Population dynamics and integrated management of *Prostephanus truncatus* (Coleoptera: Bostrichidae) in Manica Province, Mozambique

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DEDICATION

To

To my beloved daughters, Yarissa Bernardo **Muatinte** and Fatima Milagrosa Bernardo **Muatinte** and my son, Isac Bernardo **Muatinte** and

my niece Ivone de Fatima Jaime **Matiquina**

for this dissertation to be their inspiration!

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ABSTRACT

The Larger grain borer, *Prostephanus truncatus* (Coleoptera: Bostrichidae), was introduced from Southern and Central America into Africa during the late 1970s, and has since then established in 20 African countries. This pest reduces the storage period of maize grain and cassava chips in granaries of small scale farmers. This reduced storage period results from larvae and adult feeding with subsequent shortening of the period that these commodities are available as food. Depending on storage period, yield losses of up to 45% and 100% have been recorded for maize and cassava chips respectively in West Africa, while 62% yield losses of maize during storage have been reported in Mozambique. In Mozambique, *P. truncatus* was first recorded in 1980 in the Manica Province. *Prostephanus truncatus* occurs throughout Mozambique with higher population densities and maize grain damage in the Manica and Tete Provinces, where it is a severe pest of maize grain, cassava chips and other cereals. Chemical and biological control measures have been used for *P. truncatus*. However, the pest continuously disperses, colonizes new habitats and causes much injury to stored maize grain and cassava chips. This study aimed to review current literature regarding *P. truncatus* and to assess the effect of abiotic and biotic factors in spatial and temporal fluctuations of *P. truncatus* numbers. Host plant species, altitude and climatic factors were also taken in account in this study. Moreover, the study aimed at assessing the effect of mass trapping in *P. truncatus* numbers and assessing suitability of wild plants and firewood as hosts of *P. truncatus* in Mozambique with reference to the central and Southern regions. This project will provide this knowledge which is scarce or non-existent in Mozambique. Results will inform rural small farmers, government and non-government organizations, decision makers and stakeholders regarding improved pest management measures and could hence reduce population densities of the pest with particular reference to the Manica Province in Mozambique.

Prostephanus truncatus pest status in Africa is high and the degree of infestation and damage vary between regions. This variation in pest status is due to climatic conditions, food sources, and differences in storage infra-structure development and efficacy of control methods. Its temporal and spatial dispersion is unpredictable and depends on ecological factors, maize and dry cassava trade routes, and availability of forest host plants. Development of sustainable integrated management strategies is a key to future successful management of this pest. Area-wide management strategies using the predator, *Teretrius nigrescens*, parasitoids, plant derived products and environmentally friendly insecticides are needed. Integrated management practices must be based on improved knowledge of *P. truncatus* population dynamics and its determining factors.

Generalized linear models showed that abiotic and biotic factors affect *P. truncatus* numbers. However, the strength of the effect varied between villages and years. Mean numbers of host plant species, the maximum and minimum temperature, relative humidity and rainfall had an effect on *P. truncatus* number over years. Average temperature did not affect trap catches of *P. truncatus*. Models were not validated due to absence of previous similar data on *P. truncatus* in the studied villages and in Mozambique in general. Higher numbers of *P*. *truncatus* were caught in Massingir (231 individuals per trap per month) followed by Machipanda village (104). Moreover, the high numbers of beetles were present during both the dry and rainy seasons and in all land use types of the Massingir village compared to other villages. In general higher numbers of beetles were trapped during the rain season and in human settlements. Designed models and the analysis of *P. truncatus* flight activity per season and per land use type form a baseline for further studies toward predicting dispersal and potential areas of invasion by *P. truncatus* in Mozambique.

Mass trapping of *P. truncatus* with the use of universal moth traps (Uni-traps) showed that the lowest mean number of beetles per trap captured over a month-period was 26 individuals at Mapai in August while the highest was at the village of Massingir in November (8089). The highest mean beetle density per maize ear (335 individuals) was found in control granaries. The maize kernel weight reduction was higher and increased over time in granaries without traps than in those with them. These findings indicate that mass trapping with the use of Uni-traps represents a potential method for effective control of *P. truncatus* in granaries of small scale farmers.

Research on suitability of plant species sold and used as firewood recorded, *P. truncatus* in three (*Brachystegia spiciformis, Colophospermum mopane* and *Strychnos spinosa*) of the six plant species used for these purposes in Manica and Gaza Provinces. Moreover the pest survived and bred in 13 tree and 7 grass species. Dry maize stalks were also highly suitable for pest survival. Dry wood of the tree species *B. spiciformis*, *Colophospermum mopane* and *Cassia abbreviata* as well as the grasses *Acroceras macrum* and *Hyparrhenia hirta* were very good hosts for development of *P. truncatus*. The sale and transport of firewood that host *P. truncatus* may be an important driver of the spread of this species. Uninfested areas where plant hosts occur and are abundant, are likely to be infested by this pest in the future. This knowledge will contribute to the development of practical integrated measures for management of *P. truncatus*.

Key words: *Prostephanus truncatus,* population dynamics, integrated pest management, Mozambique

TABLE OF CONTENTS

CHAPTER ONE

General Introduction

1.1. Introduction

The Larger grain borer (LGB), *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) was introduced from Southern and Central America into Tanzania at the end of the 1970s, where it was first recorded in the Tambora region (Dunstan and Magazini, 1981). Afterwards it was recorded in Togo (Harnisch and Krall, 1984). In Mozambique *P. truncatus* was first recorded during 1980 in the Manica Province followed by Mutarara region of the Tete Province during 1999 (Cugala *et al.,* 2007). Since then the larger grain borer became a serious pest of stored maize and dry cassava, reducing the storage period of these commodities in granaries of small scale farmers. This reduction results from larval and adult feeding, with subsequent shortening of the period that these commodities are available as food. This pest can also infest and cause damage to stored timber and timber products (Wright, 1984). Infestation and resulting damage by *P. truncatus* is preceded by spatial and temporal expansion, habitat invasion and colonization by the pest.

Dispersal and establishment of this pest is influenced by its capacity to survive on dry wood of several forest plant species (Helbig *et al*., 1992; Nang'ayo *et al*., 1993; Nansen *et al*., 2002), predation by *Teretrius nigrescens* (Coleoptera: Histeridae) (Helbig and Schulz, 1996; Richter *et al*., 1997; Holst and Meikle 2003; Schneider *et al*., 2004; Hell *et al*., 2006), as well as climatic conditions (Hodges, 1986; Giles *et al.,* 1996; Borgemeister *et al.,* 1997; Wellington *et al.*, 1999; Farrell, 2000, Hodges *et al.,* 2003) and availability of commodity food sources (Hodges *et al*., 1983; Markham *et al*., 1991; Hodges 1994; Helbig, 1995; Borgemeister *et al.,* 1997; Roux, 1999; Hill *et al*., 2002; Cugala *et al*., 2007; Gueye *et al*., 2008). However, the potential effect of local climatic factors as well as abundance, biodiversity and availability of food sources, with particular emphasis on forest host plant species (Makundi, 1987; Nang'ayo *et al*., 1993; Helbig, 1995; Nang'ayo *et al.*, 2002; Jia *et al.*, 2008) is still unexplored in southern Africa. Modeling and multivariate analysis of *P.*

truncatus flight activity have been done to predict *P. truncatus* flight activity and for estimating likely subsequent population outbreaks and infestation of maize and cassava chips in granaries (Meikle *et al.*, 1998; Nansen *et al*., 2001; Hodges *et al.*, 2003; Omondi *et al*., 2011). However, the question arises whether flight activity models for *P. truncatus* are applicable in diverse geographical environments.

Efforts to control the Larger grain borer have largely focused on the use of pyrethroids and organophosphate dusts (Gwinner *et al.*, 1997; Richter *et al*., 1998; Holst and Meikle, 2003; Schneider *et al*., 2004; Chintzoglou *et al*., 2008; Kavallieratos *et al*., 2010a) inert dusts (Barbosa *et al*., 1994; Stathers *et al.*, 2004) and plant derived products (Berger, 1994; Bekele *et al*., 1997; Tapondjou *et al*., 2002; Smith *et al*., 2006). Other control strategies include physical methods with the use of high temperature exposure for short periods (Mourier and Poulsen, 2000) and biological control by means of the exotic predator, *Teretrius nigrescens* Lewis (Coleoptera: Histeridae) (Richter *et al*., 1997; Holst and Meikle, 2003; Hell *et al*., 2006; Cugala *et al.,* 2007; Muatinte and Cugala, 2015). The effectiveness and large scale application of plant derived products to control *P. truncatus* is still a concern. Adequate dosages need to be determined and large scale cultivation of these plant species are needed, all factors which adversely affect the cost-benefit ratio of using plant-derived products for control of Larger grain borer. The potential use of parasitoids (Helbig, 1998), entomopathogenic fungi and bacteria (Odour *et al*., 2000; Chintzoglou *et al.,* 2008; Hertlein *et al*., 2011), resistant host plants (Meikle *et al.*, 1998) and semiochemicals (Cox, 2004; Steward-Jones *et al*., 2006; Steward-Jones *et al*., 2007) for the management of *P. truncatus* are emerging and promising approaches. Pest management strategies include the use of admixed inert dusts (Golob, 1997), synthetic insecticides in combination with diatomaceous earth (Chintzoglou *et al*., 2008; Kavallieratos *et al*., 2010b), wood ash and entomopathogenic fungi (Smith *et al*., 2006). Despite the development of these management practices the beetle continuously disperses and causes severe damage to maize grain and dry cassava chips mostly in granaries of small scale farmers in Africa and particularly in Mozambique.

The general objective of this study was to investigate aspects of pest biology and ecology that could contribute to improvement of management measures for *P. truncatus* in Mozambique. This objective will be achieved by conducting research on:

(1) abiotic and biotic factors that affects *P. truncatus* population numbers in the Manica and Gaza Provinces,

(2) the potential use of mass trapping for the control of *P. truncatus* (Coleoptera: Bostrichidae) in small scale farmer granaries in the Massingir and Chicualacuala districts and,

(3) the host suitability of wild plant species and species used as fire wood for *P. truncatus* in Mozambique.

The results of the study are presented as individual chapters, dealing with the following topics:

1. The effect of abiotic and biotic factors on spatial and temporal fluctuations of *Prostephanus truncatus* populations in the Manica and Gaza Provinces, Mozambique.

2. Mass trapping of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in small scale farmer granaries in Mozambique.

3. Suitability of wild plants and firewood as hosts of *Prostephanus truncatus* in Mozambique.

CHAPTER TWO

Literature Review

2.1. *Prostephanus truncatus* origin and dispersal

Prostephanus truncatus is originally from America where, since 1981 it has spread throughout the southern region of the United States of America to Central America and Mexico (Markham *et al*., 1991). From the American continent, *P. truncatus* dispersed into Africa (Dunstan and Magazini, 1981; Harnisch and Krall, 1984; Cugala *et al.*, 2007). The term dispersal as used in this thesis denotes population redistribution, which results in a time and spatial spread of a population as a consequence of individual movements (Turchin and Omland, 1999). Accidental dispersal of the pest by means of human transport of host food products and residues (Farrell, 2000; Gnonlonfin *et al*., 2008; Muatinte and Cugala, 2015), as well as through transport of wood sticks of potential forest host plant species (Borgemeister *et al*., 1998a; Nang'ayo *et al.*, 2002; Nansen *et al*., 2004) has been taken in to account as well. Dispersal is a crucial and functional variable of population dynamics since it is determined by climate factors such as temperature and humidity, wind speed, altitude and latitude. Dispersal is affected by environmental heterogeneity, for example food quantity and quality, its distribution in time and space, disturbed and undisturbed fields or habitats, and variations in topography, soil and biota within each field (Price, 1997; Huffaker and Gutierrez, 1999; Wellington *et al.,* 1999). Dispersal of insect individuals and species can result from tritrophic metapopulation interactions, inter- and intra-specific competition for food, feeding and breeding habitats (Gutierrez, 1999). Broadly, dispersal of insects is based on ecosystem dynamics and processes (Price, 1997), trophic complexity of insect communities (Thompson and Althoff, 1999) and on insect-plant population and community interactions (Nowierski *et al*., 1999).

The dependence of dispersal on multiple factors has arisen from the assumption that insect individual variation is a key in dispersal ecology, linking movement behaviour and dispersal and population processes (Hawkes, 2009). From this approach some conceptual knowledge is generated: (1) a quantitative description of dispersal which fit distance data and incorporate realistic assumptions about the underlying movement is necessary (Okubo and Levin, 2002). This will not only improve the way in which dispersal is described, but will also increase the understanding of movement mechanisms and link dispersal and population dynamics. (2) Movement between habitat patches and breeding sites must be described as dispersal, quantitatively and qualitatively different from the migration/movement occurring within patches and which is aimed at foraging and finding of mating partners and refuges (Hanski, 1999; Fahrig, 2007).

2.2. *Prostephanus truncatus* spatial and temporal dispersal

Prostephanus truncatus long-distance dispersal has been attributed to transport and trade of commodities, particularly maize and dry cassava chips (Tyler and Hodges, 2002; Omondi *et al*., 2011). This could in fact have been the means of transport of this pest from Mexico and Central America to Africa (Markham *et al*., 1991), possibly through shipments of infested maize grain (Harnish and Krall, 1984). Inter-country transport and trade of maize grain and dry cassava chips, associated with a lack of, or inadequate quarantine regulations, measures and practices have been indicated as factors that lead to *P. truncatus* dispersal around Africa (McFarlane, 1988; Markham *et al*., 1991; Fadamiro, 1996; Tyler and Hodges, 2002).

Experiments on short-range flight ability of the Larger grain borer support the observations on long-distance dispersal reported above. For instance, Farrell and Key (1992) used a mark-release-recapture technique and showed that over a 24 hour period, *P. truncatus* could fly in a directed manner to a pheromone source in an upwind direction for 50-100 m from the release point. Distances of 250 to 340 m were the maximum distances of flight reported by Rees *et al.* (1990) and Farrell and Key (1992) for Larger grain borer flight towards a pheromone source over a 72 hr period. Pike (1993), however, considered *P. truncatus* as a fairly strong flier, after observations that beetles in tethered flight under laboratory conditions could fly 25 km over a period of 45 hours.

These findings demonstrate that the Larger grain borer is capable to disperse by flight. However, no evidence exists that flight time period in natural environments lasts as long or involve such distances as described above (Farrell, 2000). In addition, individual insect movements and, hence dispersal, can be hindered by physical barriers such as density and patchiness of forests, mountains, hills and seasonal or permanent flowing rivers. From field and empirical observations in the Manica Province, it can be assumed that frequent and seasonal forest fires can kill insects and physically destroy their habitats, and hence inhibit their capability for flight and temporal dispersal at population level. Information regarding *P. truncatus* intra- and inter-country invasion and dispersal time periods and distance could provide an estimate of dispersal rate of the pest under different environmental conditions.

Approximately 20 African countries are affected by *P. truncatus*. Estimates based on years of public notification of *P. truncatus* occurrence in the respective countries in Africa (Table 2.1) show that the pest took approximately 23 years to disperse and establish in nine countries in West Africa, 16 years in five countries of eastern and central Africa and 14 years in six countries of southern Africa. These data are rather biased due to uncertainty of the time of *P. truncatus* invasion in these countries and due to the potential delay that may have occurred in public notification about the occurrence and dispersal of the pest around Africa. Bias can be expected for example, from countries where information on *P. truncatus* occurrence is still scarce or unknown, while such a country may be located within a region where pest establishment have been confirmed for a long period of time. The size of countries could also bias data on spatial and temporal dispersal of *P. truncatus* throughout the Africas continent. For example the combined surface area of Togo, Benin and Ghana, are smaller than that of Tanzania. Therefore, *P. truncatus* could disperse faster through several and smaller countires than it could move throughout large countries. The presence of inter-country trade of *P. truncatus* host food products such as maize and cassava could also influence estimates of temporal and spatial dispersal of the pest in Africa. The long temporal differences in public notification about *P. truncatus* between, for example two neighbouring countries, can also skew this estimate. Despite the clear progress in dispersal of *P. truncatus* around African countries throughout the last decades, routes taken by the pest from eastern and southern Africa countries into Mozambique (Fig. 2.1) are still a subject of discussion.

Table 2.1. Estimated *Prostephanus truncatus* invasion, dispersal and establishment time periods in Africa (Modified after Schulten (1996) and Farrell (2000)).

Country	Year of first report	Area	Reference	Estimated dispersal and establishment time period between two neighbouring countries (years)
Eastern and central Africa				
Tanzania	1981	Tabora district	Dunstan and Magazini (1981)	Tanzania and Kenya: two years
Kenya	1983	Taveta district	Kega and Warui (1983)	
Burundi	1984	Gisuru market	Schulten (1987)	Kenya and Burundi: one year
Rwanda	1993	Kigali	Bonzi and Ntambabazi (1993)	Burundi and Rwanda: nine years
Uganda	1997	Busia district	Opolot and Odong (1999)	Rwanda and Uganda: four years
Total dispersal period in eastern and central Africa				16 years
Southern Africa				
Malawi	1991	Karonga district	Munthali (1992)	Mozambique and Malawi: one year
Zambia	1993	Nakonde district	Milimo and Munene (1993)	Malawi and Zambia: two years
Namibia	1998	Northern Namibia	Larsen (1998)	Zambia and Namibia: five years
Mozambique	1999	Mutarara district	Cugala *et al.* (unpublished)	Namibia and Mozambique: one year
South Africa	1999	Kruger Park	Roux (1999), Giliomee (2011)	Mozambique and South Africa: less than a year
Zimbabwe	2005	Northern Zimbabwe	Nyagwaya *et al*. (2010)	Zimbabwe and South Africa: 5 years
Total dispersal period in southern Africa				14 years

West Africa				
Togo	1984	Lomé area	Harnish and Krall (1984)	Central America and Togo
Benin	1986	Mono region	Anon. (1986)	Togo and Benin: two years
Guinea Conakri	1988	Fouta Djallon region	Kalivogui and Müch (1989)	Benin and Guinea Conakry: two years
Guinea Bissau	1988	Bissau region	Aman *et al*. (2007)	Guinea Conakry and Guinea Bissau: less than a year
Ghana	1989	Volta region	Dick and Rees (1989)	Guinea and Ghana: one year
Burkina Faso	1991	Togo border	Bosque-Perez *et al*. (1991)	Togo and Burkina Faso: two years
Nigeria	1992	Oyo and Ogun states	Pike *et al*. (1992)	Pukina Faso and Nigeria: one year
Niger	1994	Niamey, Dosso, Gaya	Adda *et al.* (1996)	Nigeria and Niger: two years
Senegal	2007	Vélingara Boydo	Gueye *et al.* (2008)	Guinea and Senegal: nineteen years
Total dispersal period in western Africa				23 years

For example, the yellow straight arrows show the hypothesis of *P. truncatus* directly entering into Mozambique from Tanzania through the Cabo Delgado and Niassa Provinces. The curved arrow indicates entrance of the pest through Malawi into Niassa Province. Possible *P. truncatus* dispersal trends throughout the western and northern borders of Mozambique are shown by straight green and blue arrows.

Cugala *et al.* (2007) captured up to 2797 *P. truncatus* individuals in fifteen days of trap exposition in the Tete Province and 3753 beetles at the same time period in the Manica Province. Numbers of captured *P. truncatus* in the northern Provinces, Nampula, Cabo Delgado and Niassa ranged between 2 and 5 individuals per trap. Hence, the central and northern regions of Mozambique could be possible points of entrance of the Larger grain borer into Mozambique. The hypothesis of *P. truncatus* invasion into Mozambique through the Tete and Manica Provinces from Zimbabwe is likely valid as well, following the report by Rwegasira *et al.* (2003) on the potential invasion areas by the Larger grain borer in Zimbabwe. However, these hypotheses need to be tested studing phylogenetic and geographic differenciation of *P. truncatus* collected from other provinces of Mozambique as well as other countries.

This overview on dispersal of the pest can contribute to knowledge of the general picture of the total time period of its invasion and establishment, particularly in the African continent. The present and future negative impacts in Africa will increase if appropriate pest management measures are not taken againt the Larger grain borer. Information on the levels of pest infestation, damage and distribution in relation to fluctuation of climate factors and food source abundance of the invaded areas could provide accurate estimates of areas of potential *P. truncatus* invasion, colonization and establishment in the continent.

2.3. The role of host commodities and forest host plant species in *Prostephanus truncatus* dispersal

Borgemeister *et al.* (1998a) reported that some cultivated crops as well as certain forest host plants, other than the well known main hosts, serve as alternative breeding hosts which supports survival of *P. truncatus* in certain environments. The role of host commodities in dispersal of this pest has been widely reported (Hodges *et al*., 1983; Hodges, 1986; Markham *et al*., 1991; Hodges, 1994; Helbig, 1995; Borgemeister *et al.,* 1997; Stumpf, 1998; Roux, 1999; Farrell, 2000; Cugala *et al*., 2007; Gueye *et al*., 2008).

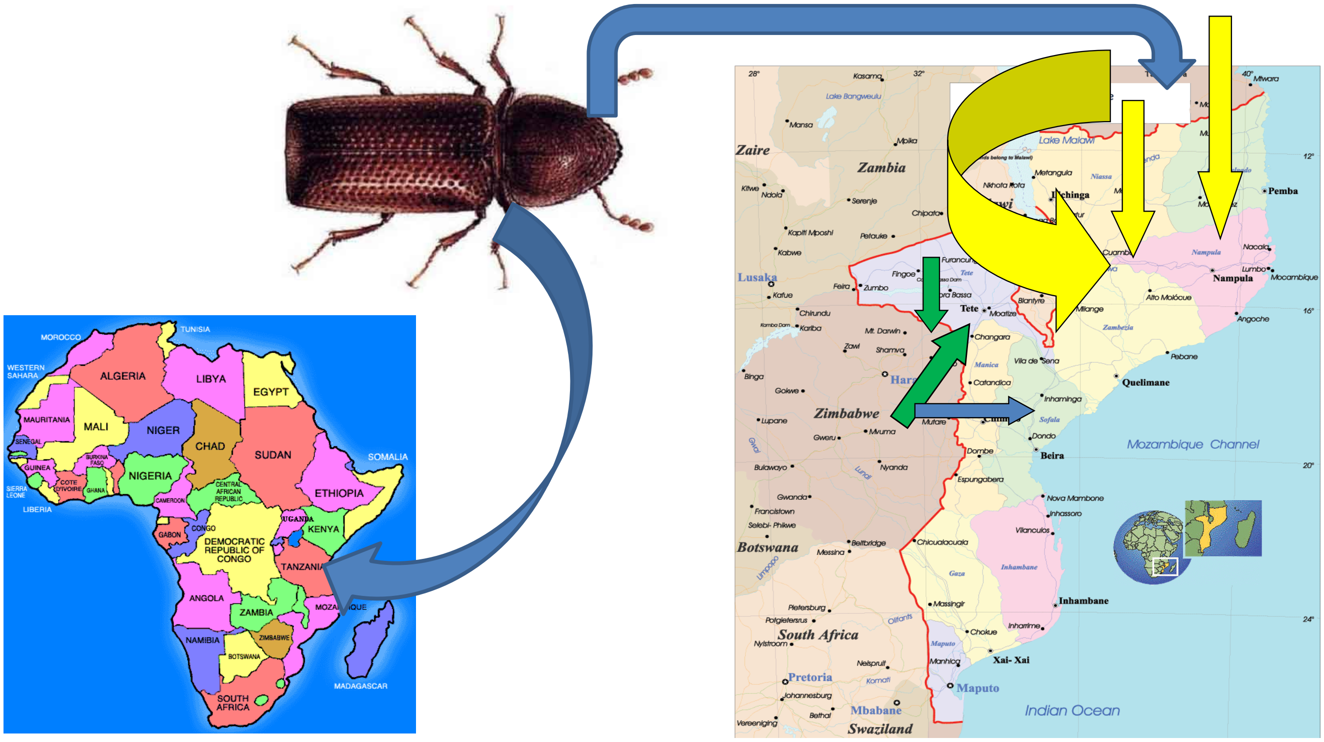

Fig. 2.1. *Prostephanus truncatus* hypothetical dispersal routes taken from East and southern Africa countries into Mozambique.

Birkinshaw *et al*. (2002) found a significant correlation between trap catch and infestation of stored maize and other products by *P. truncatus*. These results showed that pheromone-baited traps are effective tools for measuring dispersal of *P. truncatus* populations. Fadamiro and Wyatt (1995) indicated that large numbers of *P. truncatus* resulting in significant degradation of food resources could prompt dispersal of this pest. Scholz *et al.* (1998a) came to similar conclusions when studied *P. truncatus* flight initiation and flight activity in Benin. These authors observed that flight initiation depended on changes in the numbers and sizes of beetle populations in a given area, as well as on breeding site availability and suitability.

Reduction in food resources and quality can directly determine initiation of *P. truncatus* dispersal in closed commodity granaries, where the concentration of maize or cassava can be high and become reduced over time (Fadamiro and Wyatt, 1995; Scholz *et al.* 1998a). However, in open environments such as forest habitats, the occurrence, distribution and diversity of host-plant species, as well as its shortage and quality seem to determine the initiation of Larger grain borer dispersal. The capacity of the Larger grain borer to utilize forest plant species as a resource for its survival and dispersal has been published by Makundi (1987), Nang'ayo *et al*. (1993), Helbig, (1995) and Jia *et al.* (2008). Nang'ayo *et al.* (2002) studied the potential of *P. truncatus* to feed and breed on native and agroforestry trees and shrubs and reported that 27 out of 84 tree species supported the breeding of *P. truncatus* under laboratory conditions. Breeding success varied widely between tree species and showed no trends with regard to systematic position of species or wood hardness. These results suggest that determining factors, mostly secondary metabolites for forest host plant species exploitation by *P. truncatus*, should be further investigated. In addition, laboratory experiments on insect-host plant interactions should be conducted, particularly on searching, selection, acceptance and preference behavior as well as kairomones involved in the process.

Scholz *et al.* (1997) investigated *P. truncatus* host-finding behavior and concluded that kairomones, specifically those emitted by mature maize ears and probably by dried cassava functioned as short range attractants. *Prostephanus truncatus* long-range responses and hence its primary attraction to stored commodities could not be demonstrated. However, Fadamiro (1997) observed the absence of *P. truncatus* upwind flight to food volatiles or any synergism between pheromones and food volatiles, and suggested that the male-aggregation pheromone was the only known long-range semiochemical involved in dispersal and host selection. Host plant selection, infestation and successful breeding by *P. truncatus* are subjects of research importance since increased knowledge in this field could lead to predicting habitat invasion and colonization by this beetle in Africa. The use of stable isotope carbon and nitrogen marker methods (Hood-Nowotny and Knols, 2007; Mahroof and Phillips, 2007) may also be suitable for determining host plant-insect interactions.

Research on forest host plants as well as insect-commodity interactions focused on the role of these substrates as food sources that provide nutritional requirements for growth, development, reproduction and energy flow, rather than insect movements which lead to dispersal should be conducted.

2.4. Role of climate conditions in *Prostephanus truncatus* dispersal

Climate conditions which are favorable to high abundance, diversity and suitability of food sources have been suggested as driving factors of animal dispersal (White, 2008) and of *P. truncatus* in Africa (Hodges, 1986; Farrell, 2000). Giles *et al.* (1996) in Kenya and Borgemeister *et al.* (1997) in Benin found that the numbers of beetles trapped by means of pheromone traps varied seasonally and annually, signifying weather or climate effects.

At individual level, body temperature is the most basic variable determining rates of processes such as growth, development, feeding, fecundity and insect mortality (Wellington *et al.*, 1999). *Prostephanus truncatus* completes its life cycle in about 25-27 days at the optimum temperature of 32 ^{o}C and relative humidity of 70-80% under laboratory conditions on maize grain (Subramanyan and Hagstrum, 1991). Adults live for at least 4 months (Guntrip *et al*., 1996) excluding the effect of predators or other natural enemies and exogenous factors that can cause unpredicted death. The life-history of the Larger grain borer has been widely studied (Shires, 1980; Howard, 1983; Li, 1988). The capability of insects to disperse mainly by flight is generally determined by the success of their individual development and life-history trait adaptation to environmental conditions. Climate directly affects the propensity of insects to disperse through flight. Tigar *et al.* (1993) highlighted the possibility of results being influenced by rainfall, temperature, wind and trap positioning. Research on the impact of rainfall and humidity on *P. truncatus* population fluctuations, mainly mortality, particularly in the forest environment is needed. These data may show the contribution of these climate factors on the pest mortality and sustain the effectiveness of pest management measures.

2.5. The impact of semiochemicals on *Prostephanus truncatus* dispersal

Research on the effect of pheromones as a driving factor in *P. truncatus* flight activity and dispersal (Cork *et al.,* 1991) and in mating success (Johansson and Jones, 2007) has been widely conducted. This development resulted in the monitoring of flight activity of the Larger grain borer in several countries. Investigating the period of effective attraction of *P. truncatus* to synthetic pheromones over a 33-day period, Tigar *et al.* (1993) observed that the highest number of beetles was caught between 8 and 14 days after pheromone traps were put out.

The role of pheromones in female and male interactions has being published by Fadamiro *et al*. (1996), Smith *et al.* (1996), Birkinshaw and Smith (2001). The effect of the male aggregation pheromones on *P. truncatus* dispersal has been widely studied. Nang'ayo (1996) in Kenya, Borgemeister *et al.* (1998b) in southern Benin, Birkinshaw (1998) in Ghana, Hodges *et al*. (1998) and Scholz *et al*. (1998b) in Togo and Benin found that the use of synthetic pheromone traps, consisting of a mixture of Trunc-call 1 and Trunc-call for *P. truncatus* dispersal studies skewed surveyed populations by sex, because 60-70% of captured insects were females. In addition, traps captured more young beetles because they were more active fliers (Fadamiro *et al*., 1996; Scholz *et al*., 1997). Despite these disadvantages, pheromone-baited traps became the most effective method for studies of *P. truncatus* flight activity and abundance, and its relationship with climate and other environmental variables. The role that aggregation pheromones play, despite the presence of maize or other host plant volatiles in dispersal of *P. truncatus* has been demonstrated by Fadamiro *et al*. (1998). Fadamiro *et al.* (1996) demonstrated that *P. truncatus* response and dispersal could depend on the concentration and components of its pheromones. Birkinshaw *et al*. (2004) and Hodges *et al*. (2004) improved and optimized pheromone lures and trapping methodology to address the skewing of *P. truncatus* trap catches by sex and age.

Scholz *et al.* (1997) showed that commencement of infestation of maize by *P. truncatus* was prompted by releases of the male aggregation-pheromone, late in the storage season. Since the initiation of invasion of granaries is a consequence of dispersing beetle populations, it can be deducted that pheromone release by males plays an important role in pest dispersal towards maize storage facilities. It is also possible that pheromones play a role in the dispersal of beetles from granaries into forest environments. Apart from the role of pheromones in *P. truncatus* flight activity, Fadamiro (1997), hypothesized that young individuals rather than males or females played an important role in dispersal of the Larger grain borer since they could fly long distances.

2.6. Impact of predators and parasitoids on *Prostephanus truncatus* dispersal

Several studies on the impact of *Teretrius nigrescens* (Coleoptera: Histeridae) on *P. truncatus* have been conducted. These studies mostly highlighted the importance of the predator to suppress pest population density in granaries or forests (Helbig and Schulz, 1996; Richter *et al*., 1997; Schneider *et al*., 2004; Hell *et al*., 2006). Holst and Meikle (2003) reported the effect of predation by *T. nigrescens* on *P. truncatus* population dynamics. However, the direct effect of the predator specifically on flight activity patterns and dispersal is mostly unexplored. Borgemeister *et al.* (1997) observed that peaks of *T. nigrescens* flight activity were correlated with precipitation; whereas those of *P. truncatus* were only weakly related to precipitation. The latter study on the influence of seasonal and weather factors on annual flight patterns of *P. truncatus and T. nigrescens* did not show clear direct cause-effect relationships between the predator-prey population fluctuations. Omondi *et al.* (2011) monitored *P. truncatus* and *T. nigrescens* flight activity in Kenya and observed that the prediction model they used did not allow for assessment of the impact of *T. nigrescens* on *P. truncatus* density because it relied on the direct effect of temperature, humidity and precipitation and also excluded availability of stored maize grain. Some research work on monitoring *P. truncatus* trap catches after *T. nigrescens* releases has been made and showed no numerical differences in pest density and flight activity compared with periods prior to establishment of the predator (Giles *et al.,* 1996). *Teretrius nigrescens* did not reduce the abundance of pest populations in Guinea and the Sudan savannas in West Africa (Nansen *et al*., 2001; Schneider *et al*., 2004). A decrease in numbers and a hypothetical total absence of predator populations was observed a few months after their release in the western highlands of Kenya (Omondi *et al*., 2011). The theory of stable equilibrium (Hoddle, 2003) may explain the variation observed in insect population densities as observed for *T. nigrescens* and *P. truncatus*. Hypothetically, the large-scale and periodical use of pheromone sticky traps that attract and kill both the larger grain borer and the predator can gradually reduce the numbers of *T. nigrescens*. The aim of pest management is to reduce pest numbers. However, reduction of *T. nigrescens* populations in IPM and monitoring programs reduces the effectiveness of the predator and hence, its dispersal. Berryman and Gutierrez (1999) reported that predators can indirectly limit or regulate dispersal of their prey through regulation of population density. Means of search, communication and predator-prey encounter are important factors in inter and intra-specific interactions between insects (Berryman and Gutierrez, 1999; Steward-Jones *et al.,* 2007). Scholz *et al*. (1998b) conducted electro-antennogram and behavioural response studies on *P. truncatus* and its predator, *T. nigrescens*. This study showed that males and females of both the prey and the predator were similarly sensitive and responsive to aggregation pheromones of *P. truncatus*. These findings suggest that prey pheromones play a significant role in mutual dispersal of both *P. truncatus* and *T. nigrescens.*

2.7. Modelling and multivariate analysis of *Prostephanus truncatus* flight activity

Multivariate analysis has been used to design models and to predict *P. truncatus* flight activity as well as for estimating likely subsequent population outbreaks and infestation of maize and cassava chips in granaries. Meikle *et al.* (1998) in Benin designed a simulation model for *P. truncatus* and concluded that temperature affected development and flight activity more or less linearly; whereas the effect of humidity appeared to be non-linear. Nansen *et al*. (2001) investigated the response of *P. truncatus* flight activity to environmental variables in Benin and concluded that day length, minimum relative humidity, and minimum temperature were the most important variables explaining *P. truncatus* trap catches. This result provided some improvement on early attempts to predict catches. Hodges *et al.* (2003) in Ghana, examined the relationship between climatic variables, seasonal and annual variations in *P. truncatus* trap catches. These authors then developed a rule-based model, a useful tool to predict years of higher *P. truncatus* flight activity and to estimate the pest status in certain regions.

Current models for *P. truncatus* flight activity are sketchy in some aspects. The day length based-model of Nansen *et al.* (2001), which defined day length as the most important variable for predicting flight activity was able to accurately predict trap catch data between the latitudes of 6 to 9^{o} N, but the model was inaccurate in northern Benin (10^{o} N) (Hodges *et al*., 2003). This rule-based model is suitable for a range of conditions in which *P. truncatus* is likely to be a serious pest. However, it has to be tested under more extreme conditions and in different environments. It was also found to be difficult to set the scale (calibrate) for trap catches in areas where previous data were scarce or unknown. In addition, the scale of the rule-based model was seen to wrongly estimate host-plant suitability and the impact of predators and parasitoids on *P. truncatus* populations. A model based on climatic factors, designed by Omondi *et al*. (2011), accurately predicted seasonal trends of larger grain borer flight behavior in Kakamega in western Kenya and Mombasa located in coastal lowlands of the same country, but it was inaccurate in highland regions. Besides the availability of stored grain, the influence of climate factors, altitude, latitude and solar radiation on accuracy of prediction models should be considered.

The question can, therefore, be asked: “Will models that accurately predict *P. truncatus* flight activity and, hence, spatial and temporal dispersal become a reality in future, and will it be possible to use these on a large scale?” The positive answer to this question is more theoretical than practical, because variations in climate patterns and environmental variables such as habitat patches, topography, solar radiation, wind speed and host-plant species, host commodities and habitat connectivity vary significantly at local and regional level. These factors complicate the development of models which rely on large investment in resources, as well as time consumption. Simultaneous, large-scale spatial and temporal surveys needed to collect data for use in model development. It, therefore, seems more appropriate that models be developed at country or regional level.

2.8. The Impact of miscellaneous factors on *Prostephanus truncatus* dispersal

Despite all above referred factors, pathological effect in response to crowding, aggressive behavior, changes in development times and dispersal rates, genetic feedback and intra specific competition for space are some other intrinsic density dependant factors (Price, 1997) that can affect *P. truncatus* population dynamics, manly dispersal. Guntrip *et al.* (1996) observed phenotypic and genetic additive differences in body weight in emergence between and within sexes while comparing two strains of *P. truncatus* from Costa Rica and Togo. This study revealed no evidence of life-history trade-offs between the investigated strains. Scholz *et al.* (1998c) investigated physiological age-grading and ovarian physiology of *P. truncatus* and postulated that these life-traits could play a driving role in pest migration and dispersal.

These researchers, among other contributing results in adaptive capability of the Larger grain borer found that females alone could act as colonizers independently of males. In addition, Guntrip *et al*. (1997) detected life history trade-offs, mainly egg mass and clutch size in *P. truncatus* females by controlling resource acquisition of the adult beetle. Hence, research in this regard should address the impact of such differences on dispersal capacity of the Larger grain borer. Results obtained from such studies could form the basis for testing the hypotheses of the effect of genetic feedback and intra specific competition for space. This competition could act act as a potential factor influencing *P. truncatus* dispersal from and between granaries or within the forest environment. Wind and elevation gradient are factors of concern that can influence *P. truncatus* dispersal. For example, Fadamiro (1996) observed that *P. truncatus* could initiate flight under still air or at low wind speed. However, the wind speed higher than 30 cm/s could inhibit *P. truncatus* flight. Hodkinson (2005) reported the potential of elevation gradient in regulating abundance and species richness of insect communities. From that report a question is raised whether the elevation gradient could influence *P. truncatus* dispersal, colonization of new habitats and abundance followed by infestation and damage of commodities in Mozambique. Analysis of the influence of land use patterns and habitat heterogeneity on *P. truncatus* dispersal has been reported by Hodges, (1986), Makundi (1987), Markham *et al*. (1991), Helbig, (1995), Borgemeister *et al.* (1998a) and Nansen *et al.* (2004).

2.9. *Prostephanus truncatus* pest status

Prostephanus truncatus has become a serious pest of farm-stored maize, and cassava in Africa (Borgemeister *et al.*, 1994; Borgemeister *et al.*, 1998c) and worldwide (Boxall, 2002; Farrell and Schulten, 2002). The seriousness of *P. truncatus* damage to stored maize grain and cassava chips varies considerably among countries. Infested commodities are physically destroyed and become unsuitable for human consumption and trade (Richter *et al*., 1997) due to adults and larvae boring and damaging maize grain and dry cassava chips. High infestation levels result in accumulation of starch from insect metabolic excrements, fungal growth on stored produce and build-up of detritus in storage facilities. The Larger grain borer was reported to cause losses in maize of 9% percent over a five month period in western Tanzania (Golob, 1988). Pantennius (1988) reported dry weight loss of up to 45% of maize grain after eight months of storage in Togo. Shäfer *et al.* (2000) found that *P. truncatus* was the most destructive beetle of cassava chips in Benin in western Africa. Gnonlonfin *et al.* (2008), also in Benin, investigated infestation and population dynamics of insects on stored cassava and yam chips and found that *P. truncatus* was more prevalent with up to 90.9% of individuals and 100% infestation in the Northern Guinea Savannah. Hodges *et al*. (1985) reported losses up to 52.3% for fermented and 73.6% for unfermented cassava chips in Tanzania. This high level of damage was observed after a storage period of only four months. In Ghana, this beetle reduced storability of cassava chips from a previously acceptable period of one year or more, to between four and five months, with losses amounting to between 39 and 57% (Stumpf, 1998). In Mozambique, Cugala *et al*. (2007) found that *P. truncatus* infestations in maize granaries resulted in losses of up to 59% and 62% in the Manica and Tete Provinces, respectively. Maize grain storage periods in the Tete province were reduced from 10-12 to 6-8 months. These authors argued that this reduction resulted from invasion of *P. truncatus* during the early 1980's in the Mutarara district, Tete Province. Borgemeister *et al.* (1997) reported increased losses of stored cassava chips since *P. truncatus* was first reported in West Africa. Gueye *et al*. (2008) reported up to 35% of stored maize grain loss caused by mixed infestations of *P. truncatus* and *Sitophilus zeamais* Motscholsky (Coleoptera: Curculionidae), *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) and *Rhyzopertha dominica* (Fabricius) (Coleoptera: Bostrichidae) in Senegal.

Information on the exact quantities of maize and cassava chips stored by farmers is scarce. However, Helbig and Schulz (1996) estimated that 70% of the 120.000 to 150.000 metric tons of cassava produced annually in Togo was stored. This information, as well as the market prices of commodities is needed to enable a scientific estimate of the economic importance of the Larger grain borer in Africa. Compton *et al.* (1998) found that marketed maize reached its lowest price in September after the main harvest in Ghana. Prices slowly increase to a peak during the low maize production period of May-June in Ghana. The authors suggested that fluctuations of maize prices, among other factors were due to variation in maize grain damage caused by insect pests around post-harvest periods. Apart from the lack of appropriate storage infrastructure, the lack of sustainable, low-cost control methods significantly contribute to high levels of damage by *P. truncatus* to important commodities such as maize and cassava worldwide.

Apart from that, a question could be asked: "does inter-specific pest competition influence on maize grain damage in granaries?" Answers to this question are far from converging. Vowotor *et al.* (2005) observed that the degree and strength of association between *P. truncatus* and the maize weevil, *S. zeamais* increased monthly in sample granaries in Benin. However, all maize ears with high numbers of *P. truncatus* contained some individuals of *S. zeamais*. In contrats to this, no *P. truncatus* individuals were found in ears with numerical dominance by *S. zeamais*. These findings suggest that there might be interspecific competition for food between *P. truncatus* and *S. zeamais*. *Sitophilus zeamais* becomes more aggressive against the Larger grain borer in this competition. Makundi *et al.* (2010) investigated dynamics of infestation and losses of stored maize due to *P. truncatus* and *S. zeamais,* in Tanzania. These authors found that maize infestation and losses in granaries increased under inter-specific competition for food between the Larger grain borer and the maize weevil. Therefore, questions regarding the effect of inter-specific competition of *P. truncatus* with other pests in granaries on IPM practices remain unanswered. For instance, whether and how these species relationships could be exploited for IPM improvement in maize granaries? These and related questions are subjects of research concern. Hypothetically, the presence of other insect stored pests in granaries, preferable by the predator, *T. nigrescens* could regulate infestation by *P. truncatus* in maize, lowering or increasing the number of pest individuals. Factors that can influence *P. truncatus* pest status are mentioned by Osipitan *et al.* (2011) and Tefera *et al*. (2011a). Osipitan *et al.* (2011) referred to microbial composition of excrement induced by *P. truncatus* as a factor that increases damage of food commodity in granaries and subsequently increases pest status of the Larger grain borer. These researchers found in maize grain, dry root and tuber crops 10 bacterial species; *Bacillus cereus*, *B. macerans*, *Proteus mirabilis*, *P. morganic*, *P. rettgeri*, *Proteus* sp., *Pseud geniculatum*, *Pseud fragii*, *Pseud putela*, *Serratia marcences*. In addition, these authors found six fungal species, namely *Aspergillus niger*, *A. tamari*, *A. parasiticus*, *A. ochraceus*, *Fusarium compacticum* and *F. oxysporum*. Therefore, the presence of either bacteria or fungal species in infested commodities was associated with the presence of *P. truncatus'* excrement. Tefera *et al*. (2011b) reported that damage and maize grain loss due to *P. truncatus* could be affected by insect population density and by the durationof the maize storage period.

2.9.1. Infestation of alternative food sources and forest plant species

The Larger grain borer also infests and damages commodities other than maize and dry cassava chips. Wheat, *Triticum aestivum* (Poaceae), rice, *Oryza sativa* (Poaceae), chickpea, *Cicer arietinum* (Fabaceae), sweet potatoes, *Solanum tuberosum* (Solanaceae), sorghum, *Sorghum bicolor* (Poaceae), and several leguminous crops are some commodities that can host *P. truncatus* larvae and adults (Roux, 1999). Information on infestation and survival of *P. truncatus* on commodities, other than maize and cassava, in Africa is scarce. The beetle damages stored timber and timber-derived products and forest plant species. Infestation and survival of *P. truncatus* in several host plant species has been reported by Makundi (1987) and Nang'ayo *et al*. (1993) (Table 2.2). Jia *et al.* (2008) reported that several species of grasses, forbs and shrubs as well as forest trees facilitated survival as hosts of the lesser grain borer, *R. dominica* F. (Coleoptera: Bostrichidae). Since members of the Bostrichidae are evolutionary, typically wood borers, the latter authors hypothesized that *P. truncatus* had the potential to survive in several non-crop host plant species, similar to that of *R. dominica*.

Helbig (1995) detected that *P. truncatus* was capable to survive and reproduce in wood of 20 plant species including the cultivated trees *Anacardium occidentale* (Anacardiaceae), *Mangifera indica* (Anacardiaceae) and *Azadirachta indica* (Meliaceae). The use of most of these plant species for building granaries and household fences found by the authors is an additional factor contributing to *P. truncatus* breeding and dispersal especially in Africa.

Nang‘ayo *et al.* (2002) found 27 out of 84 native and agroforestry trees and shrubs which supported survival and breeding of *P. truncatus* under laboratory conditions in Kenya. These results can show a potential wide host range of *P. truncatus* in Africa, which along with other research results represent a significant contribution for the pest to be attributed the polyphagous status. However, insects in captivity may be forced to feed, survive and breed in plant species substrates not preferred under natural conditions. This fact may skew the conclusion about the real host spectrum of the Larger grain borer in the natural environment. The use of isotope markers, DNA-base gut content analysis such as polymerase chain reaction (PCR) or reverse transcription polymerase chain reaction (RT-PCR) could be alternative and feasible methods to determine the host plant range of *P. truncatus*.

Table 2.2. Host plant species with potential to breed *Prostephanus truncatus* (modified from Makundi (1987), Nang'ayo *et al*. (1993) and Helbig (1995)).

Forest plant species	**Family**	**Plant part attacked**	**Source**
Acacia spp.	Fabaceae	Seed and wood	Roux (1999)
Commiphora africana	Burseraceae	Seed and wood	Borgemeister *et al*. (1998), Roux (1999)
Delonix regia	Fabaceae	Seed	Helbig *et al*. (1992), Borgemeister *et al*. (1998)
Leucaena spp.	Fabaceae	Seed	Roux (1999)
Prosopis spp.	Fabaceae	Seed	Roux (1999)
Spondias purpurea	Anacardiaceae	Seed and wood	Ramirez-Martinez *et al.* (1994)
Ficus exasperate	Moraceae	Seed	Nang'ayo *et al.* (1993), Helbig and Schulz (1996)
Ceiba pentandra	Bombacaceae	Seed	Hill *et al*. (2002)
Lannea nigritana	Anacardiaceae	Seed and wood	Nansen *et al*. (2002)
Bursera fagaroides	Burseraceae	Seed	Ramirez-Martinez *et al.* (1994), Helbig and Schulz (1996)
Tectona grantis	Verbenaceae	Seed	Borgemeister *et al*. (1998), Nansen *et al.* (2004)
Sterculia tragacantha	Sterculiaceae	Seed and wood	Helbig and Schulz (1996)
Albizia adianthifolia	Leguminosae	Wood	Helbig (1995)

A survey done in the Herbaria of the Department of Biological Sciences, at Eduardo Mondlane University showed that the plant species listed in Table 2.2 occur widely in Mozambique. Herbarium records showed that they have been collected in the Manica, Bárue and Guro districts of the Manica Province and in the Chibabava district of the Sofala Province. The plant species occur also in the Massingir district of Gaza Province, in the Mocuba district of Zambezia Province as well as in different forests and human settlements (Senkoro *et al*., unpubl.). This finding suggests that *P. truncatus* breeding and survival, particularly in the natural forests of Mozambique, are possible. However, no study has been done to test this hypothesis.

Studies are needed to assess the role that wild host plant species play in the ecology of this pest. Therefore, more research on distribution, abundance, diversity and potential of local forest plant species in hosting *P. truncatus* is needed. This information can be used to predict temporal and spatial colonization and establishment of *P. truncatus* in different regions in Africa. Maize, cassava, wheat, sorghum, other commodities and forest host plants can play a role as food for *P. truncatus* colonization and establishment on the African continent.

2.9.2. Current status of pest management for *Prostephanus truncatus*

Integrated pest management (IPM), as defined by Kogan (1998) is the combined use of host plant resistance, biological control, cultural control and chemical control in order to keep pest populations below economic injury levels. This approach to pest management is discussed below with reference to *P. truncatus*. Chemical control based on the use of fumigants such as phosphine and methyl-bromide has been applied for the control of *P. truncatus* since it was detected in Mexico (Wong-Corral *et al.,* 2001) and invaded Africa (Golob and Hanks, 1990; Meikle *et al*., 1999; OEPP/EPPO Bulletin, 2012). Fipronil was reported to be effective against *S. oryzae* (L.), *T. confusum* Jacquelin du Val, *R. dominica* and *P. truncatus* (Kavallieratos *et al*., 2010a). Richter *et al.* (1998) investigated the efficacy of dust-formulated insecticides in traditional maize granaries, and found that pyrethroids, particularly deltamethrin, effectively controlled the Larger grain borer in West Africa. Dales and Golob (1997) found that application of 0.5 mg/kg deltamethrin with either 8 mg/kg pirimiphos-methyl or 8 mg/kg chlorpyrifosmethyl provided complete protection of maize for at least nine months against *Sitophilus* species and *P. truncatus* in Tanzania. Vassilakos *et al.* (2012) found spinetoram, a chemical insecticide of the class spynosin effective against six major stored grain insect species including *P. truncatus* in Greece. Efficacy of chemical control, particularly the use of chlorfenapyr for *P. truncatus* can be affected by abiotic factors such as temperature and humidity as well as biotic factors (Kavallieratos *et al.,* 2011).

a) Use of inert dusts

The use of inert dusts, particularly diatomaceous earths, has been tested and applied against *P. truncatus* (Golob, 1997; Korunic, 1998). Barbosa *et al*. (1994) reported that precipitated and fumed silica were effective in causing mortality of adult *P. truncatus*. Stathers *et al.* (2004) evaluated two commercially enhanced diatomaceous earth products, admixed with grain commodities and concluded that these could be effective and persistent for the control of storage pests, especially of the Larger grain borer. Stathers *et al*. (2008) in Tanzania concluded that diatomaceous earths have potential as grain protectants for small-holder farmers in sub-Saharan Africa. The use of inert dust by small scale farmers can be a sustainable alternative to conventional chemical insecticides. However, cost-effectiveness of processing diatomaceous earth products from raw material is a matter of high concern, and the development of such products remains a challenge.

b) Host plant resistance in *Prostephanus truncatus* control

Varietal resistance of host commodities or host suitability of forest plant species has potential for use in *P. truncatus* control. Meikle *et al.* (1998), in Benin Republic suggested the vigor of husks as a factor that could provide varietal resistance of maize against infestation by *P. truncatus* in granaries. Maize grain infestation, damage and its impact on *P. truncatus* population density has being reported by Hodges *et al.* (1983). Gnonlonfin *et al*. (2008) observed that infestation and population dynamics of insects seasonally fluctuated depending on the type of commodity such as cassava chips and yam (*Dioscorea* spp) (Dioscoreaceae). The variation in infestation levels could be due to varietal resistance of the commodities. Arnason *et al.* (1992) investigated the role of phenolics in resistance of maize grain to *P. truncatus* and *S. zeamais,* and found that variety-specific phenolic compounds influenced the suitability of grain for the development of the former pest. Kumar (2002) performed a series of infestation, selection and inbreeding experiments over four generations of maize land races and observed that the S^3 maize grain showed a high level of resistance against *P. truncatus*. This resistance was evident from low powder production caused by pest damage, relative to the susceptible control, as well as the small sizes of individuals developing on the resistant grains. This result suggested that antibiosis could be the mechanism of resistance operating within the S^3 progenies of selected land races. Tefera *et al*. (2011a) in Kenya, evaluated 54 hybrids and found eight to be resistant and 40 to be moderately resistant to *P. truncatus* and *S. zeamais*. This finding suggested that resistant hybrids contained genes conferring maize grain to be resistant either through antixenosis or antibiosis, resulting in reduced grain weight loss and powder production; and subsequently, an overall reduction in the impact of the two pests. However, in laboratory and field experiments, Meikle *et al*. (1998) concluded that maize kernel hardness and physical ear characteristics, such as husk extension and number of leaves might not play a role in plant resistance to *P. truncatus.* The presence of protease inhibitors in plant species represents a potential way to follow and use in *P. truncatus* control. For instance, Aguirre *et al*. (2004) discovered that the trypsin inhibitor purified and characterized from Chan seeds, *Hyptis suaveolens* (Lamiaceae) potently inhibited all trypsin-like proteases from *P. truncatus*. Hence, the authors proposed that this inhibitor could be used to enhance the defense mechanism of maize against the attack of *P. truncatus*. Research on and use of trypsin-like proteases in IPM for *P. truncatus* has also been supported by Castro-Guillén *et al.* (2012) in Mexico.

The heterogeneity in chemical and structural composition of plants, together with inter-plant variation prevents herbivorous insects from fully exploiting their host plants (Schoonhoven *et al.*, 1998). Evidence of this is supported by several authors (Berenbaum and Zangler, 1992; Olckers and Hulley, 1994). It is therefore suggested that further research on identification and practical use of digestive protein inhibitors from host commodities and forest host plant species in IPM for *P. truncatus* is needed. Such information will also contribute to better understanding of the mechanisms of *P. truncatus*-host plant interactions and, hence, identify certain habitat types/host plant communities that are vulnerable to pest invasion and colonization by *P. truncatus*.

c) Use of plant-derived products

The efficacy of plant derived products for control of stored insect pests, including *P. truncatus* has been widely investigated in Africa and worldwide (Rahman and Schmidt, 1999; Obeng-Ofori and Reichmuth, 1999; Bouda *et al*., 2001; Tapondjou *et al*., 2005; Kestenholz *et al.,* 2007; Rajendran and Sriranjini, 2008; Nukenine *et al*., 2010a; Kamanula *et al*. 2011; Silva *et al*., 2012). Locally available plant materials have been traditionally used by rural farmers in Nigeria (Poswal and Akpa, 1991), Zambia and Tanzania (Berger, 1994), Botswana (Jackai and Dust, 1986) in Mozambique (Segeren *et al*., 1993; Bila, 1996; Mapilele *et al.,* 1996) and Ghana (Owusu, 2001). Bekele *et al*. (1997) found dry ground leaves and oils of *Ocimum kenyense* (Lamiaceae) to be repellent and toxic to *S. zeamais* and *R. dominica* in Kenya. Osipitan *et al.* (2010a) in Nigeria, tested extracts of *Azadirachta indica* (Meliaceae)*, Nicotiana tabacum* (Solonaceae)*, Ocimum gratissimum* (Lamiaceae)*, Cola millenni* (Sterculiaceae)*, Tetracarpidium conophorum* (Euphorbiaceae)*, Delonix regia* (Fabaceae)*, and Vernonia amygdalina* (Asteraceae). These authors found that *A. indica* and *N. tabacum* had potential for use during post-harvest preservation of stored maize against infestation by *P. truncatus.* Tapondjou *et al*. (2002) in Cameroon tested leaf powder and essential oils of *Chenopodium ambrosioides* L. (Chenopodiaceae) against the Bruchid, *Callosobruchus chinensis*, *C. maculatus* and *Acanthoscelides obtectus*, the curculionids, *S. zeamais* and *S. granarius*, and *P. truncatus*. These researchers found *C. ambrosioides* products to provide effective protection of stored products. However, more research work is needed to determine seasonal variability of the active ingredient, effective dosages and appropriateness for use by rural small scale farmers. For example, Obeng-Ofori and Reichmuth (1997) found eugenol, a major component of essential oil of *Ocimum suave* (Wild.), bio-active against four species of stored-product Coleoptera including *P. truncatus*. Obeng-Ofori *et al*. (1998) investigating toxicity and protectant potential of camphor, a major component of essential oil of *Ocimum kilimandscharicum* against four stored product beetles recommended further research on the mode of action of plant active ingredients focusing on their penetration into insect cuticles and grain. Results from this research may contribute to determine a suitable dosage of the ingredient or plant extract and better adherent substrates for application of the insecticide. Several plant species have been tested and found with effective compounds for the control of *P. truncatus* (Table 2.3). The use of plant derived products, especially essential oils and powders with repellent, toxicant or antifeedant properties, represents a suitable way forward in development of IPM strategies against *P. truncatus* and other insect stored product pests mostly to resource-poor farmers in developing countries.

d) Biological control with the use of predators

Experimental research supporting evidence for predators in regulating insect population numbers come from several scientific sources. The predation models, Lotka-Volterra and Nicholson-Bailey (Price, 1997; Huffaker and Gutierrez, 1999) suggest that prey populations can be regulated by predators or parasitoids. Biological control with the use of the predator, *T. nigrescens* has become one of the most promising alternatives for the control of *P. truncatus* in Africa and worldwide. The effectiveness of *T. nigrescens* in suppressing population numbers of *P. truncatus* has been demonstrated under laboratory conditions and it is environmentally friendly and economically suitable for application in rural small scale farms. Helbig and Schulz (1996) found that *T. nigrescens* could control *P. truncatus* in cassava chips and cassava wood in Togo after 12 weeks of storage. Helbig (1995) in Togo investigated damage to maize grain under near-traditional storage conditions and reported that damage was reduced by approximately 23% in the presence of the predator after nine months of storage.

Holst and Meikle (2003) in Benin developed a simulation model based on life-table data and found that *T. nigrescens* significantly reduced population growth of *P. truncatus* and the non-target, *S. zeamais*. However, Ayertey *et al.* (1999) found that *T. nigrescens* preferred to attack *P. truncatus* compared to *S. zeamais*, when these pests were exposed under predation at different densities in maize in Benin. Camara *et al*. (2003) reported that among 2322 samples of *T. nigrescens* from forests and granaries of Mexico, Honduras and Benin, the predator preferred to prey on *P. truncatus* rather than *S. zeamais*. In field experiments, Richter *et al*. (1997) observed that infestation by *P. truncatus* in granaries decreased after introduction of *T. nigrescens* in Benin. The number of *P. truncatus* individuals was reduced by 93%, while damage to grains was reduced by approximately 40% in the presence of the predator. Schneider *et al*. (2004) in Benin and Togo found that *P. truncatus* numbers caught in traps decreased steadily after introduction of *T. nigrescens* during 1992.

Augmented releases of *T. nigrescens* done by Hell *et al*. (2006) for Larger grain borer control in cassava chips in Benin resulted in reductions of cassava chip losses by 5 and 11% after one and five months of storage, respectively. Contrastingly, Muatinte *et al*. (2014) similarly to the results published by Cugala *et al*. (2007) in Manica Province, Mozambique, reported that *T. nigrescens* had no impact on *P. truncatus* numbers two years after it was released.

However, the predator has established and dispersed to new localities and it can reduce *P. truncatus* numbers, indicating its usefulness for control of this pest. Establishing a biological control agent such as a predator in the field is a major challenging step in any classical control. Hence, Shea and Possingham (2000) suggested the application of stochastic dynamic programming to population management for optimal release strategies for biological control agents.

Inundated and augmented releases of the predator can increase its abundance, followed by increased efficacy in controlling *P. truncatus* in natural environments. *Teretrius nigrescens* was released in Togo in 1991 (Biliwa *et al*., 1992), Ghana (Compton and Ofosu, 1994), Kenya (Giles *et al*., 1996), Zambia and Guinea Conakry and, in Tanzania. Helbig (1999) reported that the predatory bug, *Xylocoris flavipes* (Reuter) (Heteroptera: Anthocoridae) was not effective in controlling *P. truncatus* in traditional maize granaries in southern Togo. Universal moth trap, which are suitable for capturing both *P. truncatus* and the predator without causing mortalities due to adhesives, have the advantage that individuals of the latter can be released back into granaries or into the wild.

Table 2.3. Plant species with insecticidal effects against *Prostephanus truncatus.*

Scientific species name	Taxonomic Family	References
Ocimum kenyense	Lamiaceae	Bekele *et al.* (1997)
Ocimum suave	Lamiaceae	Obeng-Ofori and Reichmuth (1997)
Ocimum kilimandscharicum	Lamiaceae	Obeng-Ofori *et al*. (1998)
Azadirachta indica	Meliaceae	Osipitan *et al.* (2010a)
		Mukanga *et al.* (2010)
Chenopodium ambrosioides	Chenopodiaceae	Tapondjou *et al*. (2002)
Nicotiana tabacum	Solonaceae	Osipitan *et al.* (2010a)
Ocimum gratissimum	Lamiaceae	Osipitan *et al.* (2010a)
Cola millenni	Sterculiaceae	Osipitan *et al.* (2010a)
Tetracarpidium conophorum	Euphorbiaceae	Osipitan *et al.* (2010a)
Delonix regia	Fabaceae	Osipitan *et al.* (2010a)
Vernonia amygdalina	Asteraceae	Osipitan *et al.* (2010a)
Clausena anisata	Rutaceae	Nukenine *et al*. (2010a)
Plectranthus glandulosus	Labiatae	Nukenine *et al*. (2010a)
Tephrosia vogelii	Meliaceae	Mukanga *et al.* (2010)
Eucalyptus globulus	Myrtaceae	Mukanga *et al.* (2010)
Psidium guajava	Myrtaceae	Mukanga *et al.* (2010)
Erchhornia crassipes	Pontederiaceae	Mukanga *et al.* (2010)
Securidaca longepedunculata	Polygalaceae	Jayasekara *et al*. (2005)

e) Use of parasitoids

Hymenopteran parasitoids have been suggested for control of *P. truncatus*. *Anisopteromalus calandrae* (Howard) and *Theocolax elegans* (Westwood) (Hymenoptera: Pteromalidae) are the parasitoids which are potential biocontrol agents to be applied against *P. truncatus* worldwide and especially in Africa where control means and measures by use of conventional technology are scarce. Helbig (1998) in Benin found that *A. calandrae* was more effective in controlling *P. truncatus* under laboratory conditions than *T. elegans*. The latter species showed more promise than *Cerchysiella* sp. (Hymenoptera: Encyrtidae), *Pediobius furvus* (Gahan) (Hymenoptera: Eulopidae) and species of Bethylidae family.

The effectiveness of parasitoids may be hindered by interspecific competitive relationships between parasitoid species (O'Neil and Cate, 1985; Bajpai *et al.,* 2006) and between a parasitoid and a predator (Bilu and Coll, 2007). Tri-trophic interations between insect-parasitoid and host plants (Mbata and Brewster, 2009; Hodge *et al.,* 2011) and interations with the environment (Agboka *et al*., 2004; Hansen and Skovgård, 2010; Evans *et al.,* 2011) may negatively influence parasitoid effectiveness. These handicaps of the parasitoid use as bio control agents, particularly against *P. truncatus* may be reduced by integrating the application of the pest predator *T. nigrescens* with parasitoids. Scientific knowledge on the effectiveness of integrated use of predation and parasitism on postharvest pest control is scarce. However, Bilu and Coll (2007) found that combined use of the intra-guild predator, *Coccinella undecimpunctata* L. (Coleoptera: Coccinellidae) with the parasitoid *Aphidius colemani* Viereck (Hymenoptera: Aphidiidae) resulted in non-the-less stronger growth of aphid population than the natural enemies used alone. These findings may bring us to hypothesis that the use of the exotic predator, *T. nigrescens* combined with natural parasitoids may effectively suppress *P. truncatus* populations. Investigations into parasitoid-pest interactions in both natural and granary environments must be intensified. In addition to this, the potential synergism between the predator and parasitoids, as well as other biological interactions are subjects for further research to better understand and exploit the role that natural enemies could play in management of *P. truncatus*.

f) Use of entomopathogenic fungi and bacteria

The use of entomopathogenic fungi (EPF) and fungus-derived products constitutes another tool applied in biological control of stored product pests. Odour *et al*. (2000) reported the presence of the entomopathogenic fungus, *Beauveria bassiana* (Balsamo) Vuillemin (Hyphomycetes) on pests of stored maize in Kenya and highlighted it as a potential control agent. Kassa *et al*. (2002) tested the efficacy of 13 isolates of entomopathogenic fungi belonging to *Beauveria* spp*., Metarhizium* spp. or *Paecilomyces* spp*.* and found that all isolates tested were virulent to *P. truncatus* causing 98-100% mortality, and median survival time ranged from 2.85±4.05 days, whereas *Metarhizium anisopliae* and *B. bassiana* were also virulent to *S. zeamais* (92-100% mortality, MST ranged from 3.58±6.28 days*.* These results showed potential of entomopathogenic fungi for the control of *P. truncatus* and other insect stored pests. Hertlein *et al*. (2011) reviewed the use of spinosad against storage pests, including *P. truncatus* and reported to be effective against *R. dominica*, *T. castaneum*, *T. confusum* and *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae). This insecticide is a reduced-risk derived by fermentation of the soil actinomycete, *Saccharopolyspora spinosa* Mertz & Yao (Bacteria: Actinobacteridae) (Chintzoglou *et al.,* 2008; Hertlein *et al*., 2011). However, its improvement and large scale use under small scale grain storage conditions requires further investigation. Smith *et al.* (1999) found that conidia of the entomopathogenic fungi *B. bassiana* caused 97-100% *P. truncatus* mortality when applied under formulations of vegetable fat pellets with pheromones of the pest.

g) Use of semiochemicals

Information on the economic impact of using semiochemicals to protect stored products from insect pest infestation, especially whether these prove effective is scarce. However, mass trapping using sex pheromones are potentially useful despite the fact that their efficacy depends on trap design and possible saturation of traps, particularly under conditions of high pest densities. Another disadvantage is single sex attraction, and the possible effects of inappropriate positioning of traps, maintenance of traps in the field, and possible immigration of individuals towards traps from outside the study areas (Cox, 2004). However, mass trapping using sex pheromone baited traps such as universal moth traps may represent a potential and an effective control method for *P. truncatus* in the granaries of small holder farmers. The role of pheromones in predator-prey interactions has being reported by Smith *et al.* (1996). Hodges and Dobson (1998) came to the conclusion that there might be complexities in predator-prey pheromone based interaction between *P. truncatus* and *T. nigrescens*, because the latter unexpectedly could not respond to the synthetic pheromone of the pest under laboratory experiment in Great Britain. Moreover, feeding or oviposition stimulants have been used, especially to improve the efficacy of insecticides and biocontrol agents. Laboratory research results from Steward-Jones *et al*. (2004; 2006) showed evidence for the existence of a high concentration of compounds in *P. truncatus* dust and/or frass that acts as a contact kairomone for *T. nigrescens* attraction. In addition, these authors suggested that this or another compound could also act as an oviposition cue for female *T. nigrescens*.

The results from the above mentioned studies explained the predator-prey attraction mechanism between *T. nigrescens* and *P. truncatus* that occurs at close range such as in granaries and conventional maize storage facilities. Additionally, these findings complement the known attraction of *T. nigrescens* to *P. truncatus* by the male aggregation pheromone. This attraction towards the *P. truncatus* aggregation pheromone, results in *T. nigrescens* flight from significant long distances in open environments such as forests and agro-ecosystems (Scholz *et al*., 1998). However, attraction of *T. nigrescens* using a synthetic pheromone of *P. truncatus* was not observed by Hodges and Dobson (1998) in laboratory experiments. This fact is contrary to the finding that *T. nigrescens* can fly or walk (Rees *et al*., 1990) into traps baited with synthetic pheromones of *P. truncatus* but stresses the hypothesis of Steward-Jones *et al*. (2004) from which there might be other compound cues involved in this predator-prey interaction.

h) Integrated Pest Management for *Prostephanus truncatus*

Integrated Pest Management (IPM) is an effective approach to management of post harvest pests (Adda *et al*., 2002). The combined use of several control methods for *P. truncatus* in granaries of small scale farmers have been investigated worldwide. Addo *et al.* (2002) found that the combined use of eight control method options for *P. truncatus* could effectively reduce pest populations in granaries in the Volta Region of Ghana. However, extension services specialists are required to systemically assist farmers in carrying out the implemented methods. Tyler and Hodges (2002) recommended implementation of phytosanitary measures, particularly quarantine inspection of large-scale traded maize, cassava and other *P. truncatus* host commodity products. However, these authors indicated that preventing *P. truncatus* long-term dispersal through Africa was unrealistic.

Some of the promising approaches towards effective integrated management for *P. truncatus* comprises of the application of spinosad combined with diatomaceous earth (Chintzoglou *et al*., 2008; Vayias *et al*., 2009; Kavallieratos *et al.*, 2010b), insect-resistant maize and biological control using *T. nigrescens* (Bergvinson and Garcia-Lara, 2011). Nukenine *et al*. (2010b) found effective against *P. truncatus* the application of fenchone and *Plectranthus glandulosus* oil. The application of wood ash combined with conidia of the fungus *B. bassiana*, as suggested by Smith *et al*. (2006) as well as the use of hermetic bags (De Groote *et al*., 2013; Garcia-Lara *et al*., 2013) hold potential for the control of the Larger grain borer. The effectiveness of hermetic storage of cereals and beans against insect stored product pests has been investigated by Varnava *et al*. (1995) in Israel. These authors found hermetic storage suitable for control purposes, because it can reduce insect pest numbers to below economic threshold. It also regulates storage temperature and humidity due to the anaerobic atmosphere generated under sealed conditions (Weinberg *et al*., 2008) and maintains the germination potential of products up to 80%. Quezada *et al*. (2006) in Mexico found effective the use of hermetic storage systems to prevent proliferation of *P. truncatus* and storage fungi in maize of rural small farmers in developing countries. Moreover, multiple-layer hermetic storage bags were found to be rational, sustainable, cost-effective, user and environmentally friendly and to make the use of pesticides unnecessary (Anankware *et al*., 2012). Ognakossan *et al.* (2013) in Benin supported the use of hermetic grain bags instead of woven polypropylene ones.

Research towards developing IPM stratgeies for the Larger grain borer is the way towards effective control of this pest. For example, Schöller *et al.* (1997) referred to biological control as a major component of IPM in stored product protection. These authors suggested that efficacy of the use of *T. nigrescens* against *P. truncatus* could be improved when combined with hygienic, structural, technological and biotechnological methods. Seck *et al*. (1996) in Belgium found effective the use of a hermetic storage method in combination with *Boscia senegalensis* (Pers.) (Lamiaceae) for protection of cowpea seed against *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae). Kumar (2002) in Mexico found that host plant resistance in maize could be used as a component of IPM for *P. truncatus* since maize lines derived from some Caribbean land races were experimentally rated highly resistant against the pest. Additionally, the lower powder production of maize grain due to pest infestation and the low insect multiplication rate on resistant ears found by Kumar (2002) reinforces the need for use of host plant resistance in maize for *P. truncatus* control. Mwololo *et al.* (2012) evaluated 85 maize hybrids and 70 maize landraces for resistance to *P. truncatus* infestation and damage. These authors found 8 and 4 resistant hybrids and landraces respectively, and suggested that Larger grain borer germplasm resistant maize varieties could be used for development of IPM programs against the pest. Tefera *et al*. (2011b) reported metal silos as an effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries. However, the relatively high costs of metal silos for African smallholder farmers raise the need for building clay stone based silos (Fig. 2.3). An IPM approach for *P. truncatus* could also include early or timely harvesting of maize, soon after physiological maturity (Borgemeister *et al.,* 1998c).

Fig. 2.3. An example of a clay and stone based silo for maize grain storage in the Chicualacuala district of Mozambique.

A relatively unique approach to IPM for *P. truncatus* is the potential use of bacteriosomes and their sensitivity to changes in ambient temperatures (Kleespies *et al*., 2001). These authors discovered that the symbiotic bacteriosomes located dorsally in the fat body parallel to the mid-gut of both larvae and adults of *P. truncatus* reduced their size with increasing temperature. Since these bacteriosomes regulate the reproduction success of the Larger grain borer, temperature management inside granaries may contribute to pest management. Pozidi-Metaxa and Athanassiou (2013) concluded that spinosad was highly effective against *P. truncatus* compared with deltamethrin, chlorpyriphos-methyl and pirimiphos-methyl at certain temperatures. Research on potential methods for suppressing *P. truncatus* populations is ongoing and often generates novel results. Adedoyin *et al.* (2010) and Osipitan *et al.* (2010b) in Nigeria, discovered that propolis produced by the honey bee, *Apis mellifera* (Horn) (Hymenoptera: Apidae) effectively controlled *P. truncatus* and had potential to be more effective when integrated with other control measures against the pest. However, integrating effective technologies and getting farmers involved in evaluating them under real conditions in order to develop sustainable IPM strategies remains a challenge.

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CHAPTER THREE

The effect of abiotic and biotic factors on spatial and temporal fluctuations of *Prostephanus truncatus* populations in the Manica and Gaza Provinces, Mozambique

Abstract

Prostephanus truncatus (Horn) (Coleoptera: Bostrichidae) is a serious pest of stored maize in Mozambique. While the pest is distributed throughout Mozambique, higher abundance and losses of stored maize are recorded in the central and southern regions of the country. This study investigated biotic and abiotic factors that could affect *P. truncatus* population fluctuations. The study was conducted between January 2013 and December 2014 in the Manica and Gaza Provinces, Mozambique. Fourteen quadrants of 250 X 250 m were randomly selected in each of four villages. Seven quadrants were selected in the Massingir village in Massingir district. The number of quadrants per village depended on the accessibility of the area and on the presence of forest areas or human settlements. One pheromone Uni-trap was set up in the centre of each quadrant and geographical coordinates of trap locations were recorded. Insects were collected at monthly intervals, identified and counted. Temperature and humidity data were daily registered by means of IButton data loggers. Rainfall data were provided from the National Meteorological Institute of Mozambique. Altitude data were determined by means of the program ArcView GIS 10.1. Plant species were counted and identified and a percentage of host plant species of *P. truncatus* was determined out off all species in each quadrant. The effect of abiotic and biotic factors on fluctuations of *P. truncatus* numbers was evaluated using multiple regression analysis and generalized linear models. Generalized linear models showed that abiotic and biotic factors affected *P. truncatus* numbers. However, the strength of the effect varied between villages and years. While mean numbers of host plant species, the maximum and minimum temperature, relative humidity and rainfall influenced the variations in *P. truncatus* numbers, mean temperature did not play a role. Higher numbers of *P. truncatus* were trapped in Massingir (231 individuals per trap and per month) followed by Machipanda village (104). Generally, higher numbers of beetles were trapped during the rainy season and in human settlements. Designed models and the analysis of *P. truncatus* flight activity per season and per land use type form a baseline for further studies toward predicting dispersal and potential areas of invasion by *P. truncatus* in Mozambique.

Key words: *Prostephanus truncatus*, abiotic and biotic factors, Mozambique

3.1. Introduction

The effect of climatic factors in *Prostephanus truncatus* ecology has been widely reported. Climatic factors can have short and long term effects on *P. truncatus* population fluctuations (Fadamiro *et al*., 1995; Scholz *et al.*, 1998; Hodges *et al.*, 2003). Other factors that influence fluctuations in pest numbers are availability of host products such as maize and cassava (Cugala *et al*., 2007; Hill *et al.,* 2003) and availability, abundance and diversity of forest host plant species (Borgemeister *et al.,* 1998; Jia *et al*., 2008). Differences in temperature, humidity and precipitation (Subramanyan *et al*. 1991; Giles *et al.*, 1995; Farrell, 2000) and wind speed (Fadamiro, 1996) may also affect *P. truncatus* numbers. The number of *P. truncatus* individuals captured using pheromone-baited flight traps has been reported to vary significantly between seasons and years in Mexico (Rees *et al.,* 1990), Honduras (Novillo, 1991), Kenya (Nang'ayo *et al.,* 1993) and Togo (Wright *et al.,* 1993). The effect of predation by *T. nigrescens* is also considered to be an important driving factor of *P. truncatus* survival and dispersal (Richter *et al.,* 1997; Schneider *et al*., 2004; Hell *et al*., 2006; Muatinte and Cugala, 2015).

However, studies on the effect of abiotic factors such as altitude (Hodkinson, 2005), temperature, humidity as well as biotic factors such as host plants and their effects on *P. truncatus* ecology remain scarce. Insect species distribution can vary along an elevation gradient, a response of which can be direct or mediated by host plant growth rates, phenology, nutrient composition concentrations of secondary and plant defensive compounds (Hodkinson, 2005). Modeling can be used to analyze these relationships since it is a suitable tool for such integrated analysis. For example, models accurately described *P. truncatus* seasonal flight activity in Kakamega and Mombasa but were not fitted in the Kitale and Thika regions of Kenya (Omondi *et al.,* 2011). These models could be used to predict developmental and population trends in time for designing of control strategies against *P. truncatus*. Recognizing the effect of temporal and spatial fluctuations in population numbers may also result in better understanding of insect pest dispersal (Hanski, 1994; Hawkes, 2009). Knowledge about the factors that drive pest dispersal and colonization of new habitats is crucial in designing pest management strategies (Stevens *et al*., 2010).

The aims of this study were to investigate the effects of factors such as altitude, temperature, humidity, precipitation and host plant species abundance on *P. truncatus* temporal and spatial abundance. The generated knowledge will be used to predict regional *P. truncatus* fluctuations and to determine areas and habitats vulnerable to colonization by *P. truncatus* in Mozambique and broadly in the Eastern African region.

3.2. Material and methods

3.2.1. General procedures

Monitoring was conducted between January 2013 and December 2014 in the Machipanda village in the Manica district, Catandica in the Bárue district, Massingir in the Massingir district and in the Chicualacuala of Chicualacuala district. Fourteen quadrants of 250 X 250 m were randomly selected in each of the study villages of the Manica, Bárue and Chicualacuala districts. Seven quadrants were selected in the Massingir district. The number of quadrants per village depended on the accessibility of the area and on the presence of forest areas or human settlements. One pheromone universal moth trap (Fig. 3.1) was set up in the centre of each quadrant and geographical coordinates of trap locations were recorded. Traps and pheromones were purchased from International Pheromone Systems Limited, England. Traps were hanged at approximately 2.0-2.5 m above the ground on a branch of a tree or shrub located inside the determined quadrant center. Pheromones were impregnated in rubber septa dispensers and consisted of a mixture of Trunc-call 1 and Trunc-call 2 in a 1:1 ratio. The rubber septa were put inside the designated container in the trap (Fig. 3.1). Moreover, maps indicating the locality of traps per village at each district were drawn by means of the programme ArcView GIS 10.1 (ESRI, 1999) and the geographical data source, Cenacarta (2012).

3.2.2. Description of study areas

a) Manica district

The Manica district is situated in the Manica Province and it covers an area of 4594 km^2. The climate is humid and the annual average temperature is 21.2 ^oC (maximum: 30.9 ^oC, minimum of 7.3 ^{o}C). The rainfall season lasts from November to April with 1000-1200 mm rainfall (INE, 2013). The Manica district has a well-defined rainfall and dry season. The main crops are maize in polyculture with sorghum (*Sorghum bicolor*) and cassava (*Manihot esculenta*). Exploration and commercialization of timber, reed and firewood are some of the non-agricultural activities that can be associated with breeding and possible dispersal of *P. truncatus* in the Manica district. Fig. 3.2 shows the trap locations in the Machipanda village, in the Manica province.

Fig.3.1. Green universal moth traps (Uni-traps) used for determining fluctuations of *Prostephanus truncatus* numbers in the Manica and Gaza Provinces of Mozambique.

b) Bárue district

The Bárue district is on the northwestern side of the Manica Province. The surface area is 5743 km^2. The climate is tropical and the annual average temperature is 25 ^{o}C (maximum: 28.8 ^{o}C, minimum of 15.7 ^{o}C) (INE, 2013). The annual precipitation average is 1591 mm with rainfall occurring mostly between November and April. The district is rich in river basins with permanent water flow. Monoculture and polyculture of maize and wheat (*Triticum aestivum*), potential *P. truncatus* host crops are, cultivated. The main plant species used for fire and charcoal wood is the bean-pod tree, *Brachystegia spiciformis* (Fabaceae). This species may play an important role in *P. truncatus* survival and dispersal. Traps were set up in Catandica village (Fig.3.3), in the Bárue district.

c) Massingir district

The Massingir district is located in the northern region of Gaza Province and covers 5893 km^2. The climate is predominantly semi-arid, with an annual average temperature of 24 ^{o}C (maximum: 30 ^{o}C, minimum of 18 ^{o}C). The annual average rainfall is 600 mm (INE, 2013). Hot seasons lasting from September to February are frequent and characterized by high rainfall and floods. The main crops and potential hosts for *P. truncatus* are sorghum and maize cultivated in polyculture systems. The district is occupied by savannah woodland and edge forests. *Colophospermum mopane, Delonix regia* and *Cassia abbreviata*, all trees of Fabaceae plant family are exploited as firewood, charcoal and in traditional house construction. These tree species may be potential host plant species that contribute to *P. truncatus* breeding and dispersal. Trap locations were distributed as indicated in Fig.3.4.

d) Chicualacuala district

The Chicualacuala district is situated in the northern region of Gaza Province. The district covers an area of 18155 km^2. The climate is tropical and dry with an annual average temperature of 24 ^{o}C (maximum: 30 ^{o}C, minimum of 15 ^{o}C) and an annual average precipitation of 500 mm (INE, 2013). The rainy seasons are short and the relief is predominantly of low altitude not exceeding 500 m above sea level. Polyculture of maize with other *P. truncatus* non-host crops is predominant in the Chicualacuala district. *Colophospermum mopane*, *C. abbreviata*, *D. regia* and *Acacia xanthophloea* (Mimosaceae) are the main tree species and potential host plant species that could contribute to dispersal of *P. truncatus*. The former three plant species are exploited as firewood, charcoal and as building material for traditional houses. The Fig. 3.5 shows the trap locations in the Chicualacuala district.

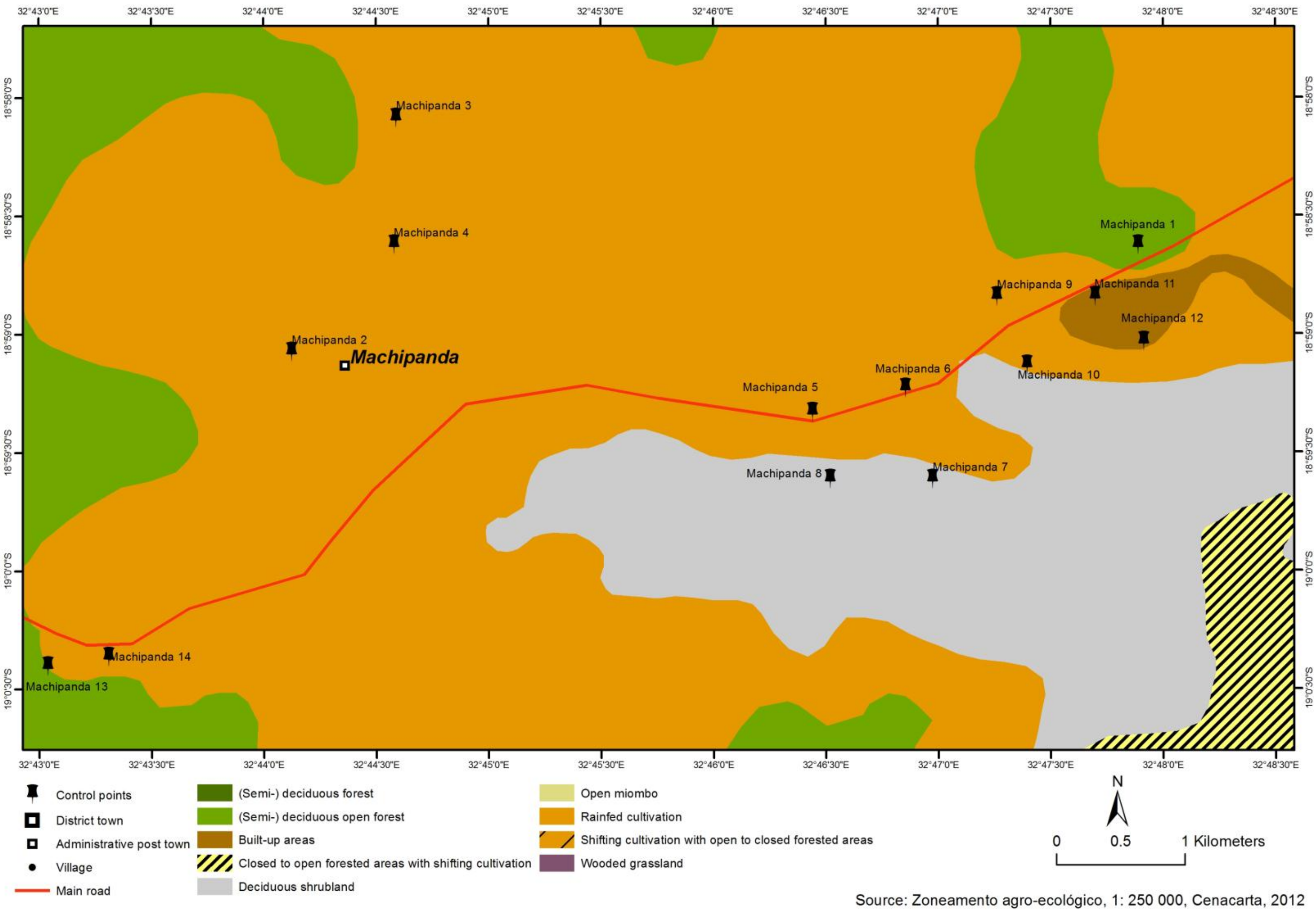
3.2.4. Insect sampling

Insects were removed from traps at each location at monthly intervals and numbers of *P. truncatus* were recorded. Individuals of *Teretrius nigrescens* (Coleoptera: Histeridae), a natural enemy of this pest, which were present in traps were immediately released back to the environment since most of them were found alive by the time of their removal from traps.

3.2.5. Climate and altitude data

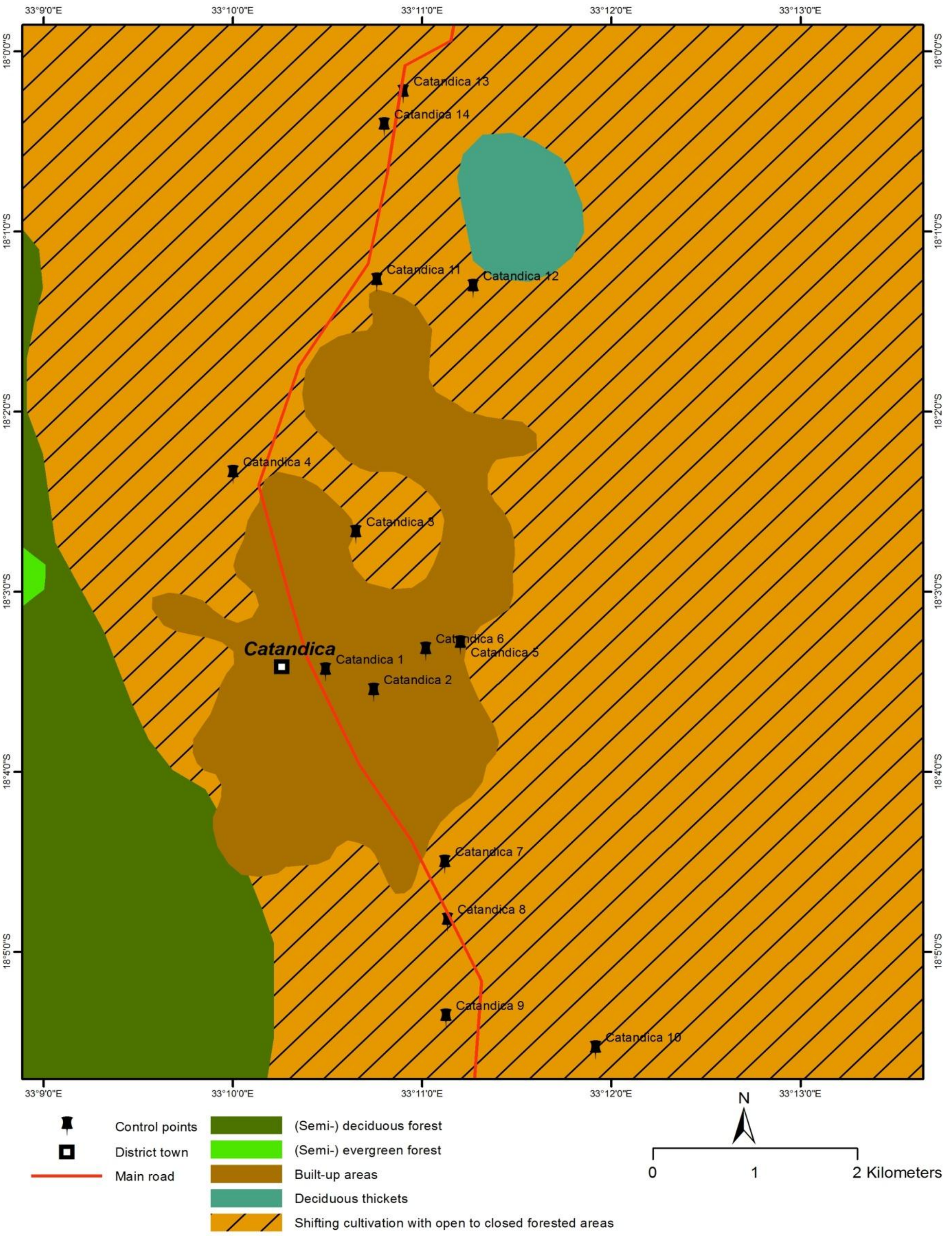
Temperature and humidity data were recorded on a daily basis by means of Maxim iButton DS 1923 Temperature and Humidity data loggers provided by Fairbridge Technologies Ltd., South Africa. Three loggers were set up per village and one each per trap. Traps with data loggers were situated at the minimum distance of 5 km between each other and at different altitudes to ensure replication of data. Recorded data were downloaded at monthly intervals and read by means of the Cold Chain Thermodynamics programme from the iButton provider. Monthly average temperature and humidity as well as the maximum and minimum temperatures were then calculated for each village using descriptive statistics (SAS, 1999).

These data were compared with those provided by the National Meteorological Institute of Mozambique (INAM) (INE, 2013; INE, 2014). This comparison aimed at ensuring that temperature and humidity values recorded by data loggers could be validated for the village and for the district. For this purpose average temperature values from data loggers were plotted in Excel data worksheets and subtracted from those of INAM. Absolute value of the number was used where negative values were obtained from the subtraction. Temperature values were considered different when the subtraction difference was higher than 5 ^{o}C. This value was determined based on the knowledge that the optimum temperature for successful development of *P. truncatus* ranges between 27 ^{o}C and 32 ^{o}C (Bell and Walter, 1982). The average humidity was also compared with that from INAM and was considered different when the subtraction value was $\geq$ 10%.



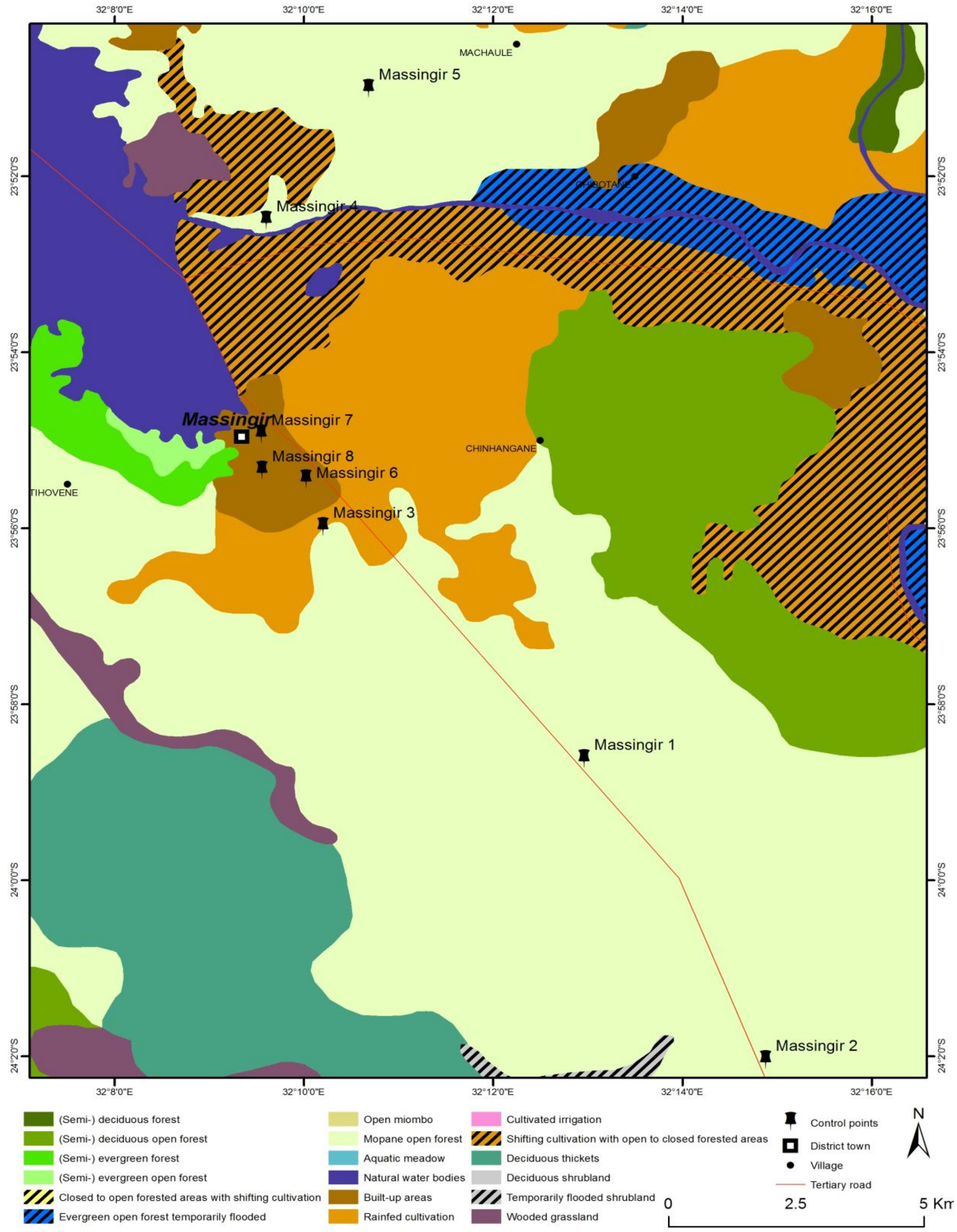
Source: Zoneamento agro-ecológico, 1: 250 000, Cenacarta, 2012

Fig.3.2. A map indicating locality of trap sites in the Machipanda village of the Manica district of Mozambique.



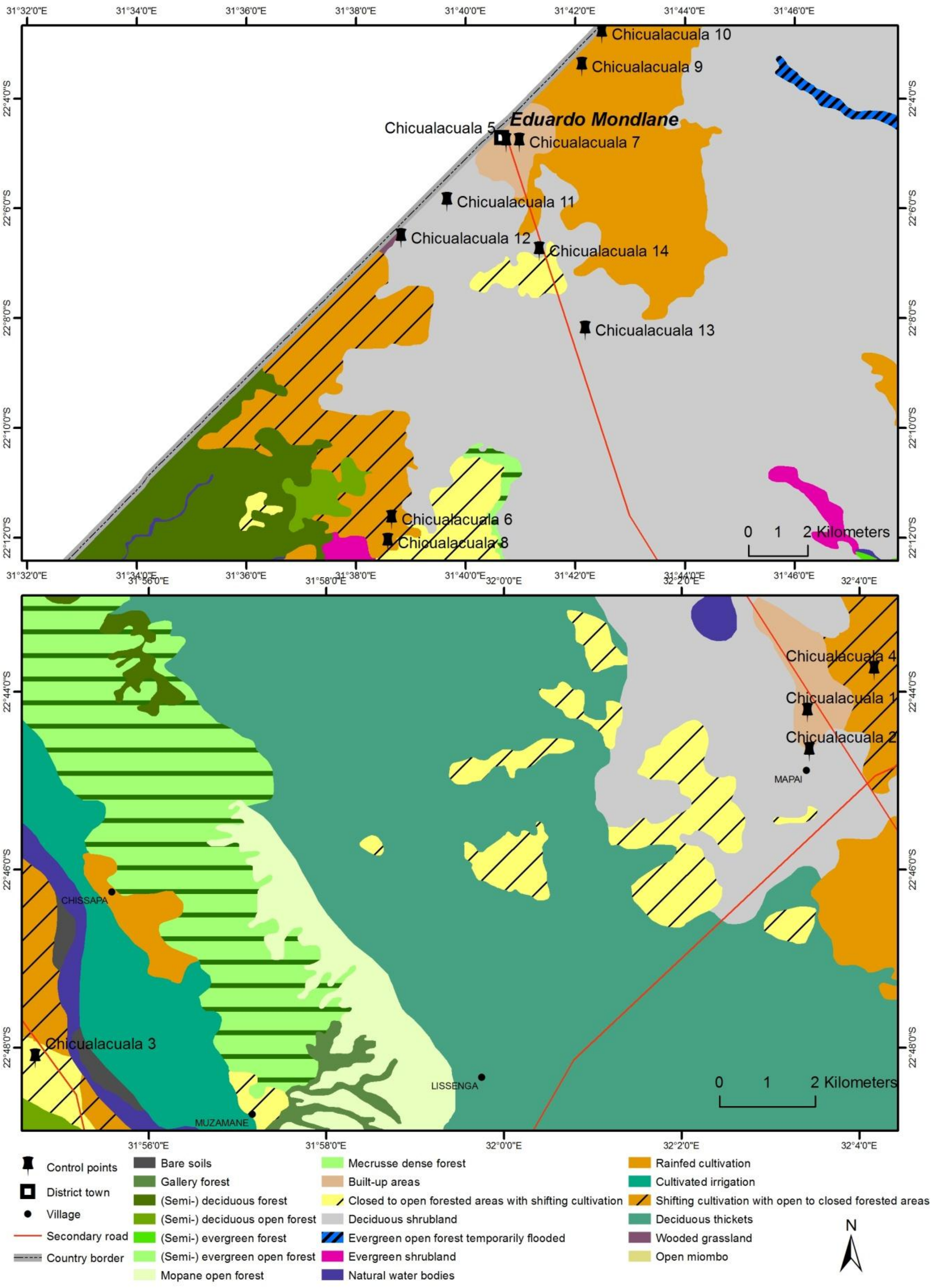
Source: Zoneamento agro-ecológico, 1: 250 000, Cenacarta, 2012

Fig. 3.3. A map indicating locality of trap sites in the Catandica village of the Bárue district of Mozambique.



Source: Zoneamento agro-ecológico, 1: 250 000, Cenacarta, 2012

Fig. 3.4. A map indicating locality of trap sites in the Massingir village of the Massingir district of Mozambique



Source: Zoneamento agro-ecológico, 1: 250 000, Cenacarta, 2012

Fig. 3.5. A map indicating locality of trap sites in the Chicualacuala village of the Chicualacuala district of Mozambique.

The relative humidity range of 70-80% is the optimum for successful *P. truncatus* development (Bell and Walter, 1982). Temperature and humidity data from loggers and from INAM did not differed and the former were applied in this work. Rainfall data of the villages were obtained from INE (2013) and INE (2014) and were provided by INAM. Altitude data from all trap sites were calculated using the programme, ArcView GIS 10.1 (ESRI, 1999).

3.2.6. Sampling of host plant species

Potential host plant species of *P. truncatus* in each quadrant were determined. For this purpose all plant species individuals in each quadrant were counted and recorded at six-month intervals. Photos and samples of leaves and flowers were taken for further taxonomic identification of species at the Herbarium of the Department of Biological Sciences, Eduardo Mondlane University. The identification of plant species was done using the system of Van Wyk and Van Wyk (1997) and Dharani (2011). The number of individuals of all plant species including *P. truncatus* host crops per quadrant was recorded and the percentage of known host plant species (Nang'yao *et al*., 1993; Nansen *et al*., 2004; Rwegasira *et al.,* 2011; Muatinte *et al.,* 2014) was calculated out of the total number of species of the quadrant.

3.2.7. Data processing and statistical analyzes

Prior to analyzes, all data were checked for normality using the Kolmogorov-Smirnov Test at $p<0.01$ level of significance. All data did not fit a normal distribution and only numbers of *P. truncatus*, the dependant variable, were log-transformed for further analysis. Spearman multiple rank correlations were applied to evaluate the degree of relationships between all variables per village for spatial and per years and seasons for their temporal fluctuations (SAS, 1999). These results were not presented and were only used for understanding and interpretation of potential variations in the effect of abiotic and biotic factors on fluctuations of *P. truncatus* numbers. The abiotic factors included in these analyses were average altitude, average monthly temperature and humidity, maximum and minimum temperatures and monthly average rainfall. The biotic factors included mean numbers expressed as percentage of host plant dominance and mean numbers of *P. truncatus.*

Mean numbers of all variables were calculated per quadrant and per village. Mean percentage of host plant dominance, altitude, temperature, relative humidity, rainfall and mean of *P. truncatus* were compared between villages applying breakdown and one-way ANOVA and Tukey honest significant differences (HSD) for unequal N (number of samples) (Spjotvoll/Stoline). Test of least significant differences (LSD) was used to compare means of above mentioned variables between the twelve months. Mean numbers of *P. truncatus* between the two years, seasons and land use types were compared using t-tests, independent by groups (SAS, 1999). All comparisons were performed at the $p<0.05$ level of significance. The effect of abiotic and biotic factors on variations of *P. truncatus* numbers was evaluated by means of multiple regression analysis and Generalized Linear Model (GLM) (Luoto *et al.,* 2001; Preacher *et al*., 2006; Faul *et al*., 2009). These analyzes were performed and equation of (GLM) was derived for each village, year and for the two year period of study. Multiple regression analyzes were run until significant differences at $p<0.05$ level for the intercept and for the relationships between independent variables and *P. truncatus* numbers were achieved. Moreover, variables that correlated poorly with the mean numbers of *P. truncatus*, (means with the coefficient “r” [between -0.2 and 0.2]) were excluded from further analyzes since it indicated weak relationships and were considered not to be important determinants of population number variations. Finally, a GLM model was developed to determine the general equation of regression analysis for the effect of abiotic and biotic factors on *P. truncatus* numbers in the Manica and Gaza Provinces. The GLM model was run applying Sigma-restricted parameters, Sweep delta=1.E-7, 100 matrix interactions, 200 maximum subset and best subsets of model building (Nicholls, 1991). Akaike Information Criteria (AIC) (Oakland, 1987; SAS, 1999) was applied to determine the maximum number of factor interactions to use in each model. The first listed model was selected as adequate to describe the effect of the mentioned factors on fluctuations of *P. truncatus* numbers. The following equation (SAS, 1999, Preacher *et al*., 2006; Faul *et al*., 2009) was written: $Ꞷ = \alpha + (\beta_1 * X_1) + (\beta_2 * X_2) + (\beta_n * X_n) + Є$; where:

Ꞷ – dependant variable (*Prostephanus truncatus* numbers); α – expected probability when all predictors are 0; β_1, β_2, β_n – values of the predictors, fluctuations of which are expected to cause changes in dependant variable Ꞷ; Є – stochastic error of interaction estimates.

3.3. Results and discussion

3.3.1. The effect of host plant species, altitude, temperature, relative humidity and rainfall on spatial fluctuations of *Prostephanus truncatus* numbers

A total of N=168 data readings were made for Machipanda, Catandica and Chicualacuala villages while N=96 were made for Massingir village (Table 3.1). The mean percentage of host plant dominance and mean values of altitude, temperature, relative humidity, rainfall and *P. truncatus* recorded during the twelve-month period (2013) are presented per village (Table 3.1). The degree of relationships of these factors with fluctuations of *P. truncatus* numbers in 2013 varied per village and levels of significance at $P<0.05$ are shown in Table 3.2. The mean percentage of host plant dominance varied between villages (N=4, df=3, F=19.1, $p<0.05$) as well as altitude (N=4, df=3, F=22.9, $p<0.05$). No significant variation in host plant dominance (N=12, df=11, F=0.00, p=1.00) was observed between months. The highest altitude was recorded in the Machipanda village and the lowest was in the Massingir (Table 3.1).

The percentage of host plant dominance (Hpd), the maximum temperature (MxT), relative humidity (Rh) and rainfall were strongly correlated with numbers of *P. truncatus* (N=168, r=0.7, $F_{4.1}=37$, $p<0.05$) in the Machipanda village. Equation 1 (below) represents a model that describes the effect of these factors on fluctuations of *P. truncatus* numbers in the Machipanda village.

$$\text{Ꙍ}_{\text{Machipanda2013}}= -4+ (0.4*\text{MxT}) + (0.4*\text{Rainfall}) + (0.1*\text{Hpd}) - (0.2*\text{Rh}) + 0.7 \qquad (1)$$

The mean percentage of host plant dominance, the maximum temperature and the average rainfall correlated strongly (N=168, r=0.8, $F_{3.2}=88$, $p<0.05$) with numbers of *P. truncatus* in the Catandica village. The effect of these factors on fluctuations of *P. truncatus* numbers was derived from the following equation (2):

$$\text{Ꙍ}_{\text{Catandica 2013}}=-2.7 + (0.5*\text{Rainfall}) + (0.4*\text{Hpd}) + (0.3*\text{MxT}) + 0.5 \qquad (2)$$

Table 3.1. Biotic and abiotic factors recorded over twelve month period (2013) in four villages in Mozambique.

Sample localities	**Machipanda**	**Catandica**	**Massingir**	**Chicualacuala**
Abiotic and biotic factors	**Mean values±SD** **(N=168)**	**Mean values±SD** **(N=168)**	**Mean values±SD** **(N=96)**	**Mean values±SD** **(168)**
Host plant dominance (%)	19.4.0±17.7a[1]	18.0±16.9a	35.1±17.0b	19.0±12.3a
Altitude (m a.s.l.)	837.3±28.9d	595.0±18.0c	138.3±22.5a	370.6.0±136.0b
Average temperature (^oC)	21.0±2.0a	22.0±2.4a	24.2±3.6b	24.0±3.0b
Maximum temperature (^oC)	27.0±2.1a	26.0±2.0a	31.0±5.0b	31.0±3.1b
Minimum temperature (^oC)	15.0±4.0a	14.0±3.3a	19.0±3.0b	18.0±3.3b
Relative humidity (%)	63.0±24.0a	65.0±22.5a	73.0±13.0b	77.0±8.0c
Rainfall (mm)	82.0±72.0b	72.0±68.0a	104.0±79.0c	100.0±89.0c
Prostephanus truncatus	104.0±95.0c	47.0±51.0a	231,1±242.0d	52.4±74.0b

[1] Means followed by the same letter within rows do not differ significantly at $p < 0.05$.

In the Massingir village, mean numbers of *P. truncatus* were strongly correlated with the average minimum temperature (MiT) and the average rainfall (N=96, r=0.6, $F_{3.2}=30.4$, $p<0.05$). This relationship was described by the equation three.

$$\omega_{\text{Massingir 2013}} = -0.4 = (0.5*MiT) + (0.3*Rainfall) + 0.6 \qquad (3)$$

In the Chicualacuala village, with the exception of the percentage of host plant dominance and the average of numbers of altitude, all factors correlated strongly with numbers of *P. truncatus* (N=168, r=0.8, $F_{5.2}=56.2$, $p<0.05$). Equation 4 describes the effect of relative humidity, rainfall, average temperature (AveT), minimum temperature and maximum temperature, on fluctuations of *P. truncatus* numbers.

$$\omega_{\text{Chicualacuala 2013}}=-2.8=(0.4*Rh)+(0.4*Rainfall)+(0.3*MiT)+(0.2*AveT)-(0.3*MxT)+0.5 \qquad (4)$$

The relevance of the biotic and abiotic factors in affecting fluctuations of *P. truncatus* numbers varied between villages.

Table 3.2. Levels of significance of correlations between abiotic and biotic factors and numbers of *Prostephanus truncatus* recorded over a twelve-month period (2013) in four villages in Mozambique.

Sample localities	**Machipanda**	**Catandica**	**Massingir**	**Chicualacuala**
Variables		**$P<0.05$**		
Host plant dominance (%)	0.02	0.01	1.00	0.43
Altitude (m a.s.l.)	0.28	1.00	0.50	1.00
Average temperature (^{o}C)	0.15	0.20	0.12	0.04
Maximum temperature (^{o}C)	0.01	0.04	0.90	0.01
Minimum temperature (^{o}C)	0.06	0.70	0.02	0.01
Relative humidity (%)	0.01	0.05	0.10	0.01
Rainfall (mm)	0.01	0.01	0.01	0.01

Therefore, analysis of the predictor value of the average rainfall that ranges from 0.3 to 0.5 and the first and second order position it appears in the equation models, makes this factor the most relevant in affecting fluctuations of *P. truncatus* numbers between villages. In addition to this, rainfall is one of the parameters of the equation model in all villages. The maximum temperature follows the relevance order with the predictor value that ranges from 0.3 to 0.4 and might define variations in *P. truncatus* numbers as first order parameter in the Machipanda village. The maximum temperature is a third and fifth order factor of the equation model in the Catandica and Chicualacuala villages, respectively. The influence of minimum temperature was observed only in the Massingir and Chicualacuala villages. This fact could be explained by the medium and long term exposure effect of minimum temperature values (Hodges *et al*., 2003) on *P. truncatus* numbers. The percentage of host plant dominance influenced *P. truncatus* numbers in the Machipanda and Catandica villages but had no effect in Massingir and Chicualacuala villages. Maize grain could be the main host in these villages, where maize crop production is predominant (SIMA, 2014) and little is known about occurrence, abundance and diversity of forest host plant species of the pest. Patterns that determined the effect of the relative humidity only in the Machipanda and Chicualacuala villages remained unclear. Numbers of this factor from the Machipanda and Catandica villages are similar (Table 3.1). Mean relative humidity recorded in the Chicualacuala village was close to that of Massingir, where this parameter had no effect on *P. truncatus* numbers.

Regression analysis summary indicated that mean percentage of host plant dominance, altitude (Alt), average temperature, minimum and maximum temperature and rainfall were strongly correlated (N=600, r=0.7; $F_{4.6=}$124, $p<0.05$) with fluctuations of *P. truncatus* in 2013. Numbers of *P. truncatus* recorded in 2013 significantly differed between villages (N=4, df=3, F=23.9, p=0.05) and between months (N=12, df=11, F=58, p=0.05). Equation 5 of the generalized linear model describing the effect of above mentioned factors on *P. truncatus* numbers for the year 2013 was derived as following:

$$\text{Ꙍ}_{2013} = -0.8 + (0.4*\text{MiT}) + (0.4*\text{Rainfall}) + (0.2*\text{Rh}) + (0.1*\text{Alt}) + 0.6 \qquad (5)$$

Mean temperature followed by rainfall had the greatest effect on variations of *P. truncatus* numbers during 2013. Additionally, the average altitude, that showed no correlation with *P. truncatus* numbers between villages and months, had an effect in the regression analysis for the year 2013. However, altitude had a very weak negative correlation ($y = 1.3918 - 0.0004*x$; $r = -0.1268$, $p = 0.0019$). Numbers of *P. truncatus* individuals decreased with increasing of altitude. This could explain why *P. truncatus* numbers were higher in the Massingir village than in other villages at higher altitudes.

Mean values of abiotic and biotic factors recorded during 2014 are presented in Table 3.3. There were differences in numbers of *P. truncatus* recorded between villages (N=4, df=3, F=68, p=0.05) and between months (N=12, df=11, F=8.0, p=0.05).

The mean percenatge of host plant dominance and the mean values of altitude, maximum and minimum temperature and relative humidity were strongly correlated with *P. truncatus* numbers (N=168, r=0.6, $F_{5.2}$=20, $p<0.05$) during 2014 in the Machipanda village. Equation 6 describes the effect of these factors on variations in *P. truncatus* numbers.

Table 3.3. Biotic and abiotic factors recorded over a twelve-month period during 2014 in four villages of Mozambique.

Sample localities	**Machipanda**	**Catandica**	**Massingir**	**Chicualacuala**
Abiotic and biotic factors	**Mean values±SD (N=168)**	**Mean values±SD (N=168)**	**Mean values±SD (N=96)**	**Mean values±SD (168)**
Host plant dominance (%)	19.3±17.0a[1]	18.0±16.9a	33.3±17.0b	20.1.0±13.3a
Altitude (m a.s.l.)	837.3±23.1d	595.0±18.3c	138.3±21.5a	375.0±136.0b
Average temperature (^{o}C)	21.0±3.0a	21.4.0±2.1a	23.5±3.5b	24.0±3.2b
Maximum temperature (^{o}C)	27.0±2.4a	27.0±2.0a	30.0±1.6b	30.0±2.0b
Minimum temperature (^{o}C)	15.0±3.6a	15.5.0±3.4a	18.2±4.0b	18.0±4.0b
Relative humidity (%)	75.0±7.2.0b	78.4.0±9.0.5c	70.0±21.3.0a	78.4±32.0c
Rainfall (mm)	55.1.0±72.0a	65.0±68.0c	59.4±65.0b	82.1±92.0d
Prostephanus truncatus	33.0±41.4c	9.0±14.0b	79.4±82.1d	5.3±7.3a

[1] Means followed by the same letter within rows do not differ significantly at $p < 0.05$.

$$\text{Ꙍ}_{\text{Machipanda2014}} = -6.0 + (0.8*MxT) + (0.2*Hpd) + (0.2*Alt) + (0.2*Rh) - (0.5*MiT) + 0.5 \qquad (6)$$

In the Catandica village only the percentage of host plant dominance correlated markedly (N=168, r=0.4, $F_{7.2}$=30, $p<0.05$) with numbers of *P. truncatus*. Equation 7 from this relationship is presented bellow.

$$\text{Ꙍ}_{\text{Catandica2014}} = -2.0 + (0.7*Hpd) + 0.4 \qquad (7)$$

The mean percentage of host plant dominance and mean numbers of altitude correlated moderately (N=96, r=0.4, $F_{2.7}$=9, $p<0.05$) with mean numbers of *P. truncatus* in the Massingir village and the following equation 8 was derived.

$$\text{Ꙍ}_{\text{Massingir2014}} = 1.2 + (0.2{*}\text{Hpd}) - (0.3{*}\text{Alt}) + 0.5 \qquad (8)$$

Multiple linear regressions indicated that, similar to observations in the Catandica village the percentage of host plant dominance and mean numbers of altitude had moderate relationship (N=168, r=0.5, $F_{2.1}$=27, $p<0.05$) with *P. truncatus* numbers in the Chicualacuala village. This relationship was described by equation 9:

$$\text{Ꙍ}_{\text{Chicualacuala2014}} = 1.0 + (0.2{*}\text{Hpd}) - (0.4{*}\text{Alt}) + 0.5 \qquad (9)$$

Analysis of the slope of regression lines from all equations showed that host plant dominance followed by altitude might have an effect on variations in *P. truncatus* numbers in all villages. The maximum temperature affected fluctuations of *P. truncatus* numbers in the Machipanda village. Relative humidity and the minimum temperature could to a lesser extent affect variations in *P. truncatus* numbers in this village. The percentage of host plant dominance, the mean altitude and the maximum temperature were factors that were moderately correlated (N=600, r=0.5, $F_{3.4}$=66.5, $p<0.05$) with numbers of *P. truncatus* as indicated by multiple regression analysis of data for the whole of 2014. Equation 10 was determined for this relationship:

$$\text{Ꙍ}_{2014} = -\,2.0 + (0.5{*}\text{Hpd}) + (0.3{*}\text{Alt}) + (0.3{*}\text{MxT}) + 0.6 \qquad (10)$$

From analysis of the generalized linear model equation of 2014 it is notable that the mean percentage of host plant dominance and mean altitude had an effect on variation of *P. truncatus* numbers similarly to Massingir and Chicualacuala villages. Mean numbers of relative humidity (N=2, df=1, F=62.4, $p<0.05$), rainfall (N=2, df=1, F=13.7, $p<0.05$), maximum temperature (N=2, df=1, F=7.1, $p<0.05$) and *P. truncatus* numbers (N=2, df=1, F=68.1, $p<0.05$) significantly defered between 2013 and 2014. However, no significant differences were observed between the percentage of host plant dominance, the average and minimum temperature between years. The overall mean values of the different abiotic and biotic factors and levels of significance at $p<0.05$ are presented in Table 3.4.

However, multiple regression analysis indicated marked correlations (N=1200, r=0.6, $F_{6.1}$=95, $p<0.05$) between all factors and fluctuations of *P. truncatus* numbers with exception of the average temperature. The equation of the generalized linear model that described the effect of the different abiotic and biotic factors on variations in *P. truncatus* numbers over the 2-year period is as follows:

$$\text{Ꙍ}_{2013\text{-}2014}=-1.5+(0.3*\mathrm{Hpd})+(0.3*\mathrm{Rainfall})+(0.2*\mathrm{Alt})+(0.2*\mathrm{MxT})+(0.1*\mathrm{MiT})-(0.1*\mathrm{Rh})+0.6 \qquad (11)$$

Table 3.4. Mean numbers of abiotic and biotic factors recorded during 2013 and 2014 and their levels of statistical significance within villages and months.

Abiotic and biotic factors	**Years 2013-2014 (N=1200, df=1199)**			**Villages (N=3, df=2)**		**Months (N=12, df=11)**	
	Mean±SD	**F**	**p**	**F**	**p**	**F**	**p**
Host plant dominance (%)	21.4±20.6	0.01	1.00	32.72	0.01	0.01	0.96
Altitude (m a.s.l.)	527.0±254.0	0.01	1.00	3751.49	0.01	0.01	0.99
Average temperature (^{o}C)	22.3±3.1	0.62	0.43	100.17	0.01	218.59	0.01
Maximum temperature (^{o}C)	28.2±3.0	7.10	0.01	199.05	0.01	101.27	0.01
Minimum temperature (^{o}C)	16.1±4.0	2.56	0.11	85.70	0.01	153.72	0.01
Relative humidity (%)	73.0±14.4.0	86.08	0.01	17.46	0.01	62.38	0.01
Rainfall (mm)	76.1±110.0	557.27	0.01	3.21	0.02	13.69	0.01
Prostephanus truncatus	55.3±195.0	41.84	0.01	59.85	0.01	68.12	0.01

An analysis of Equation 11 indicated that all abiotic and biotic factors, except the average temperature and minimum temperature influenced fluctuations of *P. truncatus* numbers over the 2-year period.

The percentage of host plant dominance followed by mean values of rainfall, altitude and maximum temperature were the most important factors affecting variations of pest numbers over the two years. However, analysis of the frequency of the predictor (independent variable) occurrence, including the order of its position in the regression model equation for each village and year, suggested that the most important variables influencing *P. truncatus* numbers are: the percentage of host plant dominance > maximum temperature > minimum temperature > rainfall. These results were supported by analysis of mean numbers of the predictor factor as well. The strength of the effect of abiotic and biotic factors on fluctuations of *P. truncatus* numbers and components of the generalized linear model varied when evaluated separately by regression analysis. Factors included in the model generally correlated strongly with fluctuations in *P. truncatus* numbers (Fig. 3.6A, Fig. 3.6B). However, exceptions could be observed from the correlation of the mean percentage of host plant dominance and the maximum temperature recorded in 2014 (Fig. 3.6C, Fig.3.6D). Variation of the strength effect of abiotic and biotic factors on fluctuations of *P. truncatus* numbers could be observed through regression analysis coefficients of determination (r and p) per village and per year (Table 3.5).

High regression coefficient values indicated strong correlations between values of individual abiotic and biotic factors and that variation in *P. truncatus* numbers within villages was higher than over seasons. For example, the coefficient "r" denoting the strength of the relationship between fluctuations of *P. truncatus* numbers and the minimum and maximum temperature and rainfall from all villages during 2013, ranged between 0.5 and 0.7 (Table 3.5A). The maximum temperature was strongly correlated with fluctuations in beetle numbers only in the Machipanda village during 2014. The minimum temperature and the average rainfall had no influence on variations of beetle numbers in any of the villages (Table 3.5A). The average minimum rainfall of all villages showed strong relationships with *P. truncatus* numbers in 2013 and similarly to the analysis per village, they had no effect in 2014 (Table 3.5B). The correlation coefficient of the three above menctioned abiotic factors was lower and ranged between 0.3 and 0.4 for the regression analysis of these relationships studied over the whole period of 2013 and 2014 (Table 3.5C). The decrease in the strength of these relationships between factors might be ascribed to the higher general variation in abiotic and biotic factors over the two-year period.

Factors that determine the relevance of the effects of abiotic and biotic factors on fluctuations in *P. truncatus* number over years remain unclear. For example, strong and negative correlations between altitude and beetle numbers were observed only in Massingir and Chicualacuala during 2013 (Table 3.5A). Altitude was weakly correlated with *P. truncatus* numbers in 2013 and 2014 (Table 3.5B).

Table 3.5. Parameters of regression analysis of correlations between *Prostephanus truncatus* numbers and the respective abiotic and biotic factors, components of generalized linear models of villages (A), in the years 2013 and 2014 (B), and during the two year period 2013-2014 (C) in Mozambique.

	years	**2013**			**2014**		
(A) Villages	**Factors**	**b***	**r**	**P<0.05**	**b***	**r**	**P<0.05**
Machipanda	Maximum temperature (°C)	0.25	0.60	0.01	0.12	0.50	0.01
	Rainfall (mm)	0.05	0.60	0.01	Not in the GLM		
	Host plant dominance (%)	0.00	0.14	0.07	0.00	0.13	0.10
	Relative humidity (%)	0.09	0.23	0.02	0.03	0.40	0.01
	Minimum temperature (°C)	Not in the GLM			0.03	0.20	0.02
Catandica	Rainfall (mm)	0.05	0.70	0.01	Not in the GLM		
	Host plant dominance (%)	0.01	0.40	0.01	0.02	0.70	0.01
	Maximum temperature (°C)	0.22	0.60	0.01	Not in the GLM		
Massingir	Minimum temperature (°C)	0.13	0.60	0.01	Not in the GLM		
	Rainfall (mm)	0.02	0.50	0.01	Not in the GLM		
	Host plant dominance (%)	Not in the GLM			0.07	0.60	0.01
	Altitude (m a.s.l.)	Not in the GLM			-0.00	-0.35	0.01
Chicualacuala	Relative humidity (%)	0.07	0.70	0.01	Not in the GLM		
	Rainfall (mm)	0.04	0.70	0.01	Not in the GLM		
	Minimum temperature (°C)	0.15	0.60	0.01	Not in the GLM		
	Average temperature (°C)	0.90	0.70	0.01	Not in the GLM		
	Host plant dominance (%)	Not in the GLM			0.01	0.40	0.01
	Altitude (m a.s.l.)	Not in the GLM			-0.01	-0.50	0.01

(B) Years	**2013**			**2014**		
Factors	**b***	**r**	**P<0.05**	**b***	**r**	**P<0.05**
Minimum temperature (^oC)	0.11	0.52	0.01	Not in the GLM		
Rainfall (mm)	0.00	0.60	0.01	Not in the GLM		
Relative humidity (%)	0.01	0.32	0.01	Not in the GLM		
Altitude (m a.s.l.)	-0.00	-0.01	0.01	0.00	0.10	0.05
Host plant dominance (%)	Not in the GLM			0.01	0.40	0.01
Maximum temperature (^oC)	Not in the GLM			0.05	0.20	0.01

(C) Year period 2013-2014			
Factors	**b***	**r**	**P<0.05**
Host plant dominance (%)	0.01	0.30	0.01
Rainfall (mm)	0.00	0.42	0.01
Altitude (m a.s.l.)	-0.00	-0.04	0.20
Maximum temperature (^oC)	0.10	0.34	0.01
Minimum temperature (^oC)	0.10	0.33	0.01
Relative humidity (%)	0.00	0.20	0.01

Hypothetically, these differences could lead to unfitness of models between villages (Omondi *et al*., 2011). All models were not validated in this work due to absence of data from previous studies in these villages and elsewhere in Mozambique.

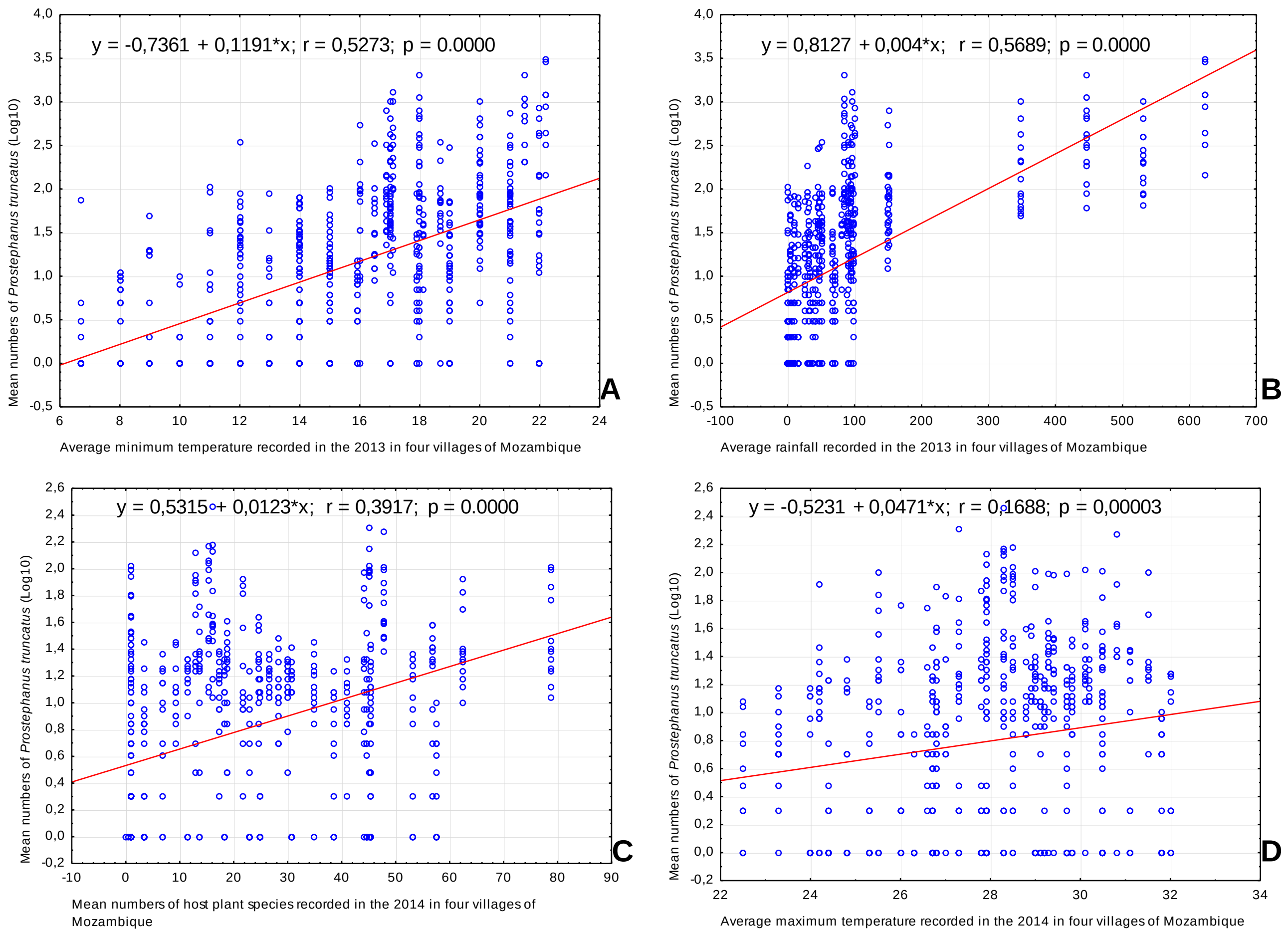


Fig. 3.6. Relationships between mean numbers of *Prostephanus truncatus* and minimum temperature (A) and rainfall (B) recorded during 2013, host plant species (C) and maximum temperature (D) recorded during 2014 in four villages of Mozambique.

3.3.2. Flight activity of *Prostephanus truncatus* in Manica and Gaza Provinces

Prostephanus truncatus trap catches fluctuated over time and differed between villages. The highest numbers of beetles were caught during January (1260 per trap) and February (756 per trap) 2013 in the Massingir village (Fig. 3.7). The lowest numbers of *P. truncatus* individuals were recorded from March to July in both years. Moreover, numbers of beetles decreased from January to July and again steadily increased from August to December in both years. More *P. truncatus* individuals were captured during January and February than during September to December in both years. This result could come from the fact that sampling of *P. truncatus* individuals by means of the funnel traps continuously removed beetles from the environment.

The flight activity of the pest slightly increased during the last four months of the year because of the increase of temperature and abundance of stored maize in granaries. The removal effect of *P. truncatus* by traps could also possibly explain the fact that numbers of beetles caught in 2013 were higher than those recorded in 2014.

Fluctuation patterns of *P. truncatus* numbers were synchronized with rain and dry seasonal periods at the studied villages. The period lasting from January to March and from September to December comprises the rain season months with optimum temperature, humidity and rainfall while the dry and cold season period with lower temperatures and drought lasts from April to August. This observation was supported by analysis of *P. truncatus* flight activity with fluctuations of studied climatic factors (Fig. 3.8). From this figure can be observed that lower trap catches of *P. truncatus* were recorded when the lowest minimum temperature (Fig. 3.8A) and minimum rainfall (Fig. 3.8B) values were registered in June and July of both years. Decreasing trends of both the minimum temperature and rainfall and of *P. truncatus* numbers from January to July are similar. Moreover, *P. truncatus* numbers increased simultaneously with the increasing trend of these climatic factors from August to December of each year.

Prostephanus truncatus trap catches were higher in the rainy (178 per trap) than in the dry (34 per trap) seasons. Trap catches differed markedly between seasons (N=600, df=599, t-test=-7.0, $p<0.05$) and between villages (N=4, df=3, F=2.1, $p<0.05$). Numbers of *P. truncatus* caught per season and per village are presented in Fig. 3.9. More *P. truncatus* beetles were trapped during both the rainy and dry season in the Massingir village compared to all other villages. *Prostephanus truncatus* trap catches were in general higher in the rainy than dry season in all villages. The fact that higher numbers of *P. truncatus* were recorded in rainy seasons could result from the prevalence of more optimum temperature, rainfall and humidity conditions for breeding and development of the pest (Hodges *et al*., 2003). Moreover, higher flight activity of beetles was observed when stored maize and other host products were available from granaries during the rainy season (Nang'ayo *et al.,* 1993; Hill *et al.,* 2003). These results support the linear relationship between the prevalence of warmer weather and shorter developement period and the longer duration of flight activity of insects (Prince, 1997;

Wellington *et al.*, 1999). Additionally, regression analysis indicated that there were marked seasonal correlations between *P. truncatus* numbers and the average minimum temperature, rainfall and mean numbers of host plant species (N=600, r=0.7, F=2.4, p<0.05).

Analysis of trap catches between land use types indicated that higher numbers of *P. truncatus* were recorded in traps located in human settlements (105 beetles per trap than those from forest areas (78 beetles per trap). *Prostephanus truncatus* trap catches differed significantly between human settlements and forest areas (N=600, t-test=2.4, F=4.3, p<0.05) (Fig. 3.9). The higher numbers of beetles trapped in human settlements compared to those in forest areas are ascribed to the fact that more maize granaries occur in the former areas. Trading in *P. truncatus* infected maize in local markets could also contribute to higher numbers of *P. truncatus* recorded in human settlements than in forest areas. Comparison of *P. truncatus* flight activity in human settlements and forest areas has for the first time been reported in this work.

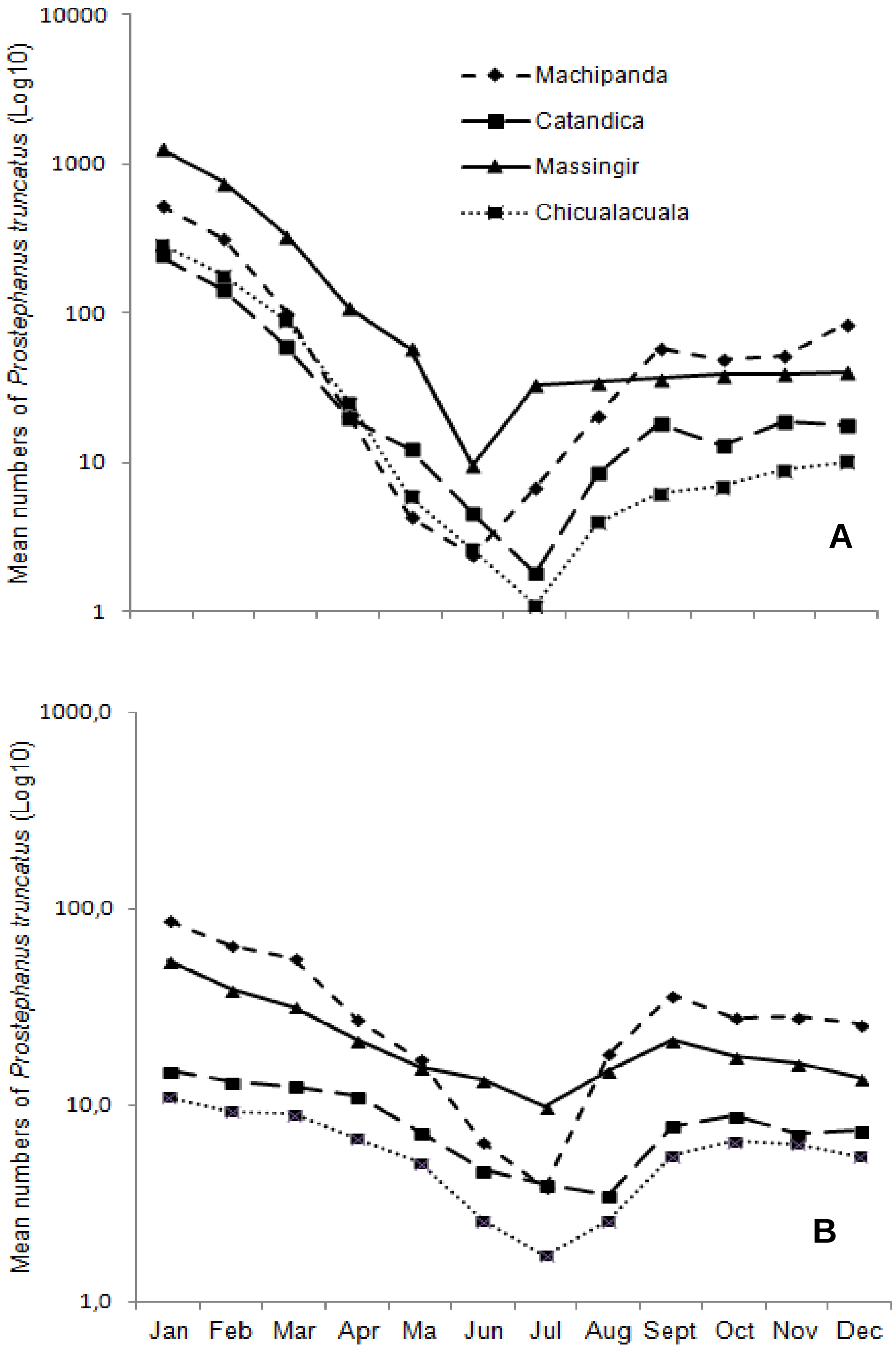


Fig. 3.7. Mean number of *Prostephanus truncatus* recorded over twelve month period in 2013 (A) and 2014 (B) in four villages of Mozambique.

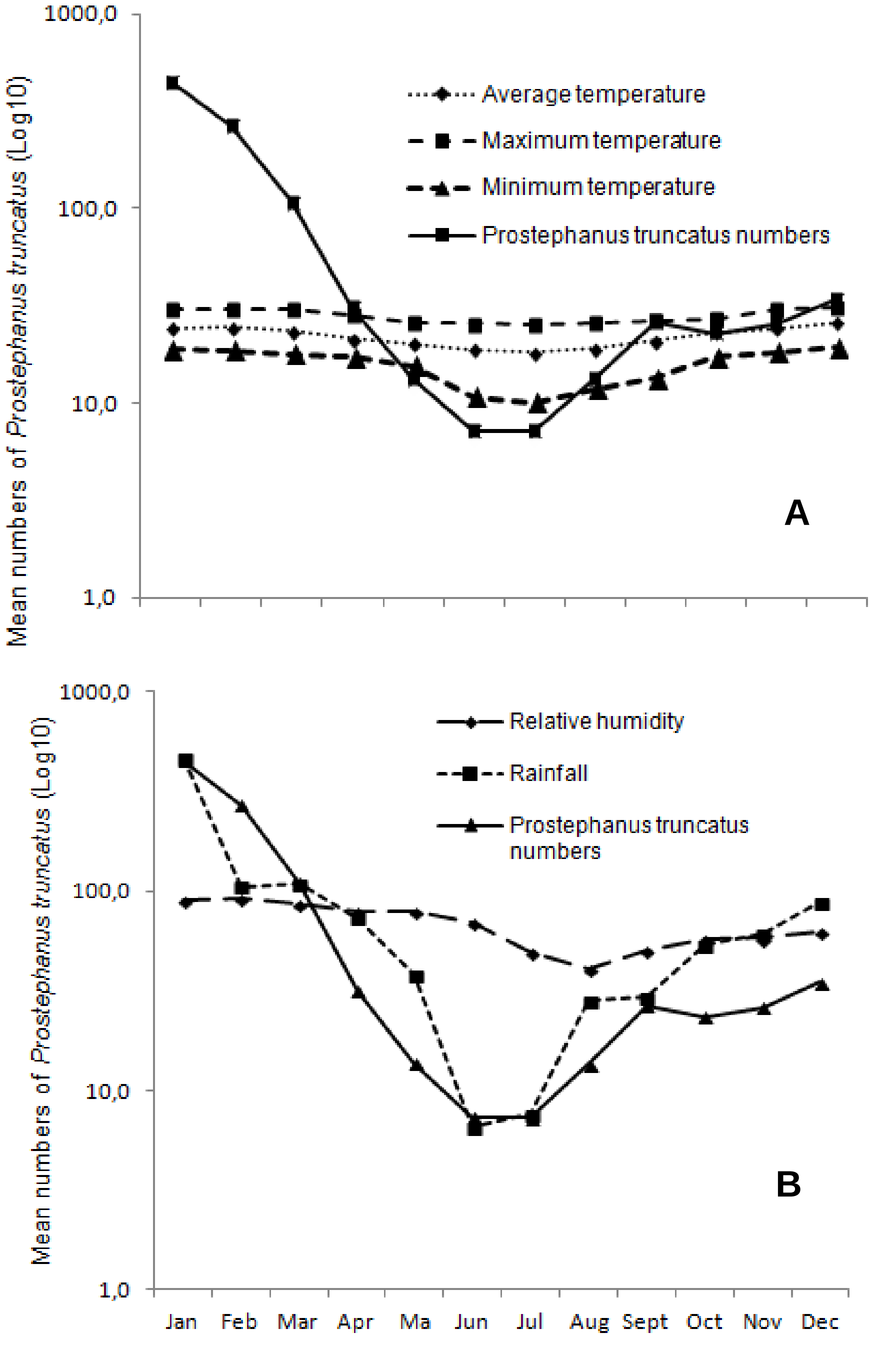


Fig. 3.8. Fluctuations of *Prostephanus truncatus* numbers per trap and temperature values (A), relative humidity and rainfall (B) recorded over twelve month period in 2013 and 2014 in four villages of Mozambique.

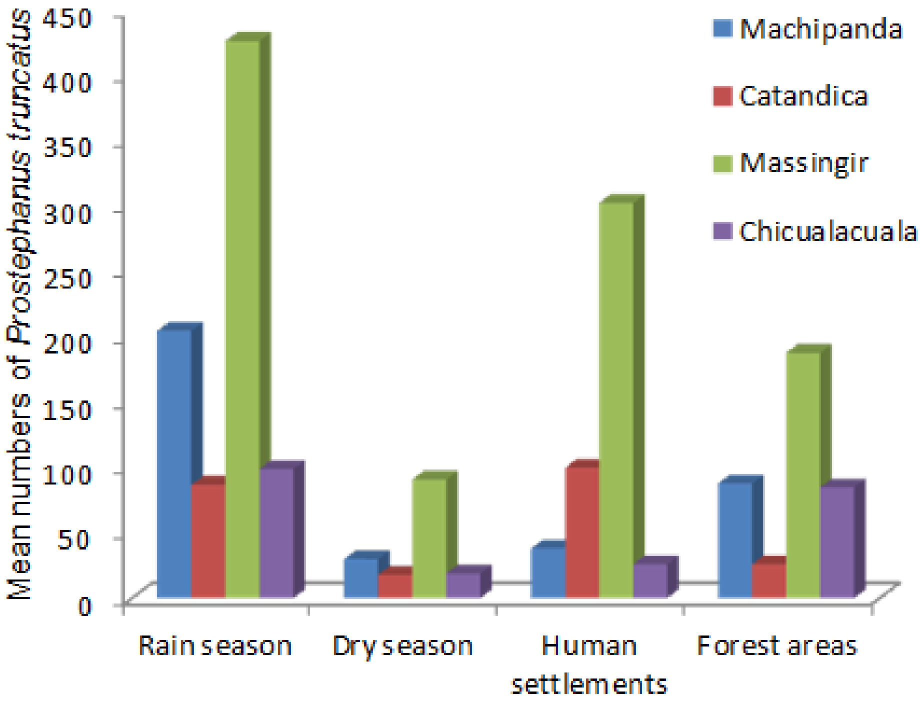


Fig. 3.9. Mean numbers of *Prostephanus truncatus* recorded during rainy and dry seasons and from human settlements and forest areas over a twelve-month period in four villages of Mozambique.

3.4. Conclusions

This study brought out the following conclusions: (1) all studied abiotic and biotic factors influenced the fluctuations in *P. truncatus* numbers with exception of the average temperature, (2) the minimum and maximum temperature as well as the average rainfall correlated strongly with *P. truncatus* trap catches in all villages over years, (3) the average altitude showed a lower and negative effect on *P. truncatus* population numbers only in the Massingir and Chicualacuala villages, (4) the strength of the effect of abiotic and biotic factors on fluctuations of *P. truncatus* numbers may differ between years. Studies on abiotic and biotic factors that influence fluctuations of *P. truncatus* population numbers should be continued. These studies will upgrade the data base on *P. truncatus* population dynamics that will allow further validation of models on dispersal and colonization of new areas by this pest.

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CHAPTER FOUR

The use of mass trapping to suppress population numbers of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in small scale farmer granaries in Mozambique

ABSTRACT

This study evaluated the potential of mass trapping to reduce *Prostephanus truncatus* population numbers in granaries and hence its possible use as pest management tool. Universal moth traps (Uni-traps) were used to trap the pest and its predator, *Teretrius nigrescens* Lewis (Coleoptera: Histeridae) in granaries of small scale farmers in three villages of the Gaza Province of Mozambique during the maize storage period of August 2013 to January 2014. Five granaries were selected in each village. Two baited pheromone traps were set up adjacent to each of three of these granaries. The other two granaries were used as controls, without traps. Population density of both the pest and its predator, were monitored in these traps as well as in stored maize ears inside granaries for a six month period. Mean numbers and densities of *P. truncatus*, the percentage damaged maize kernels and maize kernel weight loss in granaries with and without traps were compared by means of t-tests. The Cohen's standard of effect size was applied to measure the magnitude of differences between studied variables. An average of 1272 individuals of *P. truncatus* was caught per trap. Mean densities of *P. truncatus* recorded per maize ears in granaries with traps were lower (27 individuals/ ear) than of those (129) without traps. The percentage of damaged maize kernels was higher (62%) in granaries without traps than in those (22.0%) with traps. Highly significant negative correlations were found between mean numbers of *P. truncatus* caught in traps, mean densities in maize ears. These findings indicate that mass trapping is a potential method of control of *P. truncatus* in granaries of small scale farmers.

Key words: Uni-traps, maize, storage pests, *Teretrius nigrescens*

4.1. Introduction

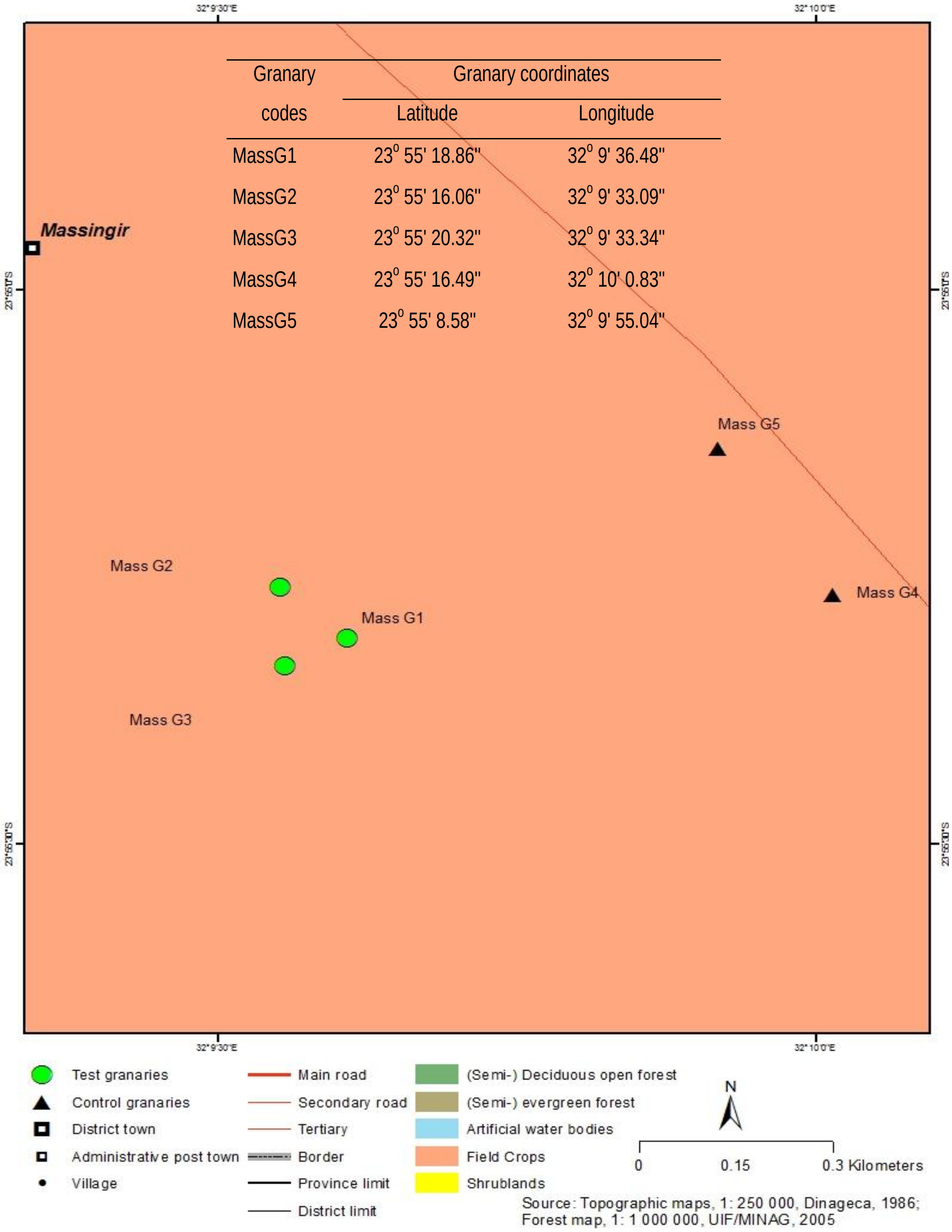
Prostephanus truncatus (Horn) (Coleoptera: Bostrichidae) is a pest of stored products and reduces the storage period of maize kernels, which usually lasts for between 10 and 12 months, to approximately 6 months. In Mozambique, this pest causes reduction of up to 62% in the granaries of stored maize kernels (Cugala *et al*., 2007; Muatinte *et al*., 2014). This pest also causes losses of cassava chips in Tanzania (Hodges *et al*., 1985), Ghana (Stumpf, 1998) and Benin (Gnonlonfin *et al.,* 2008). Fumigants based on phosphine and methyl-bromide chemicals (OEPP/EPPO, 2012), pyrethroids, deltamethrin mixed with either pirimiphos-methyl or chlorpyriphos-methyl (Dales and Golob, 1997) have been used to control this pest in Tanzania. Spinetoram has been recommended for use to control *P. truncatus* in Greece (Vassilakos *et al.,* 2012). Integrated pest management approaches for *P. truncatus* have been advocated by several authors. The combined use of spinosad with diatomaceous earths (Kavallieratos *et al*., 2010) in Greece, use of insect-resistant maize and biological control (Bergvinson and Garcia-Lara, 2011) in the United States of America (USA) as well as the use of hermitic bags (De Groote *et al*., 2013) in Kenya were reported as effective against *P. truncatus*. The use of inert dusts, mainly diatomaceous earth (Stathers *et al.,* 2008), host plant resistance (Castro-Guillén *et al.,* 2012), plant derived products (Silva *et al*., 2012) and biological control by means of the predator, *Teretrius nigrescens* Lewis (Coleoptera: Histeridae) have also been suggested (Schneider *et al.,* 2004; Muatinte and Cugala, 2015).

Semiochemical-based measures provide cost-effective and ecologically friendly strategies to manage pests of stored products (Philips and Throne, 2010; Muatinte *et al*., 2014). Effective mass trapping, using pheromone baited traps has been reported for scolytid beetles (Coleoptera) in Columbia (Lindgren, 1983), bark beetle, *Ips duplicatus* (Sahlberg) (Coleoptera: Scolytidae) in China (Schlyter *et al.,* 2001) and palm weevil, *Rhynchophorus ferrugineus* (Oliver) (Coleoptera: Rhynchophoridae) in Saudi Arabia (Abraham *et al*., 2001). Research on mass trapping for the control of *P. truncatus*, especially using Uni-traps, is a new approach to managing this pest. These traps have also been reported to have potential for control of Love bugs, *Plecia nearctica* (Diptera: Bibionidae) (Arthurs *et al*., 2015) in the USA. In the past, investigations into the use of pheromone traps have been limited largely to monitoring of pest dispersal (Phillips, 1997) or to flight activity studies (Omondi *et al.,* 2011). The use of pheromone baited Uni-traps has potential advantages since it can trap large numbers of adults of *P. truncatus* and its predator *T. nigrescens*, without killing the trapped beetles. Uni-traps might trap beetles that emerge either from maize ears and wood used for granary construction, as well as individuals that are attracted from other host products such as dry cassava chips and forest plant species. This research evaluated the potential of mass trapping to suppress *P. truncatus* numbers in granaries of small holder farmers.

4.2. Material and Methods

4.2.1. Granary selection

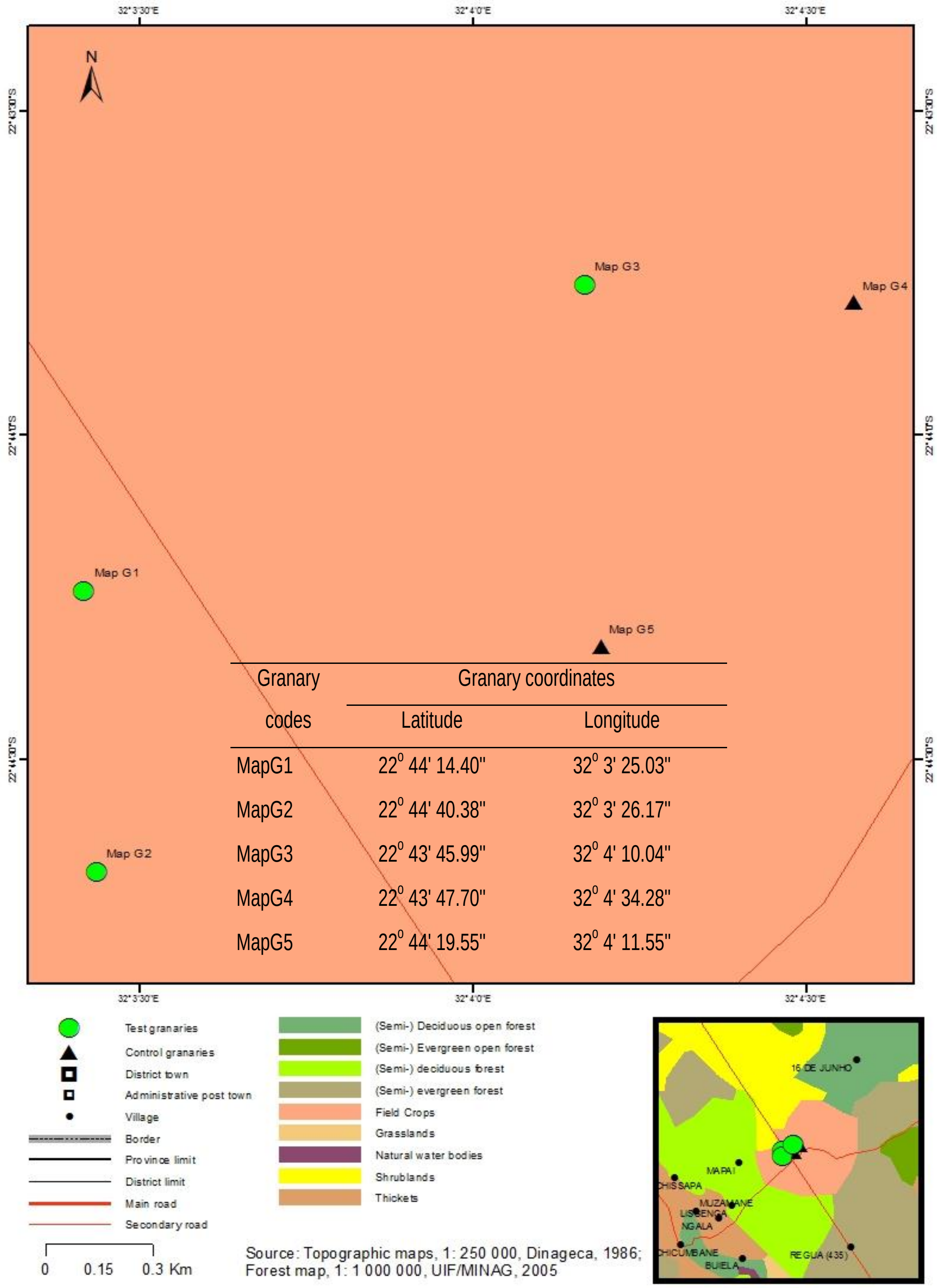
Traditionally-built maize granaries were selected in the Massingir (Fig. 4.1), Mapai (Fig. 4.2) and Chicualacuala (Fig. 4.3) villages in the Gaza province of Mozambique. The Massingir village is located at approximately 200 Km distance from Mapai and 260 Km from the Chicualacuala village. The latter villages are situated at 60 Km from each other. Five granaries were selected in each of the villages and geographical coordinates of the granary localities were recorded. Three granaries per village were treated with traps (test granaries), while the remaining two were used as controls without traps. Therefore, the granaries with and without traps were replicated six and four times respectively. The criteria for selection of granaries were as follows: it contained more than one ton of maize ears which would last for more than six months of storage to allow monitoring of *P. truncatus* populations, farmers were willing to allow for surveys to be done, granaries were easily accessible and the distance between granaries inside a village was between 1 and 2 km. Some granaries were constructed of wood of *Colophospermum mopane* (J. Kirk ex Benth) J. Kirk ex J. Léonard (Caesalpiniaceae), covered with zinc and plastic (Fig. 4.4A).Others were constructed with wood from different plant species and mud on the floor, or with wood from *C. mopane* covered with *Hyparrhenia* sp. (Poaceae) on top (Fig.4.4B). All granaries were found with stored shelled maize ears by the beginning of the survey in August. The post-harvest storage of maize in Mozambique begins in May of each year (Mudema *et al*., 2012, SIMA, 2014).



Granary codes	Granary coordinates	
	Latitude	Longitude
MassG1	23^{0} 55' 18.86"	32^{0} 9' 36.48"
MassG2	23^{0} 55' 16.06"	32^{0} 9' 33.09"
MassG3	23^{0} 55' 20.32"	32^{0} 9' 33.34"
MassG4	23^{0} 55' 16.49"	32^{0} 10' 0.83"
MassG5	23^{0} 55' 8.58"	32^{0} 9' 55.04"

Source: Topographic maps, 1: 250 000, Dinageca, 1986;
Forest map, 1: 1 000 000, UIF/MINAG, 2005

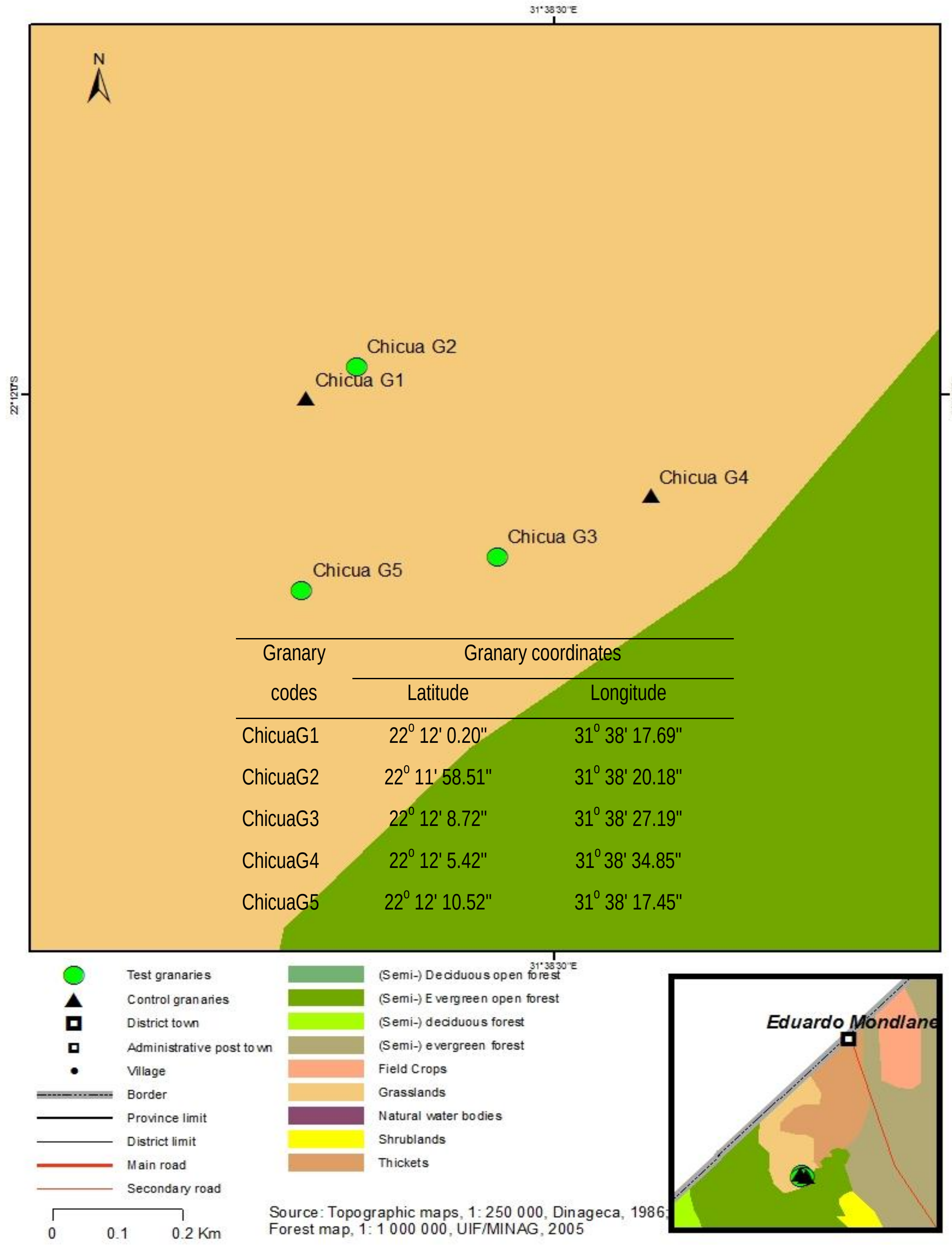
Fig.4.1. A map indicating localities of granaries and geo-referenced coordinates and vegetation types in the Massingir village of the Gaza Province of Mozambique.



Granary codes	Granary coordinates	
	Latitude	Longitude
MapG1	22^0 44' 14.40"	32^0 3' 25.03"
MapG2	22^0 44' 40.38"	32^0 3' 26.17"
MapG3	22^0 43' 45.99"	32^0 4' 10.04"
MapG4	22^0 43' 47.70"	32^0 4' 34.28"
MapG5	22^0 44' 19.55"	32^0 4' 11.55"

Source: Topographic maps, 1: 250 000, Dinageca, 1986; Forest map, 1: 1 000 000, UIF/MINAG, 2005

Fig. 4.2. A map indicating localities of granaries, geo-referenced coordinates and vegetation types in the Mapai village of the Gaza Province of Mozambique.



Granary codes	Granary coordinates	
	Latitude	Longitude
ChicuaG1	22° 12' 0.20"	31° 38' 17.69"
ChicuaG2	22° 11' 58.51"	31° 38' 20.18"
ChicuaG3	22° 12' 8.72"	31° 38' 27.19"
ChicuaG4	22° 12' 5.42"	31° 38' 34.85"
ChicuaG5	22° 12' 10.52"	31° 38' 17.45"

Source: Topographic maps, 1: 250 000, Dinageca, 1986;
Forest map, 1: 1 000 000, UIF/MINAG, 2005

Fig. 3. A map indicating localities of granaries, geo-referenced coordinates and vegetation types in the Chicualacuala village of the Gaza Province of Mozambique.

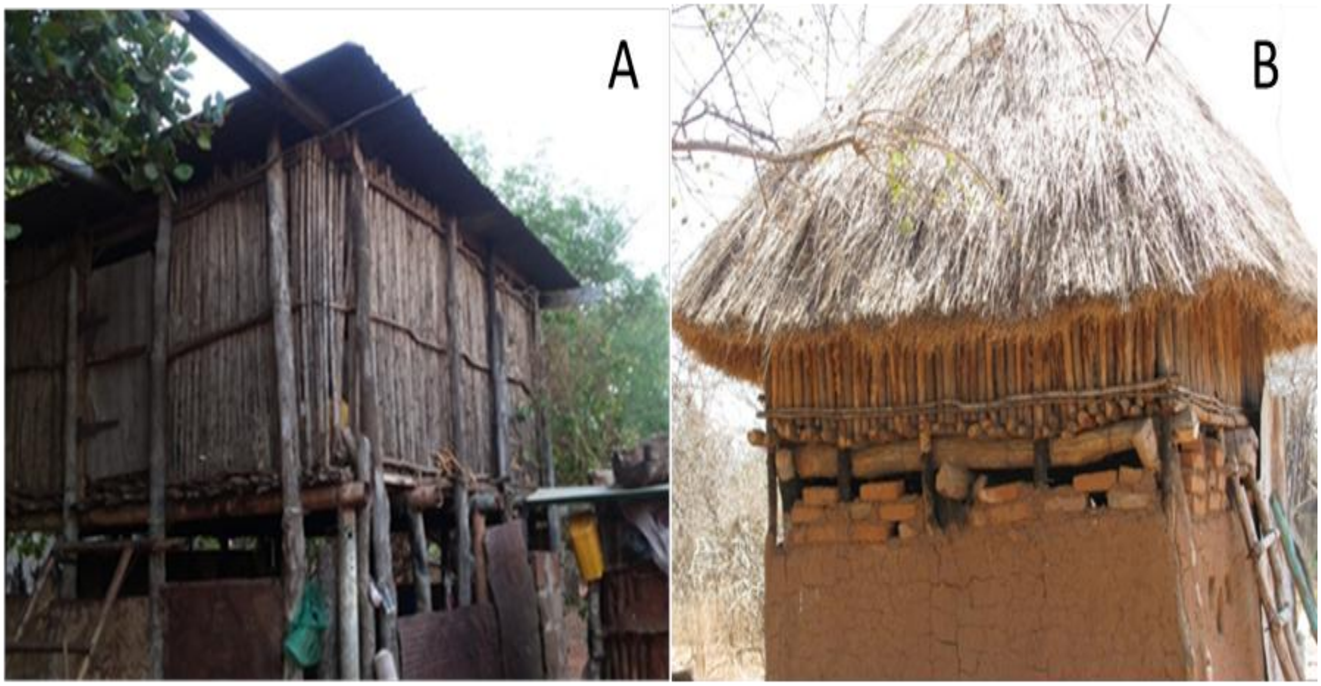


Fig. 4.4. Traditionally built granaries in the Massingir, Mapai and Chicualacuala villages of the Gaza Province of Mozambique; A, covered with zinc; B, covered with grass, *Hyparrhenia* sp.

4.2.2. The effect of mass trapping on fluctuations of *Prostephanus truncatus* and *Teretrius nigrescens* numbers

The effect of mass trapping on fluctuations of *P. truncatus* and *T. nigrescens* numbers in granaries was evaluated over a 6-month period. This was done by means of pheromone baited green universal moth traps setup outside granaries. Traps and pheromones were purchased from International Pheromone Systems Limited, England. The pheromones consisted of a mixture of Trunc-call 1 and Trunc-call 2 in a 1:1 ratio. Two pheromone baited traps were located adjacent each granary and at approximately 50 m distances from each granary, in a general upwind and down wind direction. However, further changes of wind directions in the granary and trap locations were not taken in account. Traps placed at the same granary were separated at about 100 m distances. Captured insects were collected at monthly intervals, after which they were identified and counted. These pheromone baited traps caught *T. nigrescens*, the predator of *P. truncatus* as well. There were 18 traps replicates in all study and a total of 108 trap catch samples of *P. truncatus* and *T. nigrescens* were collected in the three villages. The total number of trap catch sample came from the product of two traps per granary, per tree granaries per village, per tree villages and per six months of survey.

4.2.3. The effect of *Prostephanus truncatus* mass trapping on maize kernel damage in granaries

This objective was achieved by counting numbers of *P. truncatus* and *T. nigrescens* adults from maize ears and by counting damaged and undamaged maize kernels of maize ears in granaries. For assessing beetle densities five maize ears with husks were randomly selected and removed from each granary at monthly intervals over the 6-month period within reaching distance from the granary entrance. Therefore, the maize ear was replicated five times per granary. The Maduba local maize variety was identified in all granaries. However, data on maize variety was not taken into account in this study. No insecticide treatment was done in any of the granaries. Maize ears were transported to the laboratory and de-husked. Surveys of *P. truncatus* and *T. nigrescens* in traps and in maize ears were done simultaneously.

The total number of kernels as well as the number of damaged and undamaged kernels in a maize ear were counted and weighed separately for each of the five maize ears collected per granary. The maize powder recovered from each de-husked ear was also weighed. These data were taken to determine the percentage of maize kernel damaged per ear and reduction in kernel mass over time. The presence of other maize storage pests was not recorded. However, *Sitophilus zeamais* (Motschulsky) (Coleoptera: Curculionidae), *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) and *Tribolium castaneum* (Herbst) (Tenebrionidae) were sometimes found in maize ears and flour.

The efficacy of mass trapping on reducing numbers of *P. truncatus* was estimated by evaluating the differences between numbers of this pest and its predator and the percentage of damaged maize kernels in granaries with and without traps. Trends of pest and predator numbers caught in traps and of the maize kernel damage in granaries over a six month period were also used to evaluate the efficacy of mass trapping on reduction of *P. truncatus* numbers in maize granaries of small scale farmers.

4.2.4. Data analysis

Data were analysed using Statistica 12 (Stat soft, Inc. 1984-2013). The trap catches of *P. truncatus* and *T. nigrescens* was expressed as mean numbers of caught beetles per trap, per month and per village. These numbers were rounded up and down to the nearest whole numbers and presented in tables together with the resulting from them log-transformation data. This procedure was adopted to better illustrate the real quantity of beetles caught in traps. The population density of *P. truncatus* and *T. nigrescens* in maize ears was expressed as mean numbers of beetles per maize ear of each time period and village. Mean of total numbers of kernels per maize ear as well as the mean numbers of damaged and undamaged kernels were calculated using basic descriptive statistics. All mean numbers were expressed as percentage values except those of total number of maize kernels and mean kernel weight. The percentage of kernel weight loss was determined using the count-and-weigh method (Boxall, 1986).

The t-test for independent by variables was used to compare mean densities of *P. truncatus* and *Teretrius nigrescens* recorded in maize ears of granaries with and without traps. This test was also used to compare the percentage of damaged maize kernels and maize kernel weight loss in granaries with and without traps. The Cohen's standard effect size was applied to determine the magnitude of differences between compared variables (Cohen, 1988; Ellis, 2009; Sullivan and Feinn, 2012).

Breakdown and One Way ANOVA (SAS Institute, 1999) was used to assess differences between mean numbers of *P. truncatus* and *T. nigrescens* in traps between months and villages since these data fitted the normal distribution. Monthly beetle catches in traps and densities in maize ears in granaries were compared at 5% significance level ($p<0.05$) using the Tukey HSD Test for unequal number of samples (N) (Spjotvoll/Stoline). Mean numbers of *P. truncatus* in traps and densities in maize ears in granaries were compared between villages as well. This procedure was done to evaluate the potential spatial variation of the principle of mass trapping by means of Uni-traps. The effect of mass trapping on reducing *P.*

truncatus population numbers was considered significant when the Cohen's standard effect size d≥0.08 was found between (1) mean densities of *P. truncatus* in maize ears of granaries with and without traps and (2) the mean percentage of maize kernel damage in maize ears of granaries with and without traps. The percentage difference of maize kernel damage that was higher than 50% was used as an indicator of the efficacy of mass trapping in reducing *P. truncatus* population numbers. And it was calculated by subtracting the percentage of maize kernel damage of granaries with traps from that without traps.

Regression analysis was applied to determine relationships between mean numbers of *P. truncatus* caught in traps and the mean percentage of maize kernel damage and maize kernel weight loss in granaries with and without traps. This analysis was also used to assess the relationships between mean densities of *P. truncatus* in maize ears and the mean percentage of maize kernel damage and maize kernel weight loss in granaries with and without traps as well. The strong correlation found between studied variables was used as an indicator of the efficacy of mass trapping in suppressing *P. truncatus* numbers in granaries of small scale farmers.

4.3. Results and discussion

4.3.1. The effect of mass trapping on *Prostephanus truncatus* and *Teretrius nigrescens* numbers in traps

An average of 1272 individuals of *P. truncatus* of all villages was caught per trap during this work. Mean numbers of caught beetles significantly varied (df=17, F=3.94, $p<0.05$) between traps. The higher mean number of *P. truncatus* in a trap (5534 individuals) was observed in Mapai followed by Massingir village with 4706 beetles (Table 4.1). *Teretrius nigrescens* was caught in lower mean number (18 individuals) compared to *P. truncatus* traps from all villages. No significant variations of the predator mean numbers were found between traps (Table 4.1). Analysis of *P. truncatus* traps per granary showed that higher mean numbers of this beetle were caught in Mapai (2936 individuals) followed by Massingir village with 2602 individuals in a granary. Mean numbers of trapped *P. truncatus* varied per granary as well (Table 4.2).

Table 4.1. Mean numbers of *Prostephanus truncatus* and *Teretrius nigrescens* caught per trap in three villages of the Gaza Province of Mozambique over a six month period.

Villages	**Granaries symbols**	**Trap symbols**	***Prostephanus truncatus***		***Teretrius nigrescens***	
			Untrans-formed means	**Log_{10} (Mean±SD)**	**Untrans-formed means**	**Log_{10} Mean±SD**
Massingir	A	A1	3329	3.06±0.72c	44	1.20±1.00b
		A2	687	2.35±0.70c	18	1.00±0.50b
	B	B1	4706	3.27±0.64c	19	1.00±0.60b
		B2	497	2.35±0.61c	9	1.00±0.60b
	C	C1	2266	3.00±0.65c	21	1.00±1.00b
		C2	2030	2.44±0.92b	44	1.12±1.00b
Mapai	A	A1	5534	3.00±1.00a	19	1.00±0.60b
		A2	338	2.04±1.00b	5	1.00±0.22b
	B	B1	1391	2.00±1.20b	33	1.00±1.00b
		B2	724	2.00±1.00b	8	1.00±1.00b
	C	C1	167	2.00±1.00b	12	1.00±1.00b
		C2	40	1.20±0.60a	6	1.00±0.50b
Chicualacuala	A	A1	221	2.20±0.43b	5	0.40±0.50a
		A2	141	2.00±0.50b	4	0.40±0.40a
	B	B1	285	2.10±0.67b	3	0.40±0.31a
		B2	86	2.00±0.51b	7	0.60±0.50b
	C	C1	548	3.00±0.36a	30	1.11±1.00b
		C2	333	2.41±0.35b	44	1.17±1.00b
All traps			1272	2.24±1.00b	18	0.80±0.60b

[1] Means followed by the same letter within columns do not differ significantly at $p<0.05$.

Table 4.2. Mean numbers of *Prostephanus truncatus* and *Teretrius nigrescens* caught in traps in three villages of the Gaza Province of Mozambique over a six month period.

Villages	**Granary symbols**	***Prostephanus truncatus***		***Teretrius nigrescens***	
		Untransformed means	**Log_{10} Mean±SD**	**Untransformed means**	**Log_{10} Mean±SD**
Massingir	A	2008	2.70±0.80c	31	1.10±0.60b
	B	2602	2.80±0.80c	14	0.80±0.60b
	C	2148	2.70±0.80c	33	1.03±0.73b
Mapai	A	2936	2.40±1.00b	12	0.80±0.43b
	B	1057	2.00±1.00b	20	0.64±0.73b
	C	103	1.00±0.35a	9	0.70±0.53b
Chicualacuala	A	181	2.10±0.45b	4	0.41±0.44a
	B	185	2.00±1.00b	5	0.50±0.43a
	C	440	2.50±0.35c	37	1.15±1.00b
All villages		1272	2.24±1.00b	18	0.80±0.60b

[1] Means followed by the same letter within columns do not differ significantly at $p<0.05$.

Factors affecting the quantity and variation of caught insects between pheromone baited traps have been a subject of discussion. Trap location in relation to granaries, beetle densities in the surrounding the traps environment (Nansen *et al.,* 2008) as well as variation of wind direction and speed (Fadamiro, 1996) could be factors that affected the quantity and differences of caught beetles between traps and granaries in this study. The design and the type of material of which the granaries were built could potentially influence mean numbers of *P. truncatus* caught in traps and granaries. The latter factors could regulate the quantity of insects escaping out the granaries and hosting pest individuals inside granary built wood. The quantity of exposed traps per granary (Nansen *et al*., 2008) and the trap design (El-Sayed *et al.,* 2006; Arthurs *et al*., 2015; IPS, 2016) could hypothetically influence the quantity of beetles captured per traps. We suggest that Uni-traps being primarily designed to capture moths (IPS, 2016) act as fly intercept barrier of flying beetles attracted by pheromones located inside the pheromone dispenser cage of the trap. Hence, trap set up near the granaries previously to the beginning of storage maize period might hypothetically reduce grain infestation by the pest. Preventing attack and infestation of maize grain by disorienting *P. truncatus* to reach the granaries could be the principle mechanism of Uni-trap use in pest management. However, this Unit-trap functional approach requires further research. Therefore, the effectiveness of Uni-traps is supported by the ability of *P. truncatus* to actively fly (Nansen and Meikle, 2002) inside storage system and throughout the environment of forest host plant species (Hill *et al*., 2002; Nansen *et al*., 2004a).

Temporal analysis of trap catches revealed that the highest mean number of *P. truncatus* trap catches for a one-month period of survey, in granaries with traps was 8089 individuals in November at Massingir and the lowest was 26 beetles in August at Mapai village (Fig. 4.5A). The highest number of *T. nigrescens* (100 individuals) was caught in November at Massingir while the lowest (one individual) for a one-month period was recorded in August at Mapai and Chicualacuala villages. Monthly mean numbers of caught *P. truncatus* (Fig. 4.5A) and *T. nigrescens* (Fig. 4.5B) increased from August onwards with a peak in November followed by steady decrease towards January 2014.

These patterns suggest that beetles were already occurring and infesting maize kernels in granaries and at the surrounding environment by the beginning of the survey in August. However, the levels of initial infestation of maize kernels and other potential host of *P. truncatus* have not been assessed previously to the experiment and were unknown. The increasing beetle numbers thereupon was suppressed from November towards January in granaries with traps. Hence, this monthly trend of the pest numbers in traps suggest that mass trapping is potential for reducing pest *P. truncatus* numbers. However, the observed patterns of *P. truncatus* population number fluctuations could be influenced by variations of temperature, humidity and rainfall (Borgemeister *et al*. 1997, Hodges *et al.* 2003; Omondi *et al.* 2011). Apart from that, these results suggest that pheromone baited Uni-traps could be used in monitoring *P. truncatus* flight activity and abundance.

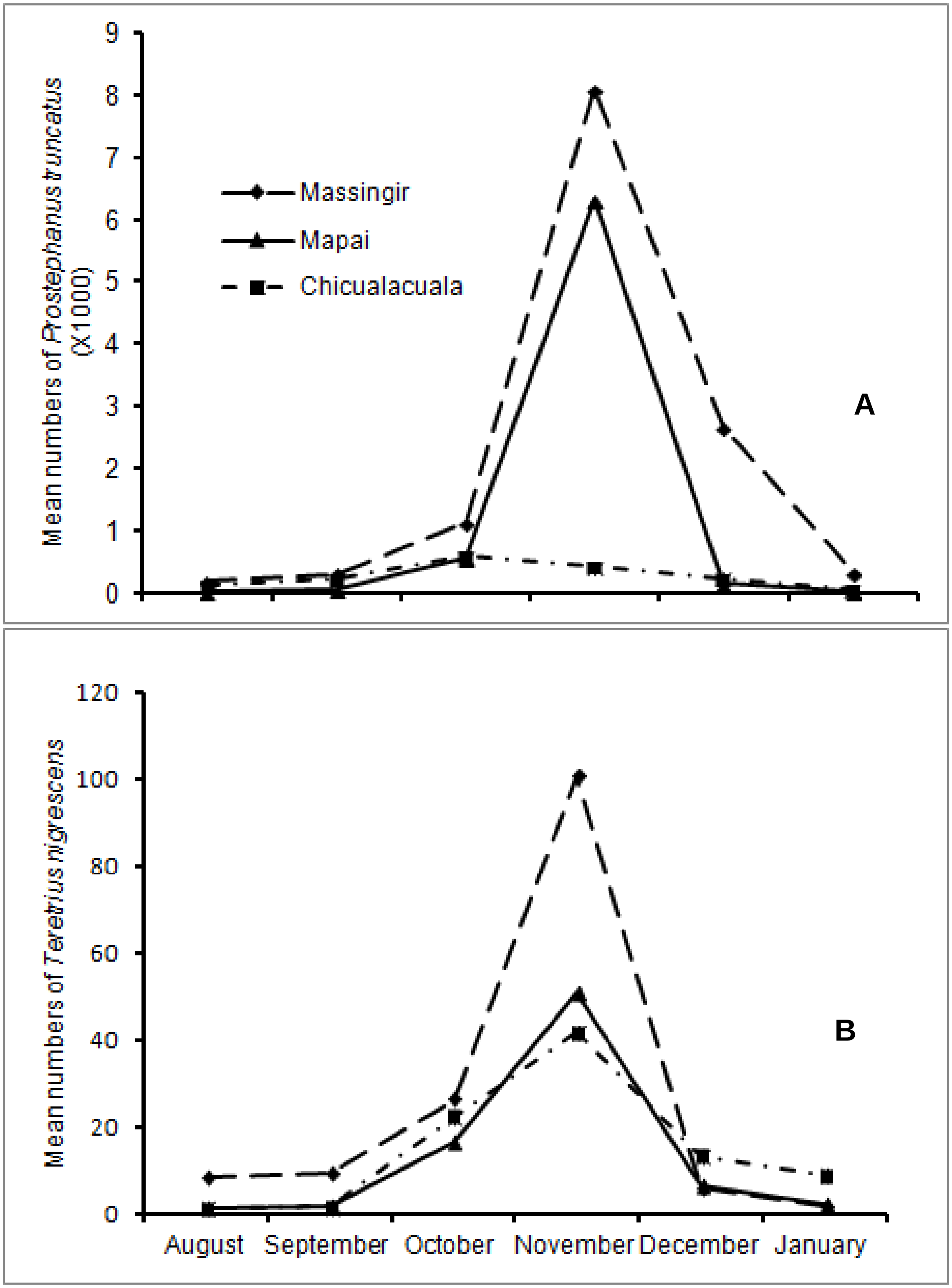


Fig.4.5. Mean numbers of *Prostephanus truncatus* (A) and *Teretrius nigrescens* (B) captured in three villages of the Gaza Province of Mozambique, over a six-month period.

Moreover, similar in relation to month patterns of insect population fluctuations were reported by Nansen *et al.* (2004b), who studied relationships between flight activity of rusty kernel beetle, *Cryptolestes ferrugineus* (Coleoptera: Cucujidae) outside kernel bins and probe trap catches inside kernel bins.

The predator catch patterns (Fig. 4.5B) were similar to those of *P. truncatus*. The similarity of temporal and spatial occurrence and distribution of *P. truncatus* and *T. nigrescens* can be supported by population dynamics and predator-prey interaction theories (Price, 1997; Abrams, 2000). However, these patterns cannot necessarily result in direct impact of the predator on prey population numbers. Borgemeister *et al.* (1997) found no clear cause-effect relationships between *P. truncatus* and *T. nigrescens* population number fluctuations in Benin. Moreover, Omondi *et al.* (2011) in Kenya observed that the prediction model they used based on flight activity did not allow for assessment of the impact of *T. nigrescens* on *P. truncatus* density because it was also influenced strongly by temperature, humidity and precipitation.

4.3.2. The effect of mass trapping on densities of *Prostephanus truncatus*, *Teretrius nigrescens* in maize ears and on maize kernel damage in granaries

Mean densities of *P. truncatus* in maize ear of granaries with traps were lower (27 individuals per maize ear) than in those (control) without traps with 129 individuals. Mean densities of *P. truncatus* in maize ears significantly varied (N=360, t-test=-10.5, F=4.9, $p<0.05$) between granaries with and without traps. Mean densities of *P. truncatus* in maize ears with and without traps per villages were illustrate in Fig. 4.6. There was significant variation (N=3, df=2, F=4.24, p=0.02) of *P. truncatus* mean densities in maize ears of granaries with and without traps between villages.

Mean densities of the predator were lower (3 individuals per maize ear) in maize ears with than in those (12 individuals) without traps. There was also significant variation in mean densities of *T. nigrescens* collected in maize ears of granaries with and without traps. However, mean densities of this predator in maize ears of granaries with and without traps did significantly not varied (N=3, df=2, F=0.02, p=1.0) between villages. Fig.4.6 illustrates these densities.

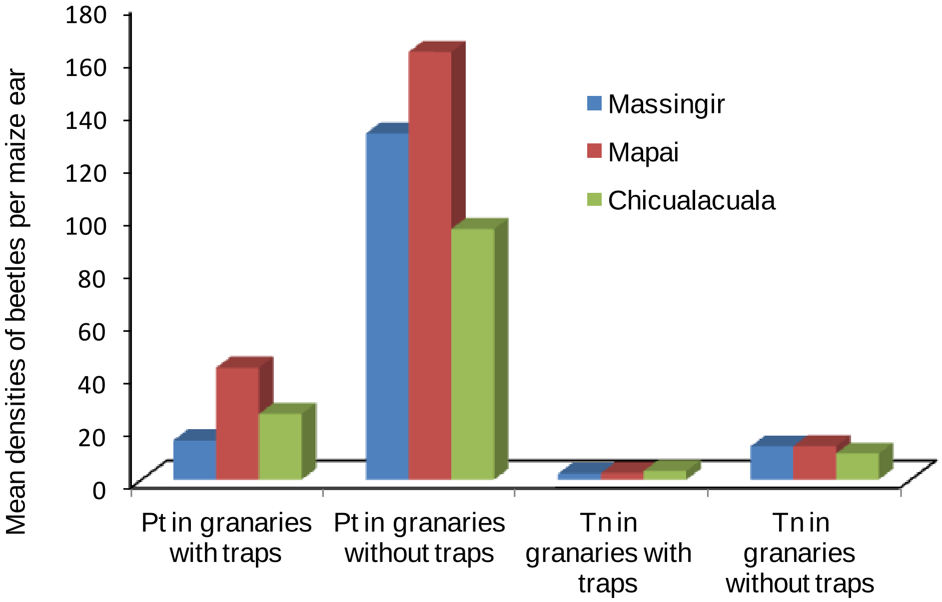


Fig. 4.6. Mean densities of *Prostephanus truncatus* (Pt) and *Teretrius nigrescens* (Tn) in maize ears sampled from granaries with and without traps in three villages of the Gaza Province, Mozambique.

The average percentage of maize kernel damage in maize ears of granaries with traps was lower (22.0% of damaged kernels per maize ear) than in those (control granaries) without traps with 62.3% of damaged maize kernels. The Cohen's standard of effect size was large (1.0) with 84% percentile standing and 55% of non-overlap. This percentage significantly varied (N=216, t-test=-7.68, F=1.7, p<0.05) between granaries with and without traps. The average percentage of maize kernel damage in maize ears of granaries with and without traps per village is presented in Fig. 4.7.

The average percentage of maize kernel weight loss was lower (13.7% of weight loss per maize ear) in granaries with traps than in those (control granaries) without traps with 53.1% of maize kernel weight loss. The Cohen's standard of effect size was similarly large as that of the average percentage of the maize kernel damage. Significant differences (N=216, t-test=-7.97, p<0.05) of maize kernel weight loss were also high between granaries with and without traps. The average percentage of maize kernel weight loss per maize ears of granaries with and without traps and between villages is presented in Fig. 4.7.

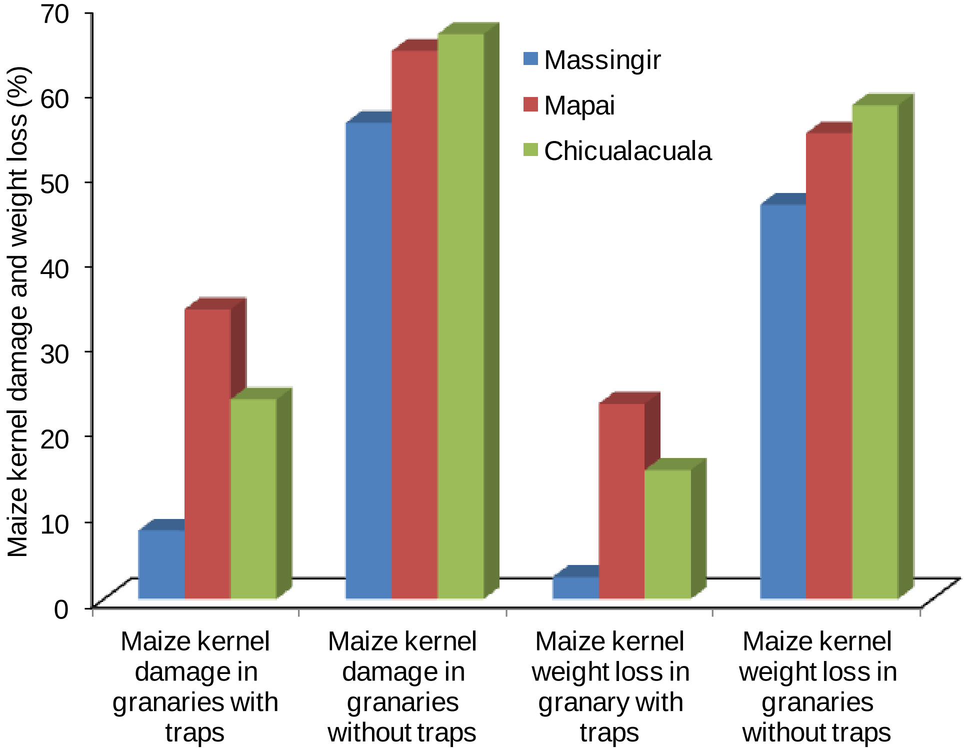


Fig. 4.7. Mean percentage of incendence of damage kernel and kernel weight loss in granaries with and without traps in three villages of the Gaza Province, Mozambique.

Stored maize losses in granaries due to *P. truncatus* infestation reached up to 62% in the Tete Province of Mozambique (Cugala *et al*., 2007) and 65.4% in the Gbonvé region of Southern Togo (Helbig, 1995). These levels of maize losses can be observed when not taken effective management measures against *P. truncatus*. Therefore, lower densities of *P. truncatus* in maize ears of granaries with traps than in those without them resulted from the use of mass trapping measure against the pest. The use of mass trapping of *P. truncatus* with subsequent reduction of densities of this pest was the reason for the lower average percentage of maize kernel damage and maize kernel weight loss observed in granaries with traps compared to that recorded in granaries without traps. Meikle *et al*. (2002), applied sofagrain (1.5% pirimiphos-methyl and 0.5% deltamethrin, Sofaco, Ivory Coast), a chemical pesticide, and found similar patterns of maize damage and weight loss reduction under *P. truncatus* infestation in traditional maize stores in central and southern Benin. However, the plan and method applied to sample maize ears (Meikle *et al.,* 2000) could affect densities of the pest recorded between granaries.

Temporal analysis revealed that monthly densities of *Prostephanus truncatus* in maize kernel ears of granaries with (N=6, df=5, F=47.2, $p<0.05$) and without (N=6, df=5, F=39.5, $P<0.05$) traps significantly varied between months. The highest monthly densities of *P. truncatus* were found in maize ears collected from granaries were no traps were used compared with those with traps (Table 4.3). Densities of *T. nigrescens* inside granaries with traps (N=6, df=5, F=24.5, p=<0.05) and without traps (N=6, df=5, F=51.7, $p<0.05$) were significantly different between months as well. Higher monthly densities of the predator were recorded in inside granaries without traps compared with those with traps (Table 4.4). In general, densities of *T. nigrescens* in maize ears of granaries with and without traps (Table 4.4) were lower than those of *P. truncatus* (Table 4.3). This fact supports the low prey-predator ratio between *P. truncatus* and *T. nigrescens* observed in natural environments (Cugala *et al*., 2007) and indicates that mass trapping is a potential control (El-Aziz, 2011) and monitoring (Nansen *et al.,* 2001; Birkinshaw *et al*., 2004, Omondi *et al*., 2011) method that can suppress population numbers of the predator particularly when using adhasive traps.

Table 4.3. Mean densities of *Prostephanus truncatus* per maize ear and per month in granaries of three villages of the Gaza Province, Mozambique.

	Massingir	**Mapai**	**Chicualacuala**
Months	**mean±SD**	**mean±SD**	**mean±SD**
	With traps		
August	3.37±3.70a[1]A[2]	1.25±1.90aA	6.12±5.22bA
September	9.75±7.99bA	9.12±6.35cA	8.25±8.41bA
October	42.12±39.21dA	168.37±129.7fB	75.12±62.22dA
November	12.00±9.72cA	78.37±49.17eC	39.12±38.28cB
December	5.37±2.87bA	15.87±10.93dB	8.50±5.07bA
January	2.00±1.51aA	7.12±11.03bB	4.12±3.90aA
	Without traps		
August	5.00±6.10aA	2.75±5.50aA	15.75±14.24aC
September	27.00±18.56bB	14.00±8.04bA	19.00±15.59aA
October	51.50±45.88cA	220.30±23.50dC	98.01±21.10cB
November	120.50±56.35eB	122.00±26.54cB	73.75±23.28bA
December	102.5±67.02dA	283.25±96.37eB	130.25±51.75dA
January	263.25±94.72fA	334.75±104.05fB	241.25±113.6egA

[1] Mean numbers with different lowercase letters within columns are significantly different. [2] Mean numbers with different uppercase letters within rows are significantly different. Significant differences at $p<0.05$.

The removal of bebeficial species such as parasitoids (Neuenschwander, 1982) and predators from the environment, by means of mass trapping using pheromone baited traps is a matter of concern which had received little attention in pest control and monitoring practices.

Table 4.4. Mean densities of *Teretrius nigrescens* per maize ear and per month in granaries of three villages in the Gaza Province, Mozambique.

	Massingir	**Mapai**	**Chicualacuala**
Months	**mean±SD**	**mean±SD**	**mean±SD**
	With traps		
August	0.75±1.16 a[1]A[2]	0.25±0.70aA	0.12±0.35aA
September	2.00±2.32aA	1.37±1.30bA	0.37±0.54aA
October	4.25±4,97bA	5.75±4.39cA	7.12±5.33bA
November	1.37±1.30aA	3.75±3.84cA	1.75±1.83aA
December	1.37±1,84aA	0.25±0.40aA	0.37±0.41aA
January	0.12±0.35aA	0.37±1.84aA	0.37±0.55aA
	Without traps		
August	0.75±1.50aA	1.50±1.73aA	0.25±0.50aA
September	3.50±1.00bB	2.30±1.00aA	1.50±1.29aA
October	5.90±4.00bA	9.5±2.38bB	11.00±1.50dB
November	13.75±6.99cB	8.50±1.29bA	7.75±4.11bA
December	12.00±5.35cA	16.00±4.69cB	13.75±3.77cA
January	21.75±11.58dB	14.25±4.03cA	12.25±3.59cA

[1]Mean numbers with different lowercase letters within columns are significantly different.[2]Mean numbers with different uppercase letters within rows are significantly different. Significant differences at $p<0.05$.

Timing of harvesting and storage of maize (Borgemeister *et al.,* 1998) and distance between traps and granaries or target maize warehouses (Nansen *et al.,* 2001; Arthurs *et al*., 2015) can influence densities of *P. truncatus* in maize ears and hence the quantity of insect catches.

Mean densities of *P. truncatus* per maize ear increased with time in granaries where no traps were setup (Fig. 4.8A).

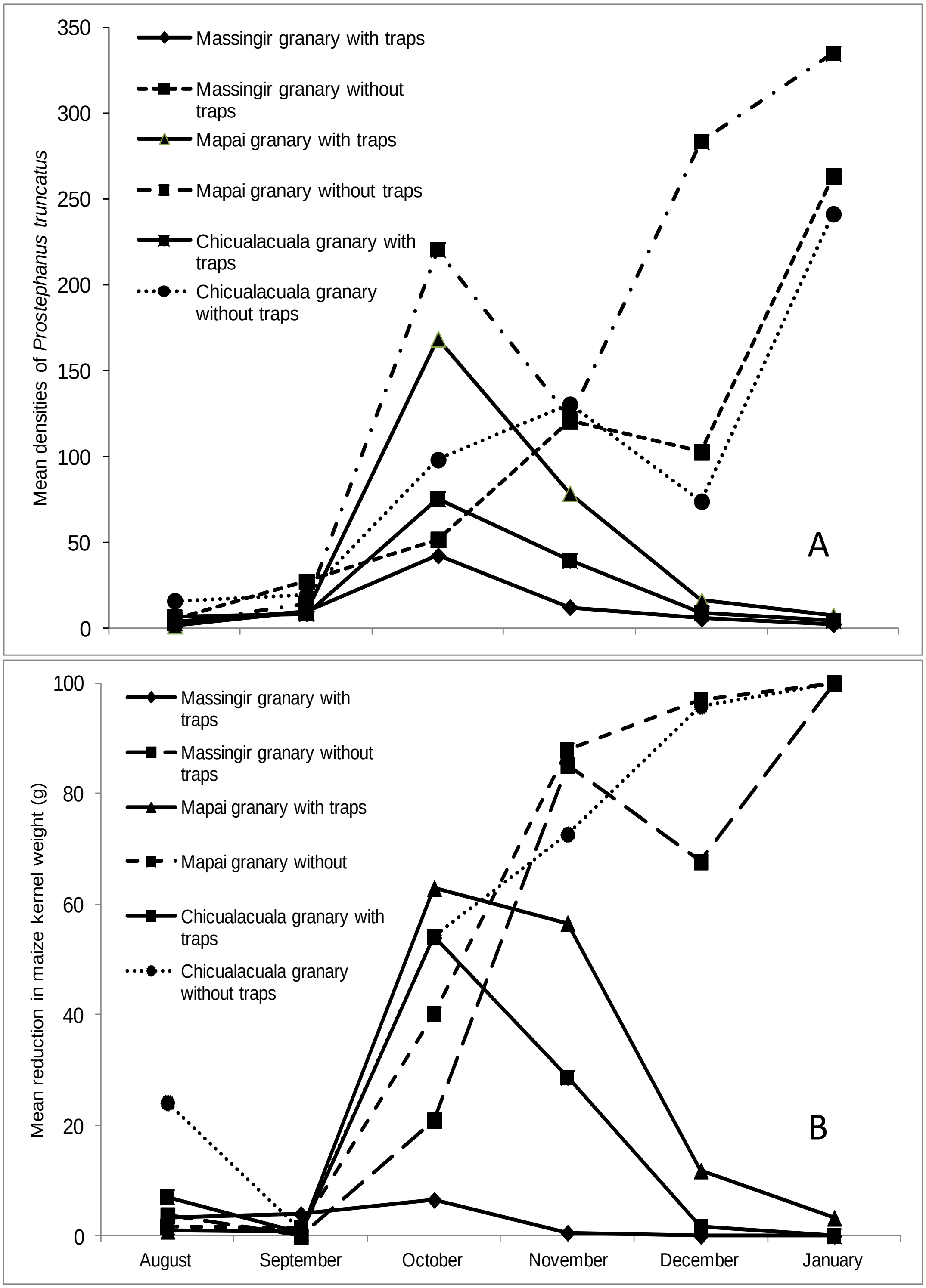


Fig. 4.8. Mean densities of *Prostephanus truncatus* per maize ear (A) and mean reduction in maize kernel weight (B) recorded in granaries with and without traps in three villages of the Gaza Province of Mozambique, over a six-month period.

Similarly to trends of monthly mean numbers of caught *P. truncatus* (Fig. 4.5A) and *T. nigrescens* (Fig. 4.5B), mean densities of these beetles in maize ears of granaries with traps increased from August onwards with a peak in October followed by steady decrease towards January 2014 (Fig. 4.8A). The t-test for independent variables indicated no significant differences (Table 4.5) between densities of *P. truncatus* and *T. nigrescens* in maize ears of granaries with and without traps during the three-month storage period of August/October of 2013. However, significant variations (Table 4.5) of beetle densities were found between granaries with and without traps during the three-month storage period of November 2013/January 2014. These findings suggest that *P. truncatus* found already being infesting maize ears by the time the investigation begin in August of 2013 increased its densities with no reduction effect by mass trapping in granaries with and without traps during the three-month storage period of August/October of 2013. Therefore, the effect of mass trapping was clearly observed with steady decrease of beetle densities from November of 2013 towards January 2014.

4.3.3. Maize kernel damage and weight reduction in granaries

While the incidence of damaged kernels steadily increased from August onwards and reached 100% in January inside granaries without traps, the incidence of damaged kernels followed a downwards trend after October (Table 4.5). The mean percentage of damaged maize kernels was lower in granaries with than in those without traps. Maize kernel weight reduction followed the pattern of maize kernel damage and reached 100% in maize ears of granaries without traps by January 2014 in all villages (Fig.4.8B). The mean percentage of maize kernel damage as well as the mean percentage of maize kernel weight loss did significantly not varied (Table 4.6) between granaries with and without traps during the three-month storage period of August/October of 2013. Significant variations (Table 4.6) were observed in mean percentage of maize kernel damage and maize kernel weight loss of granaries with and without traps during the three-month storage period November of 2013/January of 2014.

Table 4.5. Coefficients, indicating significance levels of densities of *Prostephanus truncatus* and *Teretrius nigrescens* in maize ears sampled from granaries with and without traps in three villages of Gaza Province, Mozambique.

Maize three-month storage period form August to October 2013										
	Densities of *Prostephanus truncatus*					**Densities of *Teretrius nigrescens***				
Granaries	Mean±SD	t-value	F	p-value	Cohens' d	Mean±SD	t-value	F	p-value	Cohens' d
With traps	36.1±70.3	0.20891	2.9	0.8	0.0	2.9±3.4	-0.53750	1.1	0.6	0.1
Without traps	35.5±41.1					3.3±3.2				
Maize three-month storage period from November 2013 to January 2014										
Granaries	Mean±SD	t-value	F	p-value	Cohens' d	Mean±SD	t-value	F	p-value	Cohens' d
With traps	19.2±31.2	-11.6817	13.1	0.05	2.1	1.6±1.6	-14.6110	15.5	0.05	2.4
Without traps	185.7±113					13.3±6.4				

Table 4.6. Percentage of incidence of damaged maize kernels per ear opv er time in granaries of three villages in the Gaza Province, Mozambique.

	Massingir	**Mapai**	**Chicualacuala**
Months/Years	**mean±SD**	**mean±SD**	**mean±SD**
	With traps		
August	1.76±1.35 a[1]A[2]	0.49±0.94aA	3.60±4.11aA
September	6.75±8.50bB	7.16±8.55bB	1.23±1.01aA
October	20.65±17.79dA	81.23±27.96fB	81.34±27.52dB
November	2.37±10.08aA	37.60±38.86eC	10.72±9.06cB
December	11.00±1.08cB	34.00±12.89dC	7.00±3.50bA
January	5.23±2.84bB	12.65±13.02cC	2.60±2.32aA
	Without traps		
August	1.87±2.38aA	0.85±1.25aA	6.17±7.55bB
September	18.17±12.89bB	10.56±13.11bB	3.75±3.43aA
October	45.40±23.92cA	115.1±60dC	94.15±8.54cB
November	80.33±34.99dA	97.92±0.99cB	97.26±2.51dB
December	89.63±20.72eA	98.82±3.31cB	96.88±5.46dB
January	100.00±00.00fA	100.00±00.00cA	100.00±00.00dA

[1]Mean numbers with different lowercase letters within columns are significantly different. [2]Mean numbers with different uppercase letters within rows are significantly different. Significant differences at $p < 0.05$.

These results, similarly to those of the mean densities of *P. truncatus* and *T. nigrescens* in maize ears, suggest that the reduction effect of mass trapping on maize grain damage and on maize grain weight loss due to reduction of the beetle densities in granaries could be observed during the three-month storage period of November of 2013/January of 2014.

The percentage reduction in maize kernel damage in granaries, *P. truncatus* and *T. nigrescens* population numbers from traps and beetle densities of maize ears increased with time reaching up to 99% in January 2014 (Table 4.7). However, lower reduction of maize kernel damage was observed in October in all villages.

Table 4.7. Percentage reduction in the incidence of damaged kernel and densities of *Prostephanus truncatus* and *Teretrius nigrescens* in maize ears in granaries in three villages in the Gaza Province, Mozambique.

Months	**Densities of *Prostephanus truncatus* in maize ears**			**Densities of *Teretrius nigrescens* in maize ears**			**Incidence of damaged kernels (%)**		
	Massingir	Mapai	Chicualacuala	Massingir	Mapai	Chicualacuala	Massingir	Mapai	Chicualacuala
August	34	66	61	40	83	52	5.8	42.3	40.0
September	64	36	58	43	40	75	62.5	36.3	70.0
October	18	24	24	28	40	36	54.2	29.6	13.8
November	90	36	47	90	56	77	97.0	61.8	88.6
December	95	95	94	89	98	97	87.6	64.0	89.9
January	99	98	98	99	97	97	94.7	88.0	97.4

Reasons of the maize kernel damage reduction in October are unclear. However, this could result from the hypothesis that pheromones have being exhausted by this month before they were renewed. Therefore, this was an unexpected result. However the continuous reduction in pest numbers and subsequent lower incidence of damage to maize kernel, especially from October to January illustrates that mass trapping could potentially be used as a tool in the management of *P. truncatus.* This fact is supported by the strong linear negative and inverse correlation found between mean numbers of *P. truncatus* caught in traps and the percentage of incidence of damaged maize kernel (Fig.4.9A) and kernel weight loss (Fig. 4.9B) in granaries with traps. Therefore, these figures indicate that the percentage incidence of damaged maize kernels and kernel weight loss decreased with increasing numbers of *P. truncatus* caught in traps placed near stored maize granaries.

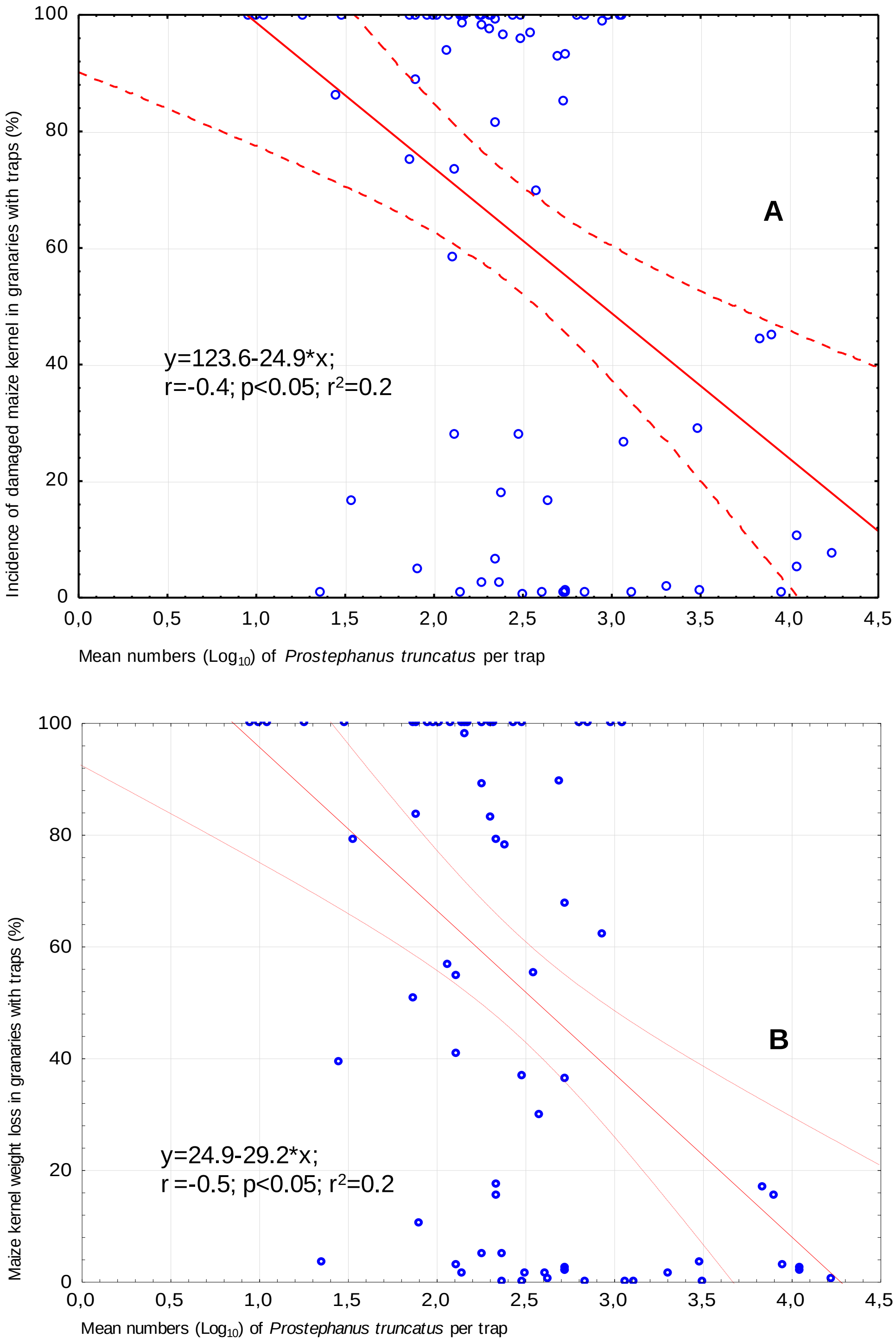


Fig.4.9. Relationships between mean numbers of *Prostephanus truncatus* caught in traps and the percentage of incidence of damaged maize kernel (A) and kernel weight loss (B) in granaries with traps in three villages of the Gaza Province, Mozambique.

Highly significant linear negative and inverse correlation was found between mean numbers of *P. truncatus* in maize ears and the percentage of incidence of damaged maize kernel (N=72, r=-0.4, p<0.05, y=123.6-24.9*x) in granaries with traps. Similar to latter correlation pattern was found between mean numbers beetles and the percentage of maize kernel weight loss in granaries with traps (N=72, r=-0.5, p<0.05, y=62.35-54.52*x).

Helbig (1995) and Cugala *et al.* (2007) reported that the incidence of damaged maize kernels increased with storage time if not taken appropriate control measures against *P. truncatus*. These findings were supported with the highly strong and positive correlation found in this work between mean densities of *P. truncatus* in maize ears and the percentage of incidence of damaged kernel (N=72, r=0.70, p<0.05, y=3.72+38.05*x) (Fig. 4.10A) and kernel weight loss (N=72, r=0.6, p<0.05, y=-2.52+36.1*x) (Fig. 4.10B) in granaries without traps. These figures show that the percentage of incidence of damaged maize kernel and weight loss increased with densities of P. truncatus in maize ears of granaries without traps.

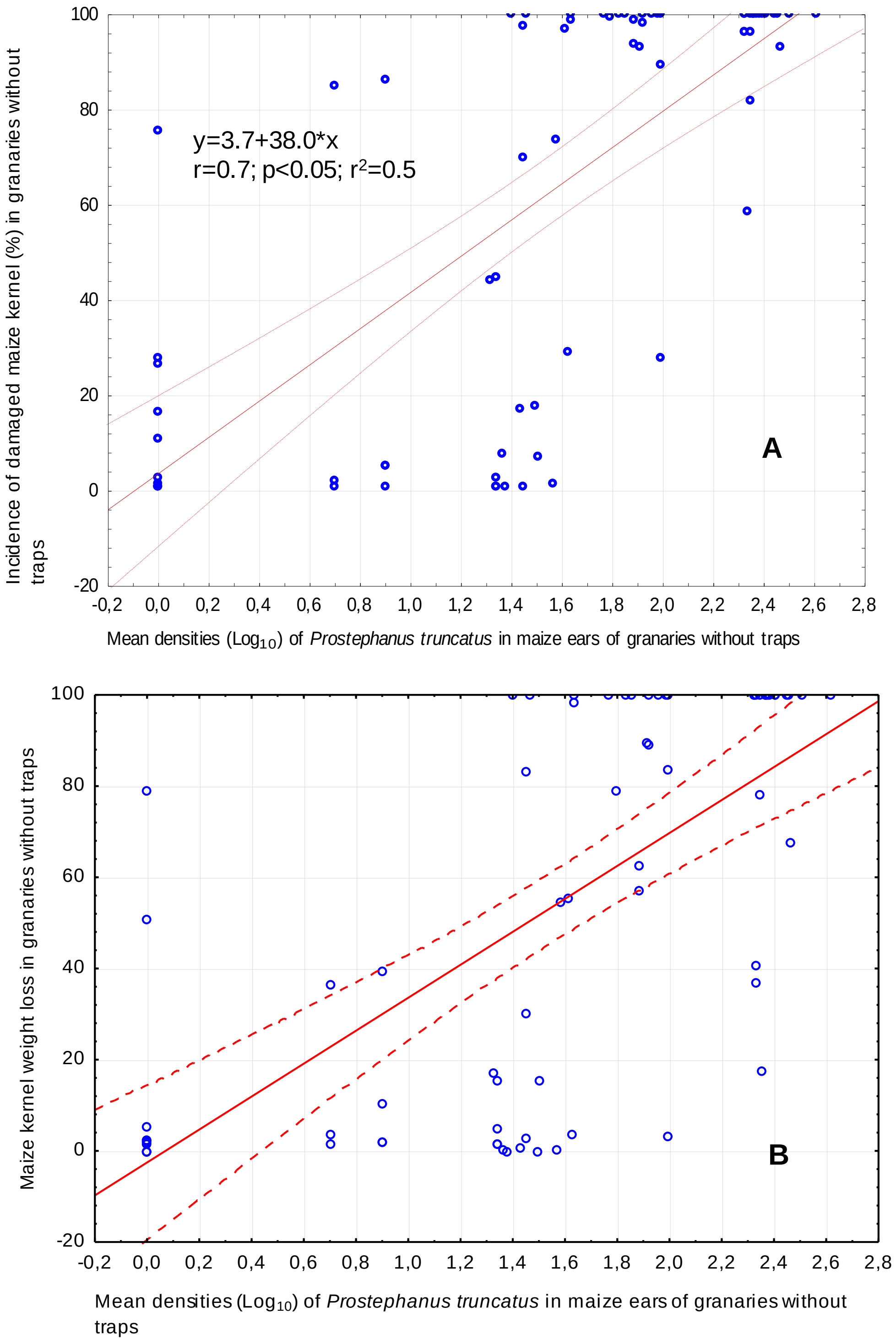


Fig.4.10. Relationships between mean densities of *Prostephanus truncatus* recorded in maize ears and the percentage of incidence of damaged maize kernel (A) and kernel weight loss (B) in granaries without traps in three villages of the Gaza Province, Mozambique.

4.4. Conclusions

This study showed that mass trapping by means of Uni-traps significantly reduced numbers of *P. truncatus* in granaries and maize ears damage over the typical 6-month period during which grain is stored, and that this technology has potential for use in management of this pest.

Local design and manufacturing of low cost traps for use by small scale farmers will be a significant contribution to pest management, if this strategy is demonstrated to be effective and sustainable on a larger scale. Additionally, mass trapping should be integrated with biological control, with the use of the predator *T. nigrescens,* as well as cultural control methods such as post-harvest drying of maize kernels, cleaning of granaries between storage seasons, use of pest resistant plant species for constructing of granaries and use of locally improved silos and hermetic bags.

In further similar to this research works especial attention should be paid to the beginning of the maize storage period, the potential infestation of initial sampling stored maize grain and the right frequency time the pheromones to be replaced in traps. Additionally, further research on the principle functional mechanism of Uni-trap use is required to improve their efficacy in pest management practices.

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CHAPTER FIVE

Suitability of wild plants and firewood as hosts of *Prostephanus truncatus* in Mozambique

Abstract

Forest host plants of the Larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) represent a serious threat to successful control of this pest since it maintains pest populations in the wild. In this study we assessed the host suitability of plant species sold as firewood as well as 58 other plant species collected in natural areas along road sides in Mozambique. Firewood sold next to main roads were collected at seven sites in the Maputo and Gaza provinces and checked for the presence of *P. truncatus* individuals. If individuals occurred in these, the wood species was evaluated for its host suitability under laboratory conditions. Plant tissue samples from 58 plant species were also collected in natural areas along road sides (29 species of trees, 12 of shrubs and 17 of grasses). These samples were collected during September-October 2014 in five natural areas next to main roads in the Massingir and Manica districts of Mozambique. Five fresh and five dry pieces of wood of each of these 58 plant species were evaluated under laboratory conditions for its suitability for survival and breeding of *P. truncatus*. Experiments were conducted in 500 ml glass jars each containing woody plant tissue of the particular species, kept at 27 ^{o}C, 90% r.h. and 12:12 photoperiod. All jars were inoculated with 50 *P. truncatus* individuals. The control treatment consisted of 100 g of maize grain, in a similar 500 ml container. Live larvae, pupae and adults of *P. truncatus* were collected and counted after 60 days. *Prostephanus truncatus* was only observed in two (*Brachystegia spiciformis* and *Strychnos spinosa*) of the six plant species sold as firewood. The pest survived and bred in 13 tree and 7 grass species. Dry maize stalks were also highly suitable for pest survival. Dry wood of the tree species, *B. spiciformis*, *Colophospermum mopane* and *Cassia abbreviata* as well as the grasses *Acroceras macrum* and *Hyparrhenia hirta* were suitable hosts for development of *P. truncatus*. The sale and transport of firewood that hosts *P. truncatus* may be an important driver of the spread of this species. Uninfested areas where plant hosts occur and are abundant, are likely to be infested by this pest in the future. This knowledge will contribute to the development of practical integrated measures for management of *P. truncatus*.

Key words: host plants, host suitability, Mozambique, pest management

5.1. Introduction

In tropical regions, *Prostephanus truncatus* does not only survive on maize grain and dry cassava wood and chips, but also occurs on and survives in several forest plant species. Dry wood of several tree species are traded as fire wood in Mozambique (Fig. 5.1). Transport of fire wood between regions can contribute to the spread of *P. truncatus*. This way of *P. truncatus* dispersal, associated with in-country and international transport and trade of primary host products, maize and dry cassava chips (Tyler and Hodges, 2002; Omondi *et al*., 2011), accelerates temporal long distance dispersal of the pest. An example of this is *P. truncatus* dispersal from Mexico and Central America to Africa (Markham *et al*., 1991). Hence, the pest may disperse quickly within African countries through transport of maize and cassava chips and in-country by means of the latter products and plant species used as firewood. However, scientific evidence regarding the survival and breeding capacity of *P. truncatus* in tree and grass species, as well as the potential of dry maize stalks, and the role of the host plants in pest dispersal is scarce.

Forest host species may play a driving role in *P. truncatus* seasonal survival, breeding and dispersal (Borgemeister *et al.,* 1998; Jia *et al.,* 2008) with consequent damage and loss of maize grain in small scale granaries in Africa. However, scientific reports on the role of these hosts in Mozambique are scarce. Dispersal of this pest is influenced by its capacity to survive on dry wood of several forest plant species (Helbig *et al*., 1992; Nang'ayo *et al*., 1993 and Nansen *et al*., 2002), and availability of commodity food sources (Hodges *et al*., 1983; Markham *et al*., 1991; Helbig*,* 1995; Borgemeister *et al.,* 1997; Roux, 1999; Hill *et al*., 2002; Cugala *et al*., 2007; Gueye *et al*., 2008). Information on the suitability of wild plant species and those used as firewood that host of *P. truncatus* may provide opportunities for development of strategies to improve management of this pest.

The aims of this study were to survey and compile a list of wild host plant species of *P. truncatus* in the Gaza and Manica Provinces of Mozambique, to assess the host plant status of the different species and to assess the role of firewood plant species in *P. truncatus* dispersal. This information will be useful in the design of control measures against *P. truncatus*.

5.2. Material and Methods

5.2.1. Collection of firewood species

Samples were collected from roadside markets where they were sold in bundles for use as fire wood (Fig. 5.1). These markets were in Compone, Benfica, Magoanine, Missão Rock and Bobole in the Maputo province as well as Chokwé and Massingir in the Gaza Province. In total, 42 bundles each of dry and freshly cut firewood were collected. This was done by collecting three bundles of both dry and fresh wood per market per locality. The number of pieces of wood per bundle ranged between five and 12. Bundles did not consist of wood of only one plant species but were made up of several species. The size of firewood pieces ranged between 30 mm and 70 mm diameter with a length of approximately 500 mm. Samples were transported and stored in plastic bags to avoid insects from escaping and transported to the laboratory of Zoology and Entomology, Department of Biological Sciences (DBC), Eduardo Mondlane University in Maputo.

Identification of the different woody plant species in bundles of firewood was done by visual comparison of their external structure and appearance with that of photographic images (Van Wyk and Van Wyk, 1997; Dharani, 2011) of known plant species. The geographic location of the origin of the firewood was also taken in to account to determine the plant species. The wood pieces were counted and separated per plant species. Afterwards, all pieces were dissected and insects were collected and separately stored in glass jars for further identification. Dissection was done by making several longitudinal and transversal cuttings into the wood by means of a machete or an axe until insects were observed. Four hundred and sixty two cuttings were dissected. From these, 294 (63%) were dead and 168 (36%) fresh wood samples. Wood of species that contained *P. truncatus* larval and adult stages were further used in host suitability assays.

5.2.2. Survey of wild host plants

A survey was conducted of potential wild host plants of *P. truncatus* in the Manica and Massingir districts. Freshly cut and dead wood of trees, shrubs and grasses were collected inside quadrants (250 x 250 m) along road sides at five localities. Samples consisting of dead and freshly cut wood of 58 forest plant species were collected to determine whether *P. truncatus* occurred in these samples and how suitable these species were as hosts for the pest. Freshly cut and dry stalk samples of maize were also taken from nearby fields. Maize stalks were included in this experiment to determine the potential of *P. truncatus* to survive and breed mainly inside maize fields during post-harvest periods. These samples constituted of 29 tree, 12 shrub and 17 grass species.

Ten samples of fresh and dry wood were collected from each tree and shrub species per site. The sizes of these of wood were as follows: 5-15 mm in diameter and 70 mm long and 30-40 mm in diameter and 50 mm long. Twenty samples of both fresh and dry stalks including those of maize were collected from each grass species per site as well. All stalk samples of grass species were taken from the lower and thicker part of the plant with the exception of those of maize and pearl millet, *Pennisetum glaucum* (Poaceae) that were taken from the middle part of the plant. The diameter of the grass stalks were between 5-15 mm while all pieces were 70 mm long. Maize and pearl millet stalks were 10-20 mm in diameter and 70 mm long. Photos of plants were taken in the field and plant stems and leaves collected for identification purposes. The identification of plant species was done at the Herbarium of the DBC, according to the systems used by Van Wyk and Van Wyk (1997) and Dharani (2011).

In order to have sufficient numbers of beetles to introduce into glass jars for the assays on host plant suitability, a *P. truncatus* culture was established on maize grain. The experiment was conducted by placing 50 unsexed 15-day old adults collected from the rearing culture for 24 hours in glass jars before adding host plant samples. One piece of freshly cut or dry wood was then placed in each glass jar. Two pieces of grass stalks or stalks of maize and pearl millet were used per jar. Each treatment was replicated five times. The control treatment consisted of 100 g of maize grain, in a similar 500 ml container, inoculated with 50 *P. truncatus* individuals.

Fig. 5.1. An example of bundles of firewood sold at the road sides in Mozambique.

The numbers of live larvae, pupae and adults of *P. truncatus* were determined after 60 days. This was done by dissecting wood and stalk samples and by counting the numbers of live insect stages. The weight of dust produced by *P. truncatus* after feeding inside containers and the number of holes caused by *P. truncatus* feeding in the different food substrates per container was also determined. Since *P. truncatus* individuals penetrated through the two cut end points of grass stalks, no clear number of holes made into stalks could be determined. The experiment was conducted at laboratory conditions under 27 ^{o}C; 90% r.h. and at a 12:12 photoperiod.

Data were analysed using descriptive statistics (SAS, 1999). Survival of *P. truncatus* was calculated following Price (1997) and Steinhaus (1999.) Mean numbers of *P. truncatus* individuals in pieces of firewood were not compared because of limited data which did not match the criteria for statistical comparison. However, One-Way ANOVA was applied to compare host plant species regarding survival and breeding of *P. truncatus*. This was done by comparing the number of live larvae, pupae and adults between host plant species. Tukey's honest significant differences (HSD) test for equal N (number of samples) was used to do these comparisons. Means were compared at $p < 0.05$ level of significance.

5.3. Results and discussion

5.3.1. Occurrence of *Prostephanus truncatus* in firewood

Six tree species were identified amongst the bundles of firewood collected in the Maputo and Gaza Provinces (Table 5.1). *Prostephanus truncatus* individuals were collected from only three species. No individuals were collected from any of the freshly cut pieces of firewood. An average of 38 individuals per piece of stem and a total of 4780 *P. truncatus* were collected from the wood of *Brachystegia spiciformis* Benth. (Fabaceae). The incidence of infested pieces of wood of *B. spiciformis* was high (67.7%; n=126). Other species that were infested by *P. truncatus* were *Strychnos spinosa* Lam. (Loganiaceae) and *Colophospermum mopane* (Kirk ex Benth.) (Fabaceae). The occurrence on and infestation of *B. spiciformis* and *S. spinosa* by *P. truncatus* observed in this study is recorded for the first time in Mozambique. The mean and total numbers of individuals collected from wood of the different species are provided in Table 5.1.

Prostephanus truncatus long-distance and inter-country dispersal has been attributed to transport and trade of commodities, particularly maize and dry cassava chips (Tyler and Hodges, 2002; Omondi *et al*., 2011). Results of this study suggest that in-country transport of firewood may contribute significantly to dispersal of *P. truncatus*. For example the large quantities of dead firewood bundles of *B. spiciformis* that have been transported from the Inharrime and Zavala districts of the Inhambane Province to Maputo City over the last decade (Personal observations) could have contributed to the rapid spread of this pest in the southern region of Mozambique.

The fact that no *P. truncatus* individuals were found in any of the freshly cut pieces of firewood raises the question whether this pest prefers to infest fresh plant tissue of wild hosts or that of primary host plants such as maize and cassava? While scientific evidence addressing this question is scarce, several studies reported survival and breeding of *P. truncatus* in forest plant species under laboratory conditions (Nanga'yao *et al.,* 2002; Nansen *et al.,* 2004).

However, the absence of the pest in freshly cut firewood collected in close proximity to dry infested wood of the same plant species could indicate that survival and reproduction of *P. truncatus* in freshly cut wood of some plant species is a response to the lack of alternative and suitable food source under laboratory conditions.

The Miombo forest with predominance of *B. spiciformis* represents 2/3 of the Mozambican territory and is an ecosystem that supports the subsistence of 90% of rural population (Maquia *et al*., 2012). Hence, management and regulation of the exploitation of *B. spiciformis* as firewood is necessary to reduce dispersal of *P. truncatus* throughout Mozambique with subsequent cause of damage and losses of stored maize and cassava ships. Burning of residual cuttings of *B. spiciformis* remaining in the forest is a measure that could avoid survival and breeding of the pest.

5.3.2. Survival of *Prostephanus truncatus* in fresh and dry stalks of grasses

Prostephanus truncatus survived and bred in seven of the 17 grass species collected along road sides (Table. 5.2). Mean numbers of live *P. truncatus* larvae (N=7, df=6; F=4.6, $p<0.05$), pupae (N=7, df=6, F=4.9, $p<0.05$) and adults (N=7, df=6, F=5.2, $p<0.05$) were significantly different between freshly cut stalks of grass species (Table 5.2). Numbers of larvae of *P. truncatus* were higher in the maize grain and stalk treatments followed by *Acroceras macrum* Stapf and *Hyparrhenia hirta* (L.) Stapf (Table 5.2). Numbers of pupae and adults followed a similar pattern and, with exception of the control treatment, more pupae and adults were collected from *H. hirta*.

Table 5.1. Mean numbers of *Prostephanus truncatus* individuals collected in pieces of firewood of six plant species in the Maputo and Gaza Provinces.

Family	**Scientific name**	**Total Infested stems/ bunch**	**Percentage of total infested stems/ bunch**	**Mean numbers of *P. truncatus* per cutting (mean±SD)**	**Total number of *P. truncatus* in cuttings**
Anacardiaceae	*Anacardium occidentale* L.	0.0	0.0	0.0	0.0
Fabaceae	*Brachystegia spiciformis* Benth.	126.0	67.7	38.5±12.3	4780.0
	Colophospermum mopane (Kirk ex Benth.)	11.0	5.9	24.0±5.0	144.0
Myrtaceae	*Eucalyptus globulus* Labill.	0.0	0.0	0±0.0	0.0
Clusiaceae	*Garcinia livingstonei* Anderson	0.0	0.0	0±0.0	0.0
Loganiaceae	*Strychnos spinosa* Lam.	49.0	29.3	18.8±14.9	468.0

No larvae or pupae emerged from the sampled fresh stalks of *Aristida congesta* Roem. and Schult. and *Digitaria eriantha* Steud. However, adults were recorded from freshly cut stalks of these grass species. High numbers of larvae, pupae and adults were also recorded from dry stalks of maize (Table 5.2). Highly significant differences in numbers of live larve (N=7, df=6, F=3.2, p=<0.05), pupae (N=7, df=6, F=4.2, p<0.05) and adults (N=7, df=6, F=4.8, p<0.05) were found between dry stalk grass species (Table 5.2). Live larvae and pupae, different of that observed in freshly cuts emerged from dry stalks of *A. congesta* and *D. eriantha*. *Acroceras macrum* Stapf is distributed throughout southern Africa and also in the Massingir and Chicualacuala districts of Mozambique (Russell *et al.,* 1990). *Hyparrhenia hirta* occurs widely in Mozambique (Russell *et al*., 1990) and is used for roofing of houses and as part of fencing structures around traditional houses. Dry maize stalks are left in fields after harvest and when they are in close proximity to some of the granaries may represent a source for survival, breeding and dispersal of flying individuals of *P. truncatus.* Burning of stubble and residual maize stalks in fields after harvest of maize is a cost-effective cultural control method (Adesiyun and Ajayi, 1980） that could avoid survival and breeding of *P. truncatus* with its subsequent dispersal.

5.3.3. Survival and breeding capacity of *Prostephanus truncatus* in freshly cut and dry wood of shrubs and trees

Prostephanus truncatus survived and bred in freshly cut and dry wood of 13 of the 29 tree species (Table 5.3). However, it did not survive or breed in any of the shrub species. Significant differences of mean numbers of live larvae (N=14, df=13, F=2.1, $p<0.05$), pupae (N=14, df=13, F=2.8, $p<0.05$) and adults (N=14, df=13, F=2.4, $p<0.05$) were found between fresh wood (30-40 mm diameter and 100 mm long) plant species. Higher mean numbers of larvae, pupae and adults were recorded in *Brachystegia spiciformis* Benth*. and* compared to other tree plant species (Table 5.3). Moreover, higher numbers of immatures and adults of *P. truncatus* were recorded in *Collophospermum mopane* (J. Kirk ex Benth.) and *Cassia abbreviata* Oliv. than those recorded in *Brachystegia boehmii* Taub*.* No immature stages were recorded from fresh stems of *Piliostigma thonningii* (Shumach) and *Terminalia sericea* (Burch. ex. DC).

Table 5.2 Mean numbers of live larvae, pupae and adults of *Prostephanus truncatus* collected from freshly (A) cut and dry (B) stalks of different grass species.

A	Fresh stalks			
Grass scientific name	Larvae	Pupae	Adults	Weight of dust (g)
	mean±SD	mean±SD	mean±SD	mean±SD
Acroceras macrum Stapf	42.2±9.1d[1]	36.8±0.3d	21.2±7.9d	0.01±0.0a
Aristida congesta Roem. and Schult.	0.0±0.0a	0.0±0.0a	3.2±0.2b	0.01±0.0a
Digitaria eriantha Steud.	0.0±0.0a	0.0±0.0a	5.9±3.1b	0.02±0.0a
Eulalia villosa (Thunb.) Nees	6.5±0.0b	5.01±0.0b	1.9±0.1a	0.01±0.0a
Hyparrhenia hirta (L.) Stapf	33.0±2.1c	43.5±10.9e	49.0±9.1e	0.01±0.0a
Pennisetum glaucum (L.) R. Br	8.5±0.2b	15.1±0.7c	16.7±9.5c	0.01±0.0a
Zea mays L. (stalks)	35.5±1.2c	40.0±0.3e	24.8±2.3d	4.2±0.0b
Maize grain (Control)	74.0±1.6e	53.0±1.5f	89.0±1.9f	5.3±0.01b

B	Dry stalks			
Grass scientific name	Larvae	Pupae	Adults	Weight of dust (g)
	mean±SD	mean±SD	mean±SD	mean±SD
Acroceras macrum Stapf	65.7±0.4d[1]	46.0±1.8e	31.2±10d	3.03±0.2b
Aristida congesta Roem. and Schult.	9.1±1.9a	5.0±2.1a	12.9±4.6b	1.01±0.0a
Digitaria eriantha Steud.	10.0±0.3a	8.6±6.7b	17.0±3.1c	1.04±0.0a
Eulalia villosa (Thunb.) Nees	12.0±9.1b	9.0±7.5b	3.0±1.1a	0.02±0.0a
Hyparrhenia hirta (L.) Stapf	69.5±11d	53.1±1.7d	81.6±8.1g	9.8±1.3d
Pennisetum glaucum (L.) R. Br	23.0±3.6c	31.4±2.6c	40.0±5.5e	5.9±1.8c
Zea mays L. (stalks)	63.1±3.1d	42.1±1.9e	65.3±2.8f	8.9±2.6d
Maize grain (Control)	100.0±1.8e	63.7±0.2f	93.3±9.7h	10.4±4.4d

[1] Means followed by the same letter within columns do not differ significantly at $p<0.05$.

The numbers of insects recorded from dry wood (30-40 mm diameter and 100 mm long) of trees followed a similar tendency to those observed in fresh wood, but numbers were generally higher in the latter (Table 5.4). *Prostephanus truncatus* survived and bred in freshly cut as well as in dead wood of *Strychnos spinosa* Lam., a species on which natural infestation by the pest was also observed. Mean numbers of live beetle larvae (N=14, df=13, F=2.6, $p<0.05$), pupae (N=14, df=13, F=2.3, $p<0.05$) and adults (N=14, df=13, F=2.9, $p<0.05$) differed significantly between plant species of which fresh wood (5-15 mm diameter and 70 mm long) was sampled (Table 5.5). Mean numbers of all immature stages and adults also differed significantly between plant species sampled as dry wood (5-15 mm diameter and 70 mm long) (Table 5.6). The hhighest numbers of beetles were recorded from both fresh and dry wood of *C. abbreviata.* Mean numbers of holes produced by *P. truncatus* in fresh samples of all plant species was lower than that observed in dry wood and was strongly correlated (n=14, r=0.98, $p<0.05$) with the number of adult insects recorded. The number of holes made by the pest was also strongly correlated (n=28, r=0.072, $p<0.05$) with the number of adults recorded per plant species in fresh and dry wood samples. An example of this is illustrated in Figure 5.2. Plant species, where *P. truncatus* did not survive and breed are shown in Table 5.7.

Table 5.3. Mean numbers of live larvae, pupae and adults of *Prostephanus truncatus* in fresh wood (30-40 mm diameter and 100 mm long) of thirteen tree species in the Manica and Massingir districts.

		Fresh wood (30-40 mm diameter and 100 mm long)				
Family	Scientific name	Larvae	Pupae	Adults	Number of holes	Weight of dust (g)
		mean±SD	mean±SD	mean±SD	mean±SD	mean±SD
Combretaceae	*Terminalia sericea* Burch. ex DC.	0.0±0.0a[1]	0.0±0.0a	1.0±1.0a	3.9±2.5b	0.0±0.0a
Euphorbiaceae	*Androstachys johnsonii* Prain	3.5±1.9b	3.2±4.1b	5.2±2.3c	10.5±6.2d	0.01±0.0a
	Julbernardia globiflora Benth.	3.3±0.1b	1.01±1.0a	0.0±0.0a	0.0±0.0a	0.01±0.0a
	Brachystegia spiciformis Benth.	21.6±9.1f	13.1±1.6	12.0±4.9e	33.9±7.3f	2.05±1.8b
	Brachystegia boehmii Taub.	12.1±0.1d	9.6±4.7c	9.5±7.2d	23.8±6.7e	1.01±0.0a
Fabaceae	*Brachystegia utilis* Burtt Davy & Hutch.	7.9±5.8c	7.8±2.1c	6.4±1.6c	21.2±8.1e	1.01±0.0a
	Cassia abbreviata Oliv.	16.8±1.9e	9.5±6.5c	6.2±4.5c	21.1±1.7e	2.04±1.6b
	Colophospermum mopane (J.Kirk ex Benth.)	17.3±1.0e	10.1±7.3c	9.8±1.3d	35.8±6.9f	2.05±2.0b
	Piliostigma thonningii (Schumach.)	0.0±0.0a	0.0±0.0a	5.2±4.1c	23.2±2.7e	0.01±0.0a
	Philenoptera violacea (Klotzsch) Schrire	5.0±2.0b	3.2±1.0b	3.9±1.2b	12.9±4.2d	0.5±0.01a
Loganiaceae	*Strychnos spinosa* Lam.	8.4±2.6c	4.0±2.0b	2.5±1.0b	5.1±3.8c	1.01±1.0a
Mimosaceae	*Acacia xanthophloea* Benth	5.1±4.4b	3.1±0.1b	6.8±0.1c	22.2±8.2e	0.02±0.0a
Rhamnaceae	*Ziziphus mauritiana* Lam.	0.0±0.0a	0.0±0.0a	3.2±2.0b	2.2±2.5a	0.01±0.0a
Poaceae	Maize grain (Control)	67.0±2.1g	42.9±7.3d	72±1.9f	125.2±3.9g	20.3±1.7c

[1] Means followed by the same letter within columns do not differ significantly at $p<0.05$.

Table 5.4. Mean numbers of live larvae, pupae and adults of *Prostephanus truncatus* in dry wood (30-40 mm diameter and 100 mm long) of thirteen tree species in the Manica and Massingir districts.

		Dry wood (30-40 mm diameter and 100 mm long)				
Family	Scientific name	Larvae	Pupae	Adults	Number of holes	Weight of dust (g)
		mean±SD	mean±SD	mean±SD	mean±SD	mean±SD
Combretaceae	*Terminalia sericea* Burch. ex DC.	0.0±0.0a[1]	0.0±0.0a	6.2±4.7b	8.8±1.2b	0.02±0.1a
Euphorbiaceae	*Androstachys johnsonii* Prain	10.3±3.7c	6.2±8.2c	9.1±1.5c	23.4±2.6c	0.8±0.0a
	Julbernardia globiflora Benth.	3.0±2.0b	1.1±1.0a	1.9±1.3a	3.2±9.2a	0.02±0.0a
	Brachystegia spiciformis Benth.	32.0±9.5f	16.8±3.1f	31.0±2.2e	54.9±3.8f	4.2±1.9c
	Brachystegia boehmii Taub.	21.7±5.2e	13.0±3.0e	6.0±4.1b	32.6±6.9d	2.6±1.0b
Fabaceae	*Brachystegia utilis Burtt* Davy & Hutch.	10.1±3.5c	9.0±3.0d	5.4±2.9b	24.2±1.9c	1.6±0.1a
	Cassia abbreviata Oliv.	23.3±7.9e	12.5±1.7e	9.0±1.9c	40.1±8.1e	3.8±1.9c
	Colophospermum mopane (J.Kirk ex Benth.)	29.8±1.9f	17.0±4.6f	25.2±7.9d	56.6±7.7f	3.7±1.0c
	Piliostigma thonningii (Schumach.)	0.0±0.0a	0.0±0.0a	8.3±6.2c	31.2±2.5d	0.06±1.0a
	Philenoptera violacea (Klotzsch) Schrire	8.0±3.4c	5.9±1.9c	5.7±4.8b	24.8±7.9c	0.9±1.0a
Loganiaceae	*Strychnos spinosa* Lam.	12.4±2.7d	7.1±5.0c	5.6±2.9b	24.1±3.1c	1.0±2.0a
Mimosaceae	*Acacia xanthophloea* Benth.	8.1±3.2c	7.6±3.2c	9.9±3.6c	32.0±1.9d	0.9±0.0a
Rhamnaceae	*Ziziphus mauritiana* Lam.	5.5±1.6b	3.6±2.9b	1.8±1.5a	5.5±3.5a	0.05±0.1a
Poaceae	Maize grain (Control)	76±5.8g	48.0±1.4g	85.1±3.1f	104.5±5.3g	25.9±3.2d

[1] Means followed by the same letter within columns do not differ significantly at $p<0.05$.

Table 5.5. Mean numbers of live larvae, pupae and adults of *Prostephanus truncatus* in fresh wood (5-15 mm diameter and 70 mm long) of thirteen tree species in the Manica and Massingir districts.

		Fresh wood (5-15 mm diameter and 70 mm long)				
Family	Scientific name	Larvae	Pupae	Adults	Number of holes	Weight of dust (g)
		mean±SD	mean±SD	mean±SD	mean±SD	mean±SD
Combretaceae	*Terminalia sericea* Burch. ex DC.	0.0±0.0a[1]	0.0±0.0a	1.2±1.0a	2.0±1.0b	0.0±0.0a
Euphorbiaceae	*Androstachys johnsonii* Prain	3.1±1.2b	3.0±1.1b	2.0±1.0b	6.0±3.3c	0.3±0.1a
	Julbernardia globiflora Benth.	3.3±2.1b	2.0±1.6b	3.0±1.2b	5.0±2.1c	0.0±0.0a
	Brachystegia spiciformis Benth.	3.1±1.2b	2.6±0.9b	1.3±1.2a	2.0±1.2b	0.0±0.0a
	Brachystegia boehmii Taub.	12.1±7.5c	6.9±2.1c	4.0±3.2b	3.0±1.7b	1.0±0.1a
Fabaceae	*Brachystegia utilis Burtt* Davy & Hutch.	5.0±2.6b	3.0±0.3b	2.0±0.8b	3.0±2.6b	0.3±0.0a
	Cassia abbreviata Oliv.	17.0±5.9d	12.0±6.1d	9.0±4.2d	13.0±2.4d	1.5±1.2b
	Colophospermum mopane (J.Kirk ex Benth.)	11.9±1.8c	9.0±1.6c	3.0±0.9b	15.0±1.6d	1.9±1.3b
	Piliostigma thonningii (Schumach.)	0.0±0.0a	0.0±0.0a	5,9±2.6c	21.0±4.5e	1.2±0.8b
	Philenoptera violacea (Klotzsch) Schrire	0.0±0.0a	0.0±0.0a	0.0±0.0a	0.0±0.0a	0.0±0.0a
Loganiaceae	*Strychnos spinosa* Lam.	5.0±1.4b	2.1±1.3b	2.1±2.0b	1.0±0.1a	0.3±0.1a
Mimosaceae	*Acacia xanthophloea* Benth	0.0±0.0a	0.0±0.0a	1.0±1.0a	1.0±0.0a	0.0±0.0a
Rhamnaceae	*Ziziphus mauritiana* Lam.	0.0±0.0a	0.0±0.0a	1.8±1.6b	1.0±1.0a	0.01±0.0a
Poaceae	Maize grain (Control)	68±3.1e	51.7±3.8e	86.4±8.1e	135±3.9f	28.6±2.9c

[1] Means followed by the same letter within columns do not differ significantly at $p<0.05$.

Table 5.6. Mean numbers of live larvae, pupae and adults of *Prostephanus truncatus* in dry wood (5-15 mm diameter and 70 mm long) of thirteen tree species in the Manica and Massingir districts.

Family	Scientific name	Dry wood (5-15 mm diameter and 70 mm long)				
		Larvae	Pupae	Adults	Number of holes	Weight of dust (g)
		mean±SD	mean±SD	mean±SD	mean±SD	mean±SD
Combretaceae	*Terminalia sericea* Burch. ex DC.	3.2±1.6b[1]	1.0±0.7a	2.0±1.6a	6.0±2.1a	0.1±0.0a
Euphorbiaceae	*Androstachys johnsonii* Prain	5.0±2.1c	3.0±1.2b	3.0±1.2a	9.0±3.2b	0.9±0.0a
	Julbernardia globiflora Benth.	6.2±2.8c	5.4±3.1b	3.1±0.9a	12.0±2.6c	0.4±0.0a
	Brachystegia spiciformis Benth.	8.6±2.1d	3.9±1.5b	3.0±1.2a	11.0±4.1c	0.8±0.0a
	Brachystegia boehmii Taub.	19.0±1.5e	9.1±2.1c	7.0±2.9c	32.0±2.1e	4.2±3.8b
Fabaceae	*Brachystegia utilis Burtt* Davy & Hutch.	9.6±3.2d	5.1±1.3b	5.3±1.8b	34.0±6.3e	1.2±1.8a
	Cassia abbreviata Oliv.	30.0±9.1f	18.7±6.5e	21.0±5.2d	42.0±2.7f	6.3±4.3c
	Colophospermum mopane (J.Kirk ex Benth.)	21.5±3.2e	12.1±5.2d	5.0±2.1b	21.0±1.4d	3.0±1.2b
	Piliostigma thonningii (Schumach.)	3.9±2.6b	5.6±6.1b	9.5±3.2c	32.0±2.8e	3.2±2.1b
	Philenoptera violacea (Klotzsch) Schrire	1.0±0.1a	1.0±0.8a	3.0±1.2a	10.0±2.1c	0.1±0.0a
Loganiaceae	*Strychnos spinosa* Lam.	11.9±7.3d	5.0±2.5b	3.0±1.6a	8.0±4.5b	2.0±1.0b
Mimosaceae	*Acacia xanthophloea* Benth	0.0±0.0a	0.0±0.0a	6.2±2.8c	13.0±5.1c	0.02±0.0a
Rhamnaceae	*Ziziphus mauritiana* Lam.	5.5±3.2c	3.6±1.3b	3.2±0.9a	6.0±2.1a	0.05±0.0a
Poaceae	Maize grain (Control)	75.4±8.1g	55.1±4.1f	84.2±2.6f	122.3±4.7g	27.3±3.3d

[1] Means followed by the same letter within columns do not differ significantly at $p<0.05$.

Table. 5.7. List of species of trees, shrubs and grasses collected in the Manica and Massingir districts in which *Prostephanus truncatus* did not survive or breed.

Family	Scientific name
	Trees
Anacardiaceae	*Sclerocarya birrea* (A.Rich.) Hochst
Annonaceae	*Annona senegalensis* Pers.
Apocynaceae	*Diplorhynchus condylocarpon* (Müll.Arg.) Pichon
	Peltophorum africanum Sond
	Guibourtia conjugata (Bolle) J. Léonard
Fabaceae	*Afzelia quanzensis* Welw.
	Senna surattensis (Burm.f.) H.S.Irwin & Barneby
	Swartzia madagascariensis Desv.
	Combretum collinum Fresen.
Combretaceae	*Combretum fragrans* Steud. ex A. Rich.
	Combretum zeyheri Sond
Euphorbiaceae	*Spirostachys africana* Sond
Malvaceae	*Azanza garckeana* (F. Hoffm.) Exell & Hillc.
Mimosaceae	*Albizia versicolor* Welw. ex Oliv.
Moraceae	*Ficus stuhlmannii* Warb.
Sapotaceae	*Manilkara discolor* (Sond.) J.H. Hemsl.
	Shrubs
Apocynaceae	*Strophanthus petersianus* Klotzsch
Capparaceae	*Boscia mossambicensis* Klotzsch
	Maerua angolensis DC.
Ceasalpiniaceae	*Bauhinia galpinii* N.E.Br.
	Bauhinia petersiana Bolle
Euphorbiaceae	*Acalypha wilkesiana*
	Flueggea virosa (Roxb.ex Willd.) Voigt
Fabaceae	*Cajanus cajan* (L.) Millsp.
Grewia caffra	*Grewia caffra* L.
Mimosaceae	*Dichrostachys cinerea* (L.) Wight & Arn
Olacaceae	*Olax dissitiflora* Oliv.
Rubiaceae	*Plectroniella armata* (K.Schum.) Robyns
	Grasses
	Andropogon appendiculatus Nees
	Cymbopogon citratus (DC.) Stapf
	Cynodon dactylon (L.) Pers.
	Elyonurus muticus (Spreng.) Kuntze
Poaceae	*Eragrostis obtusa* Munro ex Fical. & Hiern
	Heteropogon contortus (L.) P.Beauv. ex Roem. & Schul
	Hyperthelia dissoluta (Steud.) Clayton
	Panicum maximum Jacq.
	Paspalum scrobiculatum L.
	Urochloa mosambicensis (Hack.) Dandy

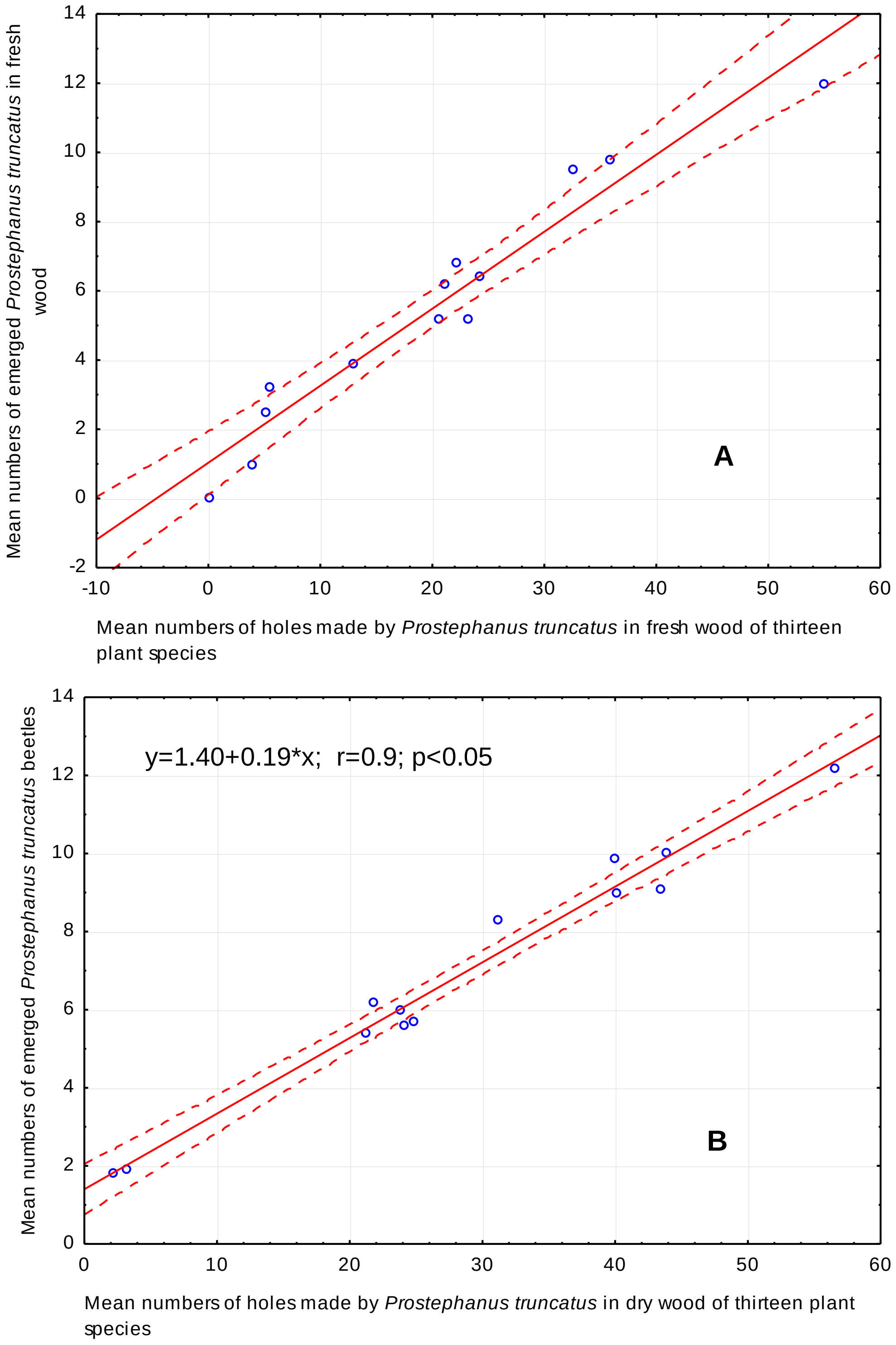

Fig. 5.2. Relationships between mean numbers of *Prostephanus truncatus* and holes recorded from fresh (A) and dry (B) wood of thirteen plant species.

5.4. Conclusions

Prostephanus truncatus can survive and reproduce in several wild host plant species as well as dry maize stalks that may be left on fields for a long time after harvest. *B. spiciformis*, *C. mopane*, *S. spinosa* and C. *abbreviata* were the plant species that were most suitable as hosts for *P. truncatus*. *Acroceras macrum* and *H. hirta* were the most important grass species hosts. Areas with high abundance of these and all plant species found positive for survival and breeding of *P. truncatus* can be a factor for prediction and potentially thread of invasion and colonization by the pest. Making roofs of granaries and fence barriers using *H. hirta* thatch is a threat to effective control of *P. truncatus*. This knowledge will contribute to designing practical integrated measures for *P. truncatus*. However, more research work is needed for consolidating and broadening the list of forest host plant species of the pest in other regions.

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CHAPTER SIX

General discussion, conclusions and recommendations

6.1. Discussion

The Larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) has been a serious pest of stored maize grain and cassava chips since it was first reported in the Manica Province of Mozambique in 1980 (Cugala *et al.,* 2007). This pest infests and damages maize grain and cassava chips with subsequent reduction of the storage period of these products in granaries of small scale farmers. The spatial and temporal dispersal ability of *P. truncatus* throughout the African continent (Harnisch and Krall, 1984; Muatinte *et al*., 2014) is influenced by its capacity to survive on dry wood of several forest plant species (Nansen *et al*. 2002), climatic conditions (Hodges *et al.,* 2003), predation by *Teretrius nigrescens* Lewis (Coleoptera: Histeridae) (Hell *et al*., 2006), as well as the wide scale availability of food sources such as maize (Gueye *et al*., 2008). However, the potential effects of local climatic factors, as well as abundance, biodiversity and availability of food sources, particularly of forest host plant species (Nang'ayo *et al.*, 2002; Jia *et al.*, 2008) is still unexplored in Mozambique. Moreover, studies on modeling of the effect of multiple factors with emphasis on temperature, humidity and availability of food sources on spatial and temporal number fluctuations of *P. truncatus* are scarce (Omondi *et al*., 2011).

Efforts to control *P. truncatus* largely addressed the use of pyrethroids (Chintzoglou *et al*., 2008; Kavallieratos *et al*., 2010), inert dusts (Stathers *et al.*, 2008), plant derived products (Smith *et al*., 2006) and the use of *T. nigrescens* (Hell *et al*., 2006; Muatinte and Cugala, 2015). Some of the management strategies for *P. truncatus* include the use of entomopathogenic fungi and bacteria (Hertlein *et al*., 2011), resistant host plants (Meikle *et al.,* 1998) and semiochemicals (Steward-Jones *et al*., 2007). The use of hermetic bags for management of *P. truncatus* has also been found effective and provides a promising control practice (De Groote *et al*., 2013; Ognakossan *et al.*, 2013). However, studies on potential effect of mass trapping of *P. truncatus* by means of traps and the potential of its integration into management strategies is non-existent.

This thesis reviewed the literature regarding *P. truncatus* (Chapter 2) and also generated new information that can be used in management of this pest. In the review, biological trends and perspectives on future pest management strategies for *P. truncatus* in Africa were provided. The main biotic and abiotic factors that drive *P. truncatus* dispersal, colonization of new habitats and injuriousness to grain in Africa were reported on. Moreover, information was provided on the rate of invasions in different countries and the period it took *P. truncatus* to disperse throughout Africa. The review provided in this thesis also summarized the latest available published information on pest management measures.

This thesis also reported on the factors that determined spatial and temporal *P. truncatus* fluctuations in numbers in the Manica and Gaza Provinces of Mozambique (Chapter 3). The effect of multiple factors such as food sources and forest host plant species, temperature, humidity and rainfall as well as elevation were reported. Recognition of factors that influence dispersal of *P. truncatus* in Mozambique may permit prediction of areas that may in future be invaded and colonized by the pest. Early warning may result in the design of cost-effective management measures for the pest.

The effect of mass trapping of *P. truncatus* and its potential for the control of *P. truncatus* has been investigated and reported on in this thesis (Chapter 4). Promising results were obtained with trapping and a significant correlation was observed between increased pest catches and reduced damage to grain inside granaries. The efficacy of management measures for *P. truncatus* may be increased with knowledge on the richness and species diversity of host plant species. Therefore, chapter 5 reported on the suitability of wild plants and firewood as hosts of *P. truncatus* in Mozambique. A list of species of trees and grasses in which *P. truncatus* is able to breed and survive, was provided. Previous reports that *P. truncatus* was able to breeding and survival in freshly cut wood in natural environments was shown not to be true in this thesis. The pest was collected under field conditions where it naturally infested dry firewood pieces of *Brachystegia spiciformis* Benth. (Fabaceae) and *Strychnos spinosa*

Lam. (Loganiaceae), located adjacent to freshly cut wood that was not infested by the pest. *Prostephanus truncatus* was however able to breed and survive in samples of freshly cut and dry wood of both plant species under laboratory conditions. Additionally, a list of tree species used as firewood and that are naturally infested by *P. truncatus* in the Maputo and Gaza Provinces was also provided. This thesis highlighted the capability of *P. truncatus* to breed and survive in several forest plant species among the Poaceae (*Acroceras macrum* Stapf and *Hyparrhenia hirta* (L.) Stapf). Breed and survive capability of *P. truncatus* in dry stalks of maize and pearl millet, *Pennisetum glaucum* (L.) R. Br (Poaceae) was also reported for first time in this thesis.

Modelling the spatial and temporal effects of multiple factors such as food source and forest host plant species, temperature, humidity, rainfall and elevation the fluctuation in numbers of *P. truncatus* was for the first time done in Mozambique.

6.2. Conclusions

With reference to the results obtained from this study, we conclude that:

6.2.1. *Prostephanus truncatus* is a serious pest in Mozambique and that its capability to disperse is influenced by availability of food sources, wild host plant diversity and abundance as well as climatic factors.

6.2.3. The abiotic and biotic factors influenced *P. truncatus* numbers. However, the strength of the effect varied between villages and years.

6.2.4. Host plant species, the maximum and minimum temperature, relative humidity and rainfall had an effect on fluctuations of *P. truncatus* numbers.

6.2.5. Higher flight activity of *P. truncatus* was observed in the rainy season and in human settlements relatively to dry season and forest areas, respectively.

6.2.6. Mass trapping with the use of universal moth traps reduces numbers of *P. truncatus* over time and represents a potential method for control of *P. truncatus* in granaries of small scale farmers.

6.2.7. Suitable wild host plants including species used as firewood are present in areas where the pest currently does not occur and spread of this pest to such areas in Mozambique is highly likely.

6.3. Recommendations

6.3.1. Monitoring and real-time information sharing of *P. truncatus* occurrence, dispersal and damage to host products should be hold on between researchers, agricultural governmental and non-governmental organizations and farmers to ensure effective application of quarantine measures against this pest.

6.3.2. Research on flight activity and on the effect of abiotic and biotic factors on variations of *P. truncatus* numbers should be continued on to enrich the data base for modeling and hence to be possible to predict dispersal and colonization of new free areas by the pest.

6.3.4. Research on mass trapping of *P. truncatus* should be continued towards designing cost-effective technologies for integration into pest management strategies.

6.3.4. Assessment of forest plant species suitable for breeding and survival of *P. truncatus* should be continued to predict areas that are likely to be infested by the pest in the future.

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