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Short communication

Reconstructing mole tunnels using frequency-domain ground penetrating radar

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ABSTRACT

The European mole (*Talpa europaea* L.) inhabits an underground tunnel system whereby the density, extent and condition of the subsurface tunnels are indicative of its activity. Currently, no survey method was able to reveal the spatial extent and condition of the mole's tunnel network. Frequency-domain ground penetrating radar (GPR) was evaluated on its potential to image these shallow tunnel systems. This technique allows for a non-invasive, high-resolution mapping of the subsurface. We examined the effectiveness of this GPR system for delineating the mole's tunnel network. The integration of different depth slices allowed a detailed overview of the tunnel system. Automatic feature recognition on these GPR images was proven valuable for the detection and representation of the mole tunnels. The GPR survey proved successful in mapping the mole's tunnel network, which facilitates the interpretation and characterization of the mole's living environment. This can be linked to the occurrence of earthworms, as the principle food source of the moles, which regulate important ecosystem processes within the soil. This offers new perspectives for the understanding of the mole's habitat.

1. Introduction

The common European mole (*Talpa europaea* L.) creates an extensive systems of permanent and semi-permanent underground tunnels, which it constantly extends (McVean, 1999; Delattre et al., 2006). This subterranean mammal spends almost its entire life in this underground tunnel system, wherein it actively seeks food, eats, makes its nest, sleeps, breeds and rears its young (Quilliam et al., 1971). Godfrey (1955) recorded that these tunnels are generally located several inches below the soil surface. Parameters of burrow systems are affected by environmental factors, particularly availability and distribution of food, soil characteristics and climate, as was defined by Šumbera et al. (2003) for subterranean rodents. It is generally believed that the depth at which digging occurs is related to both the hardness and humidity of the soil and the food supply (Edwards et al., 1999). Shallow tunnels are made when the soil is loosely packed and moist, but when it becomes hard and dry, digging occurs within the deeper soil layers. These shallow tunnels are used to hunt earthworms and insects. In areas of high food availability, a stable tunnel system gives rise to adequate food supply. In areas where food is scarce, moles need to produce new tunnels continually to gain access to sufficient food. Subsequently, the density, extent and condition of the subsurface tunnels can possibly be linked to the presence of earthworms (Edwards et al., 1999). Earthworms play a major role in the regulation of important ecosystem processes such as litter decomposition and nutrient cycling, and in the services delivered by the ecosystem (Valckx et al., 2009). Therefore, if relations between geophysical measurements and earthworm presences could be established, these measurements could be linked to soil ecological processes. However, complex inter-relationships exist between physical, chemical, and biological soil properties and their response to soil ecology (Johnson et al., 2001).

Up to date, only a few studies used non-invasive soil measurements to the detect the presence of soil fauna (Joschko et al., 2010; Valckx et al., 2009). However, no non-destructive method was applied successfully to map the small, air-filled tunnels of the mole. For studying their ecology, a demanding method of uncovering and mapping burrow systems is often used. In the past, burrow systems were excavated, measured and mapped after digitizing, as done by Rosi et al. (2000) for the subterranean rodent *Cyanomys mendocinus*. Spinks et al. (2000) trapped out colonies of the common mole-rat (*Cryptomys hottentotus hottentotus*), after which the entire burrow systems were excavated and mapped on a graph paper. A similar procedure was followed by Šklíba et al. (2012), whereby they identified the position of nests (chambers with bedding), toilets (chambers or blind tunnels filled with feces) and food stores (chambers or blind tunnels with stored food) within the

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excavated burrows of the Ansell's mole rat (*Fukomys anselli*). The most useful method for studying long-term space use of subterranean animals seems to be (radio)telemetry. Šumbera et al. (2008) excavated and mapped burrow systems of subterranean rodents after radio-tracking. Nevertheless, even the most precise radio-tracking data can barely provide comprehensive information on the actual tunnel system size and structure (Šklíba et al., 2009). Le Comber et al. (2002) mentioned the difficulty of mapping mole-rat burrows, and the destructiveness of the most commonly used methods. They indicated the potential of non-destructive techniques for mapping the underground burrow systems. Therefore, we propose to employ a ground-penetrating radar (GPR) as a non-invasive geophysical prospection technique. Kinlam et al. (2007) provided the first intact visual views of large tunnels of the Gopher Tortoise (*Gopherus polyphemus*) employing this technique. They suggested that measuring at very high GPR antenna frequencies (>900 MHz) could potentially be able to discern small burrows. The development of advanced frequency-domain GPR systems, which measure simultaneously at an wide frequency range, should allow to obtain very detailed 3-D information about the composition of both the shallow and deeper subsurface. Hence it shows potential to evaluate the effectiveness of colonization by a mole community by mapping the mole tunnel network. The primary aim of this study was to explore the possibilities of an advanced frequency-domain GPR system to account for the high-resolution mapping of the mole tunnels. Furthermore, an automatic feature detection methodology was evaluated on its potential to delineate the network of mole tunnels.

2. Materials and methods

2.1. Study site

Our study site is situated in the north of Belgium on the Maldegem-Stekene coversand ridge. This ridge consists of wind-blown, coarse sand (according to the USDA textural classification) rich in organic matter with a Podsolic type of soil development (texture: 3.6% clay, 7.4% silt and 89.0% sand). An area of about 600 m^2, that revealed many molehills, was selected on a pasture field (with central coordinates 51°09′57″N and 3°51′39″E). A small subarea of 25 m^2 was selected to perform invasive observation of the mole tunnels. Starting from the different molehills, the trace of the mole tunnels was excavated and digitized employing a DGPS.

2.2. GPR principle

The high-frequent electromagnetic waves emitted by GPR systems obey the Maxwell's Laws (Daniels, 2004), which allow approximating the downward-propagating velocity (v) in soil by:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{1}$$

with c the speed of light in a vacuum, 0.2998 m ns^{-1} and ε_r the relative dielectric permittivity (Jol, 2009).

GPR systems measure the two-way travel time of a signal from the transmitting antenna to a reflecting interface and back to a receiving antenna. Eq. (1) shows that the velocity of the downward-propagating wave depends mainly on ε_r. Therefore, permittivity contrasts cause GPR reflections (Grote et al., 2005) whereby the degree of contrast determines the amplitude of the generated reflections (Leckebusch, 2003). The travel time of the radar wave through each distinct soil layer can be calculated as the difference in arrival times of the reflections from the interface between two materials with a different ε_r. Therefore, the travel time is dependent of both the thickness and depth of the object buried within the soil and v. Inversely, v at each point of the GPR profile can be estimated by the ratio of the difference between the two-way travel times of upper and lower boundary of each layer (Δt) and the known average thickness (d) of each layer:

$$v = \frac{2 \cdot d}{\Delta t} \tag{2}$$

Finally, v can be converted into ε_r according to Eq. (1).

While some part of the GPR wave is reflected back at the reflecting interface, another part is refracted and continuous traveling through the soil until it encounters another reflecting interface (which may be repeated several more times) or until it attenuates. Attenuation is mainly an effect of the conductivity of the soil through which the pulse is passing. A large water content and elevated clay concentrations reduce propagation velocity strongly and cause attenuation of the GPR signal (Neal, 2004). Knowing ε_r and the conductivity (σ), the attenuation at depth z can be estimated by $e^{-\alpha z}$. Hereby α can be considered a measure of the decay of the strength of the initial high-frequent electromagnetic field.

The depth and resolution of the GPR surveys are also dependent on the antenna frequency. High frequency waves suffer more from attenuation than low frequency components (Xavier Neto and Medeiros, 2006). In general, the higher the antenna frequency, the shallower the depth of penetration but the finer the spatial (horizontal and vertical) resolution (Neal, 2004).

To collect GPR reflections, paired antennas (one transmitting and one receiving antenna) are moved along the soil surface in parallel transects. With frequency-domain radar systems one antenna continuously generates propagating radar waves. The second paired antenna records the amplitude and phase shift of the reflected wave, which is a superposition of the continuous reflections from the subsoil. Subsequently, the digitized wave is transformed to time-domain to depict a set of closely spaced reflection profiles. Point source reflections within these profiles originate from individual rocks, metal objects, pipes that are crossed perpendicularly, and a great variety of other smaller things of this sort. They are, in two-dimensional profiles, visible as reflection hyperbolas, even though they were generated from an area-restricted feature in the ground. These hyperbolas are generated because most GPR antennas produce a transmitted radar beam that propagates downward from the surface in a conical pattern, radiating outward as energy travels to depth. Radar energy will therefore be reflected from buried features that are not located directly below the transmitting antenna but are still within the beam of propagating waves (Conyers, 2004).

2.3. Frequency-domain GPR system

We used a stepped-frequency continuous wave GPR and a corresponding antenna array (3d-Radar AS, Trondheim, Norway). This system generates a continuous-wave signal over a bandwidth between 100 MHz and 3 GHz. The amplitude and phase of this signal, modified by any subsurface reflectors, is determined over a user-defined time (dwell time) at every frequency step, and the resulting data set is then inverted from the frequency to the time-domain using an inverse Fourier transform (Linford et al., 2010). By mixing the transmitting and receiving signal in a quadrature mixer, it is possible to determine the deviation between both signals. For every frequency in-between the minimum and maximum frequency, the amplitude and phase shift from the reflecting signal are determined. The width of the frequency step defines the resolution within the frequency-domain and determines, together with the specified frequency range and dwell time, the scan time of an antenna. The advantage of using a frequency-domain system is that a high signal to noise ratio is obtained, while the frequency range