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ORIGINAL PAPER

Monitoring a polyphagous shot hole borer infestation in an urban forest using Google street view in the City of Johannesburg, South Africa

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Abstract The Polyphagous shot hole borer (PSHB) (*Euwallacea fornicatus*) is attacking native and exotic street trees in Johannesburg's urban forest causing a disease called Fusarium dieback (FD), and the date of introduction of PSHB is not known. The novelty of using Google street view (GSV) for pest monitoring in an urban setting includes easy identification and detection of invasive pests on trees, cost effectiveness and time efficiency compared to traditional methods. The efficacy of using GSV imagery to map and monitor the spread of PSHB-FD infestation on trees in the City of Johannesburg (CoJ) was therefore evaluated. A total of 1137 trees were surveyed using GSV for PSHB-FD infestation on images from 2010 to 2022. The field survey and GSV methods showed good agreement in classifying PSHB-FD infestation on two *Platanus* species. Finally, GSV is species specific and is only applicable for certain tree species such as *Platanus x acerifolia*, *Platanus racemosa* and *Acer buergerianum* where symptoms of infestation are visible in GSV images. Findings from this study showed that PSHB-FD infestation was present in the CoJ in 2017, indicating the importance of the method in effectively tracing back the actual date of the first infestation in the city. GSV also proved to be a useful method for mapping and monitoring PSHB-FD infestation on sentinel *Platanus* trees in Johannesburg, suggesting that it could serve as a viable alternative to field surveys.

Keywords *Platanus racemosa* · Invasive pest · *Platanus x acerifolia* · Street survey · *Acer buergerianum*

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Introduction

The spread of invasive pests worldwide is a major threat to tree survival and the cause of economic loss (Eskalen et al. 2013; Paap et al. 2018). In urban areas, tree diversity can be high (Branco et al. 2019), and high species richness promotes greater host availability for invasive pests (Augustinus et al. 2024). The proliferation and spread of invasive tree pests require

an understanding of their present and past distribution patterns. Additionally, invasion pathways have been attributed to various factors including global trade (Wilson et al. 2009), human aided pathways (such as trade and intentional transportation) (Faulkner and Wilson 2018), intentional introduction, and unaided dispersal (Padayachee et al. 2017). It is important to accurately map the spread of pests for policy formulation and setting management priority areas, as mitigation measures can help reduce their further spread.

The Polyphagous shot hole borer (*Euwallacea fornicatus*) (PSHB) (Curculionidae: Scolytinae) is among many ambrosia beetle species that have been attacking trees worldwide (Eskalen et al. 2012). This invasive pest is native to Southeast Asia (Eskalen et al. 2012), and it has been reported in various regions of the world, including Israel, California, Mexico, Argentina, Palestine, New South Wales and South Africa (Eskalen et al. 2012; Mendel et al. 2012; García-Avila et al. 2016; Paap et al. 2018; Salman et al. 2019; Ceriani-Nakamurakare et al. 2023; Callaghan et al. 2024). Its primary hosts include *Acer negundo*, *Acer buergerianum*, *Platanus x acerifolia*, *Platanus racemosa*, *Quercus robur*, *Quercus suber*, *Persea americana* and *Acacia* spp. (Eskalen et al. 2012; Mendel et al. 2012; Paap et al. 2018; Van Rooyen et al. 2021). The disease caused by PSHB is called Fusarium dieback (FD) (Eskalen et al. 2012), hereafter referred to as PSHB-FD (a combination of the pest and the disease). Paap et al. (2018), first reported PSHB presence in South Africa on *Platanus x acerifolia* in the KwaZulu Natal Province in 2017. Since then, PSHB-FD has been reported in all provinces of South Africa, except Limpopo (Van Rooyen et al. 2021). An unidentified coleopteran specimen was collected in 2012 in Durban (South Africa) (from the Barcode of Life project, BOLD: ACC9773, ETKC270-13) (Stouthamer et al. 2017), with the same haplotype of PSHB reported in 2017 by Paap et al. (2018). This is a clear indication that the beetle might have been present in South Africa for some time but went undetected. It was initially reported in Johannesburg in 2019 on a website (https://www.engineeringnews.co.za/print-version/johannesburg-seeks-to-avert-ecological-disaster-from-beetle-infested-trees-2019-11-12), and PSHB was reported on *P. x acerifolia* in Somerset West, Western Cape Province in April 2019 (L.J. Potgieter, pers. Comm.; FABI 2020), leading to the conclusion that the PSHB had already spread to various parts of South Africa by the time it was first formally reported in 2017.

The PSHB attacks a variety of trees in urban areas, on agricultural commercial farms, and several native species (Paap et al. 2018; Van Rooyen et al. 2021; Potgieter et al. 2024). In South Africa, PSHB infestation has been confirmed in 130 plant species across urban environments, agricultural and native forests (Paap et al. 2018; Potgieter et al. 2024). A variety of hosts have been reported for PSHB, including non-reproductive hosts (trees that PSHB occasionally attacks but can't complete its lifecycle in) and reproductive hosts (trees that PSHB attacks and can complete its lifecycle in) (Eskalen et al. 2013; Mendel et al. 2021; Van Rooyen et al. 2021). De Wit et al. (2022) projected that the combined impact of PSHB and *Fusarium euwallaceae* (its symbiotic fungus), will cause a 3.5% -15.5% decline in tree populations over a 10-year period. The impact projections for South Africa are estimates. The impacts of PSHB are expected to be confined urban trees, natural forests, commercial forestry and avocado the industry (De Wit et al. 2022). The estimated cost of removing urban trees that die from PSHB infestation is projected to reach $18.45 billion (De Wit et al. 2022). Mapping trees is therefore essential for managing the spread and damage caused by this invasive pest. Potential management strategies could focus on managing reproductive hosts or ''amplifier trees'', as well as removing heavily infested hosts. Therefore, it is crucial to combine field surveys with geospatial technology like Google street view (GSV) to accurately map trees attacked by the PSHB, thereby providing essential information on its spread to aid forest management efforts in Johannesburg.

The exact dispersal pathway of PSHB to Johannesburg from the known KwaZulu-Natal (KZN) infestation remain unknown, but it is plausible that human-aided dispersal played a role. Faulkner and Wilson (2018) noted that alien taxa are traded and intentionally transported to all parts of South Africa and sometimes deliberately introduced to new areas, but PSHB certainly won't be traded, or intentionally introduced as it has no commercial value. Nevertheless, trade in other materials may be one of the factors contributing to the introduction of PSHB into Johannesburg, despite the significant distance of approximately 500km from the KZN region where the first infestation was reported. The movement of infested

wood (firewood) could be a pathway for PSHB spread across various parts of the country (Van Rooyen et al. 2021). Currently, the Johannesburg City Parks and Zoo (JCPZ) is removing infested wood, however the transportation of dead wood from the infested areas to disposal sites may contribute to the further spread of PSHB-FD within Johannesburg. Another factor that may contribute to the spread of the pest is the haplodiploid mating system of PSHB, which can facilitate the establishment of new populations from low initial population numbers (Van Rooyen et al. 2021; Bierman et al. 2022). The low genetic variability observed within the country supports the notion that the beetle's invasion may have originated from a small initial population (Bierman et al. 2022). Trade between South Africa and Asian countries, such as Vietnam and China, is another possible route of entry, as it has been confirmed that the *E. fornicatus* found in South Africa is the same as that found in Vietnam (Bierman et al. 2022).

Google street view (GSV) imagery is a free-of-charge geospatial platform that provides ground-based photographs of urban streets (Berland and Lange 2017; Kotowska et al. 2021). The application of GSV is reported in several studies including, *inter alia*, quantifying and mapping urban trees (Seiferling et al. 2017) and ecological studies (Rousselet et al. 2013; Kagan et al. 2021). For instance a GSV survey was used to record street trees in Thailand and the findings showed a high level of agreement in genus and species identification with field data (Meunpong et al. 2019). Ulus et al. (2021) successfully mapped *Ailanthus altissima* (an invasive species) along the streets of Istanbul (Turkey) using GSV, finding that it was a dominant species although not intentionally planted as street tree. A recent study by Liang et al. (2023) used GSV data from four African cities, Kampala (Uganda), Nairobi (Kenya), Bloemfontein and Johannesburg (South Africa) to evaluate street tree characteristics, like size, tree floristic composition, tree health, streetside development and geolocation. Their findings proved that GSV was an effective method for monitoring urban forests in Africa providing valuable information for planning purposes and management. Elsewhere, a study by Rousselet et al. (2013) explored GSV imagery to map the occurrence of pine processionary moth (*Thaumetopoea pityocampa)* in the streets of Orleans, France, and achieved an accuracy level of 96% for matching GSV data with field data. Kagan et al. (2021) used deep learning algorithms and GSV imagery to map red palm weevil (*Rhynchophorus ferrugineus* and *R. vulneratus*) infestations on palm trees in Miami, USA.

This research seeks to provide visual method for monitoring the presence and spread of the PSHB-FD infestation over time in Johannesburg. The potential of using GSV imagery to detect and map trees infested by PSHB-FD on urban streets in Johannesburg has not been explored before. When the adult female burrows into a tree, it leaves a small hole (0.8 mm diameter) that then, depending on the species of the tree, oozes sap, or frass, leaving large (roughly the size of a fingernail) stains on the bark. Thus, it is useful to evaluate the use of GSV imagery to examine signs of the infestation on street trees. This study marks a first attempt to monitor PSHB-FD infestation in Johannesburg by using freely available GSV imagery. In addition, no time series study has been conducted before, to trace back in time to when the infestation appeared on trees in Johannesburg. However, the effectiveness and accuracy of this method depends on the quality and coverage of GSV imagery for the study area and the observer's ability to accurately identify PSHB infestation signs in the available images. We explored the applicability of GSV images to detect when PSHB-FD infestation appeared on *P. x acerifolia* and some other vulnerable trees in Johannesburg, by visually surveying GSV images from 2010 to 2022. Therefore, the GSV survey was tested by comparison with field data collected by a researcher from the University of the Witwatersrand, hereafter referred as 'Wits researcher'. We hypothesized that there is no significant difference in PSHB-FD infestation detection between GSV and field survey method. The objectives of this study were;

1. To determine presence or absence of PSHB-FD infestation on trees in Johannesburg.
2. To determine the accuracy of field surveys *vs*. the GSV sampling method for PSHB-FD infestation detection on trees in Johannesburg.
3. To determine the 'terminus post quem' or the earliest date on which the event (introduction of PSHB-FD to Johannesburg) must have occurred.

Materials and methods

Study area

The study was conducted in the City of Johannesburg (CoJ) located in Gauteng Province of South Africa. The CoJ is divided into seven administrative regions namely: A (313.32 km^2), B (149.05 km^2), C (256.17 km^2), D (186.55 km^2), E (198.53 km^2), F (368 km^2), and G (219.20 km^2) (Fig. 1). Some of the trees found in the CoJ include *P. x acerifolia*, *Quercus* species, *Eucalyptus* species, *Jacaranda mimosifolia* and *Celtis africana* (Abutaleb et al. 2021). This study area was chosen because it has many *P. x acerifolia* trees, which are susceptible to PSHB attack. The *P. x acerifolia* is currently treated as sentinel species for monitoring PSHB infestation in South Africa (Paap et al. 2018).

Field data collection

Ground truthing data of *P. x acerifolia* and other potential host trees of PSHB were collected by a researcher from the University of the Witwatersrand during spring and early summer 2022 (September to December 2022) (Fig. 1). The suburbs which were surveyed include Lonehill, Noordwyk, Carlswald, Midridge Park and Kyalami Estate (region A); Greenside, Rosebank, Melville, Northcliff, Emmarentia, Parktown North, Saxonwold and Parkwood (region B), Weltevredenpark, Strubens Valley, Noordekrans, Randpark Ridge and Florida Park (region C); Soweto,

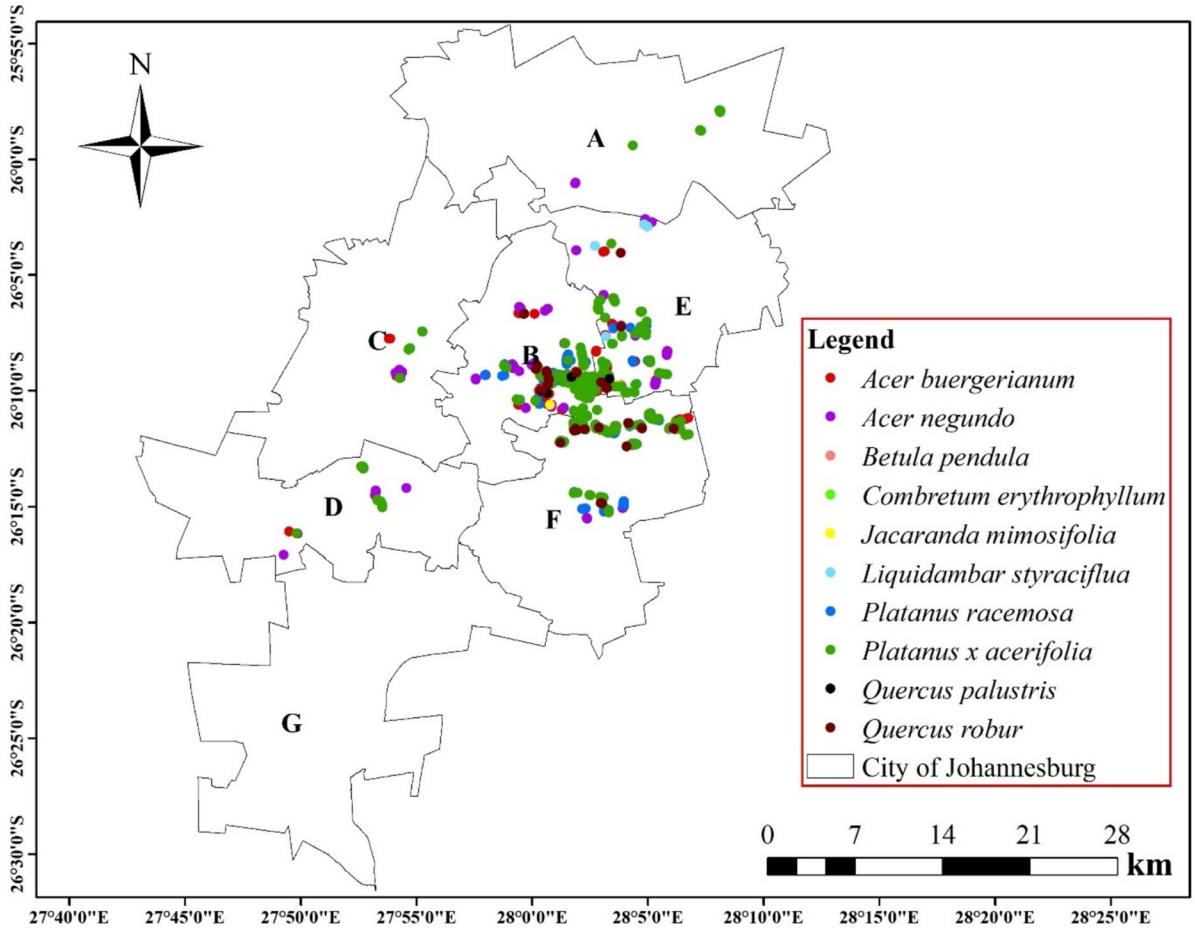


Fig. 1 Map of the City of Johannesburg (CoJ), situated in the Gauteng province of South Africa showing the seven administrative regions, and all of the georeferenced trees (n = 1137) that were surveyed for Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) infestation using field data of 2022 and Google street view (GSV) images of 2022

Protea Glen, Protea North, Orlando West, Mofolo Central and Meadowlands West Zone 10 (region D); Bramley, Wynberg, Orange Grove, Houghton Estate, Melrose Estate, Highlands North (region E); Rosettenville, Turffontein, Kensington, Jeppestown, Mayfair, Braamfontein Parktown and Bezuidenhout Valley (region F). These suburbs were surveyed based on evidence of PSHB-FD presence on host species as reported by Johannesburg City Parks and Zoo (JCPZ) (A. Chokoe, pers. comm.). The researcher first collected ground truth data of 1137 trees using random sampling, then surveyed the same trees for PSHB-FD infestation using GSV imagery. Random sampling was conducted by selecting trees of the same species occurring on either side of the street in a suburb, ensuring that each tree had an equal chance of being selected. Four species were prioritised due to their prevalence and suitability as hosts. These species included *Acer buergerianum*, *Platanus racemosa*, *P. x acerifolia* and *Acer negundo*. These species were termed target species because they are known reproductive hosts (*A. buergerianum*, *P. x acerifolia* and *A. negundo*) of PSHB in South Africa (Van Rooyen et al. 2021). However, *P. racemosa* is also classified as a reproductive host according to international records (Eskalen et al. 2013; SDMMP Repository-accessed 10 April 2025). A total of 1137 trees were surveyed, comprising target species (n = 942 trees) and non-target species (n = 195 trees).

The species identity, PSHB-FD infestation status (infested or non-infested) and the GPS coordinates were recorded for each tree. The sampling in the 2022 field survey was uneven across the city regions. Sampling in region G was not conducted due to safety concerns. Trees were surveyed for signs of PSHB-FD infestation on both sides of the street. Some trees located in backyards (i.e. private residential property) were excluded from this study. Visual assessment of PSHB entrance/ exit holes was conducted by counting the number of holes inside 315cm^2 quadrant placed at 1.3m above ground level on the North, South, East, and West sides of the trunk of all trees sampled, following a method by Mudede et al. (2024). This approach reduced the chance of missing any signs of the beetle by covering all sides of the trunk. Also, PSHB entrance holes on the main branches and the canopy branches were noted. Any evidence of PSHB activity on the trunk, or the presence of live PSHB on a tree trunk, main branches or canopy branches was considered sufficient to classify a tree as infested. Additionally, other signs of PSHB-FD infestation, included frass (powder-like residue on trunk), oozing (watery substance), gumming and stains around entrance holes were assessed during field survey (Fig. 2).

GSV data sampling

The GSV imagery is freely available online (http://www.google.com/streetview) and can also be accessed from Google Earth™ via this link (https://www.google.com/earth) (Berland and Lange 2017). The available GSV imagery was for about half of the surveyed trees, but not covering all years in the 2010 to 2022 period. These GSV images of the trees surveyed were visually assessed to check for the presence or absence of PSHB-FD infestation signs for each year from 2010 to 2022 (Fig. 2). Time spent viewing GSV images, and the time spent on field data collection was recorded in this study.

A total of 1137 trees was surveyed in GSV images from 2010 to 2022 in the CoJ. Of the 1137 trees, the proportions of the target species were 11.52% (n = 131) (*A. buergerianum*), 13.28% (n = 151) (*P. racemosa*), 48.28% (n = 549) (*P. x acerifolia*), 9.76% (n = 111) (*A. negundo*) and 26.9% (n = 195) (other trees) (Table 1). For the years of 2011, 2012, 2016, 2018, there were no GSV images available. Additionally, there was variation in the seasons surveyed for GSV images between 2010 and 2022 (Table 1). The proportion of surveyed trees that were examined using GSV imagery were: 21.7% (247/1137) in 2010, 82.9% (943/1137) in 2013, 3.5% (40/1137) in 2014, 23.7% (270/1137) in 2015, 40.3% (458/1137) in 2017, 42.0% (477/1137) in 2019, 6.3% (72/1137) in 2020, 37.3% (424/1137) in 2021 and 59.2% (673/1137) in 2022. This provided 1085 exploitable images for the whole period, covering 95.42% (1085/1137) of the surveyed trees.

Trees with no visible signs of PSHB-FD infestation were recorded as non-infested (Fig. 3), while those showing visible signs of PSHB-FD were recorded as infested (Fig. 4). Brown stains caused by the PSHB's activity are the main indicator of PSHB-FD infestation on the tree's trunk, main branches, and canopy branches (Fig. 4). Thus, the key feature of PSHB-FD infestation considered was these stains, particularly as the actual holes are not visible in the

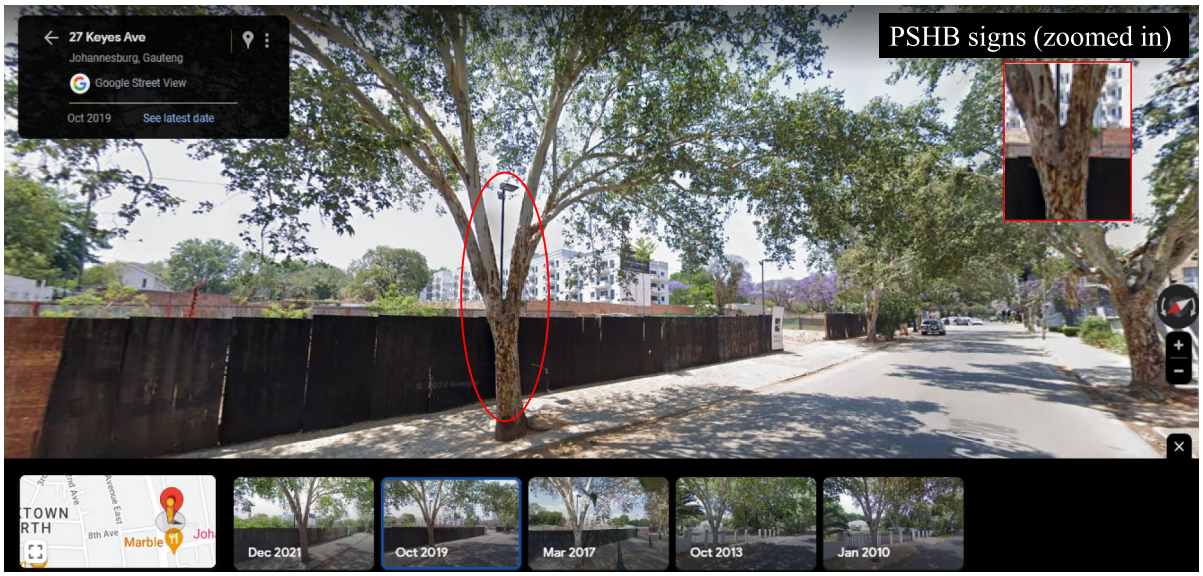


Fig. 2 Google street view (GSV) images from one site showing all available years; Red circle shows PSHB infestation signs (brown stains) on a *Platanus racemosa.* All five years with available GSV images were visually surveyed for Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) infestation status with one click on the tree's latitude and longitude coordinates in Google maps

Table 1 Proportions of trees with Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) infestation from *Acer buergerianum* (*A.b*), *Platanus racemosa* (*P.r*), *Platanus x acerifolia* (*P.xa*), *Acer negundo* (*A.n*) and other tree species [n] located in field surveys in 2022, and retrospectively examined for PSHB infestation symptoms in Google street view (GSV) imagery from 2010 to 2022

	Year	Season	Proportions of trees with PSHB-FD infestation					
			A.b	*P.r*	*P.xa*	*A.n*	Other tree species	% infestation
Field survey	2022*	S, Sp	107/131	121/151	451/549	104/111	66/195	0.75
GSV imagery	2010	W, Sp, S	0/12	0/27	0/162	0/24	0/22	0
	2013	W, Sp, S	0/96	0/138	0/464	0/80	0/165	0
	2014	Sp, S	0/13	0/2	0/12	0/13	0/0	0
	2015	A, S	0/21	0/39	0/173	0/4	0/33	0
	2017	A, S	0/37	0/39	23/262	0/40	0/80	0.05
	2019	Sp	0/58	36/69	77/171	0/51	0/128	0.24
	2020	A, S	0/11	12/13	37/45	0/3	0/0	0.68
	2021	A, Sp, S	0/55	70/73	205/231	0/29	0/36	0.65
	2022*	A, W, Sp, S	1/64	51/56	280/352	0/49	0/152	0.49

GSV imagery was not available for any trees in 2011, 2012, 2016 and 2018, and for a variable number of target trees in 2010, 2013, 2014, 2015, 2017, 2019, 2020, 2021 and 2022

A autumn, *S* summer, *Sp* spring, *W* winter

*Datasets used for detection agreement analysis

images. To access GSV imagery on Google Maps, the orange pegman icon was dragged using a mouse onto a georeferenced location of a tree and then used to navigate to the road level imagery. To view available dates of imagery, "see latest dates" was used (Fig. 2). For further details of how to navigate and visually survey streets on google street view imagery, see the link (http://maps.google.es/support/bin/answer.py?).

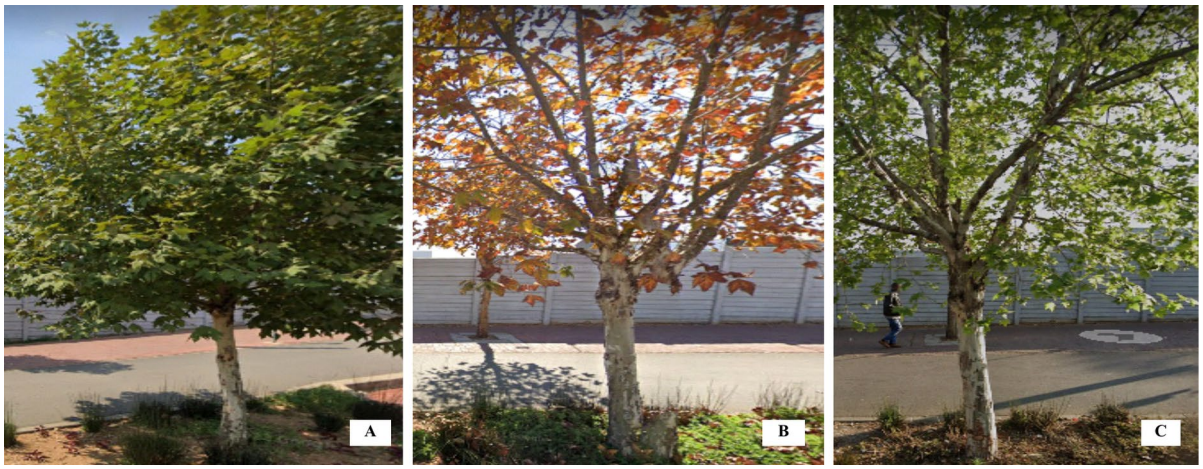


Fig. 3 Google street view (GSV) images showing a non-infested *Platanus x acerifolia* (A, B, C) in 2020, 2021 and 2022 respectively. No signs of stains from Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) can be seen in any of the three images



Fig. 4 Google street view (GSV) images showing a *Platanus racemosa* with no Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) infestation signs in 2013 (**A**), but subsequently infested in 2019 (**B**) and 2021 (**C**). The signs of PSHB-FD infestation are indicated by brown stains on trunk, and main branches circled in red on the images

Detection agreement analysis

The agreement between the field survey and GSV methods regarding PSHB-FD infestation status for the four target species surveyed in 2022 (n = 521) was assessed using the metrics sensitivity, kappa coefficient and accuracy as described by Rousselet et al. (2013). The four target species considered for accuracy assessment included both non-reproductive and reproductive hosts of PSHB and had more than 40 GSV images available in 2022. The 521 trees selected were based on the number of available GSV images, and the same GPS coordinates from the field survey dataset to avoid bias. All other species were grouped

under 'other tree species' for analysis purpose. The PSHB-FD infestation status produced four possible outcomes: TP (true positive), TN (true negative), FP (false positive) and FN (false negative), which were computed in a confusion matrix. The TP indicates presence of PSHB-FD infestation in both field surveys and GSV imagery; TN corresponds to absence of PSHB infestation in both field surveys and GSV imagery; FP represent absence of PSHB infestation in field surveys but the presence of it in GSV imagery and FN corresponds to the presence of PSHB-FD infestation in field survey but the absence of it in GSV imagery. Sensitivity and specificity were calculated as TP/P and TN/N, P and N indicate the total number of positives and negatives, respectively (Rousselet et al. 2013). The kappa coefficient is a mathematical measure that quantifies level of agreement between two raters (Cohen 1960). The kappa values range from −1 to +1. The results of kappa were interpreted following the method by McHugh (2012). Detection Agreement Analysis was performed at 5% level of significance in R software (R Core Team 2018), and a confusion matrix was computed using "*irr*" package.

Spread analysis

The number of available images showing signs of PSHB-FD infestation for each of the three target species in a given year was divided by the total number of GSV images (including both non-infested and infested trees) to calculate the percentage of infestation. The three species—*A. buergerianum*, *P. racemosa* and *P. x acerifolia* were selected as they exhibited signs of PSHB-FD in both GSV imagery and the field survey.

Results

Field monitoring and GSV imagery detection

There were 32 tree species available in 2022 GSV images (n = 673). Only three species, namely *A. buergerianum*, *P. racemosa* and *P. x acerifolia* showed signs of PSHB-FD infestation in both GSV imagery and the field survey data (Table 1). *P. x acerifolia* showed PSHB infestation symptoms on 280 trees (79.5%) in 2022. *P. x acerifolia* exhibited PSHB-FD infestation signs in the 2017, 2019, 2020, 2021 and 2022 GSV images (Fig. 5). *P. racemosa* first showed signs of PSHB-FD infestation in 2019 (Fig. 5). Nevertheless, *P. racemosa* had 51 trees (91.1%) showing PSHB-FD infestation signs in 2022. *A. buergerianum* showed evidence of PSHB signs on only one tree in the 2022 GSV images (Fig. 5). However, *A. negundo* had none detected as infested in the GSV imagery. Furthermore, none of the other species (n = 195 images) were detected as infested by PSHB between 2010 and 2022.

Detection agreement analysis

There were no false positive cases for any of the species (thus achieving a specificity of 1). *Platanus racemosa* (*P.r.*): Good identification of infested and non-infested trees, though some infested trees were missed.

Platanus x acerifolia (*P.xa.*): Similar to *P.r.*, but fewer trees overall and class imbalance, as there were very few non-infested trees. Field survey and GSV method revealed a good agreement for classifying PSHB-FD infestation on *Platanus* species with smooth bark, as indicated by high accuracies of 0.95 (*P. racemosa*) and 0.97 (*P. x acerifolia*) (Table 2).

Acer buergerianum (*A.b.*) and *Acer negundo* (*A.n.*): The assessor struggled to identify infested

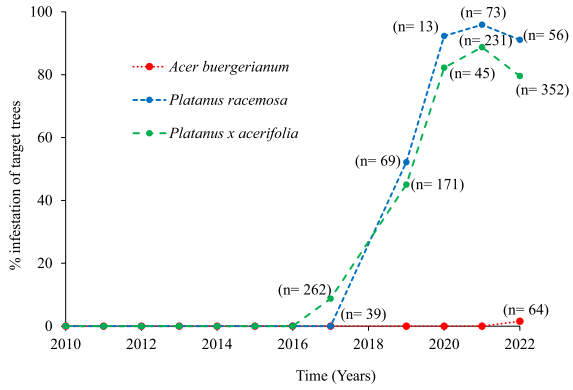


Fig. 5 The three target tree species showing evidence of Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) attack in Google street view (GSV) images surveyed, between 2017 and 2022. Note that there were no signs of PSHB-FD infestation in 2011, 2012, 2016 and 2018 images. The % infestation represents the ratio of the number of GSV images with target trees of that species infested by PSHB-FD to the total number of available GSV images of that tree species for a given year (n)

Table 2 Confusion matrix for comparing field survey and Google street view (GSV) method for classifying Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) infestation on 521 trees: *Acer buergerianum* (*A.b*), *Platanus racemosa* (*P.r*), *Platanus x acerifolia* (*P.xa*) and *Acer negundo* (*A.n*) surveyed in 2022; 0- non-infested and 1- infested

		Field survey							
		A.b		*P.r*		*P.xa*		*A.n*	
		0	1	0	1	0	1	0	1
GSV	0	TN = 8	FN = 55	TN = 2	FN = 3	TN = 62	FN = 12	TN = 2	FN = 47
	1	FP = 0	TP = 1	FP = 0	TP = 51	FP = 0	TP = 280	FP = 0	TP = 0
Specificity		1		1		1		1	
Sensitivity		0.02		0.94		0.96		0	
Kappa		0		0.55		0.89		0	
Accuracy		0.14		0.95		0.97		0.04	

trees, resulting in most of the trees being misclassified as non-infested (false negatives), leading to poor sensitivity for these two species. GSV method is not applicable to *Acer* species, as revealed by the low accuracy and no agreement with field survey (kappa = 0) (Table 2).

Spread analysis

The spread of PSHB-FD infestation through the CoJ indicated an uneven progression. Regions B and E showed the first evidence of PSHB-FD in 2017 (Fig. 6). There was no GSV survey done in 2018, and it took five years for the PSHB-FD to be detected in regions A and C even though images of *P. x acerifolia* and *P. racemosa* were available for 2019, 2020, 2021 and 2022 in these regions (Fig. 6). For region F, it took two years for PSHB-FD infestation to appear in GSV imagery. No PSHB-FD infestation was detected in region D (Fig. 6). Surveying PSHB-FD infestation symptoms using GSV images took seven days, compared to the 60 days spent on field survey data.

Discussion

GSV imagery as a valuable method for detecting PSHB-FD infestation

The decline in the percentage of PSHB-FD infestation detected by GSV on *P. racemosa* and *P. x acerifolia* in 2022 could be attributed to disappearance of some stains on the bark, rendering them not visible on GSV images. This might also be a result of GSV images being surveyed in new areas during the same year, and these areas could have been dominated by non-infested trees. Some tree species may be able to recover in certain cases for example some *P. x acerifolia* and *Quercus robur* have shown some signs of recovery following attack by PSHB. It is interesting to note that, no *Platanus* species or *A. buergerianum* showed any signs of dying despite being heavily infested. This suggests that the trees can survive for more than five years. Reproductive hosts of PSHB have been shown to exhibit varying levels of *F. euwallaceae* establishment (Mendel et al. 2017). For instance, reproduction of PSHB in *Q. robur* mainly occurs in large branches. Additionally, *A. negundo* has been observed to die within 1 year following attack, with most signs of attack occurring on the trunk and the main branches, leading to mortality due to reduced water movement in the xylem (Mendel et al. 2017). Therefore, host and susceptible trees differ in their response to PSHB attack. *Q. robur*, *Q. palustris* and *J. mimosifolia* have large trunks that could potentially allow for better visual inspection on GSV imagery. However, we were unable to detect any evidence of PSHB-FD infestation. The bark of these trees is not as smooth as the *Platanus* spp., making PSHB visibility more difficult in GSV imagery. *Betula pendula* has a silvery-white bark that might have facilitated PSHB-FD infestation detection through GSV, however most of the individuals encountered had small trunk circumferences. Consequently, GSV imagery proved effective for identifying *Platanus* species,

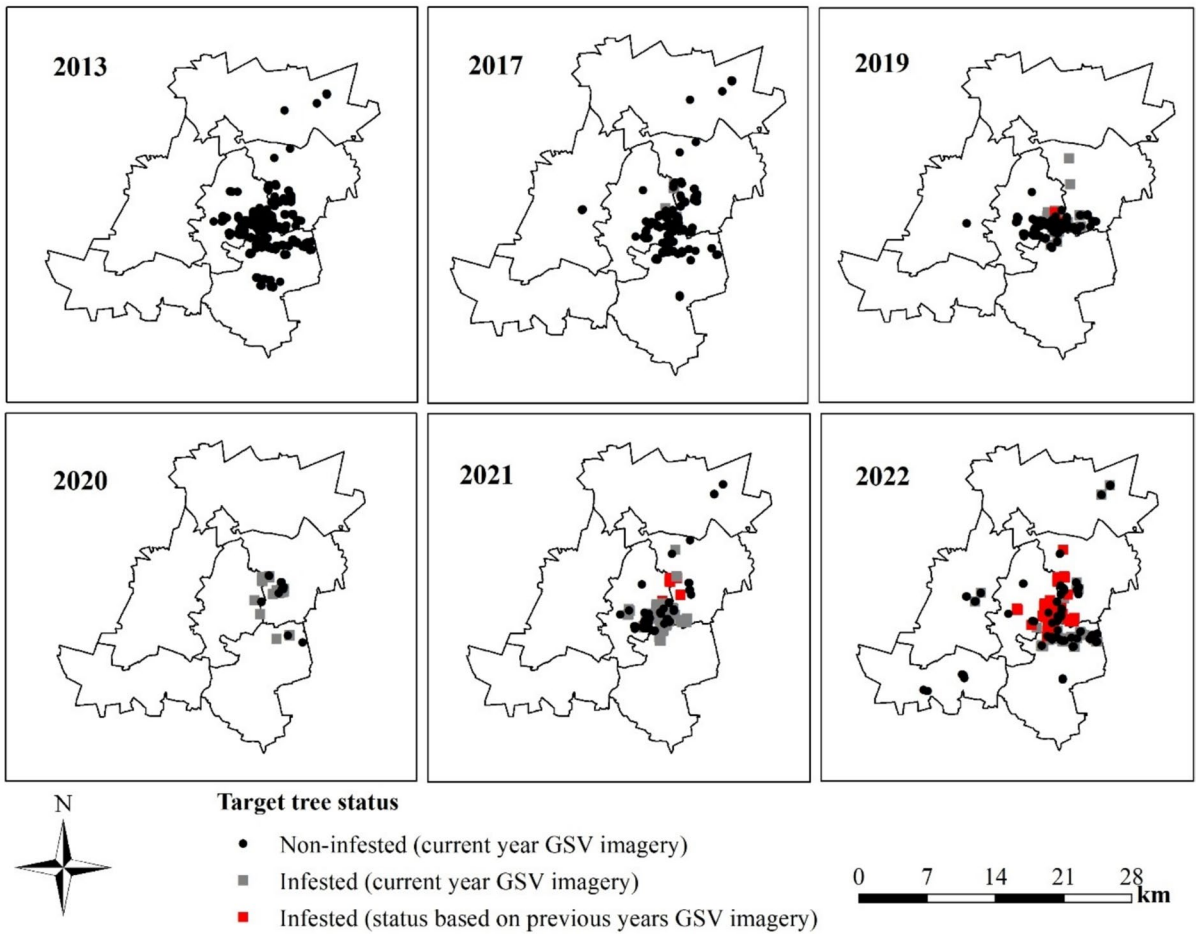


Fig. 6 Polyphagous shot hole borer-Fusarium dieback (PSHB-FD) infestation, year of first detection across regions of the City of Johannesburg (CoJ)

but failed to detect infested *Acer* species and other host species.

Accuracy of GSV in comparison to field surveys for detecting PSHB-FD infestation

The GSV surveys provide strong evidence for the presence of PSHB-FD in CoJ well before it was officially reported or detected. Additionally, GSV can serve as a supplementary tool for managing and monitoring the spread of invasive pests along urban streets. This highlights one of the strengths of using GSV, to track back in time to see changes at fixed locations (Li et al. 2015; Kagan et al. 2021). This study showed that GSV is cost effective and time efficient taking just seven days to cover 1137 trees compared to 60 days for the field survey method with an R3200.00 estimated cost of petrol. Barone et al. (2021) showed that GSV saves time, taking only 35 h to perform 2350 surveys of alien invasive plants along Italian road networks. Olea and Mateo-Tomás (2013) took less time and only 50% of the money required to conduct field work on vulture nesting habits on cliffs using a GSV survey. Pardo-Primoy and Fagúndez (2019) also found that GSV reduced costs by five times while saving time compared to a field survey of *Cortaderia selloana* (perennial alien grass) in Galacia (NorthWest Spain). Thus, GSV imagery can supplement field survey data for detecting PSHB infestation on trees, which can assist managers in saving money on field surveys, as this task can be accomplished remotely from a desk. Findings from this study

showed that there were no false positives for any of the four species, which could be attributed to the caution exercised by the assessor in assigning infested tree status. Additionally, most of the GSV imagery coverage was prevalent in the streets of regions B, E and F of CoJ where *Platanus* species were most common. This resulted in a higher likelihood of detecting any infestations. Thus, the higher the density of GSV imagery coverage, the greater the chance of encountering false positives. The high number of true positives for *P. racemosa and P. x acerifolia* resulted in high sensitivity for these two species, which could be attributed to their ease of identification and the availability of clear GSV images. It is worth noting that this finding showed the reverse trend for *Acer* species.

GSV surveys can be conducted at any time of the year without concern for seasons or weather conditions if suitable images are available (Berland and Lange 2017; Liang et al. 2023). GSV can be used to identify large individual trees at the genus and species level (Berland and Lange 2017) because some trees have more leaves and clearer bark characteristics which are sometimes captured in GSV image (Meunpong et al. 2019). This could have made it easier to identify trees infested by PSHB-FD in GSV images because *Platanus* trees have pale smooth bark on which the pest' activity causes brown stains.

GSV images are often taken in different seasons of the year (Li et al. 2015; Capecchi et al. 2023). PSHB-FD stains were visible on plane trees on the main trunk, the main branches, and the canopy branches for all GSV images across all available seasons. Our study found that 88.9% of the GSV imaging was conducted during the summer season over the nine years with available GSV images. Seasonal variation in captured GSV images in different years was uneven in space and time. Deus et al. (2016) monitoring the distribution of *Eucalyptus globulus* on roadsides using GSV imagery showed that season can affect GSV image quality when lacking adequate light, especially in the shadows from buildings or other obstacles. However, Kotowska et al. (2021) mapping golden rods (*Solidago canadensis* and *S. gigantea*) and Rousselet et al. (2013) mapping the seasonal occurrence of pine processionary moth (*Thaumetopoea pityocampa)* showed that the availability of GSV images in different seasons of the year had no significant effect. Nevertheless, different seasons can result in variation in the appearance of some species.

Ability to estimate the first urban trees attacked by PSHB-FD using GSV imagery

This study demonstrated that GSV is a viable method for monitoring PSHB-FD infestations in Johannesburg's urban forest, detecting infestations on *P. x acerifolia* (and later *P. racemosa*) from 2017 onwards. This finding agrees with Paap et al. (2018) who first detected PSHB in 2017 on *P. x acerifolia* in the KwaZulu-Natal Province, at the National Botanical Gardens, Pietermaritzburg, South Africa. GSV imagery proved sufficient to track the PSHB-FD infestation and its spread across various regions of the CoJ, of which the first evidence was seen in 2017, in regions B and E.

Historical GSV imagery might not be available for every place that has street view, and this was evident for 2011, 2012, 2016 and 2018, which could not be surveyed for any signs of PSHB infestation because GSV didn't run in those years. The period from 2010 to 2016 revealed no evidence of PSHB-FD attack on GSV images from Johannesburg. GSV imagery started from 2007 (Li et al. 2017; Seiferling et al. 2017; Biljecki and Ito 2021), when the major cities in North America were first mapped (Kotowska et al. 2021). The images can only be used retrospectively, whereas remote sensing technologies using drones/planes may provide a more targeted approach. There are some limitations of the technology: the imagery is infrequently updated (i.e. potentially only 1/year) and if trees are in backyards/blocked by vehicles they will be missed. Additionally, GSV may only be suitable for specific host-pest combinations (e.g. symptoms/signs easy to see on host at any time of year) like on *P. x acerifolia*. Furthermore, GSV may not detect low levels of infestation.

Conclusions

The results have demonstrated that GSV is a valuable tool for mapping and monitoring PSHB-FD infestations, providing a viable alternative to traditional field survey methods. Presently, *P. x acerifolia*, *P. racemosa* and *A. buergerianum* were clearly identified as infested using GSV imagery. The strong agreement between field survey and GSV method ratings for PSHB-FD infestation signs provides a baseline using GSV as a method for monitoring the

spread of PSHB-FD in the CoJ. Successful application of GSV method for urban tree pest assessment is of significance for urban forest management, offering substantial savings in terms of both time and money compared to conventional field survey. It is however species specific and can only work for some tree species and some pests. Therefore, it may be necessary to combine both GSV and field survey to achieve more comprehensive monitoring of PSHB-FD infestation.

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Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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