

## Rapid Communication

**First record of the occurrence of the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in Botswana**

Shaw Mlambo<sup>1</sup>, Honest Machezano<sup>2,3</sup>, Brighton M. Mvumi<sup>4</sup>, Chakubinga Moatswi<sup>5</sup>, Tawanda P. Makopa<sup>1</sup>, Tobias Engl<sup>6</sup> and Casper Nyamukondiwa<sup>1,7</sup>

<sup>1</sup>Department of Biological Sciences and Biotechnology, Botswana International University of Science and Technology, P. Bag 16, Palapye, Botswana

<sup>2</sup>Department of Zoology and Entomology, University of Pretoria, P. Bag X20, Hatfield 0028, Pretoria, South Africa

<sup>3</sup>Forestry and Agricultural Biotechnology Institute (FABI), University of Pretoria, Private Bag X20, Pretoria 0028, South Africa

<sup>4</sup>Department of Agricultural and Biosystems Engineering, University of Zimbabwe, P. O. Box MP167, Mt Pleasant, Harare, Zimbabwe

<sup>5</sup>Plant Health Department, Ministry of Agriculture, P O Box 93, Bobonong, Botswana

<sup>6</sup>Department of Insect Symbiosis, Max Planck Institute for Chemical Ecology, Hans-Knoell-Straße, Jena 8, Germany

<sup>7</sup>Department of Zoology and Entomology, Rhodes University, Makhanda 6140, South Africa

Corresponding author: Shaw Mlambo ([shawmlambo@gmail.com](mailto:shawmlambo@gmail.com))

**Citation:** Mlambo S, Machezano H, Mvumi BM, Moatswi C, Makopa T, Engl T, Nyamukondiwa C (2024) First record of the occurrence of the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in Botswana. *BioInvasions Records* 13(4): 909–925, <https://doi.org/10.3391/bir.2024.13.4.06>

**Received:** 5 February 2024

**Accepted:** 29 May 2024

**Published:** 28 October 2024

**Handling editor:** Laura Garzoli

**Copyright:** © Mlambo et al.

This is an open access article distributed under terms of the Creative Commons Attribution License (Attribution 4.0 International - CC BY 4.0).

## OPEN ACCESS

**Abstract**

The larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) is an invasive alien insect pest in Africa originally from Central America. Although it is a pest of mainly stored maize grain and dried cassava roots, the larger grain borer is polyphagous, damaging a wide variety of other staple grains and non-agricultural forest and household products (e.g., wood and/or trees, leather, rubber). To-date, the pest has spread to over 21 countries in Africa since its first introduction in the 1970s. Stored maize grain losses have since doubled in these countries. In Southern Africa, the pest was first reported in Malawi (1991), then Zambia (1993), Namibia (1998), South Africa (1999), Zimbabwe (2005), and Mozambique (2007). Specimens of the pest sampled through pheromone baited traps on the outskirts of Gaborone, Botswana were morphologically identified and confirmed using molecular sequencing. Therefore, we make a first report on the occurrence of the larger grain borer in Botswana and recommend urgent and concerted efforts to monitor the pest, update databases on the extent of its geographical distribution, host range (crop and non-crop products, including its prospective biosecurity threats and risks), socio-economic impacts and strategies for containing and managing this invasive quarantine pest.

**Key words:** biological invasions, food security, invasive pests, postharvest insects, stored grain

**Introduction**

Climate change and variability as well as increased international trade have broken biogeographical constraints of many insect pests, facilitating their spread from native ranges and subsequent introduction and establishment in novel environments (Hill 1987; Hulme 2009; Skendžić et al. 2021). This has increased both biosecurity threats and risks in vulnerable regions, especially tropical environments that offer conducive biological and physical environments for biodiversity (Li et al. 2016; Nyamukondiwa et al. 2022). For example, the past two decades have seen sub-Saharan Africa being invaded

by an unprecedented number of alien pests (see discussions in Seebens et al. 2017; Singano et al. 2020) including the fall armyworm, *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) (Goergen et al. 2016) and the tomato leafminer, *Phthorimaea absoluta* (Meyrick) (Lepidoptera: Gelechiidae) (Mansour et al. 2018).

The larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) is a wood-boring insect native to Central America. The pest was accidentally introduced in Africa in the 1970s and continues to spread across the continent (Hodges et al. 1983; Nyabako et al. 2020; Quellhorst et al. 2021) and other parts of the world (Arthur et al. 2019) where it has turned into a serious pest of stored maize and dried cassava roots in postharvest ecosystems causing up to 50% commodity losses (Cugala et al. 2007). As a wood-borer (Jia et al. 2008; Oppert et al. 2022), *P. truncatus* has negative effects on natural and managed forests and their ecosystem functions. The pest has also been reported to damage other miscellaneous household commodities through its boring activities including plastic, rubber, leather, firewood, furniture and others (Hodges 1986; Nyagwaya et al. 2010; Muatinte and Van den Berg 2019), increasing the magnitude and diversity of its socioeconomic and ecological impacts. *Prostephanus truncatus* can also survive on non-agricultural host plants found in the savanna forest of sub-Saharan Africa (Nang'ayo et al. 1993; Borgemeister et al. 1998; Nang'ayo et al. 2002; Nansen et al. 2004; Muatinte and Van den Berg 2019; Quellhorst et al. 2021) that act as permanent reservoirs for population inoculum for its known typical sporadic re-introductions, hence complicating the management efforts.

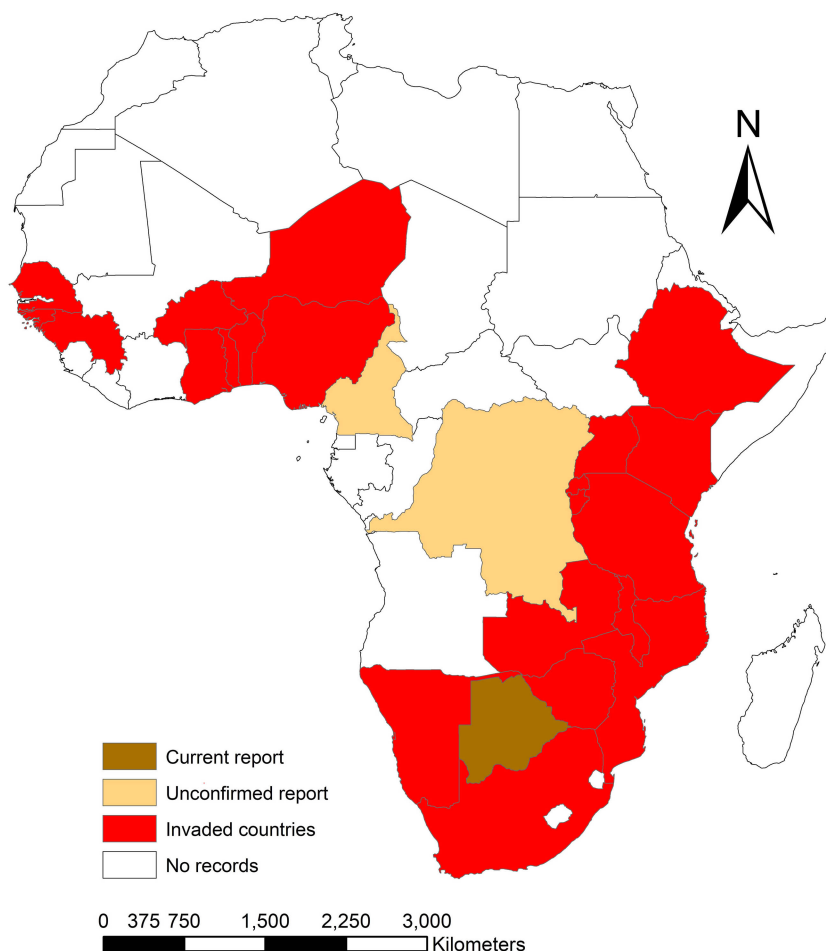
While While cobbed and/shelled maize grain and cassava roots are the preferred hosts (Hodges et al. 1983; Arthur et al. 2019), the beetle can also damage other staple food crops in Africa including sorghum, millets, wheat, cowpeas and cocoa beans (Shires 1977; Mailafiya et al. 2007; Muatinte and Van den Berg 2019; Quellhorst et al. 2021). However, literature supporting the attack, damage and reproduction thereof of *P. truncatus* on small cereal grains, especially sorghum and millets, have been highly ambivalent (Boxall 2002), particularly outside the laboratory, although anecdotal evidence suggests so (*pers. obs.*). Available reports suggest that *P. truncatus* breeding on small grain crops may be affected by grain size, starch content, grain moisture content and commodity stability for effective boring (Bell and Watters 1982; Boxall 2002).

*Prostephanus truncatus* continues to have devastating effects even after over 40 years of research efforts since its first introduction in Africa (Quellhorst et al. 2021). The major reasons for its continued spread and damage relate to increasingly favourable environments in Southern Africa due to climate change and anthropogenic activities (Arthur et al. 2019; Nyabako et al. 2020), short life cycle, high basal thermal limits (Machekano et al. 2020), considerable plasticity (Mutamiswa et al. 2021), high reproductive capacity under high tropical temperatures (Boxall 2002; Quellhorst et al. 2021) and tolerance to organophosphate- and pyrethroid-based insecticides (Rumbos et al. 2013;

Mlambo et al. 2017, 2018). Furthermore, wide host range and the alternation between cultivated and wild hosts favour its establishment across diverse habitats (Muatinte and Van den Berg 2019). For example, the beetles can thrive in dry wood and thatch grass used to construct grain stores under smallholder farmer settings, effectively providing refuge sites for the pest when stores and grains are treated and/or unavailable. This makes *P. truncatus* management especially difficult under smallholder grain storage systems (Kossou 1992; Addo et al. 2002; Nang'ayo et al. 2002; Muatinte and Van den Berg 2019). Favourable climatic conditions for development of *P. truncatus* are 32 °C and 80% relative humidity (RH) (Quellhorst et al. 2021). At these optimum conditions, the pest can complete its life cycle in 27 days, supporting multiple generations per year. These multiple generations can thus be highly damaging under high temperature tropical environments. Adult beetles tunnel into grain, producing copious amounts of grain dust on which the larvae feeds (Hodges 1986; Quellhorst et al. 2021). Commodity damage and losses vary with commodity type and length of storage period, but as much as 50% weight losses in stored maize have been reported within 6–8 months storage periods (Cugala et al. 2007).

*Prostephanus truncatus* was first reported in Southern Africa in 1991 in Malawi, Zambia in 1993, Namibia in 1998 and South Africa in 1999 (Quellhorst et al. 2021). Since then, the pest has been reported in Zimbabwe in 2005 (Nyangwaya et al. 2010; Quellhorst et al. 2021; Morey 2023) and Mozambique in 2007 (Muatinte and Cugala 2015) among others (see e.g. Gueye et al. 2008). This shows that in the last two decades or so, the pest is rapidly spreading across Africa (see distribution map in Figure 1) where maize and cassava are the staple crops. The most recent record of *P. truncatus* is from Ethiopia (Dako and Abebe 2024). However, anecdotal evidence suggest that the pest might be present in more countries in Africa e.g. in Cameroon and Democratic Republic of Congo (unconfirmed reports in Hodges 1994). More specific studies or official reports are required to confirm presence of the pest in such countries. Since *P. truncatus* has already been reported in neighbouring countries bordering Botswana, it is logical therefore that the Botswana Ministry of Agriculture has been monitoring the pest around national borders and inland. Based on their preliminary findings, there was need for confirmation through further trapping and detailed identification, resulting in the current study. We thus report the first occurrence of *P. truncatus* in the Southern district of Botswana and provide recommendations for: (i) coordinated and concerted monitoring efforts of the pest to update the extent of its geographical distribution, (ii) scoping of host plants (crop and non-crop, including its food biosecurity threats and risks), (iii) determining the socio-economic impacts, and (iv) development of policy-based strategies for managing and containing the invasive pest.

The first report of such alien, invasive economic pest species is significant not only for stakeholder awareness, but also for safeguarding the national and



**Figure 1.** Distribution map of *P. truncatus* as of April 2024 in Africa (red-shaded); unconfirmed reports (yellow-shaded); and Botswana (brown-shaded) (current study).

regional biosecurity and triggering concerted, harmonised designing and implementation of farm level and area-wide management strategies (Perrings et al. 2005; Li et al. 2016), including related policy adjustments and realignments. We present this first report of the larger grain borer in Botswana as an early warning notification to stakeholders including policymakers on the dangers that the pest poses to national forests, food and nutrition security and the broader economy (see also Mlambo et al. 2024). We also outline possible measures to control this invasive pest.

## Materials and methods

### *Study site and sampling*

Three white delta traps with sticky pads, baited with ProTru (NovAgrica, Hellas, South Africa), a pheromone dispenser for the larger grain borer (active ingredients: 1-Methylethyl (E)-2-pentenoate and 1-Methylethyl (E,E)-2,4-dimethyl-2,4-heptadienoate) were set up in Ramotswa (24°52'18"S; 25°51'47"E), a village in the South-Eastern district of Botswana bordering South Africa. Ramotswa is an arid region largely dominated by mopane trees, *Colophospermum mopane* (J.Kirk ex Benth.) J.Kirk ex J.Léonard that

make up the greater part of the savannah ecosystem. The traps, set and monitored monthly from April to August 2022, were hung about 1.5 m above ground (Hodges et al. 2004). Similar traps were also set up in the area surrounding Plant Health Department of the Ministry of Agriculture offices (24°35'01"S; 25°56'49"E) in Gaborone, Botswana and monitored on a daily basis. Live beetles trapped daily were carefully removed from the sticky pads and maintained on dried sterilised yellow maize grain (SeedCo 608 variety) in Memmert climate chambers (HPP 260, Memmert GmbH + Co.KG, Germany) at 32 °C, 70% RH and 12L: 12D photoperiod. Adult F<sub>1</sub>s from the parent colony, reared in the laboratory from the trap populations, were used for morphological identification and molecular confirmation.

### *Morphological identification*

Morphological identification was done by a team from the Plant Protection Research Institute (Gaborone) and entomologists from the Department of Biological Sciences and Biotechnology, Botswana International University of Science and Technology. Two major morphological features were used to confirm the identity of *P. truncatus* viz (i) a head curving downwards and (ii) the square-cut (truncated) posterior end of the beetles as described in Farrell and Haines (2002) and Spilman (1983) respectively. Other features such as the beetle size (~ 4 mm), mouthparts, clavate antennae and shape of the convex elytra complemented morphological features confirming positive identification (Spilman 1983; Farrell and Haines 2002; Suma and Russo 2005). Beetles were sexed using gross morphology under a stereo microscope, following methods by Shires and McCarthy (1976). Females were observed to have more pronounced and spaced clypeal tubercles than males consistent with descriptions given by Shires and McCarthy (1976).

### *Production of specimen images*

Images were acquired on a Leica M165Fc stereoscope equipped with a 1x front lens, dome illumination and a FlexacamC1 color camera (Leica Microsystems, Wetzlar, Germany). 2x/4x zoom was used for full beetle/ head images. In total, 6 images with different Z-focus were acquired spanning the entire depth of the specimen and computed into a single sharp image using the "Extended Depth of Field" algorithm integrated into the Leica application Suite software (LASX 3.8.2.27713).

### *Micro-computer tomography*

Specimens were fixated in 99.9% ethanol (Enterprise Ethanol, South Africa) and subsequently kept for one day in 100% acetone (Carl-Roth, Germany) and air dried for 4 hours before the micro-computer tomographic scan on a SkyScan 1272 equipped with a Hamamatsu XIMEA xiRAY 16 camera (Bruker, Germany). Scans were recorded with a resolution of 2452 × 1640 pixel, a 360° scan with 1° rotation steps, three frame averaging and

**Table 1.** COI Primer sequences used for larger grain borer species identification

Name of primer	Target	Sequence 5' to 3'
LCO1490	COI	GGTCAACAAATCATAAAGATATTGG
HCO2198	COI	TAAACTCAGGGTGACCAAAAAATCA

an isotropic resolution of 2.500387  $\mu\text{m}$  pixel size, source voltage of 35 kV and 150  $\mu\text{A}$  current. Cross sections were reconstructed with the NRecon software (V 2.0.0.5 Bruker, Germany) with post alignment adjustment correction of 33.50, 10% beam hardening correction and smoothing setting of 2. Files were further processed in the Dragonfly Workstation (V 2020.1 Build 1259). First, the pipette tips used for scaffolding were removed manually. The beetle was segmented with an Otsu based threshold recognition, filling of the interior space with three iterative repetitions in all individual planes. Particulate scanning artefacts were eliminated by keeping only the largest connected structure. A contour mesh was calculated with 2 or 3-fold subsampling.

#### *DNA extraction and sequencing*

Two specimens preserved in absolute ethanol (99.9% alcohol) were used for DNA extraction and sequencing. Genomic DNA was extracted at Inqaba Biotechnical Industries (Pty) Ltd, South Africa from the whole tissue specimen (identified as specimen G05 and H05) using the Quick-DNA™ Miniprep Plus Kit (Zymo Research, Catalogue No. D4068) and following the protocol of Zymo Research, USA. Sequencing of the COI gene (mitochondrial cytochrome c oxidase I) was done. The universal COI primers (LCO1490 and HCO2198) were used to amplify a fragment of the 5' end of the COI gene, which is highly informative for species identification across different taxonomic categories (Folmer et al. 1994; Hebert et al. 2003). The COI target region was amplified as presented in Table 1.

#### *Polymerase Chain Reaction (PCR)*

The general PCR protocol followed was denaturation at 94 °C for 5 minutes followed by 35 cycles of 94 °C for 30 seconds, 50 °C for 30 seconds, 68 °C for 1 minute and a final extension at 68 °C for 10 minutes, holding at 4 °C. The integrity of the PCR amplicons was visualized on a 1% agarose gel (CSL-AG500, Cleaver Scientific Ltd) stained with EZ-vision® Bluelight DNA Dye. The NEB Fast Ladder was used on all gels (N3238) as size standard. Fragments were enzymatically purified using the ExoSAP procedure (NEB M0293L; NEB M0371). The amplicons were then purified for sequencing (Zymo Research, ZR-96 DNA Sequencing Clean-up Kit™, Catalogue No. D4050), and sequenced in the forward and reverse direction (Nimagen, BrilliantDye™ Terminator Cycle Sequencing Kit V3.1, BRD3-100/1000) using the ABI 3730xl Genetic Analyzer (Applied Biosystems, Thermo Fisher Scientific).

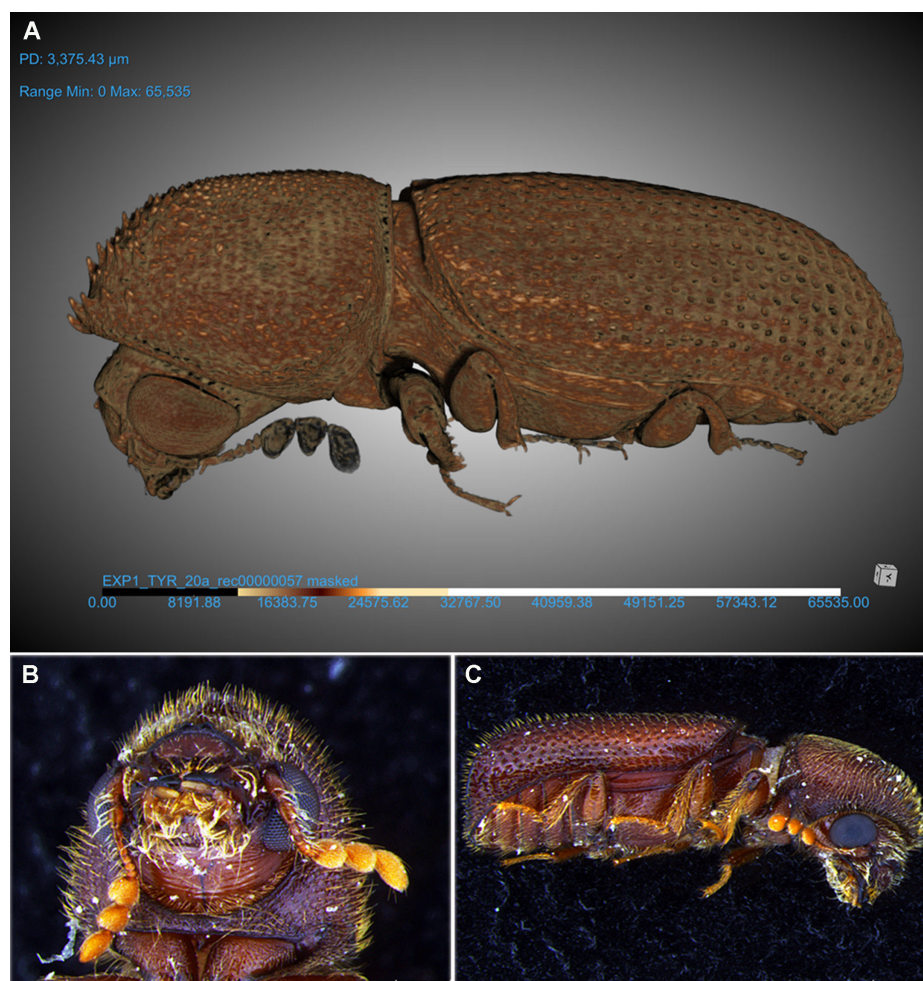
### *Sequence assembly*

FinchTV version 1.4 was used to view the raw chromatogram files (.abi). CLC Bio Main Workbench was used to assemble the forward and reverse sequencing reads to form a consensus sequence for each sample. The Basic Local Alignment Search Tool (BLASTN) analysis with default parameters (Altschul et al. 1997) was performed on the National Centre for Biotechnology Information (NCBI) website (<https://www.ncbi.nlm.nih.gov/>) to determine if a sequence in the database matched the query sequences. The nucleotide sequences of the two specimens G05 and H05 were deposited in the GenBank.

### *Evolutionary relationship of the taxa*

Phylogenetic relatedness of the Botswana specimens to those in the GenBank (Accession number: JN097721.1, JN097722.1, KP410257.1, and KP410257.1) was investigated using three different methods. First evolutionary history was inferred using the Neighbor Joining method based on the Kimura 2-parameter model (Kimura 1980) in Molecular Evolutionary Genetics Analysis software (MEGA 11) (Tamura et al. 2021). The ends of the sequences were trimmed to eliminate sequence size differences, removing primers (if any) and come up with consensus sequences (Cabras and Cruz 2016). Support was estimated with a setting of 1000 bootstrap replicates (Felsenstein 1985; Tamura et al. 2021). The analysis involved 7 nucleotide sequences. Codon positions included were 1<sup>st</sup> + 2<sup>nd</sup> + 3<sup>rd</sup>. All ambiguous positions were removed for each sequence pair by pairwise deletion option (Kumar et al. 2008). There were a total of 609 positions in the final dataset. *Anthrenus oberthueri* (Accession number MN182947.1) (see Bell and Philips 2012; Sire et al. 2019) was used as an outgroup to produce the phylogenetic tree.

Second, a Bayesian phylogenetic tree was reconstructed using Bayesian Evolutionary Analysis by Sampling Trees (BEAST2) software v.2.7.5 (Bouckaert et al. 2019). The BEAST2 v.2.5 built-in package, bModelTest (Teske and Beheregaray 2009), was used to estimate the best nucleotide substitution model. The advantage of this method is that it averages over all models and takes the uncertainty due to ambiguous positions into consideration during the phylogenetic tree-building step. BEAST2 was run for five chains, each 500 million iterations with 150 million initial burn-in steps. The convergence of the multiple runs was visually investigated in Tracer v.1.7 (Jin et al. 2020), and a consensus phylogenetic tree was reconstructed in TreeAnnotator (Drummond and Rambaut 2007) and subsequently visualised in Figtree v.1.4 (<https://github.com/rambaut/figtree>). Finally, a Maximum Likelihood tree was constructed in IQ-TREE2 v.2.2 (Stiller et al. 2022) using the program's default setting, including using the server's built-in automatic model selection tool for the selection of the best nucleotide substitution model and 1000 bootstraps for the consensus tree.



**Figure 2.** Key morphological characteristics identifying and confirming the collected *Prostephanus truncatus*: A: 3-dimensional specimen image; B: mouthparts and clavate antennae and C: head curving downwards and a truncated posterior end of the beetle.

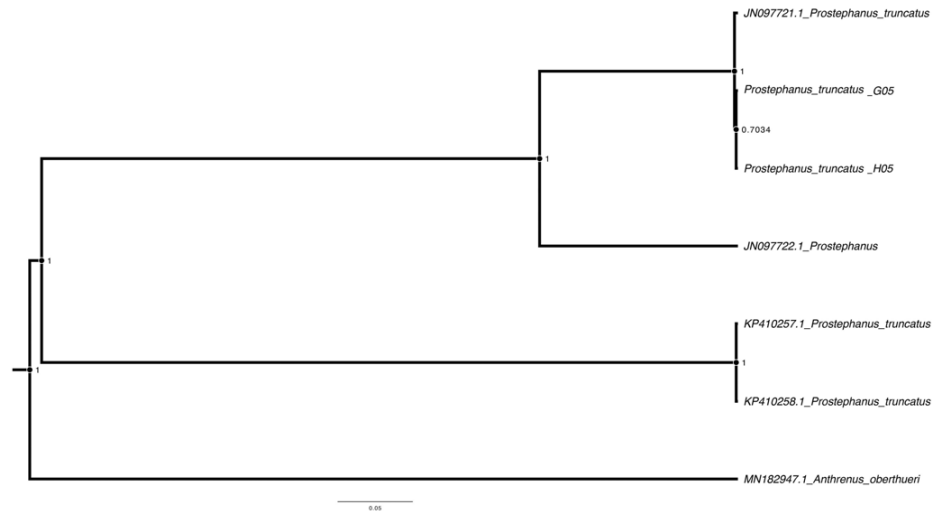
## Results

### *Pheromone trapping and morphological identification*

Pheromone-baited species-specific trap catches showed that both male and female larger grain borer beetles were attracted to the pheromones and positively identified. Morphological features consistent with *P. truncatus* were observed, including: (i) a head curving downwards and (ii) the square-cut (truncated) posterior end of the body of the beetles (Figure 2) as described in Farrell and Haines (2002) and Spilman (1983), respectively. Other features; (i) ventrally directed mouthparts; (ii) a hard, dark brown exoskeleton at adult stage, (iii) three-segmented clavate antennae and (iv) convex elytra were all consistent with the morphological features typical of *P. truncatus* taxonomy as described by Spilman (1983) and Farrell and Haines (2002). The specimens, therefore, conformed 100% to the morphological features of *P. truncatus* based on taxonomic keys described by Shires and McCarthy (1976); Spilman (1983) and Farrell and Haines (2002).

**Table 2.** Summarised results of a BLASTN showing percentage identity of Botswana specimens to those in the GenBank under accession number JN097721.1

Specimen ID	Nearest species identity	Query cover (%)	Percentage identity (%)	Accession number	Date
G05	<i>Prostephanus truncatus</i>	100	95.83	JN097721.1	23 January 2024
H05	<i>Prostephanus truncatus</i>	100	96.02	JN097721.1	23 January 2024



**Figure 3.** An ultrametric Bayesian phylogenetic tree generated in BEAST2 showing the placement of two sequences generated in this study compared to other closely related species with publically available records in the NCBI database. The scale-bar is proportional to the number of nucleotide substitutions, and the numbers next to each node shows the corresponding posterior support for the split. The figure confirms that generated sequences are almost identical to JN097721.1 with a posterior probability of 1.

### Molecular identification

Molecular analysis results matched our (Botswana) specimens G05 and H05 to sequences in the GenBank, confirming the specimens as *P. truncatus* with 95.83 % and 96.02 % identity respectively (Table 2). The nucleotide sequences of the two specimens were assigned accession numbers PP731513.1 and PP731512.1 respectively.

### Evolutionary relationship of the taxa

The COI gene sequences of the two specimens were matched with existing COI sequences of *P. truncatus* in the GenBank forming different topologies. The visual inspection of the Bayesian analysis trace files confirmed that convergence has been achieved. The specimen G05 and H05 are very similar to each other and they cluster well with JN097721.1 (Figure 3). Similarly, the Maximum Likelihood method receives the same identical topology.

### Discussion

Trapping results showed the presence of *P. truncatus* in Botswana. Use of pheromones at two sites indicated the attraction of both sexes of the adult beetle to 1-Methylethyl (E)-2-pentenoate and 1-Methylethyl (E,E)-2,4-dimethyl-2,4-heptadienoate, a pheromone specific to *P. truncatus* which confirmed the specimens' identity. Both sexes of the *P. truncatus* are attracted

by the same aggregation pheromone (Cork et al. 1991), a contributory indicator to the positive identity of the species. Furthermore, morphological identification confirmed the specimens as *P. truncatus*, consistent with the taxonomic keys for the species (see Spilman 1983; Farrell and Haines 2002). Follow-up molecular analysis of the samples through mitochondrial COI (cytochrome c oxidase subunit I) sequencing linked our specimen (the Botswana *P. truncatus* samples) to Accession number JN097721.1, with similarity of BLAST (~ 96%). The specimens G05 and H05 were, therefore, positively identified as *Prostephanus truncatus* (Horn, 1878) (Coleoptera: Bostrichidae), a wood-boring invasive, alien Bostrichidae, that has become a serious pest of stored maize and dried cassava roots globally (Hodges et al. 1983; Golob 1988; Boxall 2002; Arthur et al. 2019). The results of the current study, however, show relatively lower (95.83% and 96.02%) BLASTN similarity to other *P. truncatus* species identified (100%) (e.g., accession number JN097721.1 see Bell and Philips 2012), although the highly supported posterior probabilities show a lot of consistency in sequences alignment (Bouckaert et al. 2019). The low BLASTN similarity may indicate within species variations (Lin et al. 2015; Afizah et al. 2019), which maybe a result of mixture of populations from different areas (multiple introduction) during the years of spread since the beetle's arrival in Africa over 40 years ago (Quellhorst et al. 2021). It is, therefore, possible that with multiple introductions of *P. truncatus* from different geographical regions (Arthur et al. 2019), this could have brought about genetic diversity and facilitated hybridisation (see discussions in Guntrip et al. 1996) in the beetle populations in Africa. In most cases, therefore, to improve the robustness of DNA sequence results, as in this study, morphological identifications are used to supplement molecular technologies such as DNA barcoding (Afizah et al. 2019). Using our complementary morphological identification, we therefore positively confirmed the specimens as *P. truncatus* and herewith report, to our knowledge, the first official report of this invasive pest species in Botswana.

*Prostephanus truncatus* became established in Africa following multiple accidental introductions; the first of which was in Tanzania and then in Togo (Nang'ayo et al. 2002; Mlambo et al. 2024). Thereafter, similar introductions may have occurred, and the pest continued to spread across Africa due to favourable bio-physical conditions (Bellard et al. 2013; Seebens et al. 2015; Arthur et al. 2019). Following introduction, the beetles can spread by adult flight, and adults reportedly fly distances of 0.25 to 1 km in successive flights (Fadamiro et al. 1998). Furthermore, given its wide host range, propagules can also easily spread with transport and trade in wood, thatching grass, fodder trade and related materials (Nang'ayo et al. 1993, 2002; Muatinte and Van den Berg 2019). In line with this, our trap catches show the presence of *P. truncatus* at Ramotswa border post which is part of the regional grain trade routes connecting South Africa (which is linked to numerous cape

ports both in the South Atlantic and Indian Oceans), and also Botswana and the rest of the southern African region by land (rail and road) and air routes. The latest report on the occurrence of *P. truncatus* in Botswana follows similar reports in neighbouring countries Zambia, Namibia, South Africa and Zimbabwe in 1993, 1998, 1999 and 2005 respectively (Quellhorst et al. 2021).

The beetle has been reported to cause maize grain damage as high as 50–100% and grain weight losses of 15–50% over 6–8 months storage periods (Mutambuki and Ngatia 2006; Njoroge et al. 2014; Mlambo et al. 2018; Mutambuki et al. 2019; Mlambo et al. 2024). The damage causes massive weight loss and renders grain unfit for human consumption (Bechoff et al. 2022) while seed grain loses viability. Scattered evidence suggests that the beetle also breeds on stored sorghum grain (Verma and Lal 1987; Mailafiya et al. 2007; Osipitan et al. 2012; Machekano et al. 2020; Morey 2023). Occurrence of *P. truncatus* on sorghum is of significance because sorghum is the world's fifth most important cereal grain (Akinseye et al. 2017; Mundia et al. 2019) and Africa's second most important cereal crop after maize (Mundia et al. 2019). It is also the staple crop in Botswana (Mpofo et al. 2022). Sorghum is receiving increasing attention as the anchor for resilient cropping systems owing to its drought tolerance (Rurinda et al. 2014; Nezomba et al. 2018). Thus, its suitability as a host for *P. truncatus* can negate the resilience of tropical African climate change adaptation strategies and food security systems.

Apart from cultivated hosts, the larger grain borer also breeds on wild host tree species such as *Colophospermum mopane* (J. Kirk ex Benth.) (Muatinte and Van den Berg 2019), a common tree species in Botswana and the savanna ecosystem (Makhado et al. 2014). The prevalence of host tree species such as mopane will therefore increase the potential invasion areas across Botswana's savanna woodlands; simultaneously presenting a challenge in controlling the pest as then it would alternate between stored grain and wild hosts. Furthermore, the beetle is reported to breed on *Hyparrhenia* grass species (Muatinte and Van den Berg 2019), which is a common grass species in Botswana and one that is commonly used as thatch grass (Kabelo and Mofakate 2004). The ability of *P. truncatus* to alternate between cultivated and non-cultivated wild hosts therefore poses a challenge in its control as the forest can act as a reservoir for wild propagules that sporadically attack stored grains. *Prostephanus truncatus* can also facilitate spreading of fungal spores, predisposing stored maize grain to fungal infection leading to mycotoxin contamination thus posing major threats to human health (Danso et al. 2017).

As with most invasions, the detection of *P. truncatus* in Botswana calls for: 1. suitable quarantine measures and monitoring systems, 2. the training of extension staff and farmers to be able to recognise and identify the pest, 3. awareness campaigns, and 4. availing of efficacious control methods to enable farmers to manage the pest during grain storage (Hodges et al. 1983;

Addo et al. 2002). The efficacy of these control measures may need to be complemented by the development of an integrated management strategy for the control of this invasive pest. Furthermore, there is need to confirm its presence at various other further inland sites such as land border route areas and then tighten import inspection at ports of entry (Addo et al. 2002) as well as the trade and exports of host commodities (see discussions in Perrings et al. 2005). At farm level, the use of improved storage structures including brick and concrete made granaries (Stathers et al. 2002, 2020; Nyagwaya et al. 2010), modern airtight hermetic technologies (De Groote et al. 2013; Ndegwa et al. 2016; Mutambuki et al. 2019; Baributsa et al. 2020; Ngwenyama et al. 2022) and metal silos (Tefera et al. 2011; Chigoverah and Mvumi 2016) are effective control measures that are also encouraged, as part of an integrated management strategy.

## Conclusion

Our findings confirm the positive identification of *P. truncatus* in Botswana using a combination of gross morphology based on standard taxonomic keys and molecular confirmation. Complementary positive sex specific pheromone lure trapping for the species, and molecular techniques were used to further confirm our specimens as *P. truncatus*. We, therefore, conclude that we confirmed and do hereby present the first report of *Prostephanus truncatus* in Botswana and recommend suitable phytosanitary, quarantine and monitoring systems harmonised with appropriate policy-based control methods to reduce biosecurity risk, minimise spread and socio-economic impact of this invasive pest on local farmers, the entire grain industry and the postharvest ecosystem at large.

## Authors' contribution

Research conceptualization – CN, HM, BMM, SM, CM. Methodology – CN, HM, SM, TM, TE. Investigation and data collection – CN, HM, BMM, SM, CM. Data analysis and interpretation – CN, HM, BMM, TE, SM, TM. Writing original draft – CN, HM, BMM, TE, SM. Reviewing and editing – CN, HM, BMM, SM, CM, TE, TM.

## Acknowledgements

We acknowledge the Plant Health Department under the Botswana Ministry of Agriculture for providing the *P. truncatus* specimens used in this study. We also acknowledge Inqaba Biotechnical Industries (Pty) Ltd, South Africa for DNA analysis. The authors would like to thank Dr. Mohlamatsane Mokhatla from the University of Pretoria (South Africa) for his help with mapping and Arsalan Emami-Khoyi (Hungarian University of Agriculture and Life Sciences (MATE) for some expert opinion on phylogenetics and the Center for High-Performance Computing (CHPC), Cape Town, South Africa, for providing computational resources to analyse the data. We also acknowledge contributions made by the anonymous reviewers that helped to improve the previous versions of the manuscript.

## References

Addo S, Birkinshaw LA, Hodges RJ (2002) Ten years after the arrival in Ghana of Larger Grain Borer: Farmers' responses and adoption of IPM strategies. *International Journal of Pest Management* 48: 315–325, <https://doi.org/10.1080/09670870210151670>

- Afizah AN, Torno MM, Jannah JN, Azahari AH, Asuad MK, Nazni WA, Lee HL (2019) DNA barcoding complementing morphological taxonomic identification of mosquitoes in Peninsular Malaysia. *Southeast Asian Journal of Tropical Public Health* 50: 36–46
- Akinseye FM, Adam M, Agele SO, Hoffmann MP, Traore PCS, Whitbread AM (2017) Assessing crop model improvements through comparison of sorghum (*Sorghum bicolor* L. Moench) simulation models: A case study of West African varieties. *Field Crops Research* 201: 19–31, <https://doi.org/10.1016/j.fcr.2016.10.015>
- Altschul SF, Madden TL, Schäffer AA, Zhang J, Zhang Z, Miller W, Lipman DJ (1997) Gapped BLAST and PSI-BLAST: a new generation of protein database search programs. *Nucleic Acids Research* 25: 3389–3402, <https://doi.org/10.1093/nar/25.17.3389>
- Arthur FH, Morrison WR, Morey AC (2019) Modeling the potential range expansion of larger grain borer, *Prostephanus truncatus* (Coleoptera: Bostrichidae). *Scientific Reports* 9: 6862, <https://doi.org/10.1038/s41598-019-42974-5>
- Baributsa D, Bakoye ON, Ibrahim B, Murdock LL (2020) Performance of five postharvest storage methods for maize preservation in Northern Benin. *Insects* 11: 541, <https://doi.org/10.3390/insects11080541>
- Bechoff A, Shee A, Mvumi BM, Ngwenyama P, Debelo H, Ferruzzi MG, Tomlins KI (2022) Estimation of nutritional postharvest losses along food value chains: A case study of three key food security commodities in sub-Saharan Africa. *Food Security* 14: 571–590, <https://doi.org/10.1007/s12571-021-01238-9>
- Bell KL, Philips TK (2012) Molecular systematics and evolution of the Ptinidae (Coleoptera: Bostrichoidea) and related families. *Zoological Journal of the Linnean Society* 165: 88–108, <https://doi.org/10.1111/j.1096-3642.2011.00792.x>
- Bell RJ, Watters FL (1982) Environmental factors influencing the development and rate of increase of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) on stored maize. *Journal of Stored Products Research* 18: 131–142, [https://doi.org/10.1016/0022-474X\(82\)90013-3](https://doi.org/10.1016/0022-474X(82)90013-3)
- Bellard C, Thuiller W, Leroy B, Genovesi P, Bakkenes M, Courchamp F (2013) Will climate change promote future invasions? *Global Change Biology* 19: 3740–3748, <https://doi.org/10.1111/gcb.12344>
- Borgemeister C, Goergen G, Tchabi A, Awande S, Markham RH, Scholz D (1998) Exploitation of a woody host plant and cerambycid-associated volatiles as host-finding cues by the larger grain borer (Coleoptera: Bostrichidae). *Annals of the Entomological Society of America* 91: 741–747, <https://doi.org/10.1093/aesa/91.5.741>
- Bouckaert R, Vaughan TG, Barido-Sottani J, Duchêne S, Fourment M, Gavryushkina A, Drummond AJ (2019) BEAST 2.5: An advanced software platform for Bayesian evolutionary analysis. *PLoS Computational Biology* 15: e1006650, <https://doi.org/10.1371/journal.pcbi.1006650>
- Boxall R (2002) Damage and Loss Caused by the Larger Grain Borer *Prostephanus truncatus*. *Integrated Pest Management Reviews* 7: 105–121, <https://doi.org/10.1023/A:1026397115946>
- Cabras AA, Cruz RD (2016) DNA barcoding of selected *Pachyrhynchus* species (Coleoptera: Curculionidae) from Mt. Apo Natural Park, Philippines. *Acta Biologica Universitatis Daugavpiliensis* 16: 111–118
- Chigoverah AA, Mvumi BM (2016) Efficacy of metal silos and hermetic bags against stored-maize insect pests under simulated smallholder farmer conditions. *Journal of Stored Products Research* 69: 179–189, <https://doi.org/10.1016/j.jspr.2016.08.004>
- Cork A, Hall DR, Hodges RJ, Pickett JA (1991) Identification of major component of male-produced aggregation pheromone of larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Journal of Chemical Ecology* 17: 789–803, <https://doi.org/10.1007/BF00994201>
- Cugala D, Sidumo A, Santos L, Mariquale B, Cumba V, Bulha M (2007) Assessment of status, distribution and weight lost due to *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in Mozambique. In: Society, A.C.S. (eds), 8<sup>th</sup> African Crop Science Society Conference, El-Minia, Egypt, October 27–31, 2007. African Crop Science Society El-Minia, Egypt, pp 975–979
- Dako OD, Abede SG (2024) First report of the Larger Grain Borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) from stored maize in Ethiopia. *Ethiopian Journal of Science and Sustainable Development* 11(1): 22–29
- Danso JK, Osekre EA, Manu N, Opit GP, Armstrong P, Arthur FH, Mbata G (2017) Moisture content, insect pests and mycotoxin levels of maize at harvest and post-harvest in the Middle Belt of Ghana. *Journal of Stored Products Research* 74: 46–55, <https://doi.org/10.1016/j.jspr.2017.08.007>
- De Groote H, Kimenju SC, Likhayo P, Kanampiu F, Tefera T, Hellin J (2013) Effectiveness of hermetic systems in controlling maize storage pests in Kenya. *Journal of Stored Products Research* 53: 27–36, <https://doi.org/10.1016/j.jspr.2013.01.001>
- Drummond AJ, Rambaut A (2007) BEAST: Bayesian evolutionary analysis by sampling trees. *BMC Evolutionary Biology* 7: 214, <https://doi.org/10.1186/1471-2148-7-214>
- Fadamiro HY, Wyatt TD, Birch MC (1998) Flying beetles respond as moths predict: optomotor anemotaxis to pheromone plumes at different heights. *Journal of Insect Behavior* 11: 549–557, <https://doi.org/10.1023/A:1022367430354>

- Farrell G, Haines CP (2002) The taxonomy, systematics and identification of *Prostephanus truncatus* (Horn). *Integrated Pest Management Reviews* 7: 85–90, <https://doi.org/10.1023/A:1026349200016>
- Felsenstein J (1985) Confidence limits on phylogenies: an approach using the bootstrap. *Evolution* 39: 783–791, <https://doi.org/10.2307/2408678>
- Folmer RHA, Nilges M, Folkers PJM, Konings RNH, Hilbers CW (1994) A model of the complex between single-stranded DNA and the single-stranded DNA binding protein encoded by gene V of filamentous bacteriophage M13. *Journal of Molecular Biology* 240: 341–357, <https://doi.org/10.1006/jmbi.1994.1449>
- Goergen G, Kumar PL, Sankung SB, Togola A, Tamò M (2016) First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa. *PLoS ONE* 11: e0165632, <https://doi.org/10.1371/journal.pone.0165632>
- Golob P (1988) Current status of the Larger Grain Borer *Prostephanus truncatus* (Horn) in Africa. *International Journal of Tropical Insect Science* 9: 737–745, <https://doi.org/10.1017/S1742758400005622>
- Gueye MT, Goergen G, Badiane D, Hell K, Lamboni L (2008) First report on occurrence of the larger grain borer *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in Senegal. *African Entomology* 16: 309–311, <https://doi.org/10.4001/1021-3589-16.2.309>
- Guntrip J, Sibly RM, Smith RH (1996) A phenotypic and genetic comparison of egg to adult life-history traits between and within two strains of the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Journal of Stored Products Research* 32: 213–223, [https://doi.org/10.1016/S0022-474X\(96\)00019-7](https://doi.org/10.1016/S0022-474X(96)00019-7)
- Hebert PD, Ratnasingham S, De Waard JR (2003) Barcoding animal life: cytochrome c oxidase subunit 1 divergences among closely related species. *Proceedings of the Royal Society of London. Series B: Biological Sciences* 270: 96–99, <https://doi.org/10.1098/rsbl.2003.0025>
- Hill DS (1987) *Agricultural insect pests of the tropics and their control*. Cambridge University Press, Cambridge, UK, 746 pp
- Hodges R (1994) Recent advances in the biology and control of *Prostephanus truncatus* (Coleoptera: Bostrichidae). In: Highley E, Wright EJ, Banks HJ, Champ BR (eds), *Proceedings of the 6<sup>th</sup> International Working Conference on Stored Product Protection*, Canberra, Australia, CAB International, Wallingford, United Kingdom, pp 929–934
- Hodges RJ (1986) The biology and control of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae)—a destructive storage pest with an increasing range. *Journal of Stored Products Research* 22: 1–14, [https://doi.org/10.1016/0022-474X\(86\)90040-8](https://doi.org/10.1016/0022-474X(86)90040-8)
- Hodges RJ, Dunstan WR, Magazini I, Golob P (1983) An outbreak of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in East Africa. *Protection Ecology* 5(2): 183–194
- Hodges RJ, Addo S, Farman DI, Hall DR (2004) Optimising pheromone lures and trapping methodology for *Prostephanus truncatus* (Horn) (Coleoptera). *Journal of Stored Products Research* 40: 439–449, [https://doi.org/10.1016/S0022-474X\(03\)00047-X](https://doi.org/10.1016/S0022-474X(03)00047-X)
- Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. *Journal of Applied Ecology* 46: 10–18, <https://doi.org/10.1111/j.1365-2664.2008.01600.x>
- Jia F, Toews MD, Campbell JF, Ramaswamy SB (2008) Survival and reproduction of lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) on flora associated with native habitats in Kansas. *Journal of Stored Products Research* 44: 366–372, <https://doi.org/10.1016/j.jspr.2008.06.001>
- Jin JJ, Yu WB, Yang JB, Song Y, DePamphilis CW, Yi TS, Li DZ (2020) GetOrganelle: a fast and versatile toolkit for accurate de novo assembly of organelle genomes. *Genome Biology* 21: 1–31, <https://doi.org/10.1186/s13059-020-02154-5>
- Kabelo M, Mafokate D (2004) A checklist of Botswana grasses. Southern African Botanical Diversity Network Report No. 24. SABONET, Pretoria and Gaborone, 30 pp
- Kimura M (1980) A simple method for estimating evolutionary rates of base substitutions through comparative studies of nucleotide sequences. *Journal of Molecular Evolution* 16: 111–120, <https://doi.org/10.1007/BF01731581>
- Kossou DK (1992) The sensitivity of wood used for the construction of traditional granaries to attack by *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Insect Science and its Application* 13: 435–439, <https://doi.org/10.1017/S1742758400013734>
- Kumar S, Nei M, Dudley J, Tamura K (2008) MEGA: a biologist-centric software for evolutionary analysis of DNA and protein sequences. *Briefings in Bioinformatics* 9: 299–306, <https://doi.org/10.1093/bib/bbn017>
- Li X, Liu X, Kraus F, Tingley R, Li Y (2016) Risk of biological invasions is concentrated in biodiversity hotspots. *Frontiers in Ecology and the Environment* 14: 411–417, <https://doi.org/10.1002/fee.1321>
- Lin X, Stur E, Ekrem T (2015) Exploring genetic divergence in a species-rich insect genus using 2790 DNA barcodes. *PLoS ONE* 10: e0138993, <https://doi.org/10.1371/journal.pone.0138993>

- Machekano H, Mutamiswa R, Singano C, Joseph V, Chidawanyika F, Nyamukondiwa C (2020) Thermal resilience of *Prostephanus truncatus* (Horn): Can we derive optimum temperature-time combinations for commodity treatment? *Journal of Stored Products Research* 86: 101568, <https://doi.org/10.1016/j.jspr.2020.101568>
- Mailafiya DM, Ayertey JN, Cudjoe AR (2007) Suitability of sorghum grain for the development of the larger grain borer *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Science World Journal* 2: 21–26, <https://doi.org/10.4314/swj.v2i4.51760>
- Makhado R, Potgieter M, Timberlake J, Gumbo D (2014) A review of the significance of mopane products to rural people's livelihoods in southern Africa. *Transactions of the Royal Society of South Africa* 69: 117–122, <https://doi.org/10.1080/0035919X.2014.922512>
- Mansour R, Brévault T, Chailleux A, Cherif A, Grissa-Lebdi K, Haddi K, Biondi A (2018) Occurrence, biology, natural enemies and management of *Tuta absoluta* in Africa. *Entomologia Generalis* 38: 83–111, <https://doi.org/10.1127/entomologia/2018/0749>
- Mlambo S, Mubayiwa M, Tarusikirwa VL, Machekano H, Mvumi BM, Nyamukondiwa C (2024) The Fall Armyworm and Larger Grain Borer Pest Invasions in Africa: Drivers, Impacts and Implications for Food Systems. *Biology* 13: 160, <https://doi.org/10.3390/biology13030160>
- Mlambo S, Mvumi BM, Stathers T, Mubayiwa M, Nyabako T (2017) Field efficacy of hermetic and other maize grain storage options under smallholder farmer management. *Crop Protection* 98: 198–210, <https://doi.org/10.1016/j.cropro.2017.04.001>
- Mlambo S, Mvumi BM, Stathers T, Mubayiwa M, Nyabako T (2018) Field efficacy and persistence of synthetic pesticidal dusts on stored maize grain under contrasting agro-climatic conditions. *Journal of Stored Products Research* 76: 129–139, <https://doi.org/10.1016/j.jspr.2018.01.009>
- Mpofu P, Cuthbert RN, Machekano H, Nyamukondiwa C (2022) Transgenerational responses to heat and fasting acclimation in the Angoumois grain moth. *Journal of Stored Products Research* 97: 101979, <https://doi.org/10.1016/j.jspr.2022.101979>
- Muatinte BL, Cugala DR (2015) Monitoring the establishment and dispersal of *Teretrius nigrescens* Lewis (Coleoptera: Histeridae), a predator of *Prostephanus truncatus* Horn (Coleoptera: Bostrichidae) in Manica province, Mozambique. *African Entomology* 23: 250–254, <https://doi.org/10.4001/003.023.0123>
- Muatinte BL, Van den Berg J (2019) Suitability of Wild Host Plants and Firewood as Hosts of *Prostephanus truncatus* (Coleoptera: Bostrichidae) in Mozambique. *Journal of Economic Entomology* 112: 1705–1712, <https://doi.org/10.1093/jee/toz042>
- Mundia CW, Secchi S, Akamani K, Wang G (2019) A regional comparison of factors affecting global sorghum production: The case of North America, Asia and Africa's Sahel. *Sustainability* 11: 2135, <https://doi.org/10.3390/su11072135>
- Mutambuki K, Ngatia C (2006) Loss assessment of on-farm stored maize in semi-arid area of Kitui District, Kenya. In: Lorini I, Bacaltchuk B, Beckel H, Deckers D, Sundfeld E, dos Santos JP, Biagi JD, Celaro JC, Faroni LR D'A, Bortolini L.de O.F, Sartori MR, Elias MC, Guedes RNC, da Fonseca RG, Scussel VM (eds) Proceedings of the 9<sup>th</sup> International working conference on stored product protection. Campinas, São Paulo, Brazil, October 15–18, 2006, Brazilian Post-harvest Association - ABRAPOS, Passo Fundo, RS, Brazil, pp 15–23
- Mutambuki K, Affognon H, Likhayo P, Baributsa D (2019) Evaluation of Purdue improved crop storage triple layer hermetic storage bag against *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and *Sitophilus zeamais* (Motsch.) (Coleoptera: Curculionidae). *Insects* 10: 204, <https://doi.org/10.3390/insects10070204>
- Mutamiswa R, Machekano H, Singano C, Joseph V, Chidawanyika F, Nyamukondiwa C (2021) Desiccation and temperature resistance of the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae): pedestals for invasion success? *Physiological Entomology* 46: 157–166, <https://doi.org/10.1111/phen.12355>
- Nang'ayo FLO, Hill MG, Chandi EA, Chiro CT, Nzeve DN, Obiero J (1993) The natural environment as reservoir for the larger grain *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in Kenya. *African Crop Science Journal* 1: 39–47, <https://doi.org/10.4314/acsj.v1i1.54745>
- Nang'ayo FLO, Hill MG, Wright DJ (2002) Potential hosts of *Prostephanus truncatus* (Coleoptera: Bostrichidae) among native and agroforestry trees in Kenya. *Bulletin of Entomological Research* 92: 499–506, <https://doi.org/10.1079/BER2002202>
- Nansen C, Meikle WG, Tigar B, Harding S, Tchabi A (2004) Nonagricultural hosts of *Prostephanus truncatus* (Coleoptera: Bostrichidae) in a West African forest. *Annals of the Entomological Society of America* 97: 481–491, [https://doi.org/10.1603/0013-8746\(2004\)097\[0481:NHOPTC\]2.0.CO;2](https://doi.org/10.1603/0013-8746(2004)097[0481:NHOPTC]2.0.CO;2)
- Ndegwa MK, De Groote H, Gitonga ZM, Bruce AY (2016) Effectiveness and economics of hermetic bags for maize storage: results of a randomized controlled trial in Kenya. *Crop Protection* 90: 17–26, <https://doi.org/10.1016/j.cropro.2016.08.007>

- Nezomba H, Mtambanengwe F, Rurinda J, Mapfumo P (2018) Integrated soil fertility management sequences for reducing climate risk in smallholder crop production systems in southern Africa. *Field Crops Research* 224: 102–114, <https://doi.org/10.1016/j.fcr.2018.05.003>
- Ngwenyama P, Mvumi BM, Nyanga LK, Stathers TE, Siziba S (2022) How different hermetic bag brands and maize varieties affect grain losses during storage by smallholder farmers. *Crop Protection* 153: 105861, <https://doi.org/10.1016/j.cropro.2021.105861>
- Njoroge AW, Affognon HD, Mutungi CM, Manono J, Lamuka PO, Murdock LL (2014) Triple bag hermetic storage delivers a lethal punch to *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in stored maize. *Journal of Stored Products Research* 58: 12–19, <https://doi.org/10.1016/j.jspr.2014.02.005>
- Nyabako T, Mvumi BM, Stathers T, Mlambo S, Mubayiwa M (2020) Predicting *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) populations and associated grain damage in smallholder farmers' maize stores: A machine learning approach. *Journal of Stored Products Research* 87: 101592, <https://doi.org/10.1016/j.jspr.2020.101592>
- Nyagwaya LDM, Mvumi BM, Saunyama, IGM (2010) Occurrence and distribution of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) in Zimbabwe. *International Journal of Tropical Insect Science* 30: 221–231, <https://doi.org/10.1017/S1742758410000342>
- Nyamukondiwa C, Machekano H, Chidawanyika F, Mutamiswa R, Ma G, Ma CS (2022) Geographic dispersion of invasive crop pests: the role of basal, plastic climate stress tolerance and other complementary traits in the tropics. *Current Opinion in Insect Science* 50: 100878, <https://doi.org/10.1016/j.cois.2022.100878>
- Oppert B, Muszewska A, Steczkiewicz K, Šatović-Vukšić E, Plohl M, Fabrick JA, Vinokurov KS, Koloniuk I, Johnston JS, Smith TPL, Guedes RNC, Terra WR, Ferreira C, Dias RO, Chaply KA, Elpidina EN, Tereshchenkova VF, Mitchell RF, Jenson AJ, Campbell JF (2022) The Genome of *Rhyzopertha dominica* (Fab.) (Coleoptera: Bostrichidae): Adaptation for Success. *Genes* 13: 446, <https://doi.org/10.3390/genes13030446>
- Osipitan AA, Omotola M, Popoola KOK (2012) Evaluation of Infestation and damage by The Larger Grain Borer (*Prostephanus truncatus*) (Horn) (Coleoptera: Bostrichidae) on Selected Food Grain Crops. *Journal of Agricultural Science and Environment* 12: 15–25
- Perrings C, Dehnen-Schmutz K, Touza J, Williamson, M (2005) How to manage biological invasions under globalization. *Trends in Ecology & Evolution* 20: 212–215 <https://doi.org/10.1016/j.tree.2005.02.011>
- Quellhorst H, Athanassiou CG, Zhu KY, Morrison WR (2021) The biology, ecology and management of the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Journal of Stored Products Research* 94: 101860, <https://doi.org/10.1016/j.jspr.2021.101860>
- Rumbos CI, Dutton AC, Athanassiou CG (2013) Comparison of two pirimiphos-methyl formulations against major stored-product insect species. *Journal of Stored Products Research* 55: 106–115, <https://doi.org/10.1016/j.jspr.2013.08.003>
- Rurinda J, Mapfumo P, Wijk MT Van, Mtambanengwe F, Rufino MC (2014) Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. *European Journal of Agronomy* 55: 29–41, <https://doi.org/10.1016/j.eja.2013.12.009>
- Seebens H, Essl F, Dawson W, Fuentes N, Moser D, Pergl J, Pyšek P, van Kleunen M, Weber E, Winter M, Blasius B (2015) Global trade will accelerate plant invasions in emerging economies under climate change. *Global Change Biology* 21: 4128–4140, <https://doi.org/10.1111/gcb.13021>
- Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Essl F (2017) No saturation in the accumulation of alien species worldwide. *Nature Communications* 8: 14435, <https://doi.org/10.1038/ncomms14435>
- Shires SW (1977) Ability of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) to damage and breed on several stored food commodities. *Journal of Stored Products Research* 13: 205–208, [https://doi.org/10.1016/0022-474X\(77\)90030-3](https://doi.org/10.1016/0022-474X(77)90030-3)
- Shires SW, McCarthy S (1976) A character for sexing live adults of *Prostephanus truncatus* (Horn) (Bostrichidae, Coleoptera). *Journal of Stored Products Research* 12: 273–275, [https://doi.org/10.1016/0022-474X\(76\)90044-8](https://doi.org/10.1016/0022-474X(76)90044-8)
- Singano CD, Mvumi BM, Stathers TE, Machekano H, Nyamukondiwa C (2020) What does global warming mean for stored-grain protection? Options for *Prostephanus truncatus* (Horn) control at increased temperatures. *Journal of Stored Products Research* 85: 101532, <https://doi.org/10.1016/j.jspr.2019.101532>
- Sire L, Gey D, Debruyne R, Noblecourt T, Soldati F, Barnouin T, Rougerie R (2019) The challenge of DNA barcoding saproxylic beetles in natural history collections—exploring the potential of parallel multiplex sequencing with Illumina MiSeq. *Frontiers in Ecology and Evolution* 7: 495, <https://doi.org/10.3389/fevo.2019.00495>
- Skendžić S, Zovko M, Živković IP, Lešić V, Lemić D (2021) The impact of climate change on agricultural insect pests. *Insects* 12: 440, <https://doi.org/10.3390/insects12050440>

- Spilman TJ (1983) Identification of larvae and pupae of the larger grain borer, *Prostephanus truncatus* (Coleoptera: Bostrychidae), and the larger black flour beetle, *Cynaesus angustus* (Coleoptera: Tenebrionidae). In: Mills RB, Wright VF, Pedersen JR, McGaughey WH, Beeman RW, Kramer KJ, Speirs RD, Storey CL (eds), Proceedings of the 3<sup>rd</sup> International Working Conference on Stored-Product Entomology. Manhattan, Kansas, USA, October 23–28, 1983, Kansas State University, USA, pp 23–28
- Stathers T, Holcroft D, Kitinoja L, Mvumi BM, English A, Omotilewa O, Kocher M, Ault J, Torero M (2020) A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. *Nature Sustainability* 3: 821–835, <https://doi.org/10.1038/s41893-020-00622-1>
- Stathers TE, Mvumi BM, Golob P (2002) Field assessment of the efficacy and persistence of diatomaceous earths in protecting stored grain on small-scale farms in Zimbabwe. *Crop protection* 21: 1033–1048, [https://doi.org/10.1016/S0261-2194\(02\)00088-1](https://doi.org/10.1016/S0261-2194(02)00088-1)
- Stiller J, Short G, Hamilton H, Saarman N, Longo S, Wainwright P, Rouse GW, Simison WB (2022) Phylogenomic analysis of Syngnathidae reveals novel relationships, origins of endemic diversity and variable diversification rates. *BMC Biology* 20: 75, <https://doi.org/10.1186/s12915-022-01271-w>
- Suma P, Russo A (2005) On the presence of *Prostephanus truncatus* (Horn) (Coleoptera Bostrychidae) in Italy. *Bollettino di Zoologia agraria e di Bachicoltura, Serie II* 37(2): 135–139
- Tamura K, Stecher G, Kumar S (2021) MEGA11: molecular evolutionary genetics analysis version 11. *Molecular Biology and Evolution* 38: 3022–3027, <https://doi.org/10.1093/molbev/msab120>
- Tefera T, Kanampiu F, De Groote H, Hellin J, Mugo S, Kimenju S, Beyene Y, Boddupalli, PM, Shiferaw B, Banziger M (2011) The metal silo: An effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries. *Crop Protection* 30: 240–245, <https://doi.org/10.1016/j.cropro.2010.11.015>
- Teske PR, Beheregaray LB (2009) Evolution of seahorses' upright posture was linked to Oligocene expansion of seagrass habitats. *Biology Letters* 5: 521–523, <https://doi.org/10.1098/rsbl.2009.0152>

### Web sites, online databases and software

- Morey A (2023) *Prostephanus truncatus* (larger grain borer). CABI digital library. <https://www.cabidigitallibrary.org/doi/pdf/10.1079/cabicompendium.44524> (accessed 19 June 2023)