Development, phonotaxis and management of *Gryllotalpa africana* Palisot de Beauvois (Orthoptera: Gryllotalpidae) on turfgrass

by

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SUMMARY

Gryllotalpa africana Palisot de Beauvois only occurs in Africa and is the only mole cricket turfgrass pest known in South Africa. Life stage occurrence was ascertained over one year by using an irritating drench. Male stridulation was investigated by recordings made during autumn and spring and by measuring sound pressure levels. The phonotactic response over 12 months was quantified by broadcasting a male *G. africana* song recording at 93.7 dB. A synthetic caller was set to the carrier frequency; syllable repetition rate and duty cycle of male *G. africana* song and tested for attracting *G. africana* from November to February. Fipronil (Regent), fipronil (Termidor), thiamethoxam (Actara) and furfural (Crop Guard) were evaluated in two independent field trials, for controlling an early instar nymph population and a late instar nymph/adult population of *G. africana* over 28 days, respectively. The studies were conducted in Pretoria, Gauteng, South Africa.

Oviposition of *G. africana* took place from early October (spring). Nymphs reached the adult stage from March (late summer) and the majority of individuals over wintered in this stage. Adult numbers peaked in early September (early spring), declining through the season. *Gryllotalpa africana* was therefore univoltine in the study area. The adult population was female biased in spring. On average, the smallest individuals were sampled in December (early summer), whilst the smallest nymphs occurred in November (late spring). Male *G. africana* stridulated from spring to autumn. The carrier frequency (2.161 – 2.477 kHz) and syllable duration (7.340 – 12.078 ms) of calls showed no significant relationship with soil temperature and no significant differences between autumn and spring (soil temperature constant). Syllable period (10.455 – 17.221 ms) and inter syllable interval (1.912 – 9.607 ms) were significantly negatively correlated with soil temperature, and significantly longer in spring than in autumn (with soil temperature constant). The syllable repetition rate (0.058 – 0.096 syllables / ms) and duty cycle (43.31 – 81.72 %) showed a significant positive relationship with soil temperature and significant decrease in values (soil temperature constant) in spring (relative to autumn). Sound pressure levels of *G. africana* varied from 77.6 to 89.8 dB. Adult *G. africana* flew to the song broadcast from spring to autumn, with

activity peaking mid spring and late summer/early autumn. Only spring flights were significantly gender biased (female bias). The sex ratio of flying individuals (monthly) and mole crickets in the field was similar. Flying females were reproductively mature in spring/early summer and contained eggs from late spring. Flight activity of conspecifics and genders were significantly positively related to air and soil temperature, but unrelated to moon phase. The synthetic caller attracted *G. africana*. Low numbers attracted were attributed to the low broadcast sound pressure level. Fipronil and thiamethoxam controlled early instar nymphs and will be optimally applied during eclosion in November. Only fipronil controlled the late instar nymph/adult population.

SAMEVATTING

Gryllotalpa africana Palisot de Beauvois kom slegs in Afrika voor en is die enigste molkriek plaag spesie van turfgras in Suid-Afrika. Lewensfase voorkoms (oor 'n jaar) was bepaal deur 'n irriterende oplossing te gebruik. Manlike stridulasie was ondersoek deur opnames gedurende herfs en lente te maak en deur klank-druk-vlakke te bepaal. Die phonotaktiese reaksie oor 12 maande was bespeur deur 'n manlike *G. africana* sang opname teen 93.7 dB uit te saai. 'n Geluiduitsaaier was ingestel tot die draer frekwensie; puls-herhalings-tempo en werks-tempo van manlike *G. africana* sang en getoets van November to Februarie vir die vermoë om *G. africana* te lok. Fipronil (Regent), fipronil (Termidor), thiamethoxam (Actara) and furfural (Crop Guard) was getoets in twee onafhanklike veldproewe, om 'n vroeë instar nimf bevolking en 'n laat instar nimf/volwassene bevolking van *G. africana* oor 28 dae respektiewelik te beheer. Die studies was onderneem in Pretoria, Gauteng, Suid-Afrika.

Oviposisie van *G. africana* het vanaf vroeg Oktober (lente) voorgekom. Nimfe het ontwikkel tot volwasses vanaf Maart (laat somer) en die meerderheid van individue het as volwassenes oor-winter. Volwassenes het 'n maksimum hoeveelheid tydens vroeg September (vroeë lente) bereik, waarna hoeveelhede deur die seisoen verminder het. Derhalwe was *G. africana* univoltyn in die studie area. Die bevolking was vroulik-neigend tydens die lente. Die gemiddeld kleinste individue was in Desember (vroeë somer) gevind, terwyl die kleinste nimfe in November (laat lente) voorgekom het. Manlike *G. africana* het vanaf die lente tot die herfs gestriduleer. Die draer frekwensie (2.161 – 2.477 kHz) en puls tydperk (7.340 – 12.078 ms) van die sang het nie 'n betekenisvolle verwantskap met grond temperatuur en ook geen wesenlike verskille tussen herfs en lente getoon nie (met grondtemperatuur konstant). Die puls tydperk (10.455 – 17.221 ms) en inter-puls-interval (1.912 – 9.607 ms) was betekenisvol negatief gekorreleer met grond temperatuur, en met laasgenoemde konstant, betekenisvol langer in die lente as in die herfs. Die puls-herhalings-tempo (0.058 – 0.096 syllables / ms) en werks-tempo (43.31 – 81.72 %) het 'n wesenlike positiewe verhouding met grond temperatuur en betekenisvolle afname in waardes (grond temperatuur konstant) gedurende lente

(relatief tot herfs) getoon. Klank-druk-vlakke het gevarieer tussen 77.6 to 89.8 dB. Volwasse *G. africana* het vanaf lente tot herfs na die sang uitsending gevlieg en 'n piek in aktiwiteit gedurende middel lente en laat somer/vroeg herfs bereik. Slegs die lente vlugte was wesenlik geslagsbevooroordeel (vroulik-neigend). Die geslagsverhouding (maandeliks) van vlieënde individue en molkrieke in die veld was soortgelyk. Vlieënde wyfies was reproduktief volwasse tydens lente/vroeg somer en het eiers vanaf laat lente gehad. Die konspesifieke - en geslags vlieg aktiwiteit was betekenisvol positief verwant aan grond en lug temperatuur, maar onverwant tot maanfase. Die geluiduitsaaier het *G. africana* gelok. Die lae hoeveelhede wat aangelok is was hoofsaaklik toegeskryf aan die lae uitsending klank-druk-vlak. Fipronil en thiamethoxam het vroeë instar nimfe beheer en sal optimaal toegedien word tydens eklosie in November. Slegs fipronil het die laat instar nimf/volwassene bevolking beheer.

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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 ($\mathbf{H_A}$) hypothesis included the following:

1. $\mathbf{H_0}$: *G. africana* has a univoltine life cycle in the study area.
   $\mathbf{H_A}$: *G. africana* does not have a univoltine life cycle in the study area.
2. $\mathbf{H_0}$: The sex ratio of *G. africana* in the field is not significantly gender biased.
   $\mathbf{H_A}$: The sex ratio of *G. africana* in the field is significantly gender biased.
3. $\mathbf{H_0}$: There is no significant relationship between soil temperature and the stridulation characteristics of field-recorded mole crickets.
   $\mathbf{H_A}$: There is a significant relationship between soil temperature and the stridulation characteristics of field-recorded mole crickets.
4. $\mathbf{H_0}$: There is no significant temporal variation in the stridulation characteristics of field-recorded mole crickets.
   $\mathbf{H_A}$: There is significant temporal variation in the stridulation characteristics of field-recorded mole crickets.
5. $\mathbf{H_0}$: There is no significant relationship between temperature and moon phase with flight patterns and flying gender ratios of *G. africana*.
   $\mathbf{H_A}$: 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 (Statsoft 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 & Carlysle 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	*Gryllotalpa* Latreille	Old World
Gryllotalpinae	*Gryllotalpella* Rehn	New World
Gryllotalpinae	*Neocurtilla* Kirby	New World
Gryllotalpinae	*Triamescaptor* Tindale	New Zealand
Scapteriscinae	*Scapteriscus* 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 diapose (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 & Carlysle 1975).

Gryllotalpid males produce calling songs by rubbing the file across a scraper (*plectrum*) on the other wing (Walker & Carlysle 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 temporal climatical 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 over wintering 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 H_2O/m^2 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 H_2O/m^2. 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 m^2 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 m^2 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 m^2 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 m^2) to *G. africana* infestation (as quantified by emerging crickets after soap flushing (at the concentration stated in § 2) in 0.25 m^2) 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).

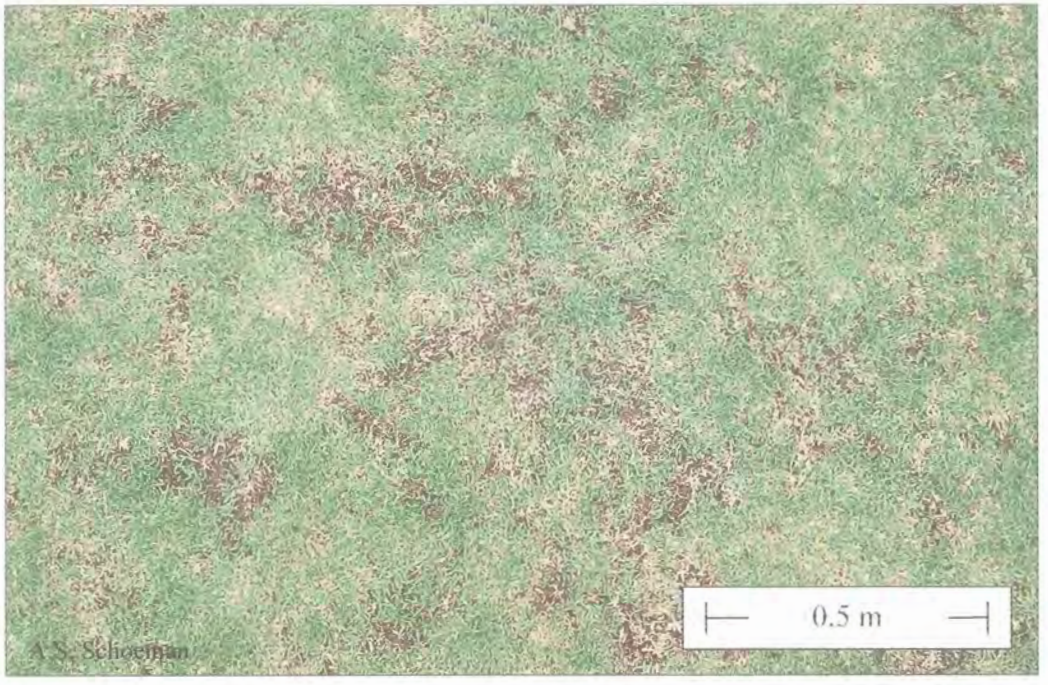

Fig. 1.3 Damage of *G. africana* to kikuyu grass (*Pennisetum clandestinum*).

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 heterozygocity 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 (Annecke & 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	*Gryllotalpa africana* Palisot de Beauvois
Southeastern USA	Immigrant	Tawny mole cricket	*Scapteriscus vicinus* Scudder [1]
Southeastern USA	Immigrant	Southern mole cricket	*Scapteriscus borellii* Giglio-Tos [2]
Southeastern USA	Immigrant	Short winged mole cricket	*Scapteriscus abbreviatus* Scudder [3]
Puerto Rico, Virgin Islands and Australia	Immigrant	West Indian mole cricket or Changa	*Scapteriscus didactylus* (Latreille) [4]
Northeastern USA	Immigrant	European mole cricket	*Gryllotalpa gryllotalpa* (L.)
Puerto Rico	Immigrant	Imitator mole cricket	*Scapteriscus imitatus* Nickle & Castner [5]
Continental USA	Native	Northern mole cricket	*Neocurtilla hexadactyla* (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 acletus* 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 subside (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 H_2O/m^2) (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 conductive 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 riobravis* 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 *Sorosporella* 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. *Cruznema brevicaudatum* (Nematoda: Rhabditidae) (Latheef & Seshadri 1972), *Indiana coimbatoriensis* (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 predating 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), emphases 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 (Emmons 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

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Chapter 2

Seasonal development of *Gryllotalpa africana*

"One difficulty encountered in implementing pest management programs for mole crickets is lack of detailed ecological information about these pests" – Hudson 1987.

Abstract

The population dynamics (in terms of seasonal development) of *G. africana* was documented for the first time in South Africa. An irritating drench (soap water solution) was used to quantify life stage occurrence on turfgrass over one year. Oviposition took place from early October (spring), with eggs incubating for approximately three weeks. Nymphs reached the adult stage from March (late summer) and the majority of individuals over wintered in this stage. Adult numbers peaked in early September (early spring), declining through the season. *Gryllotalpa africana* was therefore univoltine in the study area. The adult population was female biased in spring. The smallest individuals (in relation to mean length) were sampled in December (early summer), whilst the smallest nymphs (in relation to mean length) occurred in November (late spring).

Keywords: Univoltine, spring oviposition, life stage, absolute length, turfgrass

2.1 Introduction

Gryllotalpa africana (the African mole cricket) only occurs in Africa (Townsend 1983), from where only one account concerning the life cycle of *G. africana* is available (from Zimbabwe) (Sithole 1986), with some notes on the species in South Africa provided by Schoeman (1996) and Brandenburg *et al.* (2002).

Females lay 30-50 oval, white eggs in hardened chambers in the soil (Sithole 1986). Incubation period is temperature dependant, varying from 15-40 days (Sithole 1986). Nymphs feed on worms and roots of plants and (in favourable conditions) develop through six instars, with wing bud development visible in later instars (Sithole 1986). The nymphal period lasts three to four months. One generation per year is known (Sithole 1986). According to Schoeman (1996), there are approximately 10 nymphal instars of *G. africana* in South Africa and research by Brandenburg *et al.* (2002) showed that burrows of the African mole cricket are typically Y-shaped and range from 100 mm to 230 mm in length. The life and seasonal cycle of *G. africana* has not been investigated in South Africa and no reports on the seasonal development of *G. africana* (from Africa) on turfgrass are available.

Life cycle, seasonal development and behaviour documentations under the name *G. africana* include reports by the United States Department of Agriculture (1974) (U.S.A. introduction from Asia), Kim (1993, 1995) (Asian occurrence), Muralirangan (1979) (Asian occurrence), Tindale (1928) (Australian occurrence) and Goodyer (1985) (Australian occurrence). None of these studies probably refer to "true" *G. africana* from Africa.

Life cycle and seasonal development reports (including voltinism) of similar mole cricket species may however vary significantly between different geographical areas. In a specific area, different species and even different genera may show general life cycle similarity (including voltinism) (Frank *et al.* 1998). Species will, however, show some variation in life cycle, seasonality and behaviour, but areas of comparable climates may therefore provide a more accurate life cycle and seasonal development estimation than a mole cricket species alone.

2.2 Material and methods

Infested kikuyu grass areas at Pretoria Country Club (25°47'16''S; 28°15'28''E) were flushed with soapy water (50 ml Sunlight® dishwashing soap/5 litres H_2O/m^2), a simple, inexpensive and effective surveillance material (Short & Koehler 1979). Sampling areas consisted of four sites, with each site comprising 150 m^2. The sites were selected by stratifying the golf course in four topographical/geographical areas, randomly selecting one infested site within each area and sampling from a surface area of 150 m^2 at that site. A total of four sampling areas were therefore used, which were distributed throughout the golf course.

Flushes started at noon, the sequence of areas randomised per sampling date (with equal sampling intensity (10 litres soap water) at each site) over an annual period (October 2001 – November 2002). The fortnightly sampling was conducted in such a manner that flushed areas were chosen at random within each site, not overlapping for the duration of the experiment. Emerging crickets were counted and measured from the posterior of the abdomen (excluding cerci) to the distal end of the labrum. Adults were sexed and females dissected to determine egg and oocyte presence per sampling date. Oocytes were deemed mature (eggs) when covered by an egg shell (vitelline membrane and chorion). The long axis of eggs was generally longer than 2.5 mm. All sampled areas were under similar irrigation programs and soap flushing efficiency was assumed to be homogenous for adults and nymphs between and within sites over the study period. Immigration and emigration (especially through flight) were also assumed to be at equilibrium and not to effect absolute cricket sizes and life stage percentages during the study.

2.3 Results

The life cycle (as the ontogenic stage percentage of the total population) of *G. africana* over an annual period is graphically presented in Fig. 2.1. Percentages were calculated by determining adult and nymphal percentages for a specific sampling date. The egg percentage on that date was calculated (eggs could not be sufficiently sampled in the field) as equal to the mean first instar nymph population percentage three weeks (mean egg hatch time (Schoeman, pers. comm.)) from that

date. The egg percentage over time therefore only refers to fertilized eggs and may be subject to some variation, as incubation period is temperature dependant (Frank *et al.* 1998 and Potter 1998). Life stage percentages were subsequently determined from the ontogenic ratio obtained. To obtain an annual presentation (from November 2001 to October 2002), data were therefore needed from October 2001 to November 2002. Fig. 2.1 shows 61 % adults and 39 % late instar nymphs comprised the over wintering population. Patchy, relatively small samples (<40 individuals) were obtained during winter, which may contribute to the inconsistent results obtained over that period (Fig. 2.1). After over wintering, adult numbers (as a population percentage) peaked at 64 % and diminished to 1 % during September/October (spring) and November/December (spring/summer), respectively (Fig. 2.1). The egg population peaked in end October (spring) at 41.52 %, further following the adult percentage inclination, but with some eggs laid until late February (Fig. 2.1). Oviposited eggs ranged from 2.5 – 3.5 mm in length. The graph of nymphal percentages showed an approximate direct inverse relationship with the adult-percentage-graph when no eggs were present (Fig. 2.1). High egg percentages were associated with the lowest nymphal percentages (Fig. 2.1). *Gryllotalpa africana* had a univoltine life cycle in the study area (Fig. 2.1). There is a lack of complete percentage overlap for each ontogenic stage at the beginning and end of the graph (Fig. 2.1).

The mean monthly nymph and overall (adult and nymph) length (from the posterior of the abdomen (excluding cerci) to the distal end of the labrum) of *G. africana* for twelve-months are shown in Fig. 2.2. First instar nymphs were 5.95 ± 0.218 mm (mean ± SD) long, with a midline pronotal length of 1.52 ± 0.054 mm (mean ± SD) (data not shown). The mean monthly nymphal length varied from 6.6 ± 2.56 mm (± SD) to 25.8 ± 3.70 mm (± SD) from November 2001 (first and second instar nymphs present) to October 2002 (late instar nymphs present), respectively (Fig. 2.2) and nymphs over wintered from early June 2002 when they were 23.0 ± 4.16 mm (mean ± SD) in length (data not shown), averaging 22.1 ± 3.9 mm (± SD) over the month (Fig. 2.2). The mean monthly overall (adult and nymph) length was at a minimum (10.3 ± 6.51 mm) (mean ± SD) and maximum (31.1 ±

5.53 mm) (mean ± SD) in December 2001 and October 2002, respectively (Fig. 2.2). The mean monthly length of sampled nymphs and the total (nymphs and adults) population showed a relative decline during the winter (Fig. 2.2). Fig. 2.3 illustrates the mean monthly length (from the posterior of the abdomen (excluding cerci) to the distal end of the labrum) of the adult population over an annual period. No females were sampled in January and February 2002, when one male in each month was flushed (resulting in no standard deviation values) (Fig. 2.3). Genders were not distinctly segregated by mean length over monthly intervals, except for spring and early summer months, when females tended to be longer (Fig. 2.3). Males and females were at a maximum length of 36.7 ± 2.33 mm (mean ± SD) and 37.2 ± 1.85 mm (mean ± SD), respectively in November 2001 and at a minimum of 30.8 ± 1.61 mm (mean ± SD) and 30.2 ± 1.27 mm (mean ± SD), respectively in July 2002 (Fig. 2.3). The mean adult length over one year was 34.1 ± 3.87 mm (mean ± SD), with a midline pronotal length of 7.8 ± 0.31 mm (mean ± SD) (data not shown) (the pronotal length was within the ranges reported by Townsend 1983). Development may be measured by other parameters than absolute length, but this study is also concerned with management, where an absolute length measurement is more practically relatable, especially to turf managers. Management related sizes for other mole cricket species have also been reported in absolute length (Potter 1998 and Brandenburg & Williams 1993).

Table 2.1 summarizes female reproductive activity and the sex ratio of *G. africana* per month over an annual period. Female oocytes started to develop from April and the percentage females with oocytes peaked in the winter months (Table 2.1). During July 2002, 92.3 ± 10.13 % (mean ± SD) of females contained oocytes, a figure which was 20.0 ± 42.16 % (mean ± SD) in December 2001 (Table 2.1). The mean percentage oocytes per female was highly variable in December 2001, but appeared to fit a declining pattern (Table 2.1). Oocytes smaller than one millimetre in length were found in females from April 2002 to August 2002 and increased to 1.5 – 2.0 mm in September 2002 and 2.0 – 2.5 mm during October 2002, November 2001 and December 2001 (data not shown). Females containing internal eggs (2.5 mm to 3.5 mm long) were sampled regularly in September 2002,

October 2002, November 2001 and December 2001, but peaked in October 2002 at 43.0 ± 0.00 % (mean ± SD) of the female population (Table 2.1). The highest number of internal eggs per female was found in September 2002 (38.4 ± 8.55) (mean ± SD), progressively declining to December 2001 (12.3 ± 9.78) (mean ± SD) (Table 2.1). Deviation from an equal sex ratio was investigated using the binomial distribution (two-tailed) (Sokal & Rohlf 1997 and "Statistica" Version: 5 (Statsoft Inc. 1995)). The Bonferroni method was used to lower the type one error probability for each comparison, resulting in an overall significance level not exceeding 0.05 in the entire series of tests (Sokal & Rohlf 1997). The significance level for each sample was calculated as $p = 0.00217$ ($p = 0.05/23$ comparisons). Table 2.1 summarizes the mean (± SD) monthly percentage males of the adult population over twelve months. The adult field sex ratio was male biased one sampling date in May 2002 (date 1: 82.22 % males, $p = 0.00002$, $N = 45$, date 2: 51.61 % males, $p = 0.89908$, $N = 62$). Female bias (in the adult population) was found in both August 2002 samples (date 1: 12.12 % males, $p = 0.00001$, $N = 33$, date 2: 24.53 % males, $p = 0.00027$, $N = 53$). The first September 2002 adult sample was also female biased (date 1: 25 % males, $p = 0.00023$, $N = 56$, date 2: 30.65 % males, $p = 0.00316$, $N = 62$). The statistical results also exemplified a female bias for the first October 2002 adult sample (date 1: 18.87 % males, $p = 0.00001$, $N = 53$, date 2: 27.5 % males, $p = 0.00643$, $N = 40$).

Field (Table 2.1) and flight (data not shown) sex ratio data (as a male percentage, respectively) were normally distributed in the linear scale (Sokal & Rohlf 1997) for comparable months (Kolmogorov-Smirnov test, $p > 0.05$) ("Statistica" Version: 5 (Statsoft Inc. 1995)). Between comparable months (November and December 2001, March to May 2002 and September and October 2002), a T-test (for dependant samples) (parametric test) (Sokal & Rohlf 1997) showed no significant difference between the field and flight sex ratios of mole crickets at Pretoria Country Club ($t = -2.399$, $p = 0.053$) ("Statistica" Version: 5 (Statsoft Inc. 1995)).

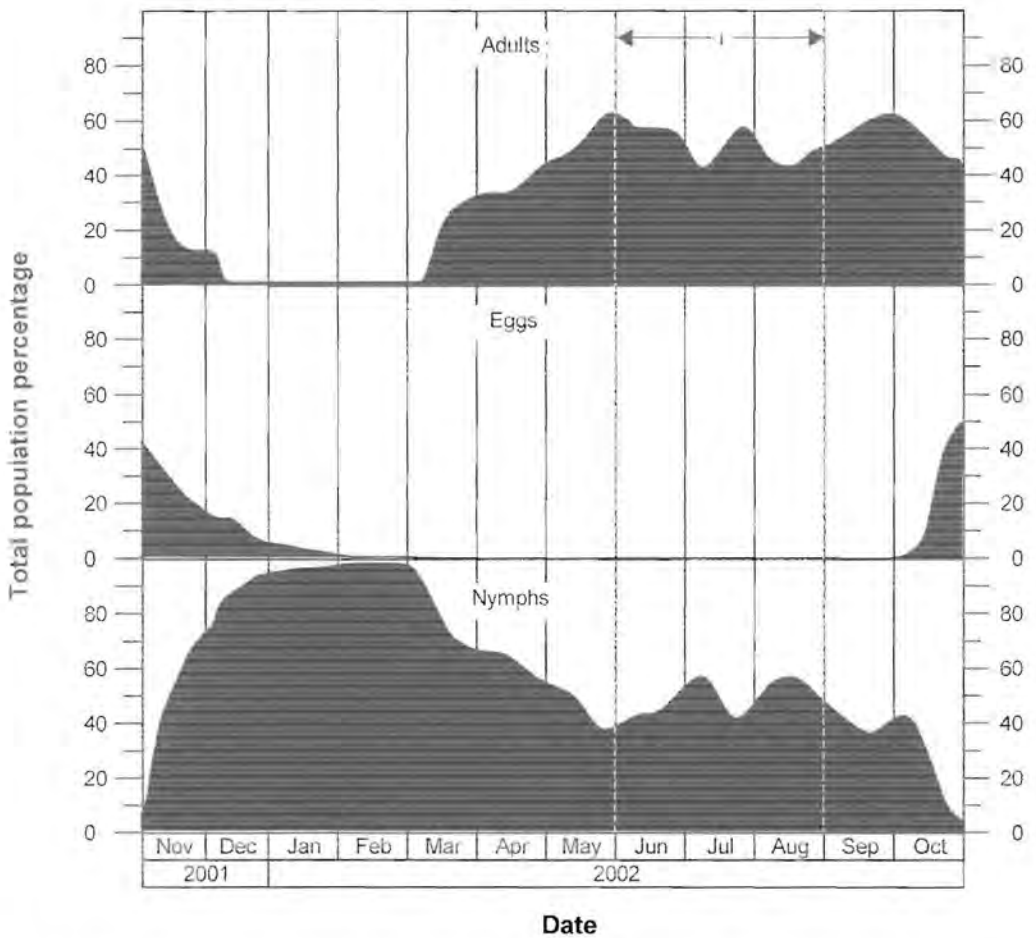

Fig. 2.1 The ontogenic stage population percentage of *G. africana* at Pretoria Country Club from November 2001 to October 2002. [1] Winter period.

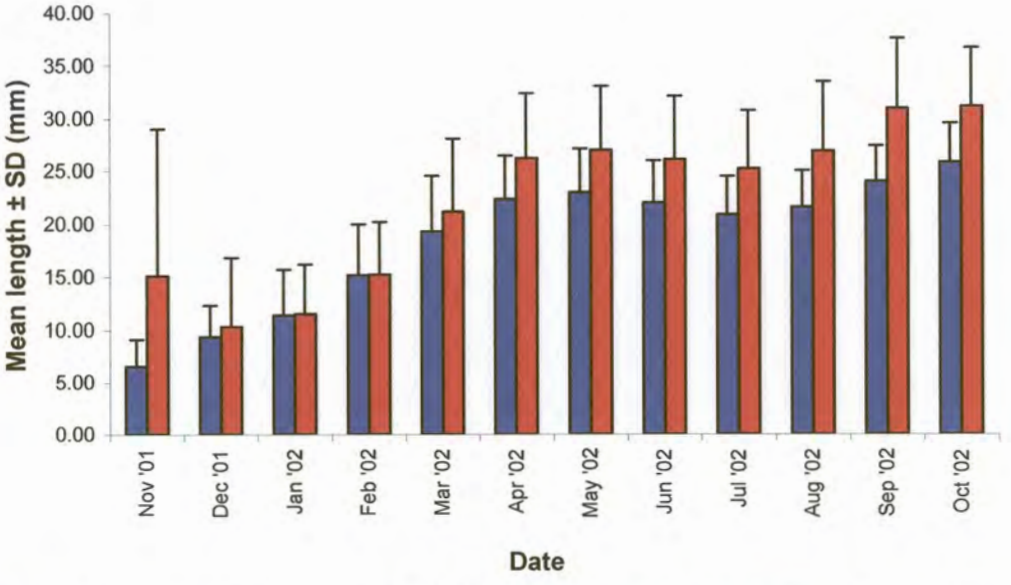

Fig. 2.2 The monthly mean (± SD) length (from the posterior of the abdomen (excluding cerci) to the distal end of the labrum) of the nymph and total (adult + immature) population of *G. africana* at Pretoria Country Club from November 2001 to October 2002. Total = red, nymphs = blue.

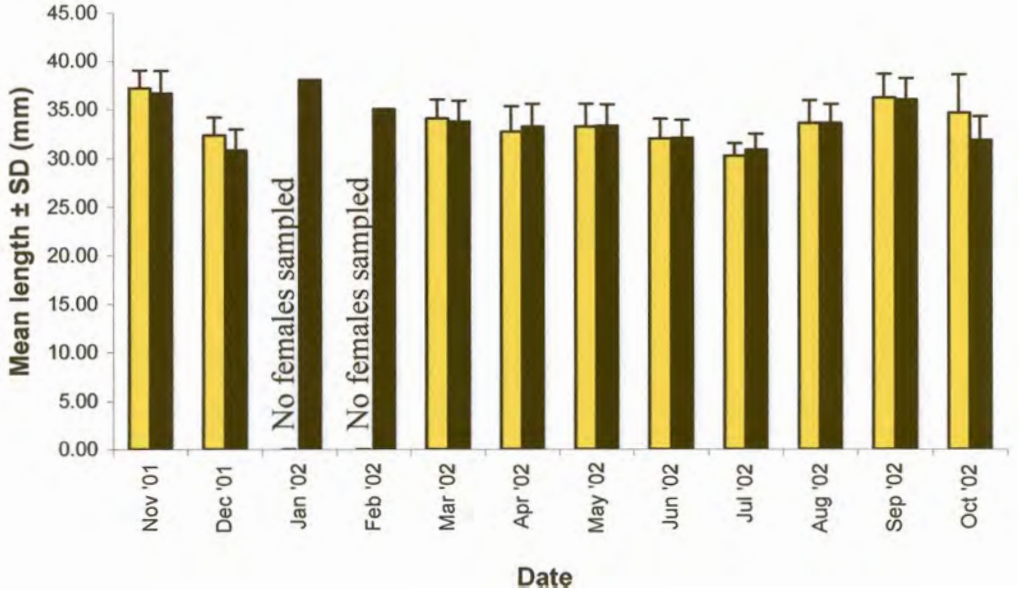

Fig. 2.3 The monthly mean length (± SD) (from the abdomen (posterior, excluding cerci) to the labrum (distal end)) of adult male (black bars) and female (yellow bars) *G. africana* at Pretoria Country Club from November 2001 to October 2002.

Table 2.1 Adult females containing immature and mature oocytes (eggs) (as a female population percentage (mean ± SD), respectively), eggs per adult female (mean ± SD) and the adult sex ratio (mean ± SD) (as the percentage males of the adult population) of *G. africana* at Pretoria Country Club from November 2001 to October 2002. (Immature oocytes < 2.5 mm and mature oocytes (eggs) > 2.5 mm).

Date	Percentage females containing oocytes (mean ± SD)	Percentage females containing eggs (mean ± SD) (number of eggs per female) (mean ± SD)	Percentage males in population (mean ± SD)
November 2001	51.9 ± 16.94	35.71 ± 12.83 (23.4 ± 8.20)	36.1 ± 1.78
December 2001	20.0 ± 42.16	40.0 ± 21.09 (12.3 ± 9.78)	40.0 ± 16.24
January 2002	No females	No females	100 [a]
February 2002	No females	No females	100 [a]
March 2002	0.0	0.0 (0.0)	65.5 ± 11.92
April 2002	22.1 ± 14.67	0.0 (0.0)	53.0 ± 5.08
May 2002	36.6 ± 7.11	0.0 (0.0)	64.5 ± 15.18 *
June 2002	91.8 ± 7.06	0.0 (0.0)	50.5 ± 0.63
July 2002	92.3 ± 10.13	0.0 (0.0)	36.6 ± 9.32
August 2002	80.0 ± 17.58	0.0 (0.0)	19.8 ± 6.07 *
September 2002	62.7 ± 3.87	32.7 ± 8.60 (38.4 ± 8.55)	28.0 ± 2.83 *
October 2002	45.6 ± 7.95	43.0 ± 0.00 (31.3 ± 9.15)	22.58 ± 0.04 *

[a] Only one male and no females sampled (insufficient n for an inference).

* $p < 0.001$ in at least one sample (see results) (Two tailed binomial distribution, Bonferroni correction ($p = 0.05/23 = 0.002$)).

2.4 Discussion

During the study period, vitellogenesis was observed from September and *G. africana* females laid fertilized eggs (Fig. 2.4) from October (mid spring). The highest number of fertilized eggs in the field was calculated as being during the end of October. Oviposition was in clutches (personal observation) but the subterranean nature of egg laying and clutches per female is unknown. The number of eggs per female and the adult population started declining from late September, with some fertilized eggs laid until February, when adults represented one percent of the population. The monthly spring oviposition period was characterised by the longest females over an annual period that also comprised a significant proportion of the adult population. Female abdomen length appeared to increase with egg containment, as females were on average longer than males only at this time. Female abdomen length did however not appear to be linearly related to fecundity. Absolute length may therefore not be the best measure to quantify adult size. Gender behavioural changes may also have influenced sampling results (lengths) over this period, but were assumed not to cause significant prejudice.

The data suggested mortality in males was high during late winter/early spring (causing a female bias). Migration through flight was not responsible for temporal gender bias in the field, as the monthly flight sex ratio was not significantly different to the monthly field sex ratio and also showed similar patterns. High male mortality after mating has been reported for other mole crickets with a univoltine life cycle (Brandenburg & Williams 1993 and Buss *et al.* 2002), which suggests, if *G. africana* males show a similar tendency, that mating of *G. africana* occurred before spring in the present study. Mating may have occurred in autumn, which has been reported for univoltine *S. borellii* (Walker & Nation 1982), who also oviposit during spring (Frank *et al.* 1998). Further research (analysing female spermathecae for sperm) will confirm mating period(s). The majority of adults were presumed dead (not soap flushed from the soil) by December (early summer), when the sex ratio approached an even relation. The former suggest that high female mortality occurred after the oviposition period as reported for other mole crickets with a univoltine life cycle (Brandenburg & Williams 1993 and Buss *et al.* 2002).

Eclosion (egg hatch) began in November, when distinctive first and second instar nymphs were abundant, and continued up to mid March. First instars were dorsally black with thin, white, horizontal, abdominal stripes, apterous and from personal observations, were the only active jumpers (up to approximately 7 mm from the posterior of the abdomen (excluding cerci) to the distal end of the labrum). Second instars were dorsally brown, apterous and up to 9 mm from the posterior of the abdomen (excluding cerci) to the distal end of the labrum. All following instars were dorsally greyish-brown (adults and nymphs are light yellow on the ventral side) and resembled adults in appearance but were smaller and only developed wing buds in later instars (Fig. 2.5). The relatively long oviposition period caused some nymphal instar overlap, as evident from standard deviation values in mean nymph absolute length. The overall (adult and nymph) mean absolute population length was highly variable in November, but relatively shorter with less variability in December, as a result of the adult population that decreased over the two months. Nymphal development rate increased with relative warmer temperatures and the new generation adults appeared from late summer/early autumn. Adults have fully developed tegmina and hind wings and are capable of flight. The new generation adults consisted of more males during autumn, with a significant male inclination in May (although May samples were subject to relatively high variance). This occurrence may support earlier reasoning, as males may eclose before females and subsequently die before them. The data indicated a minimum period of five months from oviposition to adult. The life cycle may, however, only have been completed in eight or nine months if oviposition took place in late summer. The seasonal ontogenic stage occurrence was relatively similar in flush samples from over the Pretoria region.

The majority of nymphs completed their development by early June, when an over wintering phase was entered to the end of August, during which time individuals may have moved lower down in the soil profile. During this period, small, patchy infestations (lowest density sampled during late July) were found in moist turf areas with relatively high soil temperatures (usually northern exposures). Sampling bias may have caused relative high variability in life stage constitution

during over wintering. Factors including behavioural changes, relative smaller samples constituting to higher variability and/or destructive sampling may have contributed to the bias. Absolute length during winter samples showed a relative decline and may also have been due to sampling bias. Behavioural changes and destructive sampling may have been the main factors that influenced length sampling. Smaller (in relation to length) individuals sampled may have reflected a tendency of younger (and shorter) adults and nymphs to stay active a long as possible to attain a larger size (longer length) to increase their fitness during the following spring reproductive period. Larger males of *Scapteriscus* produce louder calls and attract more females (Forrest 1980, 1983, 1991), whilst larger *Scapteriscus* females produce three times more offspring and 1.5 times as many eggs per clutch than smaller females (Forrest 1986). The *G. africana* population became more adult biased during spring, when the ontogeny was completed. Adult length during spring was monthly variable, but may support a contention of Forrest (1987), that as the spring reproductive period season progresses, a greater proportion of smaller individuals (of both genders) should mature because cost due to delaying reproduction increase.

There was annual variation (on a constant spatial scale) in the development of *G. africana* and mean egg hatch in 2002 were 2 weeks later than in 2001. Soap flushes should therefore be conducted on a regular basis to quantify spatial and temporal variance (especially important for management practices). The seasonal development of *G. africana* reported in this study is closely related to reports of univoltine *Scapteriscus* species in the southeastern U.S.A. (Brandenburg & Williams 1993).

Preliminary studies indicated peak ovipositioning occurred a few weeks later on golf courses in the cooler, southern regions (Johannesburg), an inclination also followed by some New World species (Brandenburg 1997 and Potter 1998). Temperature therefore appeared to be an important factor influencing egg laying period in *G. africana*. Brandenburg (1997), however, found that timing and intensity of egg-laying and egg hatch do not seem to be closely related to soil temperature or the number of *S. vicinus* and *S. borellii* females captured in acoustic

traps. Hertl *et al.* (2001) found a significant positive linear relationship between ovipositing females (number of eggs laid per female were constant) and soil moisture in *S. borellii*. Soil moisture may therefore also influence ovipositioning in *G. africana*.

Preliminary studies also showed that the proportion of adults in the population prior to over wintering might be smaller in the more southern areas (Johannesburg region). (Adult over wintering proportions are variable (on a constant spatial scale) for *S. vicinus* (Brandenburg 1997), suggesting that values reported in this study may also be variable between years).

Some specific behaviours of *G. africana* were observed during the course of this study. Adults were found to be cannibalistic, especially at high densities. *Gryllotalpa africana* adults usually expelled a characteristic non-sticky, pungent smelling, dark brown fluid when handled, possibly as a deterrence or defence mechanism (personal observation). Other genera (*Neocurtilla* and *Scapteriscus*) and *Gryllotalpa* species (*G. oya*) are also known for secreting fluids (from anal glands) that may be smelly and vary from a low to high viscosity (Baumgartner 1910, Tindale 1928 and Walker & Masaki 1989). Anal glands may also be responsible for fluid production in *G. africana*, but was not experimentally investigated.

2.5 Acknowledgements

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Fig. 2.4 Mature fertilized *G. africana* eggs.

Fig. 2.5 Late instar *G. africana* nymph with tegmina and hind wing development.

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Chapter 3

Stridulation of *Gryllotalpa africana*

"Trills are the most common kinds of signals in cricket species and probably represent the ancestral condition" – Hoffart *et al.* 2002.

Abstract

During spring to autumn, *Gryllotalpa africana* males stridulated (produced phonotactic calling songs) from specially constructed acoustical burrows. Songs started just after dusk and continued for several hours. The characteristics of the trilling song and sound pressure levels produced were investigated by near field digital recordings made during autumn 2002 and spring 2002 (with soil temperatures noted) and measuring sound pressures (beyond the near field) with a sound level meter in spring 2002, respectively. The carrier frequency (2.161 – 2.477 kHz) and syllable duration (7.340 – 12.078 ms) of calls showed no significant relationship with soil temperature and no significant differences between autumn and spring (with soil temperature constant). Syllable period (10.455 – 17.221 ms) and inter syllable interval (1.912 – 9.607 ms) were significantly negatively correlated with soil temperature, and with the latter being constant, significantly longer in spring than in autumn. The syllable repetition rate (0.058 – 0.096 syllables/ms) and duty cycle (43.31 – 81.72 %) showed a significant positive relationship with soil temperature and significant decrease in values (with soil temperature constant) in spring (relative to autumn). Sound pressure levels (re. 20 µPa) at 200 mm from the burrow varied from 77.6 to 89.8 dB.

Keywords: Male song characters, seasonal variance, soil temperature, sound pressure level, turfgrass

3.1 Introduction

Numerous insect species produce stereotyped acoustic signals that are important in intraspecific communication (Kavanagh 1987). In most species that communicate by sound, the male's calling song, which appears to attract conspecific females, is the most obvious and imperative component of the repertoire (Kavanagh 1987).

Male African mole crickets 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) (Figs. 3.1 & 3.2). Males usually stridulate at night, using the entrance of borrows as sound amplifiers (De Villiers 1985). Singing position of *Gryllotalpa* appears to be very similar, although acoustic burrows may have two (*G. vineae*, *G. gryllotalpa* and *G. africana*) (Bennet-Clarke 1970a and Brandenburg *et al.* 2002) to four horn-shaped openings (*G. australis*) (Kavanagh & Young 1989). The division between openings may collapse over time, producing fewer openings (Bennet-Clarke 1970a and Kavanagh & Young 1989).

Variation between temporally segregated songs of chirping and trilling mole crickets may be caused by environmental factor dependence. Chirp rate and syllable or pulse repetition rate in crickets and mole crickets increase linearly with soil temperature over an intermediate temperature range (Bennet-Clark 1970a, Bennet-Clarke 1989, Kavanagh & Young 1989, Doherty & Callos 1991, Ciceran *et al.* 1994 and Hill 1998, 2000). Inter syllable interval is usually negatively correlated with temperature in the Gryllotalpinae and carrier frequency appears to be temperature independent in mole crickets (Bennet-Clark 1989). In the Oecanthinae (Gryllidae), however, the carrier frequency is positively correlated to temperature, but with a smaller slope than for syllable rate (Bennet-Clarke 1989). Walker (1962) also reported carrier frequency to be a regression function of air temperature (at low and moderate temperatures) for crickets presenting three genera and three subfamilies. Another potential factor contributing to variation may be physiological of nature (size, condition etc.). In the Gryllidae, song structure does not; however, appear to vary with male mass or age (Souroukis *et al.* 1992 and Ciceran *et al.* 1994). In trilling *Gryllotalpa*, the song differences appear to be of fundamental frequency (Bennet-Clark 1970a), whilst in gryllids, the interval between syllables may be

more important (Walker 1962). Male song characteristics in mole crickets are species specific (Bennet-Clark 1970a, b, Otte & Alexander 1983, Nickle & Castner 1984, Kavanagh & Young 1989, Walker & Figg 1990 and Broza *et al.* 1998) and provide a key to determine the validity of reports of *G. africana* occurrence.

Sound pressure levels (measured just beyond the near field (15-20 cm in line with the burrow, re. 20 µPa) may vary from 65 to 97 dB between trilling mole cricket species (highest intraspecific sound pressure level variation of 67 to 91 dB) (Ulagaraj 1976, Forrest 1983, Bennet-Clarke 1987, Kavanagh & Young 1989 and Walker & Forrest 1989). Song intensity of trilling species is positively correlated to male size and usually to temperature and rainfall (soil moisture) (Bennet-Clarke 1970a, Ulagaraj 1976 and Forrest 1980, 1983, 1991).

Some song characteristics reported for the African mole cricket include a phonotaxis study by Kim (1993) in Hwaseong-gun, Kyonggi-do Korea, who found intensities of calling songs vary between 77 and 80 dB at 150 mm above the openings of calling chambers. The study of Kim (1993) does probably not refer to the "true" *G. africana*. Other song characters of *G. africana* are based on four recordings (Townsend 1983) and vary between reports (Nickle & Castner 1984). Calling song intensities of *G. africana* from Africa has not been measured.

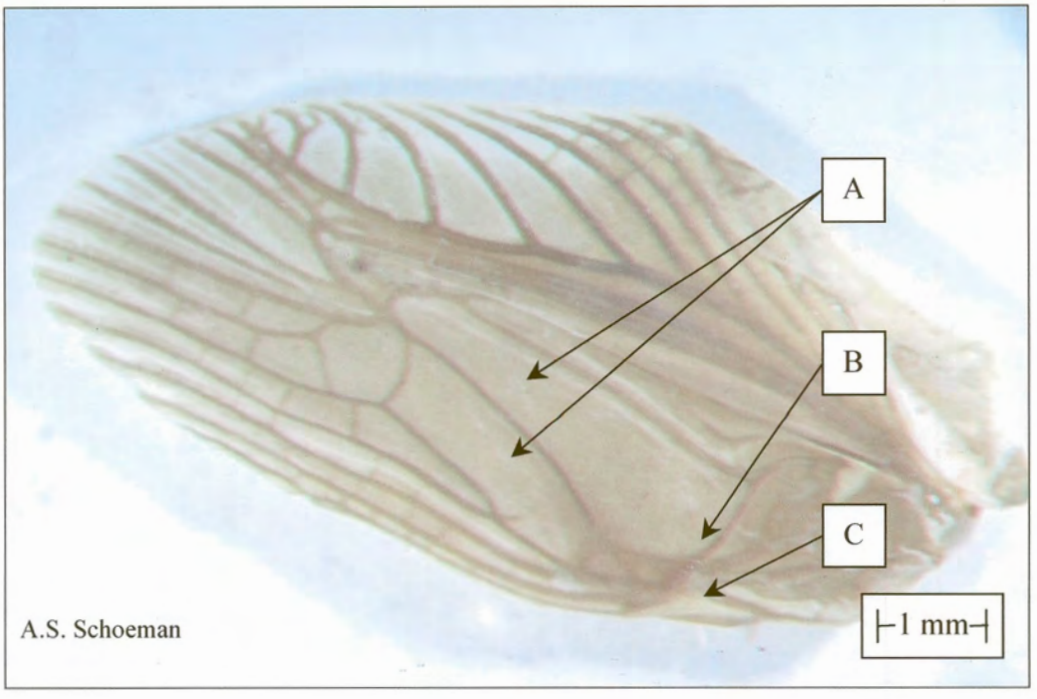

Fig. 3.1 Ventral view of right male tegmen, showing stridulatory area. A = Stridulatory area, B = File (*pars stridens*) and C = Scraper (*plectrum*).

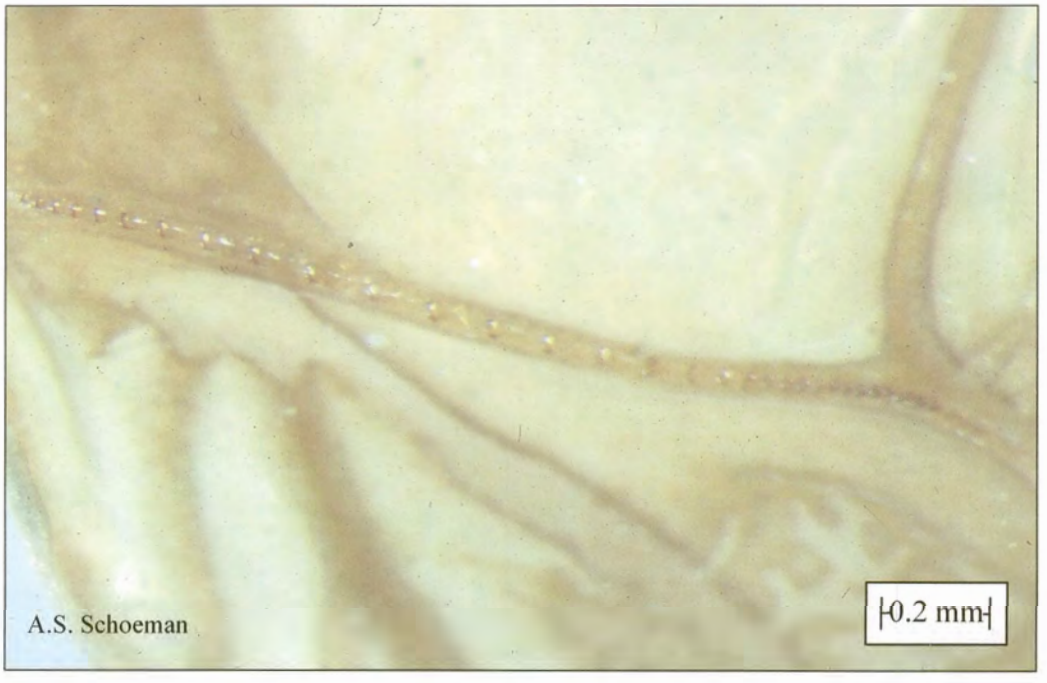

Fig. 3.2 Ventral view of male tegmen, showing stridulatory teeth arrangement on the file or *pars stridens* of *G. africana*.

3.2 Material and methods

Field recordings (20) of the calling song of *G. africana* males (chosen at random but not overlapping) were made in a kikuyu grass area of approximately 300 m^2 (between and surrounding of the putting green and green no. 18) at the Pretoria Country Club from March 2002 to April 2002. Soil temperatures were measured at a vertical depth of 100 mm in the soil profile immediately after recordings were made. Recordings were made between 19h30 and 21h15, local time (GMT + 2 hours). Soil moisture was assumed to be constant. During October 2002 and November 2002, 20 stridulating males were recorded according to a similar methodology, but at a nearby site (comprising a kikuyu grass area (300 m^2) between and surrounding of the chipping and bowling green at Pretoria Country Club) (with a similar irrigation program than the previous site). Recordings between and within the two periods were assumed to be of different males, as no recording sites overlapped. The calls were recorded with a Nomad DAP-3201 digital recorder (Creative Technology Ltd.), with the self-contained microphone held 50 mm from the burrow opening, longitudinal to the long axis of the burrow. Recording distance was within the near field, or distance covered by one wavelength at the carrier frequency of this call (s/2300 cycles × 343 m/s at 20°C = 149.13 mm) (Hill 2000).

All the recordings were analysed using the computer software program "Canary" V1.2.4 (Cornell Laboratory of Ornithology 1998). A power spectrum (Fig. 3.3) and oscillogram (Fig. 3.4) were used to measure three different call characteristics for nine syllables (three successive syllables randomly selected at the beginning, middle and end of each recording, respectively) per recording: Carrier frequency (Fig. 3.3), syllable duration (Fig. 3.4) and syllable period (Fig. 3.4). The inter syllable interval (syllable period – syllable duration), mean syllable repetition rate (inverse of syllable period) and duty cycle ((syllable duration/syllable period) × 100) were calculated from the measured parameters.

The sound pressure level of twenty different calling males (which was all assumed to be *G. africana*) was also measured according to the methodology for each recording (but at a distance of 200 mm (beyond the near field) from the burrow opening (longitudinal to the long axis)) on a night (between 20h00 and

20h30, local time (GMT + 2 hours)) in late November 2002. A kikuyu grass area of approximately 300 m^2 (including and surrounding of the first tee at Pretoria Country Club) was used for measurements. The area sampled had a similar irrigation program. Sound level measurements were made with a precision integrating sound level meter (Rion Type NL-14), calibrated by a Rion Type NC-73 sound level calibrator (equipment was within annual calibration). The sound level meter was used in L_{Aeq} mode, which records the time-weighted average of a series of fast root mean square (RMS) recordings (time constant 125 ms). This gave the A-weighted sound pressure level (dB A scale) (at re. 20 µPa) that was the equivalent continuous level as the fluctuating signal being recorded. A period of approximately 20 s was sufficient to provide a stable level for *G. africana*.

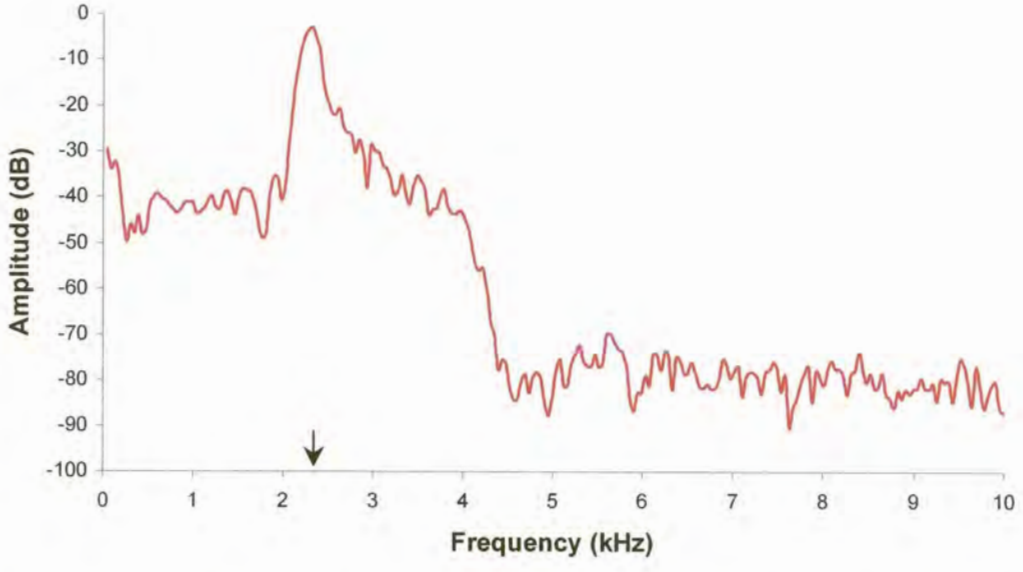

Fig. 3.3 The power spectrum of a field recorded *G. africana* call (up to 10 kHz), indicating a carrier frequency of approximately 2.3 kHz.

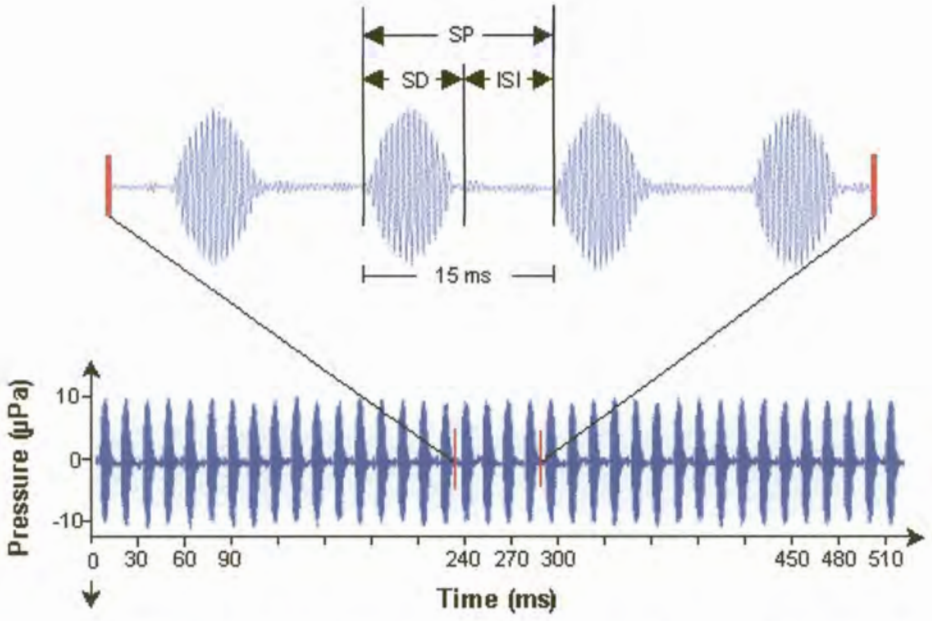

Fig. 3.4 Oscillogram of a field recorded *G. africana* trilling call over 510 ms. The thickened red lines indicate an approximate eight times shorter temporal scale with the different measurements made. SD = Syllable duration, ISI = Inter syllable interval and SP = Syllable period.

3.3 Results

The relationship of call characteristics (measured in autumn (March/April) and spring (October/November) of 2002) with soil temperature (100 mm in the soil profile) is represented in Table 3.1. Soil temperature ranged from 20.7 °C to 24.8 °C (23.2 ± 1.24 °C (mean ± SD)) in March/April 2002 recordings and 22.3 °C to 26.8 °C (23.5 ± 1.16 °C (mean ± SD)) in October/November 2002 recordings. The data of all the sound characters (except syllable period) fitted a normal distribution (Kolmogorov-Smirnov test, $p > 0.05$) ("Statistica" Version: 5 (Statsoft Inc. 1995)) without transformation (Sokal & Rohlf 1997). The syllable period data for both sampling periods was not significantly different from a normal distribution only after logarithmic transformation (Sokal & Rohlf 1997) (Kolmogorov-Smirnov test, $p > 0.05$) ("Statistica" Version: 5 (Statsoft Inc. 1995)).

The parametric test (multiple regression) ("Statistica" Version: 5 (Statsoft Inc. 1995)) showed a highly significant relationship of syllable period, inter syllable

interval, syllable repetition rate and duty cycle with soil temperature for both recording periods (Table 3.1). Carrier frequency variation of *G. africana* males was not significantly related to the tested temperature range (Table 3.1). The results showed a negative relationship between syllable period (data was transformed back to linear scale before presentation) and soil temperature for both sampling periods, with the latter constantly explaining more than 80 % of the variation in the former (Table 3.1). The rate of decline in the syllable period was slightly higher in the spring recordings (Table 3.1). The syllable duration had no significant relationship with soil temperature (Table 3.1). Inter syllable interval was negatively correlated with soil temperature, with R^2 values under 0.50 (Table 3.1). The rate of decline, however, was slightly higher for the spring recordings (relative to that in autumn) (Table 3.1). The syllable repetition rate was positively related to soil temperature during spring and autumn (Table 3.1). In the latter season recordings, the rate of syllable increase was lower than during the spring recordings over a similar range of soil temperatures (Table 3.1). Soil temperature was a relatively good predictor (R^2 approximately 0.80) of syllable repetition rate in both recording periods (Table 3.1). The duty cycle increased significantly with soil temperature, but with relatively low R^2 values, during both recording periods, respectively (Table 3.1). The rate of increase with soil temperature was higher in spring (relative to autumn values) (Table 3.1). Slopes of regression lines should be compared with caution, as they are dependant on the measurement scale.

The values for the different measured and calculated sound characteristics (at variable soil temperatures) and differences between autumn 2002 and spring 2002 recordings (with soil temperature constant) are summarized in Table 3.2. Only syllable repetition rate needed to be transformed (arcsine) (Sokal & Rohlf 1997) for all the dependant variables to be normally distributed (Kolmogorov-Smirnov test, $p > 0.05$) ("Statistica" Version: 5 (Statsoft Inc. 1995)). A multi analysis of variance (MANCOVA) (parametric test) (Sokal & Rohlf 1997 and "Statistica" Version: 5 (Statsoft Inc. 1995)), with soil temperature entered as a covariate, was used to determine significant song character differences between the two temporally segregated field recordings (Table 3.2).

Table 3.1 Relationship between male *G. africana* song characters and soil temperatures (at a vertical depth of 100 mm in the soil profile) of 23.2 ± 1.24 °C (mean ± SD) and 23.5 ± 1.16 °C (mean ± SD) for March/April 2002 (Recording 1) and October/November 2002 (Recording 2), respectively, at Pretoria Country Club.

Data		Regression variable				
Song character	**Recording**	**Slope**	**Intercept**	**R^2**	**F**	**p**
Carrier	1	0.001	2.311	0.0004	0.019	0.891
frequency (kHz)	2	-0.009	2.569	0.0228	0.931	0.340
Syllable period	1 **	-1.067	63.826	0.8092	195.174	0.0000001
(ms)	2 **	-1.127	41.089	0.8139	174.960	0.0000001
Syllable	1	-0.079	11.104	0.0118	0.552	0.461
duration (ms)	2	-0.198	13.702	0.0412	1.7205	0.197
Inter syllable	1 **	-0.874	25.395	0.4521	37.968	0.0000001
interval (ms)	2 **	-0.929	27.387	0.3913	25.712	0.000009
Syllable	1 **	0.004	-0.031	0.7926	175.781	0.0000001
repetition rate (Syllable. ms^{-1})	2 **	0.007	-0.084	0.8406	210.990	0.0000001
Duty cycle (%)	1 **	3.485	-15.92	0.2755	17.495	0.000128
	2 **	4.245	-37.13	0.2581	13.915	0.000593

* $p < 0.05$

** $p < 0.001$

Table 3.2 Values of male *G. africana* song characteristics recorded at Pretoria Country Club, at soil temperatures (at a vertical depth of 100 mm in the soil) of 23.2 ± 1.24 °C (mean ± SD) and 23.5 ± 1.16 °C (mean ± SD) for March/April 2002 (Recording 1) and October/November 2002 (Recording 2), respectively. Significant differences between recordings (with soil temperature constant) are shown.

Data		Value		MANCOVA variable	
Song character (Unit)	**Recording**	**Range**	**Mean ± SD**	**F**	**p**
Carrier frequency (kHz)	1	2.198 – 2.476	2.34 ± 0.067	0.096	0.757
	2	2.161 – 2.477	2.34 ± 0.075		
Syllable period (ms) **	1	12.031 – 17.061	14.3 ± 1.09	21.226	0.00001
	2	10.455 – 17.221	14.6 ± 1.45		
Syllable duration (ms)	1	7.340 – 10.959	9.3 ± 0.91	1.826	0.180
	2	7.372 – 12.078	9.1 ± 1.13		
Inter syllable interval (ms) *	1	2.979 – 9.607	5.1 ± 1.62	11.548	0.00104
	2	1.912 – 7.779	5.6 ± 1.72		
Syllable repetition rate (Syllable. ms $^{-1}$) **	1	0.059 – 0.083	0.070 ± 0.0061	14.724	0.00024
	2	0.058 – 0.096	0.069 ± 0.0082		
Duty cycle (%) *	1	43.31 – 78.15	64.9 ± 8.25	7.276	0.00845
	2	48.66 – 81.72	62.44 ± 0.097		

* $p < 0.05$

** $p < 0.001$

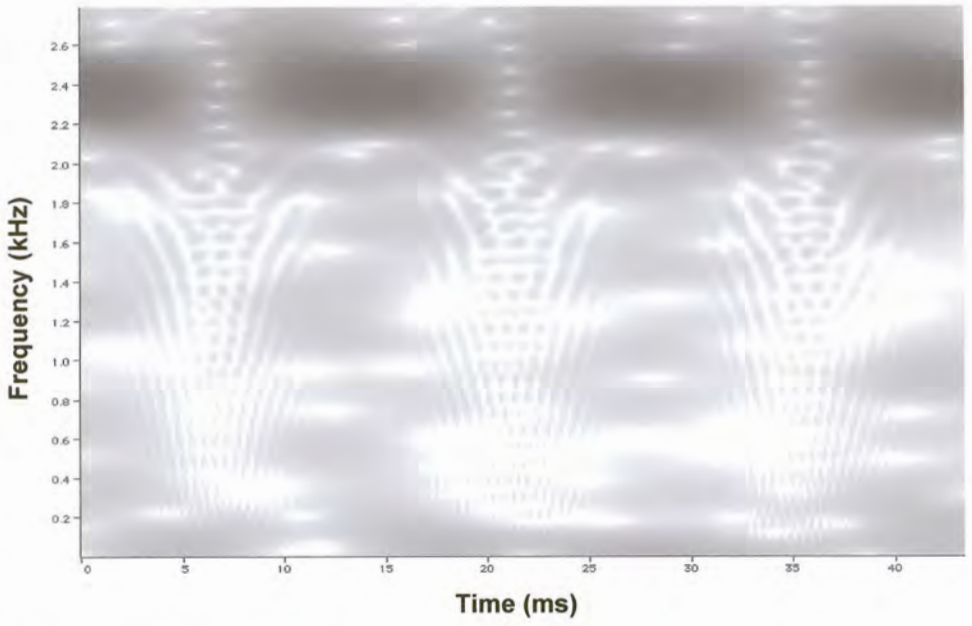

Fig. 3.5 The spectrogram presenting two complete syllables of a field recorded *G. africana* call (up to approximately 2.7 kHz).

The results showed that the carrier frequency of *G. africana* males was constant between autumn and spring at approximately 2340 cycles per second (Table 3.2). The power spectrum (Fig. 3.3) (representative for most songs) graphically represents the carrier frequency and shows a low frequency component and no clear harmonics for *G. africana* males. The spectrogram (Fig. 3.5) of a general sound recording shows the sound structure during and between syllables. Fig. 3.5 shows the low frequency observed in the power spectrum was also present between syllables and therefore when no mole cricket sound was produced (Fig. 3.5).

Syllable duration did not vary significantly between seasons and was usually just longer than nine milli-seconds (Table 3.2). The syllable period, inter syllable interval, syllable repetition rate and duty cycle were significantly different (with soil temperature constant) between the autumn and spring recordings (Table 3.2). The syllable period and inter syllable interval were significantly longer and the syllable repetition rate and duty cycle significantly shorter in spring than in autumn, respectively (Table 3.2).

During the spring recordings, one individual was recorded (at a soil

temperature of 21.9 °C) with the following sound characters (mean ± SD): carrier frequency: 2.638 ± 0.0068 kHz, syllable period: 17.89 ± 0.085 ms, syllable duration: 7.9 ± 0.30 ms. Inter syllable interval, syllable repetition rate and duty cycle was calculated as (mean ± SD) 10.00 ± 0.217 ms, 0.0559 ± 0.00026 syllables/ms and 44.1 ± 1.47 %, respectively.

The sound pressure levels (re. 20 µPa) of *G. africana* varied from 77.6 to 89.8 dB at 200 mm from the burrow. The ambient - and soil temperature (average of five measurements) at the onset of the experiment were 21.5 ± 0.30 °C and 23.24 ± 0.112 °C, respectively. At the end of the experiment, ambient - and soil temperatures (average of five measurements) were 21.15 ± 0.263 °C and 23.03 ± 0.217 °C. Due to the relative homogeneity (including irrigation program, turfgrass and soil) of the experimental area and relatively short temporal measurement period, moisture levels was considered constant.

3.4 Discussion

Gryllotalpa africana males constructed acoustical burrows with one or two horn-shaped openings observed (two openings may initially have been constructed, but may have collapsed over time). Male African mole crickets started calling just after sunset and, especially during the warm summer months, called until midnight, attracting flying conspecifics and even walking nymphs. Calling activity was generally limited to soil temperatures exceeding 14 °C (late August to late May, when conspecifics flew). Initial calling was characterised by a distinctive warm up period. The sound matured from the initial slow erratic trill to a constant trilling call. Some male callers exploited microclimatical conditions near brick walls and concrete slabs. These spatial orientations (which artificially increased soil temperatures) were especially utilized during times of relatively low soil temperatures. Males called singularly, but were usually observed in calling groups (individuals separated by a few meters) during stridulation.

Males (randomly selected from the field in spring and autumn) acclimatized for one week at L: D 12h: 12h (which was a relative shorter daily light cycle) and 28 ± 1 °C, did not call in the laboratory, suggesting photoperiod as a factor contributing

to stridulation activity. This observation may have been biased by the fact that mole crickets were kept in containers, which have been found to influence their behaviour (Walker 1979 and Hudson 1988).

Songs of *G. africana* males were produced at sound pressure levels of 77.6 to 89.8 dB and characterised by a carrier frequency of approximately 2.34 kHz (with some variation between males), of which the latter did not vary significantly between autumn and spring and with soil temperature. If the song had a low frequency component, it could not be distinguished from background noise in the current study. Harmonics, which were generally not clearly visible, are usually at a relatively low level in the family (Bennet-Clark 1987). African mole cricket males usually stopped calling (usually less than one minute) when the burrow opening was approached (usually within a one meter radius) (personal observation) and was therefore deemed to show some seismic sensitivity. Males in full song were usually less sensitive. Trilling species are generally not very sensitive to substrate vibrations (Bennet-Clarke 1970a and Forrest 1991), although Bennet-Clark (1970a) reported *G. gryllotalpa* to be highly sensitive. Sensitivity may be related to sound pressure level, which may saturate mechano-receptors at high intensities (Bennet-Clark 1970a).

The syllable duration of male *G. africana* calls did not vary significantly between autumn and spring and with soil temperature, but did show some variation between males. Syllable period was negatively related with soil temperature and varied significantly (with soil temperature constant) between autumn and spring. Additional sound characters calculated from the syllable period or syllable period and syllable duration, reflected their relationships with the tendencies of the measured variables.

Townsend (1983) reported a mean syllable repetition rate of 49.1-57.8 per second and a mean carrier frequency of 2.1-2.4 kHz for the calling song of *G. africana* (based on four recordings). No temperature values or other variables were annotated during these recordings. The calling song frequency of *G. africana* reported from Hawaii is 3.3 kHz, with a syllable repetition rate of 56 per second (Nickle & Castner 1984). Although syllable repetition rates were similar between the two reports, it is not comparable without any temperature information. The carrier

frequency values of the present study correspond with that reported by Townsend (1983). Differences in calling song carrier frequency have been used to distinguish between *Gryllotalpa* species (Bennet-Clark 1970b, Nevo & Blondheim 1972). These stridulatory character differences therefore support reports that the Hawaiian species is in fact not *G. africana*. Frank *et al.* (1998) also stated that the immigrant mole cricket to Hawaii was misidentified as *Gryllotalpa africana*. According Frank *et al.* (1998) the species occurring in Hawaii is *G. orientalis*, a species originating from Asia, not Africa.

It appears that a mole cricket species, other than *G. africana*, also inhabited Pretoria Country Club in spring 2002. The distinction of the species was in its higher carrier frequency values. The carrier frequency of *G. devia* is unknown. *Gryllotalpa robusta* have a carrier frequency of 1.6 kHz (based on one recording) and *G. parva* have a carrier frequency of 2.9-3.3 kHz (based on two recordings) (Townsend 1983). Hence, the carrier frequency of the unidentified species does not correspond to known values of species occurring in South Africa.

3.5 Acknowledgements

Thanks to K. Drews (South African Bureau of Standards (SABS)), who assisted in sound pressure level measurements. J.W.H. Ferguson (University of Pretoria), who assisted with the interpretation of sound results, statistical analysis and for the use of his laboratory. A.S. Schoeman (University of Pretoria) for the use of his digital recorder. P. Kryger (University of Pretoria), M. Ferreira (University of Pretoria) and L. Verburgt (University of Pretoria), who assisted with some technical aspects.

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Chapter 4

Flight patterns of *Gryllotalpa africana*

"When mole crickets fly they move "curso undoso", rising and falling in curves" - White (1789).

Abstract

Flights of univoltine mole crickets are usually female inclined and peak during spring and autumn. A male *G. africana* song recording was broadcast weekly at 93.7 dB (200 mm from speakers, re. 20 µPa) just after sunset for 1.5 hours over an annual period. Attracted individuals (conspecifics) were sexed and females dissected. Temperatures were measured per sampling date and moon phase calculated. Adult *G. africana* flew to the song broadcast from spring to autumn, with activity peaking mid spring and late summer/early autumn. Spring flights were characterised by a significant female bias, whilst sexes were present in equal proportions during summer and autumn. The monthly sex ratio of flying individuals was not significantly different to that of mole crickets sampled in the field. Flying females were only reproductively mature in spring/early summer and contained eggs from late spring. Eggs per flying female declined into summer. Flight activity of conspecifics and genders were significantly positively related to temperature, with air temperature showing the highest degree of relation. Moon phase showed no significant relationship with flying conspecifics or gender.

Keywords: Male song broadcast, flight peaks, sex ratio, moon phases, temperature

4.1 Introduction

Mole crickets occupy temporary habitats and flights are therefore adaptive to individuals (Ulagaraj 1975). Members of the genus *Scapteriscus*, in geographical areas where the life cycle is univoltine, have flight periods that generally peak in spring and autumn (Ulagaraj 1975 and Potter 1998). 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 over wintering sites or simply for dispersal (Ulagaraj & Walker 1973 and Potter 1998). Conspecifics are attracted to and end their flights at stridulating males. Predatory selection pressures (from visual diurnal predators (e.g. birds)) and energetic restraints on flight may be responsible for aerial activity generally occurring at the warmest dark time, i.e. soon after sunset (Forrest 1983). Synchronous, early evening flight may also have evolved to enhance the dilution effect to escape predation from nocturnal predators (e.g. bats) (Hamilton 1971 and Forrest 1983). The sex ratio of flying adults is female biased (Ulagaraj 1975, Forrest 1983 and Matheny *et al.* 1983). Mean sex ratios of *Scapteriscus* species vary from 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). Female mole crickets 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).

Ulagaraj (1975) showed that males of *S. borellii* tend to land outside a 0.6 m radius from a male song, consistent with Matheny *et al.* (1983) and Walker & Forrest (1989), who found the sex ratio of *Scapteriscus* to be less female inclined as landing distance from the sound source increased. This phenomenon was constant at different relatively high song intensities (Walker & Forrest 1989). Ulagaraj & Walker (1973) hypothesized that mated and virgin females will end their flights similarly, from where virgin females will enter male burrows and mated females will burrow elsewhere.

Goodyer (1985) documented swarming of *G. africana* in New South Wales (Australia). The study, however, probably did not refer to the "true" *G. africana* from Africa (Otte & Alexander 1983 and Townsend 1983). Kim (1993) studied *G. africana* phonotaxis in Hwaseong-gun, Kyonggi-do Korea, and found females comprised 66.7-74.3% of attracted adults and suggested this reflected the sex ratio of the population in the field. The study of Kim (1993) probably also referred to a Gryllotalpid species other than *G. africana* (Townsend 1983).

Owing the fact that flight appears to be part of a seasonal reproductive life cycle (Potter 1998), is endothermic (Ulagaraj 1975) and temperature therefore influence the flying ability of mole crickets (Forrest 1983); similarities in geography, life cycle and seasonal development of winged mole crickets (of different species) may show a higher level of flight pattern resemblance than similar species in different geographical areas.

4.2 Material and methods

A recording of a stridulating *G. africana* male was made on a kikuyu grass area at the University of Pretoria (25°45'24''S; 28°13'87''E), Pretoria, Gauteng, on 2001/10/03 (20h30 local time, (GMT + 2 hours)) at an average ambient and soil temperature of 20.1 °C (100 mm vertically above surface) and 20.0 °C (at a vertical depth of 100 mm in the soil profile), respectively. The song was recorded in the near field with a Rion NL-14 sound level meter (held 50 mm from the borrow opening, longitudinal to the long axis of the borrow) on a Sony DAT tape with a Tascam DA-P1 digital audio tape recorder. The sound recording was filtered under 1 kHz and above 8 kHz with a Brüel & Kjær Type 2131 digital frequency analyser and saved on Compact Disc. The recording was analysed using the computer software program "Canary" V1.2.4 (Cornell Laboratory of Ornithology 1998). The call characteristics (carrier frequency, syllable period and syllable duration) were determined from 30 syllables (10 successive syllables randomly selected at the beginning, middle and end of the recording, respectively). The following results were obtained (mean ± SD): carrier frequency: 2.3158 ± 0.00217 kHz, syllable period: 14.77 ± 0.056 ms, syllable duration: 9.47 ± 0.171 ms. Inter syllable interval,

syllable repetition rate and duty cycle was calculated as (mean ± SD) 5.31 ± 0.117 ms, 0.06770 ± 0.000252 syllables/ms and 64.1 ± 0.93 %, respectively (for calculations, more details on sound analysis and *G. africana* song relationships, refer to Chapter 4: Stridulation of *G. africana*).

A Sansui PRC-D450Z mini hi-fi, powered by 12V, 7.0 amp-hour lead acid rechargeable batteries (Uniross ULA12V7), was used to broadcast the song recording continuously (at a constant volume setting) just after sunset for one and a half hours. Starting time was calibrated monthly. The sound pressure level produced was quantified with a precision integrating sound level meter (Rion Type NL-14), calibrated by a Rion Type NC-73 sound level calibrator (equipment was within annual calibration). The sound level meter was used in L_{Aeq} mode, which records the time-weighted average of a series of fast root mean square (RMS) recordings (time constant 125 ms). This gave the A-weighted sound pressure level (dB A scale) (at re. 20 μPa) that was the equivalent continuous level as the fluctuating signal being recorded. A period of approximately 20 s was sufficient to provide a stable level for the *G. africana* recording. The instrument showed a level of 93.7 dB at 200 mm (beyond the near field) from the centre, mid way between the two speakers. Batteries were regularly charged. The mini hi-fi was moved randomly at 30-minute intervals between infested areas per experimental date. The experiment was conducted weekly at Pretoria Country Club for twelve months (November 2001 to October 2002). Soil (at a vertical depth of 100 mm in the soil profile) and ambient (100 mm vertically above surface) temperatures were measured at half-hourly intervals and averaged per night. A two-meter radius surrounding the hi-fi (assumed to provide no error in the number of males and/or females attracted) was inspected (using a flash light) in five-minute intervals and attracted individuals collected and sexed. Adult females were dissected to determine egg presence per sampling date. Oocytes were deemed mature (eggs) when covered by an egg shell (vitelline membrane and chorion). Moon phase (as a percentage of full moon) was calculated (by linear extrapolation) per sampling date. Relative humidity was not included as an independent variable, as sampled areas were under similar irrigation programs.

4.3 Results

Adults responded through phonotaxis to the male song recording throughout the year (except during winter) (Fig. 4.1). The number of individuals attracted (from sunset for 1.5 hours) peaked during February/March (late summer/early autumn) and October (mid spring), with the maximum mean absolute response in February (Fig. 4.1). The greatest response per sampling date occurred in late October 2002, with 40 individuals attracted (data not shown). The phonotactic response was variable throughout the sampling period. The lowest and highest levels of variation were found in January 2002 and October 2002, respectively (Fig. 4.1).

Periods of female reproductive activity and the sex ratio of flying *G. africana* over an annual period are summarized in Table 4.1. Oocytes smaller than one millimetre in length were found in dissected females from March 2002 to May 2002, a figure that increased to 1.5 mm in September 2002 and October 2002 and to 2.0 mm during November 2001 to February 2002 (data not shown). The percentage females with oocytes was lowest at 37.6 ± 26.95 % (mean ± SD) in February 2002, increasing to 100.0 ± 0.00 % (mean ± SD) in October 2002 (Table 4.1). Variance in the monthly (oocyte containing females) data was high, but means generally did, however, follow a progressive pattern during the sampling period (Table 4.1). Flying females containing eggs (ranging from 2.5 mm to 3.5 mm in length) were sampled in September and November to February (September 2002 and November 2001 to February 2002) (Table 4.1). Means were variable, but showed females during the early spring flight period (Fig. 4.1) usually did not contain fully developed eggs (Table 4.1). The maximum percentage females containing eggs was sampled in December 2001 (50.0 ± 0.0 %) (mean ± SD) and reached a minimum in February 2002 at 6.3 ± 9.58 % (mean ± SD) (Table 4.1). Eggs per flying female peaked in November 2001 at 41.0 ± 6.36 (mean ± SD), versus the minimum value of 2.0 ± 0.0 (mean ± SD) eggs per female in September 2002 (Table 4.1). Deviation from an equal sex ratio was investigated using the binomial distribution (two-tailed) (Sokal & Rohlf 1997 and "Statistica" Version: 5 (Statsoft Inc. 1995)). The Bonferroni method was used to lower the type one error probability for each comparison, resulting in an overall significance level not exceeding 0.05 in the

entire series of tests (Sokal & Rohlf 1997). The significance level for each flight sample was calculated as p = 0.00185 (p = 0.05/27 comparisons). Table 4.1 summarizes the monthly mean (± SD) percentage males of the flying adults over twelve months. The sex ratio of flying adults was female inclined in two of three samples when mole crickets were attracted in September 2002 (date 1: 0.00 % males, p = 1.0, N = 1, date 2: 0.00 % males, p = 0.00098, N = 11, date 3: 0.00 % males, p = 0.00049, N = 12). Female bias was also found in one of three samples (when mole crickets were attracted) in October 2002 (date 1: 25.00 % males, p = 0.625, N = 4, date 2: 7.50 % males, p = 0.00000002, N = 40, date 3: 20.00 % males, p = 0.375, N = 5).

Field (data not shown) and flight (Table 4.1) sex ratio data (as a male percentage, respectively) were normally distributed in the linear scale (Sokal & Rohlf 1997) for comparable months (Kolmogorov-Smirnov test, p > 0.05) ("Statistica" Version: 5 (Statsoft Inc. 1995)). Between comparable months (November and December 2001, March to May 2002 and September and October 2002), a T-test (for dependant samples) (parametric test) (Sokal & Rohlf 1997) showed no significant difference between the field and flight sex ratios of mole crickets at Pretoria Country Club (t = -2.399, p = 0.053) ("Statistica" Version: 5 (Statsoft Inc. 1995)).

The data of male, female and total number of adult mole crickets attracted to the recorded song was significantly different from the normal distribution (Kolmogorov-Smirnov test, p > 0.05) ("Statistica" Version: 5 (Statsoft Inc. 1995)) in linear and transformed states (Sokal & Rohlf 1997). Hence, the non-parametric Spearman correlation (Sokal & Rohlf 1997 and "Statistica" Version: 5 (Statsoft Inc. 1995)) was used to quantify relationships between flying individuals and air temperature, soil temperature and moon phase at Pretoria Country Club (Table 4.2). The Bonferroni method was used to correct for the number of comparisons with each independent variable (p = 0.05/3 comparisons = 0.01667) (Sokal & Rohlf 1997). Table 4.2 shows a significant correlation of overall (males + females) flight density with ambient and soil temperature. Air temperature explained more variation in overall flight activity than soil temperature, with r^2 values of 0.48 and

0.29, respectively (Table 4.2). Moon phase was not significantly correlated with overall flight activity (Table 4.2). Gender segregation of the flying individuals revealed similar significance results with temperature and moon phase (Table 4.2). Of the independent variables, air temperature explained the majority of variance in the number of flying males and females, with r^2 values of 0.42 and 0.45, respectively (Table 4.2). Comparatively, soil temperature explained 35 % and 24 % of the variability in the number of flying males and females, respectively (Table 4.2). Flight threshold in the field was an ambient temperature of 14.5 °C (at 100 mm vertically above the surface) (data not shown).

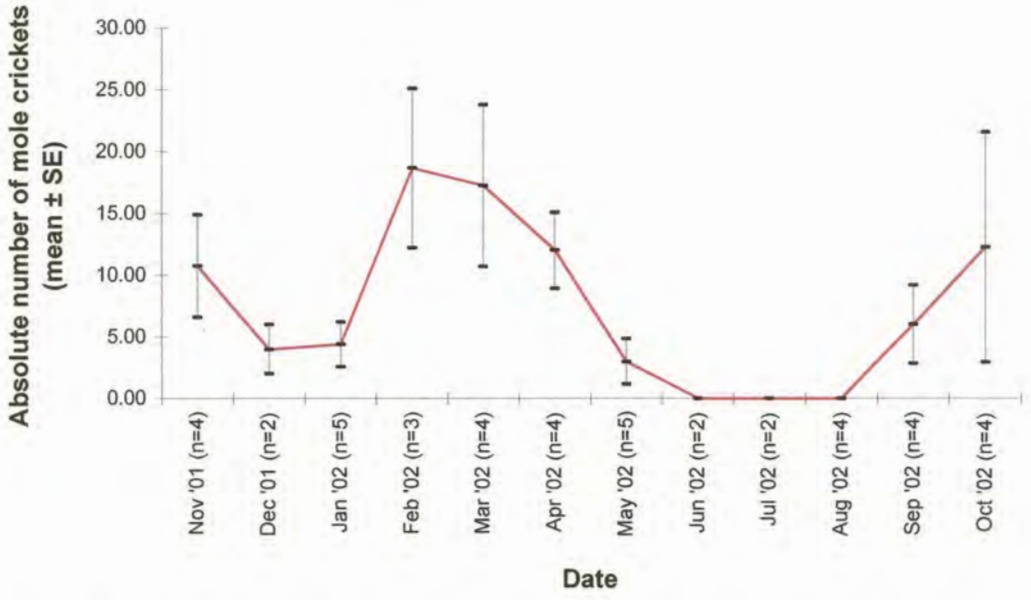

Fig. 4.1 Flying *G. africana* individuals attracted to a conspecific male song recording just after sunset for 1.5 hours, from November 2001 to October 2002 at Pretoria Country Club.

Table 4.1 Adult females containing immature and mature oocytes (eggs) (mean ± SD) (as a percentage of flying females, respectively), eggs per adult flying female (mean ± SD) and the adult sex ratio (mean ± SD) (as the percentage males of the flying population) of *G. africana* at Pretoria Country Club from November 2001 to October 2002. (Immature oocytes < 2.5 mm and mature oocytes (eggs) > 2.5 mm).

Date	Percentage females containing oocytes (mean ± SD)	Percentage females containing eggs (mean ± SD) (number of eggs per female) (mean ± SD)	Percentage flying males (mean ± SD)
November 2001	75.13 ± 10.803	12.5 ± 13.36 (41.0 ± 6.36)	44.2 ± 29.12
December 2001	50.0 ± 0.0	50.0 ± 0.0 (18.0 ± 8.49)	37.5 ± 23.15
January 2002	44.56 ± 21.214	33.33 ± 31.62 (24.3 ± 23.44)	42.9 ± 20.46
February 2002	37.6 ± 26.95	6.3 ± 9.58 (4.5 ± 3.54)	48.2 ± 7.53
March 2002	47.4 ± 40.98	0.0 (0.0)	42.0 ± 8.67
April 2002	69.15 ± 30.410	0.0 (0.0)	45.8 ± 15.01
May 2002	75.3 ± 16.50	0.0 (0.0)	53.3 ± 31.35
June 2002	No activity	No activity	No activity
July 2002	No activity	No activity	No activity
August 2002	No activity	No activity	No activity
September 2002	92.2 ± 8.82	7.7 ± 8.64 (2.0 ± 0.0)	0.0 *
October 2002	100.0 ± 0.00	0.0 (0.0)	10.2 ± 5.86 *

* $p < 0.001$ in at least one sample (see results) (Two tailed binomial distribution, Bonferroni correction ($p = 0.05/27 = 0.002$)).

Table 4.2 Spearman correlation of the number of flying *G. africana* males, females and total individuals, with ambient temperature, soil temperature and moon phase, at Pretoria Country Club from November 2001 to October 2002.

Data		Correlation variable			
Flight constitution	**Environmental variable**	**Relationship**	r^2	**t**	**p**
Total number	Ambient temperature	Positive *	0.4761	6.101	0.0000001
	Soil temperature	Positive *	0.2916	4.129	0.000175
	Moon phase	None	0.0144	0.759	0.451913
Number of males	Ambient temperature	Positive *	0.4225	5.434	0.000003
	Soil temperature	Positive *	0.3481	4.660	0.000033
	Moon phase	None	0.0036	0.399	0.692306
Number of females	Ambient temperature	Positive *	0.4489	5.835	0.000001
	Soil temperature	Positive *	0.2401	3.567	0.000937
	Moon phase	None	0.0196	0.915	0.365421

* $p < 0.01$

4.4 Discussion

The African mole cricket flew during the moderate and warm seasons (spring to autumn (September to May)) at ambient temperatures that exceeded 14.5 °C. Flying individuals peaked in late summer/early autumn and mid spring. Crickets prepared for flight by warming their flight muscles (raising and then rapidly moving their tegmina laterally), followed by several flight leaps of ± 300 mm, (personal observation). Vitellogenesis in flying females occurred from September (early spring) and females generally flew during the early to mid spring months containing immature eggs. From late spring, approximately one in ten flying females contained

mature eggs. As the flight activity declined in early to mid summer, females that contained immature and mature eggs occurred at relative equal proportions. The data suggested that flying female clutch size (as the number of eggs per flying female) decreased as the late spring/early summer flight period progressed. During spring and early summer, the vast majority of flying females were reproductively mature (contained developing oocytes or mature eggs). A small proportion of females flying in late summer also contained mature eggs, but the majority were not reproductively mature (did not contain mature or developing oocytes). No flying females were reproductively mature in autumn (no oocyte vitellogenesis occurred). The flying reproductive data combined with the seasonal life cycle and ontogenic stage occurrences in the field, indicated individuals flying from September to February were individuals that over wintered as adults and late instar nymphs. In the field, more females contained mature eggs than flying females in early spring, which may reflect small flight sample sizes or that females with immature oocytes tended to fly. Some newly developed adults probably started flying from February. Over wintered adults appeared to be dead by March and females flying from March to May, may therefore comprise newly developed adults. From a more holistic point of view, it appeared that females did not fly as a response to being reproductively mature or containing mature eggs.

The sex ratio of flying individuals was significantly female biased in September and October. The remainder of the flight period was not significantly gender biased, although slightly more females were usually attracted to male songs. The sample sizes of flying individuals were relatively small, but monthly sex ratios were not significantly different to that found in the field.

Flight activity and moon phases were not significantly correlated over the study period. Flight activity was, however, significantly positively related to temperature over the study period. Air temperature (at 100 mm vertically above the surface) showed a higher degree of relation than soil temperature to male, female and overall conspecific flight activity, accounting for 42 %, 45 % and 48 % of the variation in the data, respectively. Flight activity also showed a general decline during the nightly sampling period (as temperatures decreased) (as reported by

Forrest (1983) for *Scapteriscus* species), with the majority of *G. africana* individuals usually attracted during the first 45 minutes (associated with the highest nightly temperatures).

Only *G. africana* adults flew to the conspecific male song broadcast and attempted to burrow in the turf near the sound origin (personal observation). Females are probably attracted to male calls for mating and/or dispersing and/or obtaining suitable over wintering sites during autumn and egg laying and/or mating and/or dispersing to other favourable areas during spring. One male was observed flying to the sound source in early February 2002, after which it started stridulating on the turf surface, one metre away. Males may therefore not only be attracted during the flight period to other male calls for distribution, to find good calling sites (and good over wintering sites in autumn) and to form temporal calling aggregations (sprees) (Walker 1983) (a common spatial orientation for *G. africana* observed in this study), but also to intercept attracted females. Nymphs also approached the natural song broadcast (during late January, mid March and the end of September), possibly attracted to disperse to other favourable turf areas.

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Chapter 5

Development of an Electronic Acoustic Caller for Mole Crickets in South Africa

"... those individuals which were able to make the loudest or most continuous noise would gain partners before those which were less noisy..." – Darwin.

Contribution of co-authors other than supervisor:

R.L. Brandenbug initialized the collection of the data and supplied the electronic acoustic caller for the experiment.

The chapter is written in the first person for thesis purposes.

No comparison with data presented in Chapter 3 was made, as this study started more than two years before that of Chapter 3.

Abstract

An acoustic caller for the African mole cricket, *Gryllotalpa africana*, was developed in collaboration with Precision Technologies Company, Inc. (Durham, NC, USA). The design was modified from that developed for use in *Scapteriscus* species in the United States. The caller was run two or three times per week for 14 weeks. On these night's, operation began as soon as mole crickets were heard calling (usually around 20:00, local time (GMT + 2 hours)) and continued for one and a half hours. Observations were made every 15 minutes and mole crickets approaching within 5 m of the speaker were collected and sexed. The caller attracted mole crickets on approximately half the nights it was operated. Recordings of 10 calling mole crickets were made at 50 mm (within the near field of the sound) from the tunnel entrance. Analyses of recordings indicate the frequency of the calls varied less than 10% and the frequency of the electronic caller fell within that range. The volume of the caller was similar to that of the actual crickets, which probably limited its ability to compete with calling males. Notes on differences observed in calling behaviour were also noted.

Keywords: Mole crickets, turfgrass, acoustic caller, calling behaviour

5.1 Introduction

Mole crickets are serious pests of highly managed turfgrass throughout the world. The African mole cricket, *Gryllotalpa africana*, has been reported as an important pest in many areas and particularly in South Africa on golf courses (Brandenburg & Schoeman in prep.). Although *G. africana* has been reported from many parts of the world, Townsend (1983) reports this species is found only on the continent of Africa. The calling parameters reported for *G. africana* from other parts of the world were therefore discounted for the purposes of this study.

The subterranean nature of mole crickets makes early detection difficult and serious damage often results. The inability to detect the early instars of the mole crickets, the buffering effect of the soil environment, and various other aspects of mole cricket behaviour render management with synthetic chemical insecticides quite difficult. The results obtained are often less than satisfactory and the cost of managing mole cricket infestations can be relatively high. Since the early instars of mole crickets are generally the easiest to control with insecticides, accurate timing of application is critical (Brandenburg *et al.* 1997, 2000). However, at this developmental stage, damage from the feeding of the small nymphs is not detectable. An accurate knowledge of pest biology and ecology is therefore important to develop effective management programs. Very little information on the biology and ecology of *Gryllotalpa africana* is available for South Africa, and the effective management of this pest based upon limited current knowledge is difficult. This study sought to contribute to understanding of mole cricket ecology through the development of an electronic acoustic caller and using it to gain insight into mole cricket flight activity.

The primary function of the acoustic signals produced by male insects is to attract sexually responsive females (Alexander 1975) and in most crickets the sound is produced by tegminal stridulation. The stridulating mechanism and sound production of *Gryllotalpa* mole crickets was described in detail by Bennet-Clark (1970a), and is similar to that observed in other Gryllotalpids. The two species studied by Bennet-Clark (1970a), *G. gryllotalpa* and *G. vineae* Bennet-Clark, both form singing burrows at the soil surface and begin calling shortly after sunset.

Scapteriscus males also create calling chambers (Nickerson *et al.* 1979) and Forrest (1991) showed that males singing from chambers constructed in moist soil often produce the loudest calls. The louder calls are more attractive to females (Forrest 1980, 1981), who often lay their eggs in these moist areas, which enhance egg viability and hatch. Because of the similarities in the habits and life history of Gryllotalpids, it is likely that there is a similar relationship between moisture and calling intensity in *Gryllotalpa* species. *Scapteriscus* females may fly more than once to the calls and occasionally males also arrive at the site (Ulagaraj & Walker 1973). Once mating has occurred, eggs are laid and hatch follows approximately 20 days after oviposition.

Ulagaraj & Walker (1973) were the first to perform controlled studies to demonstrate that flying mole crickets are attracted to electronic reproductions of conspecific calling songs. Basic techniques for using acoustic callers to trap mole crickets were developed by Ulagaraj (1975) and Ulagaraj & Walker (1973, 1975). Since then acoustic callers have been used in a variety of studies to monitor mole cricket flight activity and abundance (Walker 1982, Walker & Fritz 1983), study the geographic variation in flights (Walker *et al.* 1983 and Braman & Hudson 1993), and to collect live crickets for research (Walker 1982, 1988), or to be used as fish or animal food (Walker 1988). Fowler (1988) developed traps using electronically produced calls of *Scapteriscus* to attract and collect live specimens of the mole cricket parasitoid *Ormia depleta* (= *Euphasiopteryx depleta*) for biological studies and Forrest (1983) used the phonotactic response to synthesized songs to differentiate *Scapteriscus* species in Puerto Rico from those found on the U.S. mainland. Ngo & Beck (1982) investigated flight behaviour and the potential for controlling the southern mole cricket, *Scapteriscus borellii* using sound traps. Acoustic calling traps have also been used to inoculate mole crickets at the sound source with entomopathogenic nematodes for biological control (Parkman & Frank 1993), attract crickets into nematode-treated areas to increase the probability of infection (Parkman *et al.* 1993), and quantify the level of nematode infection in mole cricket populations (Parkman & Frank 1992). Additionally, the callers have been used to attract crickets into insecticide-treated areas, or away from areas of managed

turfgrass. Acoustic calling traps in the United States (North Carolina) have been used to monitor flights and develop techniques for predicting oviposition and egg-hatch.

Studies on *Scapteriscus* species in North Carolina have utilized two models of electronic callers, capable of simulating the mating call of the tawny mole cricket, *Scapteriscus vicinus* and the southern mole cricket. The first model used was the Mans Artificial Cricket (B. J. Mans, Mountain View, CA), and later, the Night Caller™ (Eco-Sim, Gainesville, FL), a modification and improvement on the Mans design. Both types were developed for use in the turfgrass research program at the University of Florida. Each unit consists of a sound-synthesizer computer chip, programmed with the song of both species (selectable by internal switch in Mans, external switch in Night-Caller), an amplifier, a speaker, and a photocell to initiate calling at dusk. The unit can be powered with either a 12V DC battery, or an 115V AC/12V DC invertor. Beginning at sunset, each unit would automatically broadcast the song selected at 105 dB for two hours.

Previous acoustical works on *Gryllotalpa* species include two studies where differences in calling songs were used taxonomically to distinguish between species (Bennet-Clark 1970b, Nevo & Blondheim 1972). Kavanagh (1987) studied the efficiency of sound production in *G. australis*, and Chuckanov & Zhantiev (1987) reported on the attraction of two *Gryllotalpa* species to artificial male calling songs. Townsend (1983) reported on the mating call parameters for several *Gryllotalpa* species, including *G. africana*. Due to the increasing importance of this species on golf courses in South Africa, I pursued the development and testing of an acoustic caller.

5.2 Material and methods

The new type of caller utilized here was designed and developed by Precision Technologies Company, Inc. (Durham, NC, USA) and powered by a 12-volt "motorcycle" type battery. The new units can be programmed to call any species of which the calling parameters are known. For this study the calling parameters of the units were modified to produce continuous calls in the middle of the ranges for a

mean carrier frequency of 2.1 -2.4 kHz and a mean syllable repetition rate of 49.1 - 57.8/sec. as reported by Townsend (1983). Duty cycle was set to 50 %. The caller was then tested at the Silver Lakes Country Club (25°46'30''S; 28°22'20''E), located on the southeastern edge of Pretoria, Gauteng, South Africa. The caller unit was deployed two to three times per week from mid November 1999 to late February 2000 (Table 5.1). The unit was operated on one of three putting greens, located within 75 m of the clubhouse. The entire unit was placed on the turfgrass surface. A significant amount of male calling was heard in this area each evening prior to the use of the caller. The speaker of the unit was directed toward areas of the golf course known to be infested by mole crickets. Observations indicate the mole crickets began calling 30 to 45 minutes after dark. This was usually around 20:00, local time (GMT + 2 hours) and the caller unit was turned on at that time and run for approximately one and a half hours. The area around the caller (a circle 10 m in diameter) was checked every 15 minutes with a flashlight for the presence of any crickets moving towards the caller. All crickets found were collected for subsequent identification and determination of sex.

The calls of 10 mole crickets were recorded in numerous locations on the course during March 2000, at a mean (± SD) soil temperature (at a vertical depth of 100 mm in the soil profile) of 20.3 °C (± 3.61 °C) (range: 18 °C – 25 °C). The field recordings were made using a hand-held digital recorder with a self-contained microphone (Nomad DAP-3201 (Creative Technology Ltd.)), held 50 cm from the mole cricket tunnel opening, longitudinal to the long axis of the burrow. The recording distance was within the near field of *G. africana* song (see Hill 2000 for calculation). "Canary" V1.2.4 (Cornell Laboratory of Ornithology 1998) software was used to analyse 30 syllables (10 successive syllables randomly selected at the beginning, middle and end per recording, respectively) of each recording for mean carrier frequency, mean syllable repetition rate, and mean duty cycle.

Table 5.1 Number of *Gryllotalpa africana* attracted to the electronically synthesized call from 20:00 to 21:30 (local time (GMT + 2 hours)) at Silver Lakes Country Club, Pretoria, South Africa, from November 1999 to February 2000.

Date	Absolute number attracted	Date	Absolute number attracted
1999/11/15	2	2000/01/01	1
1999/11/16	3	2000/01/04	1
1999/11/18	3	2000/01/06	0
1999/11/27	2	2000/01/09	0
1999/11/28	0	2000/01/11	0
1999/11/30	0	2000/01/20	2
1999/12/04	0	2000/01/21	1
1999/12/05	2	2000/01/26	0
1999/12/07	0	2000/01/27	1
1999/12/09	1	2000/02/01	4
1999/12/13	0	2000/02/02	0
1999/12/14	0	2000/02/09	4
1999/12/15	3	2000/02/16	0
1999/12/19	0	2000/02/17	1
1999/12/21	0	2000/02/21	2
1999/12/22	0		
1999/12/29	0		
1999/12/30	2		

5.3 Results and discussion

The synthetic caller proved capable of attracting mole crickets within 15 minutes on the first night. It was ascertained that the mole crickets were attracted to the caller by the fact that periodic checks throughout a much larger perimeter (25 meter diameter) did not reveal any mole crickets on the greens. In addition, mole crickets often

would crawl under or attempt to crawl on top of the speaker, indicating an obvious attraction to the sound. All crickets captured were female *G. africana*. During four of the six nights the caller was operated in November, crickets were attracted with the maximum number being three. In December, crickets were attracted on only four out of twelve nights the caller was operated and the maximum number was three crickets in an evening. Data collected in January indicate that crickets were attracted on five out of the nine nights the caller was operated and the maximum number caught in a single night was two. Results in February found crickets attracted to the caller on four out of six nights with a maximum number of four attracted in a single evening. All crickets captured landed within 10 m of the caller and crawled to within a meter or closer of the speaker. Matheny *et al.* (1983) studied *Scapteriscus* species in the U.S. and reported that not all of the mole crickets land close to, or at the sound source and that males land further away than females. Overall, crickets were captured on 17 of the 33 nights the caller was operated.

The mean carrier frequency of the recorded cricket calls was 2.216 kHz (range: 2.114-2.359 kHz) and the mean syllable repetition rate was 57.57 syllables/s (range: 50.74-70.10 syllables/s), all mean values of which are within the ranges determined by Townsend (1983) by which the electronic caller was programmed. The mean duty cycle of the recorded calls was 52.6% (range: 38.47-64.75%), which was set to 50% on the electronic caller (standard for *Scapteriscus*), as Townsend (1983) did not provide values for this variable. The volume of the caller was similar to that of the actual crickets, which probably limited its ability to compete with calling males. Walker & Forrest (1989) found that increasing the sound intensity of the callers (dB) increased trap catch for *Scapteriscus* species and Forrest (1980, 1981) found more *Scapteriscus* females attracted by louder conspecific calls. This may be even more important in *G. africana*, as the calls of the males appear to be significantly louder than those of some *Scapteriscus* species. The fact that the volume of the caller was not as high relative to the background level of the actual crickets calling, as those used in North Carolina for *Scapteriscus* species, may explain the relatively low number of crickets captured in an evening. Studies in North Carolina indicate that even during the peak flight times, numbers of flying

females varies greatly from one night to another. Traps in North Carolina operate nightly, whereas the traps in South Africa were operated on a sporadic basis approximately once every third night. In effect, the evenings may have been "missed" when larger numbers were flying. Currently design modifications are pursued to increase the volume (sound pressure level) of the callers used in this study to make them more effective for this species. The caller sound parameters, based upon the findings of Townsend (1983), in which only four recordings were used for sound analysis, appear appropriate for continued use.

This electronic caller attracted *G. africana*, and proved it has potential to monitor mole cricket flight activity in South Africa. Enhancements in the sound production volume, frequency and pulse rate, based upon digital recordings made on site, should enhance the effectiveness of this unit to more accurately monitor flight activity. Recent advances in low cost digital recorders and sound analysis software make the potential for the development of such callers for species worldwide, a rather simple procedure. Once modified, these callers may prove useful in further studies of mole crickets in South Africa and thus aid in the effective management of this serious turfgrass pest. The callers may also prove useful in identifying and collecting predators and parasitoids for biological control of these pests.

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Chapter 6

Management of *Gryllotalpa africana*

"... applying an insecticide may be the only practical way to prevent severe damage when sudden or unexpected outbreaks of pest insects occur." – Potter (1998).

Abstract

The African mole cricket is a serious economical pest of turfgrass in South Africa. The most important aspect of chemical management of mole crickets is the timing of insecticide application. Fipronil (Regent), fipronil (Termidor), thiamethoxam (Actara) and furfural (Crop Guard) were evaluated in two independent field trials for efficacy in controlling an early instar nymph population and a late instar nymph/adult population of *G. africana* over 28 days, respectively. Treatments were applied to randomly selected blocks and infestation quantified by a soap water flush. Fipronil (both trade names) and thiamethoxam were effective in controlling early instar nymphs and will be optimally applied during eclosion in November. Only fipronil (both trade names) was effective in controlling the late instar nymph/adult population. Late summer, autumn and winter chemical application is not recommended.

Keywords: Fipronil, thiamethoxam, optimal treatment period, eclosion, early instar nymphs, turfgrass

6.1 Introduction

The African mole cricket is a serious economic pest of turfgrass in South Africa. Different chemicals have been applied all over the world to control supposed populations of *G. africana* on different crops. *Gryllotalpa africana* were found to be responsible for damage to the roots of Chinese yam in Japan (Matsuura *et al.* 1985). Soil application of micro-granules of isoxathion during the active period of *G. africana* was effective in preventing injury (Matsuura *et al.* 1985) (the study probably did not refer to the "true" *G. africana*). Granular formulations of chlorpyrifos were found to be highly effective in Senegal (North Africa) against *G. africana* on potatoes (Collingwood *et al.* 1980). Sithole (1986) stated that insecticidal dusts (carbaryl and phostoxin) placed in the entrance of burrows should be effective (in the absence of a registered insecticide) for mole cricket control in Zimbabwe. With heavy infestations, the insecticide may be applied as a drench spray or watered on to the lawn or field (Sithole 1986).

Carbamate and organophosphorous chemicals are currently registered against mole crickets in the U.S.A., but are slowly losing their registration 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).

Relatively new insecticidal chemical classes include the phenyl pyrazoles, neonicotinoids and aldehydes. Phenyl pyrazoles have a unique mode of action in that they block the passage of chloride ions through the gamma-aminobutyric acid (GABA) regulated chlorine channel, disrupting the nervous system of the insect (Potter 1998). Fipronil (a phenyl pyrazole) is a broad-spectrum insecticide (Natural Resources Institute 2000), systemic when applied as a soil treatment and provides long residual control (Potter 1998). Fipronil is toxic to certain groups of gallinaceous birds and some fish species (Natural Resources Institute 2000). Fipronil is also toxic to aquatic invertebrates and some beneficial insects (including bees), but virtually non-toxic to earthworms (Natural Resources Institute 2000). Neonicotinoids have long residual activity (Potter 1998), with a primary mode of action of blocking the nicotinic acetylcholine receptor sites of the insect nerve, thereby disrupting the

nervous system, resulting in death (Potter 1998 and Syngenta 2003). Thiamethoxam (a neonicotinoid) is a systemic, broad-spectrum insecticide (Syngenta 2003) and is toxic to bees, fish and aquatic invertebrates (Delahaut 2001). The mode of action of aldehydes (e.g. furfural) as insecticides has not been documented.

The current optimal management strategy for mole crickets appears to be integrated pest management (Frank & Parkman 1999). Some potential biological control agents and cultural control methods have been identified for *G. africana* and will be thoroughly investigated and incorporated with chemical management in future studies. Chemical management is currently the main management tool used to control *G. africana* in South Africa in absence of any products specifically registered for mole crickets.

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). 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 conductive to high pesticide efficiency (Brandenburg & Williams 1993). As a guideline, control strategies can be initiated 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).

6.2 Material and methods

Two field trials were conducted on turf infested with *G. africana*, using similar chemicals, but on different temporal and spatial scales. The first field trial was conducted on a kikuyu grass area of 500 m^2 (five 10 m × 10 m blocks), at the Silver Lakes Country Club, Pretoria, Gauteng, during January 2002. The second field trial was conducted on a kikuyu grass area of 415 m^2 (five blocks that varied in length and width), at the University of Pretoria (Pretoria, Gauteng) during March/April

2002. Blocks within the turfgrass areas of the two trials were randomly allocated to one of four insecticides and a control (untreated) area (Figs. 6.1, 6.2). The respective recommended product dosages (Table 6.1) were applied to grass surfaces (approximately at 8h30 local time (GMT + 2 hours), to minimize photodecomposition) with a Knapsack sprayer at both sites, after which the insecticide - and control blocks were immediately watered for 15 minutes (using the golf course irrigation system at Silver Lakes Country Club and lawn irrigation system at the University of Pretoria, delivering a similar water volume per unit time, respectively). The insecticide chemical groups, trade names, formulations, active ingredients and gram active ingredient per 100 m^2 are presented in Table 6.1. Infestation was quantified at both sites by flushing the treated and untreated block with soapy water (50 ml Sunlight® dishwashing soap/5 litres H_2O/m^2) in 0.25 m^2 randomly selected infested areas (three replicates per block) at 0, 3, 7, 14, 21 and 28 days after treatment. No samples were taken within 0.5 m from block perimeters (to counteract the edge effect of spray drift). Flushes started at noon on each sampling date during both trials. Emerging crickets were counted per replicate per treatment per sampling date during each trial. All the flushed crickets were also measured (from the posterior of the abdomen (excluding cerci) to the distal end of the labrum) before treatment (zero days after treatment) at both trial sites. All sampled blocks within and between field trials were under a similar irrigation program and soap flushing efficiency was assumed to be homogenous for adults and nymphs between and within blocks and trials over the study period. Immigration and emigration (especially through flight in trial 2) were also assumed to be at equilibrium and not to effect absolute cricket sizes, life stage percentages and infestation density during each trial. Mole cricket infestation densities were constant between blocks at the onset of each trial (no significant differences were found between blocks before treatment (zero days after treatment) – refer to results section) and assumed to be relatively evenly distributed within infested turf per block over the study period.

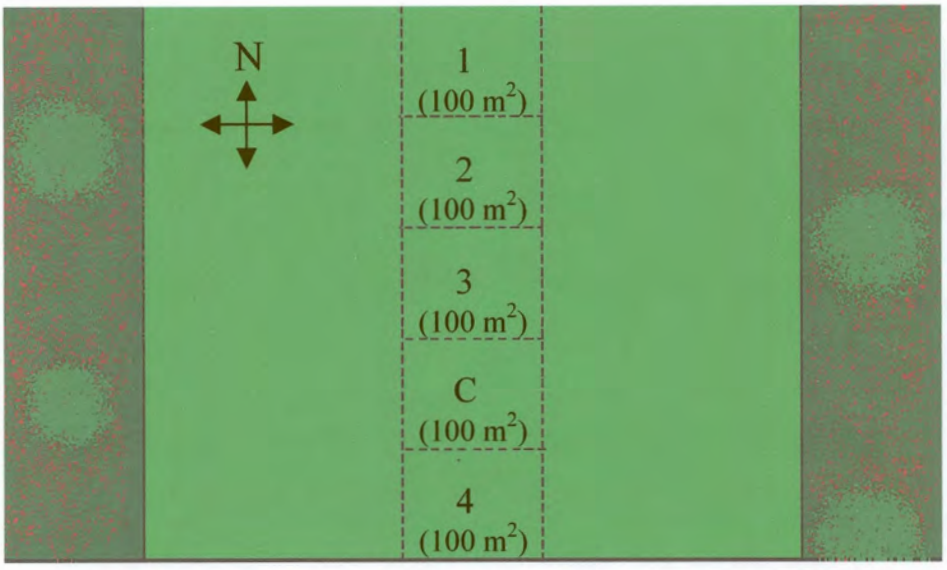

Fig. 6.1 Schematic representation of the chemical control experiment at Silver Lakes Country Club. Blocks were treated with Actara (1), Termidor (2), Crop Guard (3), Regent (4) and untreated (C). The green areas represent fairway turfgrass (kikuyu grass), the brown and dark green areas the rough surface with trees, next to the fairway. The figure is not to scale.

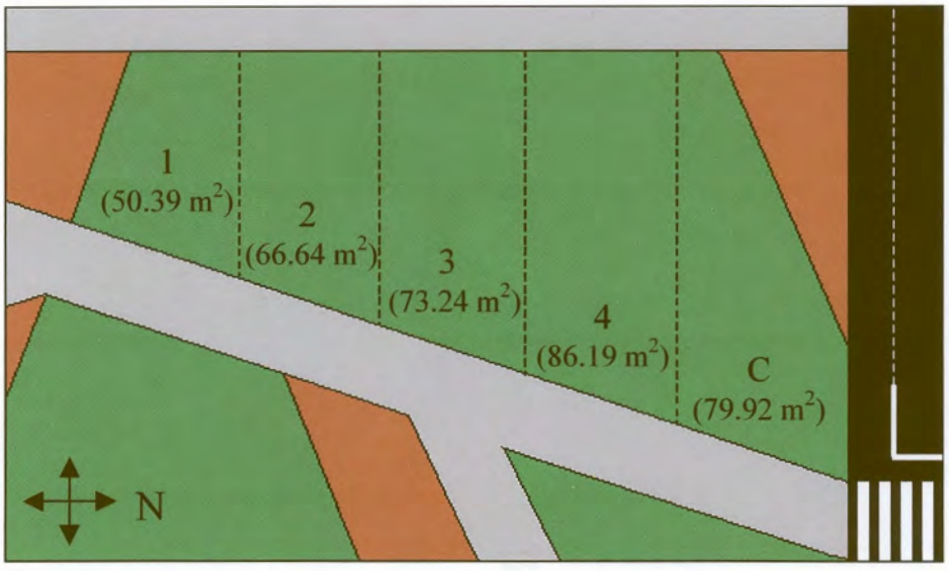

Fig. 6.2 Schematic representation of the chemical control experiment at the University of Pretoria. Blocks were treated with Termidor (1), Regent (2), Actara (3), Crop Guard (4) and untreated (C). The green areas represent turfgrass (kikuyu grass), the brown areas shrub beds, the grey areas concrete pathways and the black area a road. The white parallel lines represent a pedestrian crossing. The figure is not to scale.

Table 6.1 Chemical groups, trade names, formulations, active ingredients, gram active ingredient per 100 m^2 and recommended product dosages of four insecticides evaluated against *Gryllotalpa africana* at Silver Lakes Country Club (trial 1) and the University of Pretoria (trial 2).

Chemical group	Trade name (Formulation)	Active ingredient (ai)	Gram active ingredient (gai) per 100 m^2	Recommended product dosage/ha
Phenyl pyrazole	Termidor (EC)	Fipronil (25 $g.l^{-1}$)	0.38	1 500 ml
Phenyl pyrazole	Regent (SC)	Fipronil (200 $g.l^{-1}$)	0.40	200 ml
Neonicotinoid	Actara (SC)	Thiamethoxam (240 $g.l^{-1}$)	2.81	1 170 ml
Aldehyde	Crop Guard (EC)	Furfural (900 $g.l^{-1}$)	270.00	30 000 ml

6.3 Results

The weekly density data of each field trial were normally distributed (Kolmogorov-Smirnov test, $p > 0.05$) ("Statistica" Version: 5 (Statsoft Inc. 1995)) in the linear state (Sokal & Rohlf 1997). The parametric one-way ANOVA (Analysis of variance) (Sokal & Rohlf 1997) and post hoc Tukey HSD (Honestly Significant Difference) test (Sokal & Rohlf 1997) were used to quantify differences between treatments per date. Tables 6.2, 6.3 summarizes the weekly mean number of mole crickets on each chemically treated block and the control (untreated) block, as well as significant differences between them for each respective field trial ("Statistica" Version: 5 (Statsoft Inc. 1995)). Initial infestation (zero days after treatment) between blocks was homogenous at the first and second field trial at Silver Lakes

Country Club and University of Pretoria, respectively (Tables 6.2, 6.3). The initial (at zero days after treatment) mean population size (in terms of absolute length of all sampled individuals) was 9.2 ± 1.1 mm (mean ± SD) and 21.8 ± 5.42 mm (mean ± SD) in field trial 1 (January 2002) and field trial 2 (March/April 2002), respectively. The mole cricket population consisted only of early instar nymphs in the first field trial, with the population comprising of adults (8.2 ± 2.90 %) (mean ± SD) and late instar individuals (91.8 ± 2.90 %) (mean ± SD) during the second field trial.

Significant differences were found between treatments and the control block from three and 14 days after treatment, in the first and second field trial, respectively (Tables 6.2, 6.3).

In the first field trial, fipronil (Regent) was the only chemical which resulted in a significant reduction in the population (relative to the control block) at three days after treatment (Table 6.2). Seven days after treatment, the fipronil (Termidor) treated block showed the lowest infestation, but not significantly lower than the thiamethoxam treatment (Table 6.2). At 14 days post treatment, the fipronil (Regent) treated block had a mean of 1.33 mole crickets per square metre, a value that was significantly lower than that of the thiamethoxam treated block, but not significantly different from the fipronil (Termidor) treated block (Table 6.2). Three and four weeks after the insecticides were applied, both fipronil treated blocks and the thiamethoxam treated block had zero mole crickets per square metre (Table 6.2). The fu.fural treated block showed the highest infestations per square metre of all insecticide treatments over the 28-day monitoring period. Furfural caused a gradual decline in infestation, levels that were significantly lower than the control block at seven, 21 and 28 days post treatment (Table 6.2). No phytotoxicity of any of the treated blocks was observed during the experiment.

In the second field trial, the control block infestation declined over the monitoring period (Table 6.3). Fipronil (Regent) and fipronil (Termidor) were the first (at 14 days after treatment) and only of all the tested insecticides that resulted in significantly lower infestation levels than the control block 28 days after treatment (Table 6.3). At three and four weeks after initial treatment, the infestation

on the thiamethoxam treated block was not significantly different from the fipronil treatments (Table 6.3). Furfural treated turf did not show a significant reduction in *G. africana* infestation over the 28 days of monitoring (relative to the control block) (Table 6.3). There was also no phytotoxicity of any of the treated blocks observed during the second field trial.

Table 6.2 The mean number of mole crickets per m^2 on the insecticide treated blocks and control block over four weeks at Silver Lakes Country Club (trial 1). (Means in columns with letters in common are not significantly different ($p > 0.05$)). DAT = days after treatment.

Chemical	*** Mean number of mole crickets per m^2**					
(Trade name)	**0 DAT**	**3 DAT**	**7 DAT**	**14 DAT**	**21 DAT**	**28 DAT**
Fipronil (Termidor)	73.33^{A}	57.33^{A}	17.33^{A}	5.33^{BC}	0.0^{B}	0.0^{B}
Fipronil (Regent)	77.33^{A}	38.67^{B}	46.67^{C}	1.33^{C}	0.0^{B}	0.0^{B}
Thiamethoxam (Actara)	72.0^{A}	56.0^{AB}	25.33^{B}	6.67^{B}	0.0^{B}	0.0^{B}
Furfural (Crop Guard)	73.33^{A}	65.33^{A}	58.67^{C}	56.0^{A}	52.0^{C}	49.0^{C}
Control (untreated)	73.33^{A}	73.33^{A}	74.67^{A}	76.0^{A}	69.33^{A}	68.67^{A}

* Sampled in 0.25 m^2 grids.

Table 6.3 The mean number of mole crickets per m^2 on the insecticide treated blocks and control block over four weeks at the University of Pretoria (trial 2). (Means in columns with letters in common are not significantly different ($p > 0.05$)). DAT = days after treatment.

Chemical	* Mean number of mole crickets per m^2					
(Trade name)	0 DAT	3 DAT	7 DAT	14 DAT	21 DAT	28 DAT
Fipronil (Termidor)	57.33^a	46.67^a	36.0^a	20.0^b	5.33^b	4.0^b
Fipronil (Regent)	40.0^a	37.33^a	12.0^a	13.33^b	2.67^b	1.33^b
Thiamethoxam (Actara)	44.0^a	44.0^a	44.0^a	49.33^a	18.67^{ab}	16.0^{ab}
Furfural (Crop Guard)	56.0^a	74.67^a	26.67^a	49.33^a	29.33^a	24.0^a
Control (untreated)	58.67^a	56.0^a	45.33^a	49.33^a	21.33^{ab}	24.0^a

* Sampled in 0.25 m^2 grids.

6.4 Discussion

Insecticides were efficient in controlling *G. africana* populations of different sizes (in relation to absolute length) and consisting of early instar nymphs or late instar nymphs and adults. The efficacy of different chemicals in controlling *G. africana* of different lengths and population constitutions (in relation to ontogenic stage) was however variable.

When the mean nymph population size (in terms of absolute length) was relatively small (mean length of 9.2 mm), fipronil (Regent), fipronil (Termidor) and thiamethoxam (Actara) were effective in reducing mole cricket infestations at relative homogenous rates from more than $70/m^2$ to $0/m^2$ in three weeks. The lower fipronil concentration of the Termidor (relative to Regent) treated block did not significantly influence efficacy. Furfural (Crop Guard) showed the lowest level of mole cricket control and was relatively ineffective.

Fipronil and thiamethoxam should therefore be used to control early instar nymphs. Both active ingredients are systemic and may show long residual activity (Potter 1998 and Syngenta 2003). Treatments will therefore be optimally applied during the eclosion (egg hatch) period, generally during November in Pretoria, Gauteng. During this period, fipronil application can be seasonally and spatially altered with thiamethoxam.

The mole cricket population during the start of the second field trial (March/April 2002) included late instar nymphs and some adults. The latter may have increased during the evaluation period. During the March/April insecticide efficacy study, the mole cricket density also declined unexpectedly (over the monitoring period) in the control block. The fact that adult numbers were relatively constant in the control block over the study period may indicate that adults emigrated (at a higher rate than immigration) by flight during this period and that moulting final instar nymphs (to become adults) maintained constant adult numbers. The rate of density decline was assumed to be homogenous over the experimental area.

Late instar mole cricket nymphs and adults (mean absolute individual length of 21.8 mm) were only controlled with fipronil. The rate of control of fipronil was lower for large nymphs and adults than for smaller nymphs. The lower fipronil concentration of the Termidor (relative to Regent) treated block did not significantly influence efficacy. Thiamethoxam did provide some control at a relatively low rate, but was not efficient. Furfural showed no significant density reduction of relatively large mole crickets.

Periods when nymphs were larger (in terms of absolute length) and developed into adults were therefore not optimal for insecticidal control. If treatment is absolutely essential, fipronil should be applied. Late autumn applications will not be effective, as the majority of crickets enter an over wintering phase, minimizing insecticide exposure.

In a preliminary study, fipronil was found to be effective in controlling *G. africana* up to a year after surface application to an early instar nymph population.

No evidence of poisoning of non-target species (including earthworms and birds) was observed during both field trials. Earwigs and spiders were also still present at 28 days after treatment in both studies, but a decline in the population was not empirically tested.

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Chapter 7
Glossary

"Each scientific and technical field has a particular vocabulary... it results from the need for precision in terminology, whilst avoiding, for example, misplaced anthropocentric terms derived from human anatomy." – Gullan & Cranston (1994).

7.1 Glossary of relevant entomological and selected technical terms

Active ingredient (ai): The actual toxic material present in a pesticide formulation (Potter 1998).

Adjuvant: Any ingredient that improves the properties of a pesticide formulation (Potter 1998).

Antixenosis: A term derived from the Greek word *xenos* (guest), the inability of a plant to serve as a host to an insect herbivore due to deterrent factors (Smith *et al.* 1994).

Apterous: Wingless (Scholtz & Holm 1985).

Augmentative biological control: The supplementation of natural enemy numbers when low densities are inefficient in controlling a pest. The method relies on successful laboratory mass production of the natural enemy (Frank *et al.* 1998).

Biopesticide: Pesticides composed of high densities of a biological control agent, generally a pathogen. It can be produced on an industrial scale and is usually not pest specific, but generally non-toxic to birds, amphibians, reptiles, mammals and fish (groundwater) (Frank *et al.* 1998 and Potter 1998) (also see pesticide definition).

Brachypterous: With short or abbreviated wings (De la Torre-Bueno 1978).

Chorion: The outermost shell of an insect egg, which may be multilayered, including exo - and endochorion and wax layer (Gullan & Cranston 1994).

Conspecific: An organism of the same species as another (MSN Encarta World English Dictionary 2002).

Coring: Using hollow metal tubes (called spoons or open tines) to remove a core of soil from the turf to reduce thatch and compaction (also known as core cultivation or aerating) (Emmons 1995 and Christians 1998).

Eclosion: Emergence of the adult from the pupa, or the process of hatching from the egg (Scholtz & Holm 1985).

Fossorial: Formed for or with the habit of digging or burrowing (De la Torre-Bueno 1978).

Germarium: The structure within an **ovariole** in which the **oogonia** give rise to **oocytes** (Gullan & Cranston 1994).

Glabrous: Smooth, hairless (Scholtz & Holm 1985).

Imago: The adult and sexually developed insect (De la Torre-Bueno 1978).

Integrated pest management: An environmentally responsible approach to pest control, minimizing harmful side effects and combining different preventative and corrective control methods, to increase cost-effectiveness and long-term reliability to maintain pest densities below levels of unacceptable damage (Dent 1991 and Potter 1998), based on pest biology, especially population dynamics (Frank *et al.* 1998).

Macropterous: Long or large winged (De la Torre-Bueno 1978).

Microorganism: A living organism, microscopic in size, such as a bacterium, fungus or virus (Potter 1998).

Micropterous: Small winged (De la Torre-Bueno 1978).

Moulting: The periodic process of loosening and discarding the cuticula, accompanied by the formation of a new cuticula, and often by structural changes in the body wall and other organs (De la Torre-Bueno 1978).

Ontogeny: The development from egg to adult (Gullan & Cranston 1994).

Oocyte: An immature egg cell formed from the **oogonium** within the **ovariole** (Gullan & Cranston 1994).

Oogonium: The first stage in the development in the **germarium** of an egg from a female germ cell (Gullan & Cranston 1994).

Ovariole: One of several ovarian tubes that form the ovary, each consisting of a **germarium**, a **vitellarium** and a stalk or **pedicel** (Gullan & Cranston 1994).

Pedicel: The stem or stalk of an organ; the stalk of an **ovariole**, the second antennal segment; the "waist" of a Formicid (Gullan & Cranston 1994).

Pesticide: Any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pests, as well as any substance or mixture of substances intended for use as a plant growth regulator, defoliant, or desiccant (Potter 1998). Pesticides may be residual or non-residual (contact), with different formulations available. Pesticides are classified (according to pest class) as insecticides, herbicides, fungicides, and nematicides, which can be toxic to birds, amphibians, reptiles, mammals and/or fish (Frank *et al.* 1998) (also see biopesticide definition).

Phonotaxis: Orientation to sound in animals; or a positive reaction to sound (modified from **phototaxis** definition) (De la Torre-Bueno 1978).

Phototaxis: Orientation to light in animals; or a positive reaction to light (De la Torre-Bueno 1978).

Pubescent: Downy (Scholtz & Holm 1985).

Pyrethroid: An organic synthetic insecticide with a structure based on that of **pyrethrum** (Potter 1998).

Pyrethrum: A natural botanical insecticide derived from *Chrysanthemum* flowers (Potter 1998).

Saltatorial: Adapted for leaping; having the power of leaping (De la Torre-Bueno 1978).

Spermatheca: The saclike structure or reservoir in female insects that receives the sperm during coitus and often stores sperm (Potter 1998 and Scholtz & Holm 1985).

Spermatophore: An encapsulated package of spermatozoa (Gullan & Cranston 1994).

Tegmen (pl., tegmina): A covering, the hardened leathery forewing in Orthoptera, sometimes employed also in the Heteroptera for the hemelytra (De la Torre-Bueno 1978).

Thatch: A tightly intermingled layer of living and dead roots, crowns, rhizomes, stolons and organic debris that accumulates between the zone of green vegetation and the soil surface (Christians 1998 and Potter 1998). Thatch is a result of an imbalance between the production and decomposition of organic matter at the soil surface (Potter 1994).

Topdress: Spreading a thin layer of soil mix or other finely granulated material over a turf area and working it into the turf to stimulate thatch decomposition and to smooth the surface (Emmons 1995 and Christians 1998).

Turfgrass: A species or cultivar of grass, usually of spreading habit, which is maintained as a mowed turf (Emmons 1995 and Potter 1998).

Vertical cutting: Cutting slices in the turf with a machine that has blades mounted on a vertically rotating shaft (also referred to as vertical mowing) (Emmons 1995).

Vitellarium: The structure within the **ovariole** in which **oocytes** develop and yolk is

provided to them (Gullan & Cranston 1994).

Vitelline membrane: The outer layer of an **oocyte**, surrounding the yolk (Gullan & Cranston 1994).

Vitellogenesis: The process by which oocytes grow by yolk deposition (Gullan & Cranston 1994).

Voltinism: The number of generations per year. The prefix annotates the number of generations, e.g. semi-, uni-, bi and multivoltine refer to a half, one, two and several generations in one year, respectively (Gullan & Cranston 1994).

7.2 Glossary of relevant acoustic terms

Carrier frequency: Frequency of maximum power in cricket songs, often subjectively described as **pitch**. It is generally set by the rate of movement of the plectrum on one forewing (tegmen) moving against the teeth of the file on the under surface of the opposite tegmen and by tuned physical (skeletal) characteristics of the tegmina (Moore 1989). (Unit: Hz or kHz). (Also see Fig. 3.3).

Chirp: A short, discrete group of simple or complex syllables (pulses) of sound, usually of less than 0.5 s duration (Moore 1989) (also see **trill** definition).

Duty cycle: Percentage of the total time in a period for the duration of sound (the remaining percentage of a period represents the silent intersound interval) (Moore 1989). (Formula: Syllable duration (s). (Syllable period (s))$^{-1}$ × 100).

Inter syllable interval: The silent time from the end of sound in one sound unit to the beginning of sound in the next similar sound unit (Moore 1989). (Unit. s or ms). (Formula: Syllable period (s) – syllable duration (s)). (Also see Fig. 3.4).

Pitch: A measure determined by frequency, but also dependant on loudness (Unit: Hz or kHz) (Giancoli 1995) (also see **sound pressure level**).

Sound pressure level (SPL): Acoustic decibels, measured at a stated distance in relation to pressure (microbars or micropascal) in a logarithmic scale. Sound pressure level may be loosely equated with sound intensity and sound power level (these two terms refer to power, watts, rather than pressure) and with loudness. Apparent loudness (sound intensity), by contrast, varies subjectively, depending especially on carrier frequency, wave form and sound pressure level (Unit: dB)

(Moore 1989).

Stridulation: The production of sound by rubbing two roughed or ridged surfaces together (Gullan & Cranston 1994).

Syllable duration: Time from the beginning of a sound unit (syllable) to the end of sound in that unit (Moore 1989), produced by a single closing wing stroke (Bennet-Clark 1970a). (Unit: s or ms). (Also see Fig. 3.4).

Syllable period: Time required for any cyclic event in cricket song; 360° of phase. (Time from the beginning of a sound unit (syllable) to the end of the silence interval after that sound unit). (Moore 1989). (Unit s or ms). (Also see Fig. 3.4).

Syllable repetition rate: Number of syllables produced per unit time (Moore 1989), corresponding to the wing stroke rate (Bennet-Clark 1970a and Kavanagh 1987)). (Unit: Syllable.s^{-1}). (Formula: (Syllable period (s))$^{-1}$).

Trill: A series of syllables (pulses) produced together, too long to be termed a chirp (also see chirp definition) (Moore 1989). Also see Fig. 3.4.

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