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Assessing the extent and connectivity of animal burrows using smoke: a practical tool for levee inspections

Heleen Keirsebelik[1], Vana Tsimopoulou[2], Robert Lanzafame[3], Niels Van Putte[4], André Koelewijn[5], Stephan Rikkert[6], Timothy De Kleyn[7] and Jonas Schoelynck[8]

Abstract

This short communication presents a practical tool for assessing the subsurface connectivity of animal burrows. It focuses on its potential for early detection and evaluation of animal-induced damages in levees that can compromise their structure during high water episodes.

Drawing inspiration from fundamental biology research and plumbing leak testing, the technique involves injection of coloured smoke into burrows using smoke bombs. A leaf blower then propels the smoke through the burrow network, enabling the identification of openings and providing insights into subsurface connections.

The technique was systematically tested in various environments and applied to investigate burrow networks of diverse animal species, including crabs, voles, and moles. The results underscore the efficacy of the smoke test as a rapid, non-destructive, and cost-effective approach for detecting interconnected burrow networks.

Keywords

Animal burrows, smoke testing, wildlife monitoring, burrow detection, subsurface, levee inspection, low-cost survey

1 Introduction

Burrowing animals, including insects, crustaceans and mammals, are able to modify the subsurface environment in a profound way. Some of these burrow systems can severely damage the environment, including man-made infrastructure like levees, creating large economic costs (Bayoumi & Meguid, 2011). Levees are an essential component of flood prevention systems in low-lying areas. In various regions worldwide and countries like the Netherlands and Belgium, they protect millions of people against floods, and therefore any damage to them could pose a serious safety risk. Numerous instances of levee failures

[1] heleen.keirsebelik@uantwerpen.be, ECOSPHERE research group; Universiteit Antwerpen, Belgium
[2] v.tsimopoulou@hz.nl, Domain of Technology, Water and Environment, HZ University of Applied Sciences, The Netherlands
[3] r.c.lanzafame@tudelft.nl, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands
[4] niels.vanputte@uantwerpen.be, ECOSPHERE research group; Universiteit Antwerpen, Belgium and iFLUX, Belgium
[5] andre.koelewijn@deltares.nl, Deltares, The Netherlands
[6] stephan.rikkert@deltares.nl, Deltares, The Netherlands
[7] timothy@ifluxsampling.com, iFLUX, Belgium
[8] jonas.schoelynck@uantwerpen.be, ECOSPHERE research group; Universiteit Antwerpen, Belgium

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worldwide have been linked, partly or fully, to the presence of animal burrows (Bayoumi & Meguid, 2011; Taccari, 2015; Tarrant et al., 2018; Tsimopoulou & Koelewijn, 2022). One of the most studied failure mechanisms of levee sections that contain burrows is ‘internal erosion’ or ‘piping’ (Orlandini et al., 2015; Palladino et al., 2020; Saghaee et al., 2016). This occurs when a difference in hydraulic gradient between the river- and landside of the levee causes seepage, which erodes fine soil particles. Other examples include external erosion and an increased risk of shallow slope failure or local overtopping following the collapse of a burrow. Recent experimental research in the Netherlands and Belgium showed how external erosion of levee sections with burrows can accelerate the formation of a breach. Large-scale overflow experiments on levee sections with fox and rabbit holes led to severe erosion of the structure within a considerably short time (Depreiter et al., 2022; Koelewijn et al., 2022). Levee sections with mole burrows failed catastrophically during wave overtopping experiments (Daamen et al., 2023; Van Dijk, 2021).

The abovementioned experimental results have provided strong evidence about the severe impact that animal burrows, even those of small rodents, can have on the structural integrity of levees. This clarifies the need for early detection, assessment of their extent, and correction. Inspecting these subsurface burrows in general can be challenging as many of the methods available are destructive, time consuming or dependent on specialised equipment. Some examples of common methods are creating and excavating (epoxy or cement grout) casts of burrows (e.g., Rudnick et al., 2005; Idsinga, 2022), ground-penetrating-radar (e.g., Allroggen et al., 2019; Di Prinzio et al., 2010) and electrical resistivity tomography (e.g., White et al., 2023). In this study we propose a technique that is based on the injection of smoke in the burrow system to assess the extent of the subsurface cavities. By observing the exit points of the injected smoke, an approximation of the spatial extent of the burrow system can be made. When the burrow system is in a levee, this information can be used for a preliminary assessment of the risk that a burrow system imposes on the structure's integrity.

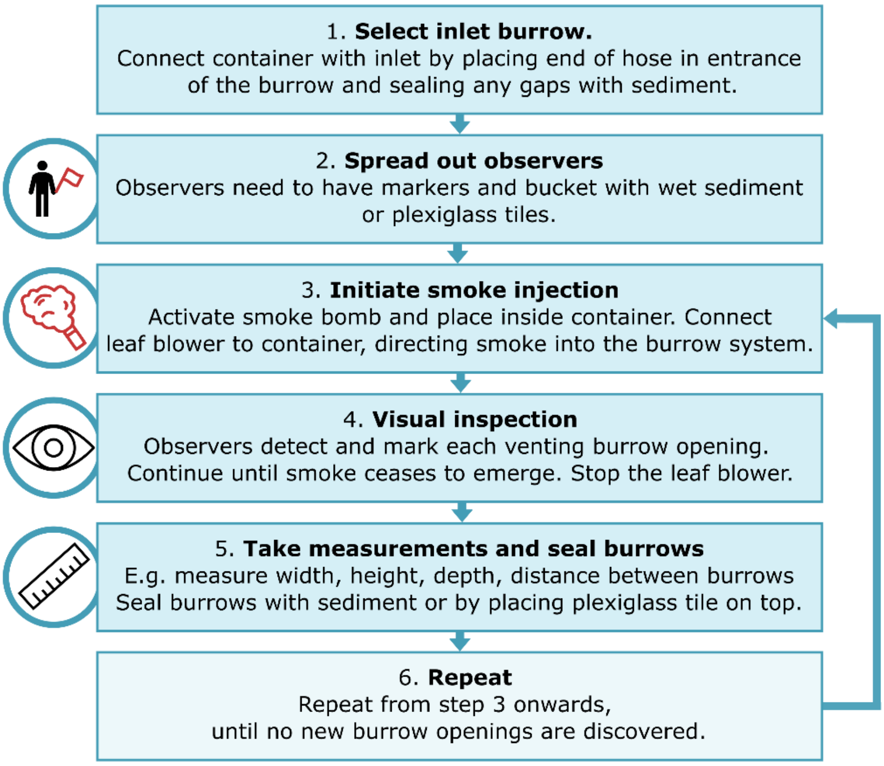
The suitability of smoke for these types of measurements has been demonstrated in the past for (abiotic) pores, crevices and caves (e.g., Nielsen et al., 2015; Petersen et al., 2012). Smoke has also occasionally been described as a method to study the presence of animals or burrows, and the connectivity and functionality of these burrows (e.g., Owings and Borchert, 1975; Shipitalo and Gibbs, 2000; Stoeckel et al., 2021; Stromberg, 1978; Vogel et al., 1973). However, the method itself has not received much attention, nor has its applicability been tested for the inspection of levees.

Identifying potential weak surfaces on a levee is essential for levee safety. Therefore, this study aimed to develop a practical and low-cost approach utilizing smoke for the quick detection of interconnected burrow openings on the surface, signifying the presence of interconnected cavities in the subsurface.

2 Methodology

The extent of animal burrow networks and the interconnectedness between adjacent burrows was estimated with a smoke test in two different case studies. The general concept is based on the leak tests that are used in plumbing and sewer systems. Hands-on descriptions of leak tests using smoke can be found in numerous commercial websites of plumbing companies, but have not been reported in scientific literature.

The smoke of a coloured smoke bomb is injected in the burrow network through a selected burrow opening. Next, the burrows from which the smoke emerges are identified, measured and sealed, after which the test is repeated (Fig. 1). By sealing the burrow openings, pressure builds up in the burrow network during the next test, which helps identify burrows that were not detected during a first test. By repeating the test multiple times, the complete extent of the burrow network can be identified. Starting from a basic setup, this method was tested and further developed in different locations, using different configurations (Fig. 2).



1. **Select inlet burrow.**
Connect container with inlet by placing end of hose in entrance of the burrow and sealing any gaps with sediment.

2. **Spread out observers**
Observers need to have markers and bucket with wet sediment or plexiglass tiles.

3. **Initiate smoke injection**
Activate smoke bomb and place inside container. Connect leaf blower to container, directing smoke into the burrow system.

4. **Visual inspection**
Observers detect and mark each venting burrow opening. Continue until smoke ceases to emerge. Stop the leaf blower.

5. **Take measurements and seal burrows**
E.g. measure width, height, depth, distance between burrows
Seal burrows with sediment or by placing plexiglass tile on top.

6. **Repeat**
Repeat from step 3 onwards,
until no new burrow openings are discovered.

Figure 1: Scheme indicating the different steps of the smoke test with configuration 1 in chronological order.

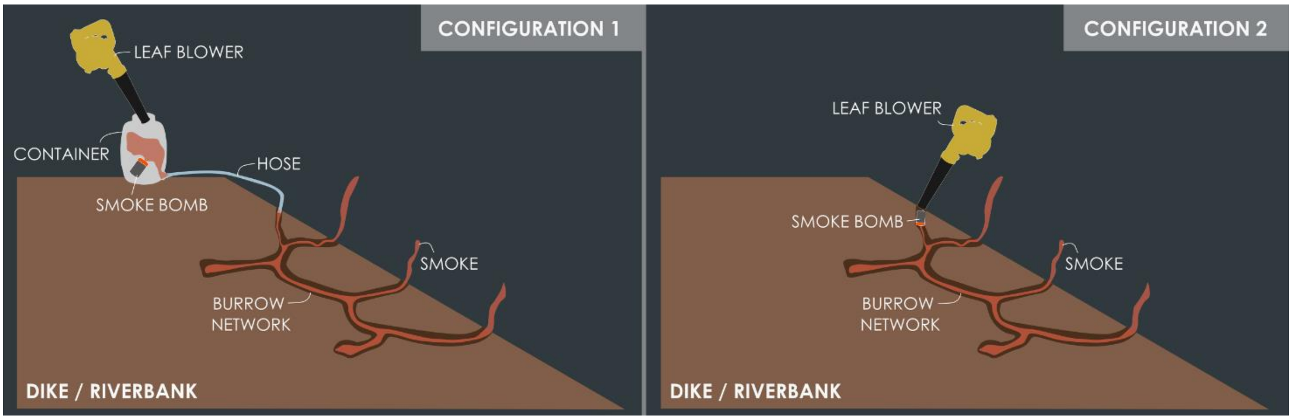


Figure 2: Schematic overview of two configurations of the smoke test setup. Configuration 1 (left) makes use of a container and hose to insert the smoke into the burrow network. In configuration 2 (right) the smoke bomb is placed directly into the burrow network.

2.1 Case study 1: Burrow network of the invasive Chinese mitten crab in a tidal area

2.1.1 Context

Listed as one of the 100 worst invasive species globally, the Chinese mitten crab (*Eriocheir sinensis*) is known to have severe ecological and economic impacts (Dittel & Epifanio, 2009; and references therein). One of the noted impacts originates from its burrowing behaviour in tidal areas. These burrows have been described before (Rudnick et al., 2005), but quantitative data on the subsurface connectivity and spatial extent of the burrow networks is limited. It was hypothesised that intense bioturbation (up to 100 holes/m², based on visual observations by the authors) could have a significant impact on erosion of creek banks (Harvey et al., 2019). On a larger scale, this could affect erosion rates in tidal marshes situated in front of levees, which are of great importance as they constitute nature-based flood protection (Marijnissen et al., 2020; Zhu et al., 2020). The authors thus set out to map and measure the characteristics (morphology, connectivity and spatial extent) of these burrow networks using a smoke test.

2.1.2 Study area

The study was performed in Lippenbroek (51°05'06.0"N, 4°10'17.4"E), a restored tidal area in Hamme, Belgium, along the freshwater part of the Scheldt River (Fig. 3a). Lippenbroek is a former agricultural polder with a total area of 10 ha. The area has a controlled and reduced tidal regime (Cox et al., 2006). Since its restoration in 2006, a loosely packed, macroporous layer of tidally deposited sediment (between 0 and 100 cm in thickness, varying throughout the area), has accreted on top of the old, compact agricultural soil (Van Putte et al., 2020). The smoke tests took place in the banks of the main creek during low tide (Fig. 3b, 4a). The main creek, a former agricultural ditch, intersects both soil layers. The majority of the crab burrows are located within the former agricultural soil layer. Here, the highly cohesive sediment is mainly silt (D50 = 37 ± 15 μm). The creek has a length of 500 m and, within the studied section, is on average 9.1 ± 1.5 m wide, and the banks are on average 2.1 ± 0.4 m high. The slopes of the bank are in general unvegetated, while the top of the bank is vegetated with various marsh plants (e.g., *Phragmites australis*) and willow trees (*Salix species*).

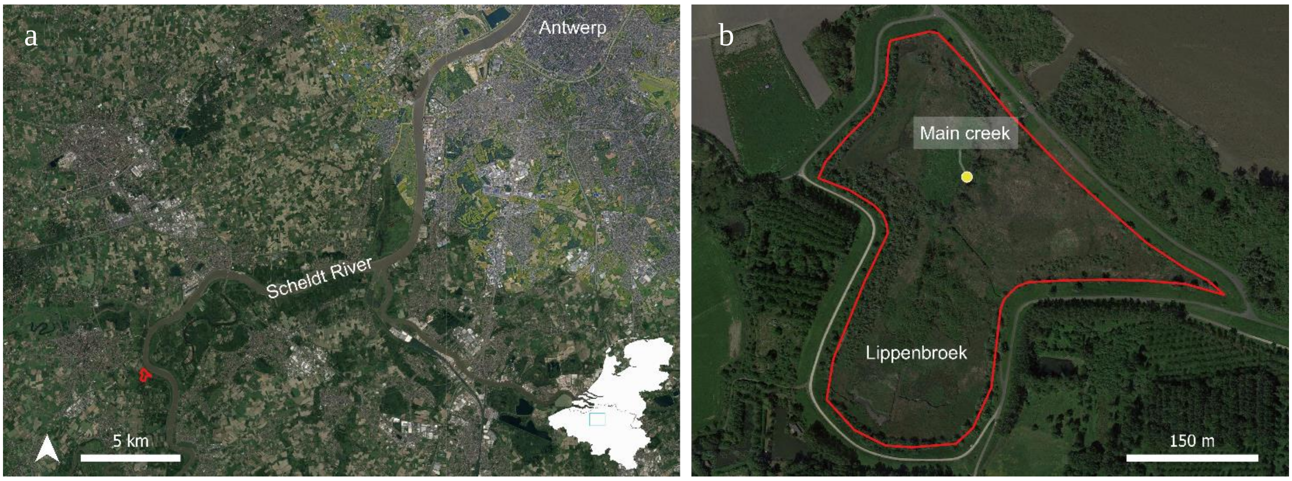


Figure 3: (a) Aerial picture (basemap: Google satellite, HCMGIS plugin QGIS) showing the location of Lippenbroek (red) along the Scheldt River, (b) The smoke test was performed in the main creek of Lippenbroek. Indicated in red is the border of the area with the surrounding levees.

2.1.3 Method

Prior to the smoke test, a visual inspection of the burrow openings in the bank was performed. A quadrant (0.5 × 0.5 m) was placed randomly three times onto the surface of the creek bank (Fig. 4b) within the study area (± 3 m²). All burrows within the quadrant were counted and the local surface burrow density was determined. Next, the smoke test was performed according to configuration 1 (Fig. 2a).

Configuration 1 (Fig. 2): The tests were performed on a dry day with a calm to light air wind level. A plastic container (25 L, height 40 cm, diameter 28 cm) was connected via its venting hole at the bottom to the selected burrow opening (smoke inlet) with a plastic hose (diameter 28 mm, length 4.5 m). To minimise the loss of smoke, the gaps around the hose were sealed with sediment. A coloured smoke bomb (length 60 mm × diameter 80 mm, ignition by drawstring, burning time 60 s, colour red, orange or pink) was ignited and placed inside the container. A leaf blower (Stiga, type SBL 327 V, gasoline engine power 800 W and 27.6 cm³, maximum air flow rate 10.2 m³/min, maximum air speed 72 m/s) was placed with its outlet on top of the opening of the container. Through the pressure of the leaf blower, the smoke was blown from the container, through the hose, inside the burrow network. While blowing, the bank was inspected visually by multiple surveyors for the emergence of smoke. Every hole that was venting smoke was marked with a flag (Fig. 5a). After the first test, the width and height of all burrow openings were measured (up to 0.5 cm precision) with a feeler gauge or measuring tape for large burrows. Using measuring tape, the distance between the flagged burrow opening and the smoke inlet was measured. Next, all the burrows were sealed (Fig. 5b), using the local silty sediment, and the whole smoke test was performed again using the same burrow as inlet to identify extra connected borrows that had been missed in the first test. Practice showed that, at this site and for this type of burrow network, repeating the smoke test more than two times per burrow inlet did not reveal new burrow openings from connected burrows.

Figure 4: (a) The main creek of Lippenbroek at low tide, (b) Quadrants are placed randomly on the bank to determine local burrow density.

Figure 5: (a) Smoke is inserted into the burrow network through a hose in a burrow opening (left) and the smoke emerges from interconnected burrows, which are marked with red flags. (b) After measuring, the burrow openings are closed off with local sediment before the second round of the smoke test.

2.2 Case study 2: Burrow network inspection in levees

2.2.1 Context

Assessing the presence, extent and structural impact of animal burrows on levees proves to be a challenging task for levee management authorities, partly because study methods can damage the levee. The transformation of the Hedwige-Prosperpolder from agricultural polder to tidal nature presented the perfect opportunity to experimentally investigate animal burrows since the levee was not used anymore as a flood defence and there were no concerns about damaging it. The levee would be breached after a year, while a new one had already been built further inland to take over the flood defence function.

The size and morphology of burrow systems vary per species, but there is a lack of consensus between management authorities on the level of risk posed by different burrow types (Tsimopoulou & Koelewijn, 2022). Although smaller burrows (e.g. of moles and rodents) are considered less risky, they are hard to spot and their full extent is difficult to uncover. The smoke test was used to investigate the superficial spatial configuration and dimensions of these type of burrow networks on levees.

2.2.2 Study area

The study was performed on different grass covered levees in the Hedwige-Prosperpolder (HPP). HPP is a former agricultural area of 465 ha that is located along the brackish part of the Scheldt Estuary at the Belgian-Dutch border (Fig. 6a). The area has been transformed recently into a restored tidal area and was inundated for the first time in 2022.

The smoke test was performed in 2021 on the landward slope of the levee that was later removed to facilitate the expansion of the tidal area. The test was performed in two different locations (Fig. 6b); location 1 on the Hedwigepolder levee (51°20’53.3”N, 4°13’44.4”E) and location 2 on the Prosperpolder levee (51°20’26.5”N, 4°14’22.2”E). In both locations, the cross-section of the levee consists of a sandy core that is covered by a clay layer. Location 1 is in the Netherlands, where the levee has an average height (i.e., vertical distance from crest to toe) equal to 7.5 m, a slope 1:2.6 and a typical thickness of the clay layer 80 – 100 cm. In this location, the test was performed in mole (*Talpa europaea*) burrows spread in a 3 m-wide levee section. Location 2 is in Belgium where the levee has an average height of 7 m, a slope 1:3.3 and a typical thickness of the clay layer 30-50 cm. In this location, the test was performed on burrows of small rodents (Rodentia indet.) in a 4 m-wide levee section.

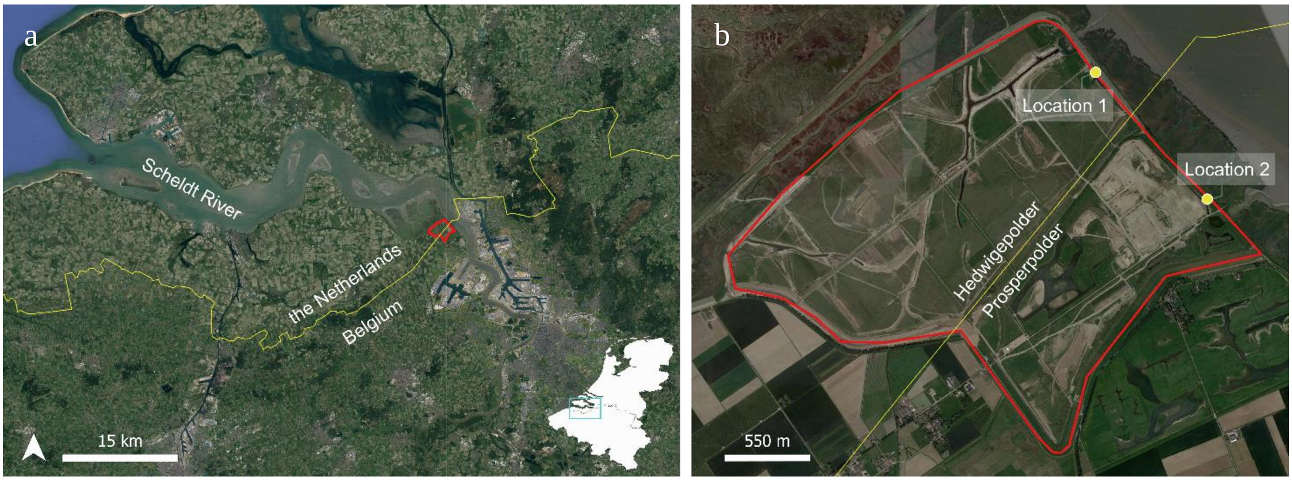


Figure 6: (a) Aerial picture (basemap: Google satellite, HCMGIS plugin QGIS) showing the location of Hedwige-Prosperpolder (red) at the border (yellow) of the Netherlands and Belgium and along the Scheldt River, (b) the smoke tests were performed on two locations within het Hedwige-Prosperpolder.

2.2.3 Method

Prior to the smoke tests, visual inspections were carried out. At both locations, a levee stretch of 100 m was inspected from crest to toe (approximately 250 m^2) by four surveyors that walked the levee in horizontal and vertical transects to search for burrows. All detected burrows were mapped and their locations noted using measuring tapes and grid paper, including their measurable depth (precision up to 1 cm) and diameter (precision up to 1 cm) (Tsimopoulou & Koelewijn, 2022). Depth was measured using inspection probes (Fig. 7a). The map helped the team identify clusters of burrows of small rodents and moles that could be leading to subsurface dens. At location 1, a section with mole burrows was selected. The smoke test was successfully performed at this location twice with two different configurations (Fig. 2a, b). At location 2 a 4 m-wide section was selected for the smoke test, where a relatively higher density of burrows was mapped. Within this section sand was found at the periphery of a burrow, indicating that the subsoil cavities reached the sand core of the levee. The smoke test was successfully performed once at this location with configuration 1 (Fig. 2a). At both locations, no animal activity was observed prior to the smoke test.

Configuration 1 (Fig. 2): This configuration is the same as the one used in the first case study, but with variations in the dimensions and materials of its basic components (i.e., leaf blower, container, hose). The variations were only made because the team did not have access to the exact same components that were used in the first case study. A container (200 L, height 876 mm, diameter 584 mm) was connected via its venting hole at the top to the burrow opening using a standard garden hose (diameter 12 mm, length 1.5 m). A coloured smoke bomb (orange, red) was ignited and placed inside the container. Using a leaf blower (WORX, type WG549E.5, 18V battery powered, maximum air speed 56 m/s) the smoke was blown through the hose into the burrow network (Fig. 7b).

Configuration 2 (Fig. 2): A coloured smoke bomb (red, blue, purple) was ignited and placed directly inside the burrow. The outlet of a leaf blower (BGA 45, 18V battery powered, maximum air speed 38 m/s) was placed on the opening of the burrow (Fig. 9), blowing the smoke inside the burrow network.

In both variations of the experiment, the levee was inspected for smoke emerging from holes (Fig. 8a) by multiple surveyors and the discovered burrow openings were promptly sealed using sediment (wet clay, Fig. 8b) or plexiglass plates. The smoke test was repeated twice to ensure that all burrows in the same cluster were discovered. During these tests, the wind conditions were limited to little more than a small breeze (cf. Fig. 7b). On later occasions, sometimes a stronger wind was present, which made it more difficult to detect smoke coming out of the burrows.

Figure 7: (a) A probe was used to measure the depth of the burrows during the visual inspection of the levee. The burrow openings were not clearly visible because of the vegetation. (b) The smoke test was performed using configuration 1: with a leaf blower the smoke is blown from a container through a hose into the burrow network.

Figure 8: (a) Smoke emerges from two burrow openings. (b) The burrows that were emitting smoke were closed off with wet clay.

Figure 9: The smoke test was performed using configuration 2: with a leaf blower the smoke is blown directly into the burrow network. Diffuse smoke can be seen exiting from the burrows (source: Interreg 2 Seas project Polder2C's, Courtesy of Wouter Zomer, BZ Ingenieurs & Managers).

3 Results

Various animal burrow networks were investigated (Table 1), differing in size and morphology. The smallest burrows tested were those of the Chinese mitten crab. These burrows were elliptical in shape, with varying burrow width but on average only a height of 1.6 cm (Table 1). The burrow networks of the crabs reached high densities in the banks of the creek (Table 1); however, they were connected over a relatively small surface area. The largest burrows investigated were those of moles, with a burrow diameter of about 5 cm (Table 1). The overall largest distance measured between the inlet and outlet burrow opening was 4 m (Table 1). Although measurements with inspection probes indicated that burrow depth was in general less deep than the clay layer of the levee at the respective locations, evidence was found in later research that some burrows at location 2 of case study 2 reached the sand core (Tsimopoulou & Koelewijn, 2022). The variety of characteristics of burrows tested shows that the smoke test is suitable for a wide range of burrow types, without the need to change the configuration of the test.

Table 1: Overview of the characteristics of the different burrow networks that were studied. Data are derived from the smoke test and the inspections prior to the test. In case-study 1, multiple burrow networks were tested, therefore the average values are shown with standard deviation when applicable.

	Case-study 1	Case-study 2	
Animal species	Chinese mitten crab	Mole	Small rodent
Number of networks tested	7	1	1
Area studied (m²)	± 20	72	105
Surface burrow density (nr. of burrows/m²)	53 ± 23	0.3	0.6
Number of burrows interconnected	10 ± 6	7	17
Interconnected surface area (m²)	0.3 ± 0.2	9	21
Maximum distance inlet and outlet (m)	0.7	4	3.5
Burrow width (cm)	3.5 ± 1.8 × 1.6 ± 0.7*	5	3
Burrow depth (cm)	≤ 50 (Rudnick et al., 2005)	12-76	5-17

*Burrows are elliptical in shape, therefore burrow width (cm) × burrow height (cm) are shown.

The use of the smoke test led to the identification of interconnected burrows, including the discovery of burrow openings that were not detected during prior visual inspection, and gave a clear indication of the approximate area that was affected by the burrowing behaviour of the animals (Fig. 10). Furthermore, different characteristics of the burrow network (Table 1) could be determined, including number of interconnected burrows, the distance over which they are connected and burrow density.

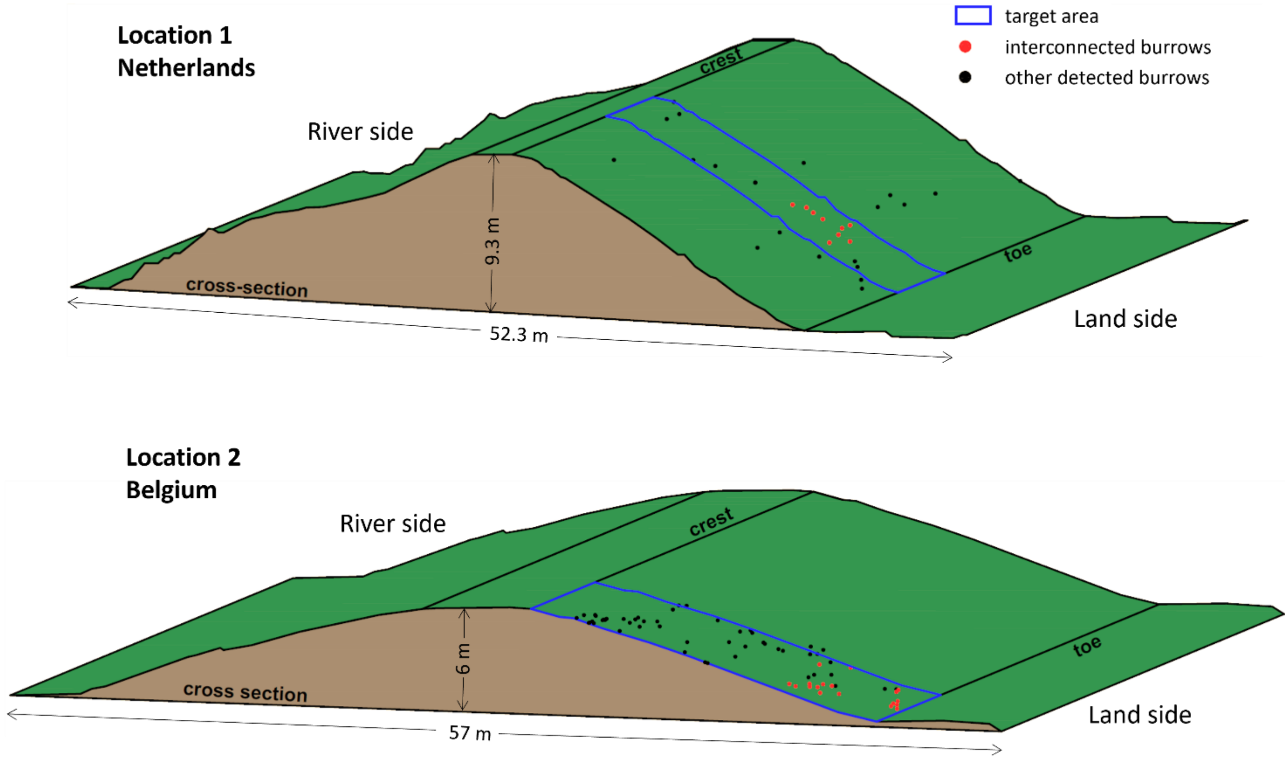


Figure 10: Illustration of the results of case study 2. Each dot (black) represents a burrow opening that was identified during the visual inspection of the levee. Indicated in red are the interconnected burrows that were identified through the smoke test, some of these burrow openings were already discovered during the visual inspection while others were only detected during the smoke test.

4 Discussion

The different experiments showed that the use of a container and a hose (configuration 1, Fig. 2) allows to direct the smoke into the burrows in a more precise manner compared to placing the smoke bomb directly into the burrow (configuration 2, Fig. 2). Thanks to this, there is less diffuse smoke, which makes it easier to spot the smoke that is exiting from other burrow openings. This also minimises the contact of researchers or inspectors with the smoke. Provided that the right type of container (heat-resistant material, lightweight and a suitable volume of about 30 L) is used, the disadvantage of carrying the extra material into the field is limited.

It is advised that the test is carried out by multiple surveyors, minimum two but preferably more. The smoke bombs utilised in this investigation are commercially available for outdoor applications. It is imperative to carefully review and adhere to the safety guidelines outlined by the manufacturer of the smoke device used. To minimise exposure to the smoke, the technique should be exclusively tested and employed in an open-air setting. Individuals handling the smoke device and/or leaf blower are advised to wear appropriate safety gear, including heat-resistant gloves, protective eyewear and face mask. In addition to smoke, a powder-like byproduct is released as the material inside the canister burns, leaving a coloured residue nearby. Depending on the test setup, after several experiments this residue is capable of clogging equipment (e.g., a hose and nozzle), and stains surfaces. Care should be taken to facilitate periodic cleaning of the equipment, as well as storage in sealed containers to avoid accidental staining of nearby surfaces in transit.

The experiments demonstrated that the smoke inlet can be chosen randomly, and smoke was observed exiting from burrow openings located at the same height, but also above and below the inlet burrow. The brightly coloured smoke significantly enhances the detection of smoke emerging from burrow openings. In this study, five distinct colours were tested: red, orange, pink, blue and purple. During the tests on unvegetated slopes, all different colours of smoke were clearly visible. On slopes covered with dry grass, blue and purple smoke were generally well visible, while orange and red smoke were less favourable. Strong winds during an experiment for case study 2 caused smoke exiting the burrow network to disperse to an invisible level within a few cm of the exit holes. Increasing the concentration and flux of the smoke represents a potential avenue to maximise the visibility of smoke in such conditions. To achieve this, the use of a smoke source with greater smoke output and a leaf blower with a higher air flow rate or different specialised equipment can be explored.

A note of caution is warranted for experiments that are performed in environments with water saturated soils. A tunnel or burrow blocked by water can obstruct the smoke test. In the tidal area (case study 1) investigated in this research, the pressure exerted by the leaf blower was observed to overcome this limitation, as water was seen bubbling up from burrow openings during the test. The fact that the test was performed successfully in waterlogged tidal areas is encouraging for its applicability in various environments. In the future, the use of a drone (potentially equipped with an infrared sensor) to detect smoke emerging from burrows could be explored to aid burrow detection during the smoke test. The drone could also aid in identifying burrow locations over a large area more efficiently, prior to the smoke test (i.e., replacing the tape measure mapping approach).

In this study the authors used smoke bombs that are generally available in retail. Although the properties (e.g., smoke duration, colour, human risk, price) of these smoke bombs were adequate and suitable for these tests, there are uncertainties about the potential effect on animal health and on the environment that should be addressed in the future. Alternative non-toxic smoke sources could be considered, for instance machines designed for testing plumbing systems (e.g., Nyquist et al., 2005), or smoke fluids used at parties, events or in theme parks. The benefit is that these machines can continuously inject smoke at the same rate and are usually easy to carry. The disadvantage is that this requires the purchase of specialised equipment and that these machines often do not have battery options. The toxicity of the smoke for both animals and humans should be examined in advance, as well as the presence of persistent environmental pollutants.

Inserting smoke in a burrow network may cause stress for the animals inhabiting the burrows. It is important to note that this type of test cannot be performed in burrow networks that are actively used by protected species such as beavers or badgers. To mitigate the effects on potential resident animals, monitoring of the burrows prior to the smoke test is advised to confirm their presence or absence. In case animals are present, it is preferable to capture and relocate them before testing. The animal species within this study were either invasive invertebrate species or considered harmful species. During the first field study, some crabs emerged and escaped from their burrow during or after the smoke test. In the second field study no animals were encountered. Prospective users are strongly advised to consult local authorities before application of this technique. Despite the fact that the technique requires mindful use, it should be emphasised that it has unparalleled advantages when it comes to its use for early detection of levee damages. When this is done prior to possible high-water episodic events, identifying weak spots on a levee is crucial for safeguarding human life, which is considered to be the top priority.

The use of the smoke test can play a pivotal role in levee inspections. Its rapid deployment and immediate results facilitate inspectors in quickly identifying burrow openings in a non-destructive way, thereby revealing potential weak points in the levee. The speed of this approach addresses a critical gap in current inspection methods, providing inspectors with a valuable tool and a distinct advantage in scenarios where time is limited. The method's primary focus is on protecting human life during levee failures, particularly in emergency situations, despite acknowledging its potential impact on animals. Beyond mere identification, the technique offers a unique advantage by unveiling the proportion of interconnected burrows, providing critical insights into the complexity of the subsurface network. While the smoke test can significantly improve the efficiency of inspections, it is crucial to acknowledge that the technique does not provide information about the 3D structure, and more essentially, the actual depth of burrows. This limitation highlights the need for a comprehensive risk assessment approach, as burrows penetrating the sand core of structures are likely to be more dangerous (Koelewijn, 2023).

5 Conclusions

The smoke test demonstrated its efficacy as an easy, practical, and low-cost technique for detecting interconnected burrow networks. The test (1) is less time consuming than regular visual inspections of levees, (2) does not require specialised equipment like a ground penetrating radar and (3) can be used in various environments, including soil with a high clay, silt, and moisture content, and (4) visualises the burrows immediately and does not require post-processing of data. It provided complementary information to visual inspections, aiding identification of burrows that may have been overlooked. The technique successfully detected exit points at relatively long distances from entry points, indicating its capability to identify extensive underground tunnels.

It is recommended to conduct additional research on factors influencing test outcomes, including burrow size, soil properties, and soil water content. Moreover, further investigation into elements that maximise smoke visibility, such as smoke concentration and flux, is also advisable. Collaboration with experts in biology and chemistry will contribute to refining the methodology and ensuring the safety and welfare of animals during the implementation of this technique.

The findings of this study have significant implications for levee management and wildlife monitoring practices. By accurately identifying interconnected burrow systems, potential weak spots on levees can be promptly addressed, minimizing the risk of structural damage and enhancing flood prevention measures.

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Author contributions (CRediT)

HK: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing; VT: Data curation, Investigation, Visualization, Writing; RL: Investigation; NVP: Conceptualization, Investigation, Methodology. AK: Investigation; SR: Investigation; TDK: Conceptualization, Investigation, Methodology; JS: Conceptualization, Data curation, Funding acquisition, Methodology, Supervision.

Data access statement

The data acquired in the study and reported in this paper is available from the authors upon request.

Declaration of interests

All authors declare that they have no conflict of interest.

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