetry of sound production in the mole cricket, *Gryllotalpa australis*. *Journal of Comparative Physiology A* 166: 43-49.
- KIM, K.W. 2000. Non-chemical or low-chemical control measures against key insect pests and rats in the ginseng fields. *Korean Journal of Applied Entomology* 39: 281-286 (Abstract cited).
- LATHEEF, M.A. & SESHADRI, A.R. 1972. *Cruznama brevicaudatum* n. sp. (Nematoda: Rhabditidae) and *Indiana coimboriensis* n. sp. (Nematoda: Pulchrocephalidae) from the mole-cricket, *Gryllotalpa africana* Beauvois, from India. *Canadian Journal of Zoology* 50: 1457-1462.
- LAWRENCE, K.O. 1982. A linear pitfall trap for mole crickets and other soil arthropods. *Florida Entomologist* 65: 376-377.
- LOHER, W. & DAMBACH, M. 1989. Reproductive behavior. In: Huber, F., Moore, T.E. & Loher, W. (Eds.) *Cricket Behavior and Neurobiology*. 43-82. Cornell University Press, Ithaca.
- MASTERS, W.M. 1980. Insect disturbance stridulation: characterization of airborne and vibrational components of the sound. *Journal of Comparative Physiology* 135: 259-268.
- MATHENY, E.L. 1981. Contrasting feeding habits of pest mole cricket species. *Journal of Economic Entomology* 74: 444-445.

- MATHENY, E.L., KEPNER, R.L. & PORTIER, K.M. 1983. Landing distribution and density of two sound attracted mole crickets (Orthoptera: Gryllotalpidae: *Scapteriscus*). *Annals of the Entomological Society of America* 76: 278-281.
- MATSUURA, H., ODA, H. & ISHIZAKI, H. 1985. Damage to Chinese yam by the African mole cricket, *Gryllotalpa africana* Palisot de Beauvois, and its control by chemicals. *Japanese Journal of Applied Entomology and Zoology* 29: 36-40 (Abstract cited).
- NEL, A., KRAUSE, M., RAMAUTAR, N. & VAN ZYL, K. 1999. *A Guide for the control of plant pests*. 93-94. National Department of Agriculture, Republic of South Africa.
- NEVO, E. & BLONDHEIM, A. 1972. Acoustic isolation in the speciation of mole crickets. *Annals of the Entomological Society of America*. 65: 980-981.
- NGO, D. & BECK, H.W. 1982. Mark-release of sound-attracted mole crickets: Flight behavior and implications for control. *Florida Entomologist* 65: 531-538.
- NICKERSON, J.C., SNYDER, D.E. & OLIVER, C.C. 1979. Acoustical burrows constructed by mole crickets. *Annals of the Entomological Society of America* 72: 438-440.
- NICKLE, D.A. & CARLYSLE, T.C. 1975. Morphology and function of female sound producing structures in Ensiferan orthoptera with special emphasis on the Phaneropterinae. *International journal of Insect Morphology and Embryology* 4: 159-168.
- NICKLE, D.A. & CASTNER, J.L. 1984. Introduced species of mole crickets in the United States, Puerto Rico, and the Virgin Islands (Orthoptera: Gryllotalpidae). *Annals of the Entomological Society of America* 77: 450-465.
- OTTE, D. 1994a. *Orthoptera Species File 1. Crickets (Grylloidea)*. 98-100. The Academy of Natural Sciences of Philadelphia, PA.
- OTTE, D. 1994b. Osf 1: Additions and corrections-October 1994. *Journal of Orthoptera Research* 3: 1-4, 86, 90.
- OTTE, D. & ALEXANDER, R.D. 1983. *The Australian Crickets (Orthoptera: Gryllidae)*. 17, 448-463. The Academy of Natural Sciences of Philadelphia, PA.

- PARVEEN, R. & JAIRAJPURI, D.S. 1981. Two new species of insect nematodes of the family Thelastomatidae. *Revista Iberica de Parassitologia* 42: 261-266 (Abstract cited).
- PARVEEN, R. & JAIRAJPURI, D.S. 1982. *Isobinema dimorphicauda* from the intestine of the mole cricket, *Gryllotalpa africana* from Aligarh (Nematoda: Oxyuriodea). *Revista Iberica de Parassitologia* 43: 113-115 (Abstract cited).
- PARVEEN, R. & JAIRAJPURI, D.S. 1984a. *Chitwoodiella neoformis* n. sp. (Nematoda: Oxyuridae) from the mole cricket, *Gryllotalpa africana* from Aligarh. *Revista Iberica de Parassitologia* 44: 147-152 (Abstract cited).
- PARVEEN, R. & JAIRAJPURI, D.S. 1984b. *Cameronia klossi* n. sp. (Nematoda: Thelastomatidae) from the mole cricket, *Gryllotalpa africana* from Aligarh. *Revista Iberica de Parassitologia* 44: 153-158 (Abstract cited).
- PARVEEN, R. & JAIRAJPURI, D.S. 1985a. *Psilocephala nisari* (Nematoda: Thelastomatidae), a new nematode parasite of the mole cricket, *Gryllotalpa africana* from Aligarh, India. *Helminthologia* 22: 263-266 (Abstract cited).
- PARVEEN, R. & JAIRAJPURI, D.S. 1985b. *Binema parva* sp. n., a parasitic nematode of the mole cricket *Gryllotalpa africana*. *Revista di Parassitologia* 46: 347-350 (Abstract cited).
- POTTER, D.A. 1998. *Destructive turfgrass pests*. Ann Arbor Press, Michigan.
- POTTER, D.A. & BRAMAN, S.K. 1991. Ecology and management of turfgrass insects. *Annual Review of Entomology* 36: 383-406.
- RAMLOGUN, H.G.S. 1971. The pests and diseases of tea in Mauritius. *Revue Agricole et Sucriere de l'Ile Maurice* 50: 48-67 (Abstract cited).
- RENTZ, D.C.F. 1996. The changa mole cricket, *Scapteriscus didactylus* (Latreille), a New World pest established in Australia. *Journal of the Australian Entomological Society* 34: 303-306.
- RIZVI, A.N. & JAIRAJPURI, D.S. 2000a. Studies on a new and two known species of Travassosinematidae (Oxyurida). *International Journal of Nematology* 10: 112-117 (Abstract cited).

- RIZVI, A.N. & JAIRAJPURI, D.S. 2000b. Study on gametogenesis in *Mirzaiella asiatica* (Oxyurida: Thelastomatoidea) from *Gryllotalpa africana*. *Journal of Parasitic Diseases* 24: 73-76 (Abstract cited).
- RIZVI, A.N., JAIRAJPURI, D.S. & SHAH, M.M. 1998. *Chitwoodiella tridentata* sp. n. (Travassosinematidae) from a mole cricket from India, with SEM observations on *Leidyneia appendiculatum* (Thelastomatidae). *International Journal of Nematology* 8: 13-16 (Abstract cited).
- SEMLITSCH, R.D. 1986. Life history of the northern mole cricket, *Neocurtilla hexadactyla* (Orthoptera: Gryllotalpidae) utilizing Carolina-bay habitats. *Annals of the Entomological Society of America* 79: 256-261.
- SCHOEMAN, A.S. 1996. Turfgrass insect pests in South Africa. *Turf and Landscape Maintenance* 7: 15.
- SHORT, D.E. & KOEHLER, P.G. 1979. A sampling technique for mole crickets and other pests in turf grass and pasture. *Florida Entomologist* 62: 282-283.
- SINGH, H.S. & SINGH, K. 1990. A new species of the genus *Mirzaiella* (Basir). *Indian Journal of Parasitology* 14: 201-202.
- SITHOLE, S.Z. 1986. Mole cricket (*Gryllotalpa africana*). *Zimbabwe Agricultural Journal* 83: 21-22.
- SMITH, H.H. 1893. Fowls killed by mole crickets. *Insect Life* 5: 265.
- SOKAL, R.R. & ROHLF, F.J. 1997. *Biometry*. 57, 61-123, 135, 179-260, 392-440, 451-678. W.H. Freeman and Company, New York.
- STATSOFT INCORPORATED. 1995. *Statistica*. Version 5.0.
- TEWARSON, N.C. & GUPTA, V. 1978. Nematode parasites of invertebrates. *Indian Journal of Zootomy* 17: 21-24 (Abstract cited).
- TINDALE, N.B. 1928. Australasian mole-crickets of the family Gryllotalpidae (Orthoptera). *Records of the South Australian Museum* 4: 1-42.
- TOWNSEND, B.C. 1983. A revision of the Afrotropical mole-crickets (Orthoptera: Gryllotalpidae). *Bulletin of the British Museum of Natural History (Entomology)* 46: 175-203.

- ULAGARAJ, S.M. 1975. Mole crickets: Ecology, behavior, and dispersal flight (Orthoptera: Gryllotalpidae: *Scapteriscus*). *Environmental Entomology* 4: 265-273.
- ULAGARAJ, S.M. 1976. Sound production in mole crickets (Orthoptera: Gryllotalpidae: *Scapteriscus*). *Annals of the Entomological Society of America* 69: 299-306.
- ULAGARAJ, S.M. & WALKER, T.J. 1973. Phonotaxis of crickets in flight: attraction of male and female crickets to male calling songs. *Science* 182: 1278-1279.
- ULAGARAJ, S.M. & WALKER, T.J. 1975. Response of flying mole crickets to three parameters of synthetic songs broadcast outdoors. *Nature* 253: 530-532.
- VILLANI, M.G. & WRIGHT, R.J. 1988. Use of radiograph in behavioral studies of turfgrass-infesting scarab grub species (Coleoptera: Scarabaeidae). *Bulletin of the Entomological Society of America* 1988: 132-144.
- VITTUM, P.J., VILLANI, M.G. & TASHIRO, H. 1999. *Turfgrass insects of the United States and Canada*. Cornell University Press, Ithaca.
- WALKER, S.L. 1979. *Population estimation, damage evaluation and behavioral studies on mole crickets Scapteriscus vicinus and S. acletus (Orthoptera: Gryllotalpidae)*. M.S. Thesis, University of Florida, Gainesville.
- WALKER, T.J. 1982. Sound traps for sampling mole cricket flights (Orthoptera: Gryllotalpidae: *Scapteriscus*). *Florida Entomologist* 65: 105-110.
- WALKER, T.J. 1983. Diel patterns of calling in nocturnal Orthoptera. In: Gwynne, D.T. & Morris, G.K. (Eds.) *Orthopteran Mating Systems: Sexual Selection in a Diverse Group of Insects*. 45-72. Westview Press, Boulder, CO.
- WALKER, T.J. 1985. Systematics and life cycles. In: Walker, T.J. (Ed.) *Mole crickets in Florida*. 3-10. *Bulletin – University of Florida, Agricultural Experiment Stations* 846 (1984).
- WALKER, T.J. 1988. Acoustic traps for agriculturally important insects. *Florida Entomologist* 71: 484-492.

- WALKER, T.J. & CARLYSLE, T.C. 1975. Stridulatory file teeth in crickets: taxonomic and acoustic implications (Orthoptera: Gryllidae). *International Journal of Insect Morphology and Embryology* 4: 151-158.
- WALKER, T.J. & FIGG, D.E. 1990. Song and acoustic burrow of the prairie mole cricket, *Gryllotalpa major* (Orthoptera: Gryllidae). *Journal of the Kansas Entomological society* 63: 237-242.
- WALKER, T.J. & FORREST, T.G. 1989. Mole cricket phonotaxis: effects of intensity of synthetic calling song (Orthoptera: Gryllotalpidae: *Scapteriscus acletus*). *Florida Entomologist* 72: 655-659.
- WALKER, T.J. & FRITZ, G.N. 1983. Migratory and local flights in mole crickets, *Scapteriscus* spp. (Gryllotalpidae). *Environmental entomology*, 12: 953-958.
- WALKER, T.J., LITTELL, R.C. & DONG, N. 1982. Which mole crickets damage bahiagrass pastures? *Florida Entomologist* 65: 110-116.
- WALKER, T.J. & MASAKI, S. 1989. Natural history. In: Huber, F., Moore, T.E. & Loher, W. (Eds.) *Cricket Behavior and Neurobiology*. 1-42. Cornell University Press, Ithaca.
- WALKER, T.J. & MOORE, T.E. 2002. Singing insects of North America. *World Wide Web*: <http://buzz.ifas.ufl.edu>
- WALKER, T.J. & NATION, J.L. 1982. Sperm storage in mole crickets: fall matings fertilize spring eggs in *Scapteriscus acletus*. *Florida Entomologist* 65: 283-285.
- WALKER, T.J. & NICKLE, D.A. 1981. Introduction and spread of pest mole crickets: *Scapteriscus vicinus* and *S. acletus* reexamined. *Annals of the Entomological Society of America* 74: 158-163.
- WALKER, T.J., REINERT, J.A. & SCHUSTER, D.J. 1983. Geographical variation in flights of the mole cricket, *Scapteriscus* spp. (Orthoptera: Gryllotalpidae). *Annals of the Entomological Society of America* 76: 507-517.
- WILLIAMS, J.J. & SHAW, L.N. 1982. A soil corer for sampling mole crickets. *Florida Entomologist* 65: 192-194.

- XIA, Y. & BRANDENBURG, R.L. 2000. Effect of irrigation on the efficacy of insecticides for controlling two species of mole crickets (Orthoptera: Gryllotalpidae) on golf courses. *Journal of Economic Entomology* 93: 852-857.
- ZHANG, Z.Q. 1994. Neothrombiidae (Acari: Trombidioidea) of the world: systematic review with a phylogenetic analysis and descriptions of two new genera. *Oriental Insects* 28: 205-237 (Abstract cited).