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Use of Ground Penetrating Radar to Image Burrows of the Gopher Tortoise (*Gopherus polyphemus*)

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The Gopher Tortoise (*Gopherus polyphemus*) is a large fossorial chelonian, averaging 23–28 cm in carapace length, that constructs extensive underground burrows in pyrogenic ecosystems of the southeastern US, especially favoring the sandhill and scrub vegetative communities (Auffenberg and Franz 1982; Diemer 1992). Because an entire community of at least 362 species of vertebrates and invertebrates use these burrows at some stage in their life or seasonal cycle (Jackson and Milstrey 1989), the Gopher Tortoise has been referred to as a keystone species (Eisenberg 1983). Gopher Tortoise burrows vary in diameter, depth, and complexity and play a critical role in the ecological processes of sandhill and scrub communities of Florida. They impact geomorphology (Butler 1995), soil dynamics (Gardner and Landers 1981), vegetation patterns (Kaczor and Hartnett 1990; Tuberville, 1998), animal community diversity (Milstrey 1987 for invertebrates, Franz 1986 for vertebrates), and possibly hydrology, at scales ranging from microsites to landscapes. Some species, such as Florida Mice (*Podomys floridanus;* Jones and Franz 1990), Eastern Cottontail Rabbits (*Sylvilagus floridanus;* Kinlaw 1999), and Armadillo (*Dasypus novemcinctus*; Guyer and Hermann 1997), will modify tortoise burrows for their own needs, adding complexity over time. Gopher Tortoise populations currently are in decline throughout the species' range (Auffenberg and Franz 1982; Diemer 1986; Estes and Mann 1996). The Florida Fish and Wildlife Commission (FWC) is currently reclassifying the tortoise from its present status as a 'Species of Special Concern' (FWC 2004) to a Threatened status (FWC 2006a), along with strengthening protection of its burrows (FWC 2006b).

Data on the internal geometry of a burrow can be obtained using simple measurement tools such as calipers, calibrated flexible rods, or by measuring dimensions of casts of burrows made from hardening agents. In the southeastern US, Gopher Tortoises are collected on sites slated for development by excavating their burrows using heavy equipment (Blankenship and Thomas 2005). Although general information about the depth and extent of burrows can be learned by this method, it destroys burrows, along with any opportunity for repeat measurements of burrow geometry. With excavation, any beneficial ecological effects of the destroyed burrow are lost. Invasive probing methods can cause burrow abandonment or behavioral disruption of the burrow inhabitants (A. Kinlaw, pers. obs.). Some success in understanding underground burrow structure for other animals has been achieved in the UK using geophysical methods. Butler et al. (1994) were successful in determining size for six badger (*Meles meles*) setts using soil resistivity but were unsuccessful using magnetmometry. Any approach to modeling changes of burrow structure over time, such as Meadow's (1991) model, which is based on tortuosity and complexity, requires a method to image burrows that is non-invasive, repeatable, and relatively quick.

Ground penetrating radar methodology.—Ground penetrating radar (GPR) is a non-invasive subsurface imaging technology which uses a surface antenna to transmit electromagnetic energy pulses in the form of radar waves, downward into the ground (Conyers 2004). Waves of varying amplitudes are then reflected back from buried interfaces to a receiving antenna, which is assembled together with the transmitting antennae on a movable sled or cart. The time elapsed between transmission and reception, the amplitude and phase of the received waves, and the frequency of those waves are recorded on the hard drive of a computer which interfaces with the antennas. Of the waves reflected back from buried interfaces, the largest amounts of energy are reflected back from highly contrasting media. In the case of air-filled burrows, a good deal of radar energy is reflected from the interface between the sandy sediment and the void of the burrow itself; other reflections can occur from tree roots, shallower burrows of other animals and sedimentary or soil beds. As the sled is slowly moved along pre-determined surface transects, a series of reflections can be collected at a programmed distance, determined by the revolutions of a survey wheel attached to the sled (Fig. 1A). All reflections are collected in radar travel times measured as two way-travel time in units of nanoseconds. These times can be converted to approximate depth in the ground when the velocity of the radar energy travel is calculated. When many hundreds of these reflections from varying depths are stacked and viewed in a two-dimensional vertical profile, a "cross-section" of the ground is produced.

Radar energy propagation occurs best in dry sandy soils, however good penetration also can occur in a number of other ground conditions (Conyers 2004). The applicability of GPR to locate cavities such as pipes or tunnels was recognized in the 1970s (Fullagar and Livleybrooks 1994). Since air-filled voids provide an excellent dielectric constant contrast (Daniels et al. 1992), GPR is used to identify animal burrows in earthen dams in the United States which might cause collapse of dams (ASDSO 1999).

Field Site Description and Burrow Selection.—Three study sites were located in the Ocala National Forest, Marion County, Florida, USA. The sandhill site (Kerr site) is located along the north shore of Lake Kerr, in the Lake George District of the Forest. The two oak scrub sites were located adjacent to the US Naval Reservation in the Seminole District of the Forest. In Florida, sandhill vegetative communities are rolling park-like woodlands of Longleaf Pines (*Pinus palustris*) rising above a continuous cover of Wiregrass (*Aristida stricta*) with other grasses and forbs, and occasional clumps of deciduous oaks, mostly Turkey Oak (*Quercus laevis*; Myers 1990). Visually, sandhills are open and one can often see for a hundred meters or so. Uncut Sand Pine scrub is a vegetative community of tall, twisted, leaning Sand Pine trees (*Pinus clausa*) rising above a thick understory of evergreen scrub oaks (*Q. geminata*, *Q. myrtifolia*, *Q. inopina*, *Q. chapmanii*), Florida Rosemary (*Ceratiola ericoides*), interspersed with Rusty Lyonia (*Lyonia ferruginea*), Scrub Holly (*Ilex opaca* var. *arenicola*), Silk Bay (*Persea humilis*), and Scrub Hickory (*Carya floridana*; Myers 1990). However, scrub vegetation often has open areas. Our GPR scrub sites had been logged within 10 years previous to our study, thus the Sand Pine trees were between one and five meters high. The soil type in both sandhill and Sand Pine scrub vegetation is classified as entisols, dominated by gently sloping, well-drained thick sands (Brown et al. 1990). These excessively drained soils are derived from quartz sand (Brown, et al. 1990) and are mostly devoid of silt and clay.

Our plots and burrows were chosen as part of a related research project. Many sandhill plots were available, thus a map of this vegetative community was gridded into one hectare squares and each square assigned a number. The plots were then selected using a random numbers table (Steele and Torie 1980). Gopher tortoises seem to prefer sand pine scrub areas that have undergone succession three to five years after a clear-cut, so the scrub plots were chosen from the few appropriately aged plots available. We tried to select only burrows that appeared to have been recently dug or were actively being used by the tortoises, since the literature indicated that these provided the most biological insight.

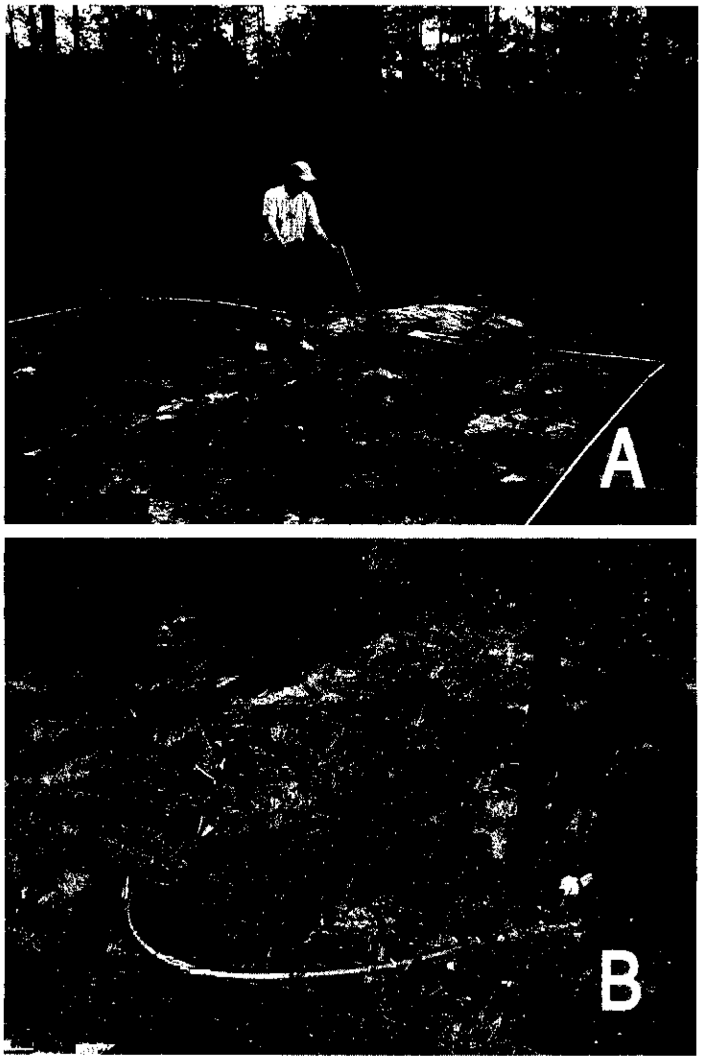

FIG. 1. A) Pulling GPR antenna in perpendicular direction across the long axis of gopher tortoise burrow in sandhills plant community, Ocala National Forest, Florida, USA. Note mound of sand behind antenna, indicating where tortoise piled up sand from digging activities. B) Two-dimensional profile of burrow Kerr6 on ground surface. The path of the burrow is outlined by the line marked by flags and spray paint, with the tube of the video camera also aligned along the path. View is opposite to the digging direction of the tortoise, with the burrow opening at the upper center of photo.

Prior to testing with GPR all burrows were examined with an infrared video probe camera attached to a 7.7 m section of polybutylene tubing (assembled by Edward E. Wester, Southern Ecosystems Research, 6485 Lee Road 54, Auburn, Alabama 36830, USA). This examination found that six of the burrows each contained a tortoise. The length of four others exceeded the length of the camera tether and occupancy could not be confirmed, but recent tracks, skid marks, and other surface signs indicated obvious use within a day or two prior to our testing. Finally, four burrows had sign that was somewhat deteriorated and did not have a resident tortoise (Table 1). Under the current scheme in use in the southeastern US to classify the status of Gopher Tortoise burrows (Auffenburg and Franz 1982), ten would be classified as "active" and four as "inactive."

GPR Collection Procedure.—The GPR antennae at our test sites were first calibrated for ground conditions that were often unique to each area. This included setting automatic range gain settings to enhance the reflection amplitudes with depth due to normal energy attenuation in the ground (Conyers 2004). A time window was selected, measured in nanoseconds, which preliminary velocity tests showed to be consistent with the maximum depth of the burrows. This time window varied between 50 and 70 nanoseconds, which corresponded to a maximum energy penetration depth of about 4–5 m. Optimal energy penetration occurs when the antennae are in direct contact with the ground surface at all times (Conyers 2004). To facilitate this, ca. 20–80 m^2 of vegetation immediately above each burrow was mowed. We then followed a two step procedure to map the burrows in the field. First, each burrow was probed with a piece of flexible electrical conduit to determine its beginning direction and maximum extent. Then, using a 900 MHz frequency antenna (Geophysical Survey Systems, Inc., 13 Klein Drive, PO Box 97, North Salem, New Hampshire 03073-0097, USA), we collected a series of "trial and error" transects at orientations estimated (from the initial probings) to be perpendicular to the burrow. In this way radar reflections when viewed in profile would produce a hyperbolic shaped reflection, with the apex of each hyperbola (Fig. 2A) denoting the top of the burrow tunnel. The location of each hyperbola apex was marked with a pin flag at the ground surface immediately over the section of tunnel that had just been crossed by the GPR antenna. This preliminary process of profile collection and immediate interpretation was continued until an approximate burrow path was delineated by flags, and then its total extent was marked with spray paint. During this preliminary step it was quickly determined that most burrows were not straight, but angled quickly from the surface as they continued down to greater depths. When many reflection profiles were collected in this way and viewed on the computer screen in "real time," the depth and orientation of the burrow void spaces could be determined. Often this process was confusing, as shallower burrow reflections, tree roots and the complex nature of reflections from curving tortoise burrows that often reached three and a half meters in depth produced an array of reflections with many different orientations.

Following Stott (1996), we wanted to verify that the hyperbole reflected by the GPR antenna was in fact the subsurface tortoise burrow we believed we were imaging, not a different burrow, unknown air void, or a sampling artifact. During this pilot step, we confirmed that the GPR antenna was actually imaging the burrow path by examining the section of tunnel directly underneath with the video probe camera slid down the tunnel. By treating the vertical distance between the antenna and the burrow immediately below the antenna as side A of a right triangle, and the horizontal distance between the antenna and the burrow entrance on the ground surface as side B of the triangle, we used the Pythagorean Theorem to calculate the correct distance (hypotenuse) to slide the camera down the burrow to be immediately underneath the antenna. This confirmation step was only conducted near the entrance of the first few burrows we imaged before the burrow curved.

To accurately map the depth of the burrows, we conducted a velocity analysis to calibrate the relationship between radar travel time and depth. At several locations along the first three burrows we processed, a calibrated steel rod was inserted from the ground surface to the top of the burrow; the point of insertion into the burrow could be determined by a relaxation of insertion pressure as it entered the void space. Correct placement of the rod in the burrow chamber was confirmed by observation with the videoprobe camera. These depths were then measured and the elapsed radar time measured in the GPR reflection profile at that location was then obtained. In these tests an average radar travel velocity was calculated to be 8 cm/nanosecond. Using this average velocity a two-way radar travel time of 45 nanoseconds was equivalent to ca. 3.6 m in the ground. This velocity was used to convert all measured times of burrow reflections to depth at all test sites. For all the sites tested this average velocity appeared to be consistent, which is understandable as all the burrows tested were found in the same type of dry aeolian sand. Ground moisture conditions, which can sometimes dramatically change radar velocities, were similar during GPR data acquisition. By following this process, an accurate depth profile of each burrow was made.

In the second step, a rectangular grid was then arranged over the total extent of each burrow with tape measures and their surface extent was mapped as x and y coordinates, measured from the southwest datum of each grid. The GPR antennae were moved in four meter transects perpendicularly across the burrow to collect reflection profiles normal to the orientation of the burrow (Fig. 1a). The middle of the profile (at ca. 2 m) therefore denoted the approximate center of each burrow, no matter what its depth. Reflection transects were placed every 50 cm along each surface-outlined burrow in this second step, which was a more formal process than our preliminary trial and error step. Paint and surveyor flags were used to mark the orientation and extent of each burrow (Fig. 1b), and photographs were taken. In this fashion the x and y coordinates of the burrow were determined from the surface measurements with z values (depth) obtained for each profile by measuring from the surface down to the apex of each reflection hyperbola (Fig. 2a). On each burrow, we made a final longitudinal transect along the ground surface that followed the path of the burrow; the resulting profile illustrated the gradual vertical drop of the burrow as the antenna moved (Fig. 2B).

Image Analysis.—Data points were transferred to two programs which translate three-dimensional spatial data into visual displays. Slicer-Dicer (Pixotec, LLC, 15917 S.E. Fairwood Blvd, Renton, Washington 98058, USA) is a program that allows the user to visualize three-dimensional data as a projected volume. This program creates isosurfaces from the data, meaning that the inter-

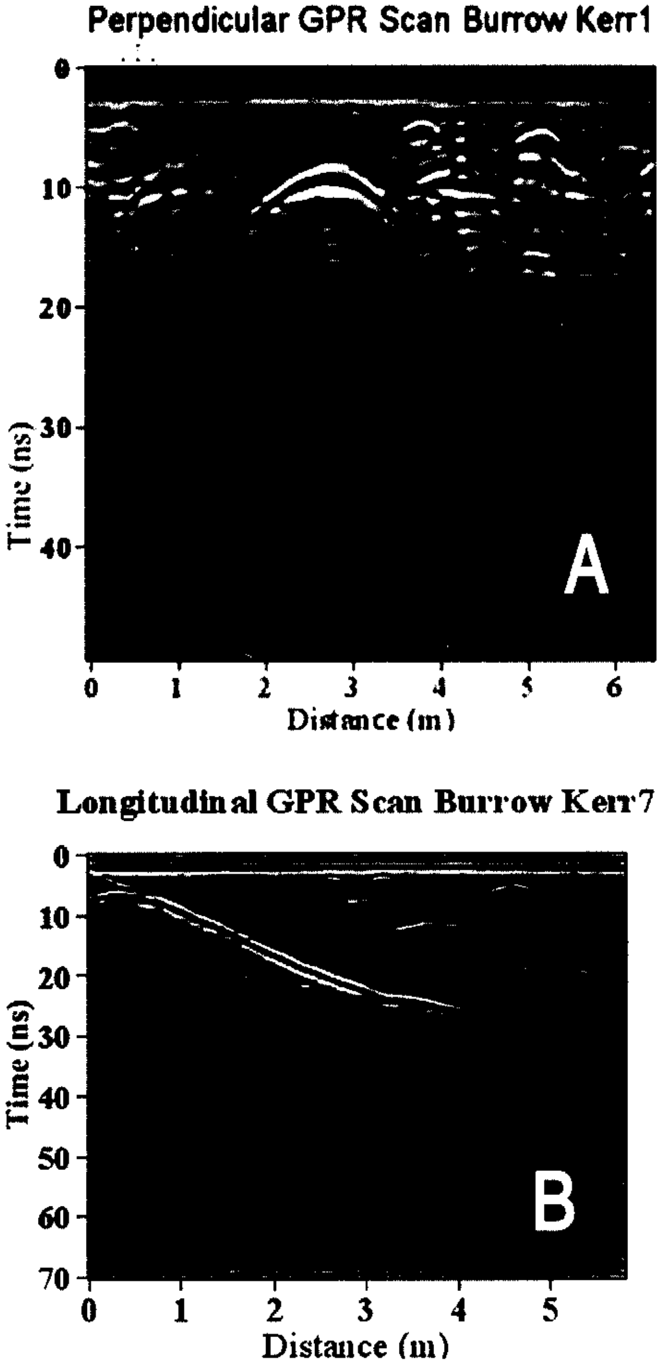

FIG. 2. A) Hyperbole (indicated by arrow) shown in GPR reflection profile, collected by moving the GPR antenna on the ground surface over the burrow at a 90° angle to the orientation of the burrow. B) GPR Longitudinal profile of burrow, collected by moving the GPR antenna on the ground surface following the path of the burrow.

faces producing the GPR reflections are placed in three dimensions, and a pattern or color is assigned to specific amplitudes in order for them to be visible (Heinz and Aigner 2003). The second program, FormZ (Auto·des·sys Inc., 2011 Riverside Drive, Columbus, Ohio 43221, USA), is a general-purpose solid and surface modeler with which the user can generate highly articulated renderings of most three-dimensional forms from x, y, and z data. To determine how accurately these renderings describe real burrow geometry, we compared them with physical casts of burrows prepared at a Clermont, Florida site where the burrows were being excavated for relocation purposes, with photos taken during these burrow excavations, and with one literature account.

Results.—The two dimensional outlines on the ground surface showed that nine burrows turned to the left within two to three meters of their opening, three turned right, and one was fairly straight (Table 1). Data were incomplete for one burrow which had collapsed about three m from the entrance. A 3-dimensional profile was developed for one burrow using the Slicer-Dicer visualization program, showing a downward corkscrew turn to the left (Fig. 3A). Three-dimensional profiles were developed for four burrows using the FormZ modeling program, which showed the burrow tunnels had smooth sides, some up and down loops or twists, and an overall "jagged" corkscrew shape (Fig. 3B). Examinations of hardened foam burrow casts and photos from the Clermont relocation site confirmed that those burrows had the same properties.

Discussion.—This research provided the first intact visual views of gopher tortoise burrows. The two-dimensional outlines on the ground surface show that most burrows investigated in this study turn in some fashion. The three-dimensional profile showing a corkscrew shape coincides with observations by Smith et al. (2005) for burrows that were excavated during a drought in east-central Florida. They reported burrows which angled down in a corkscrew fashion and attributed this to tortoises digging until they reached a cool hardpan layer under sand during the drought. Moreover, our comparison with the appearance and orientation of the FormZ three-dimensional renderings with actual hardened foam casts of burrows indicates that the models developed with this program accurately compares with the orientation and shape, including turns, of real burrows. Since the resolution of the GPR system we used was not detailed enough to image smaller side tunnels or rough surfaces along the side of the main tunnel, these features would not be represented in the visualization programs. Although the FormZ program smoothes the surface of a tunnel, this did not affect our results, as our burrow casts show fairly smooth surface features. These foam casts were taken in an area without shrubs or trees; we caution that the sides of burrows occurring in areas with more roots may not be as smooth. The longitudinal GPR profiles produced at each site clearly show burrows descending into the ground, sometimes leveling out, and again descending to their end. The FormZ models illustrate well both the up and down undulations of the burrows, as well as the turns, and the foam casts confirmed that these features occur in real burrows. All bio-mathematical models are approximations, and there is no reason why our three-dimensional renderings of burrows should be different. Thus, comparisons with features of real burrows show that these visualization programs using GPR data do provide reasonable models of burrows.

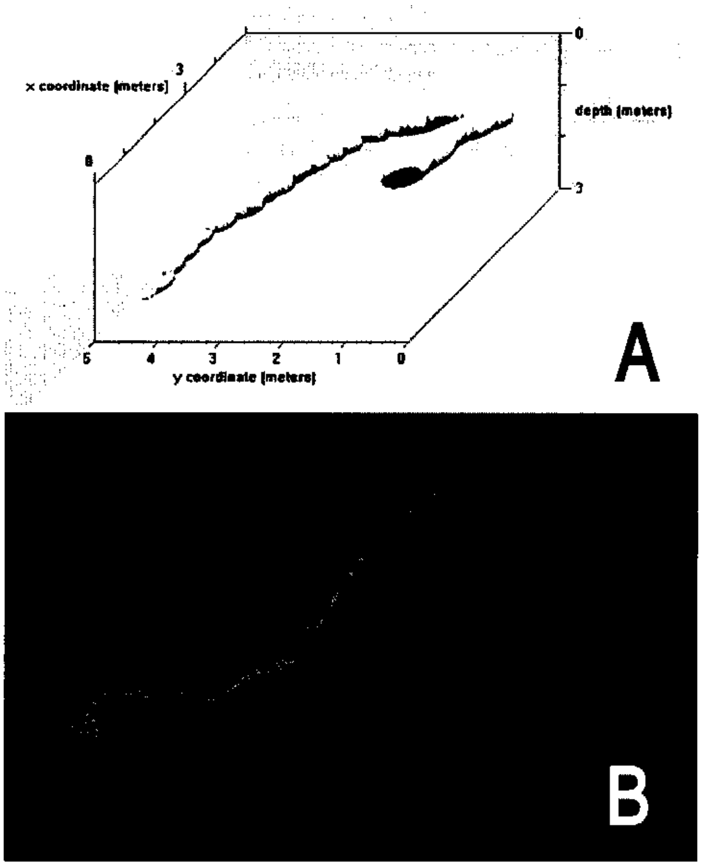

FIG. 3. A) Three-dimensional image of burrow Kerr3 developed using the Slicer-Dicer isosurface modeling program. B) Black on white three-dimensional rendering of burrow Kerr6 developed with the FormZ program.

Ground penetrating radar can assist with practical conservation efforts of the Gopher Tortoise. Gopher tortoises occur in a number of national forests and military reservations throughout the southeast. GPR could be used to assess or estimate the damage caused by heavy equipment, such as forestry skidders or military tanks, which can cause the collapse of burrow entrances. Gopher tortoises will also dig burrows in suitable soil occurring on cattle ranches. Trampling by cattle can collapse the opening or shallower sections of burrows, especially in overgrazed areas (A. Kinlaw, pers. obs.). The single collapsed burrow (NE2) found in this study was encountered very early in our study and we did not attempt to thoroughly map it. However, our subsequent mappings demonstrated that intact tortoise burrows could be imaged even if the entrance was completely sealed, because our GPR ground profiles showed other burrows underground (near our imaged burrows) that could be traced to old soil mounds.

By imaging the internal architecture of burrows, GPR technology could clarify issues relating to energy expenditure in building the burrows, flooding of burrows, respiratory environment, and amount of living space for invertebrates and commensal vertebrates. By collecting a time series of profiles at the same burrow, changes in the architecture of a burrow can be better understood, as well as changes in architecture brought about by other animals that modify a burrow.

There are many advantages of using GPR for mapping and vi-

TABLE 1. Data for Gopher Tortoise burrow study collected without and with ground penetrating radar.

	Data gathered before use of GPR			Additional data gathered with GPR			
Burrow Number	Habitat	Length Probed (m)	Tortoise Present?	Beginning Direction	Ending Direction	Configuration	Maximum Depth (m)
NE1	Scrub	4.9	N	160 °	?	turned left	2.48
NE2	Scrub	2.1 (a)	N?	260 °	?	straight (?)	1.28
Nor1	Scrub	4.1 (b)	Y	330 °	225 °	turned left	1.76
Nor2	Scrub	5.9 (b)	Y	170 °	55 °	turned left	1.52
Nor3	Scrub	3.4	Y	215 °	105 °	turned left	1.84
Nor4	Scrub	5.9	Y	315 °	30 °	turned right	2.88
KerrA	Sandhill	>7.6 (c)	?	60 °	75 °	straight	1.92
Kerr1	Sandhill	>7.9 (c)	?	310 °	210 °	turned left	1.04
Kerr2	Sandhill	>7.9 (c)	?	295 °	190 °	turned left	3.68
Kerr3	Sandhill	3.6 (b)	Y	200 °	?	turned left	2.0
Kerr4	Sandhill	6.7 (b)	Y	320 °	125 °	turned right	3.2
Kerr5	Sandhill	5.8	N	40 °	230 °	turned left	1.92
Kerr6	Sandhill	>6.4(c)	N	240 °	120 °	turned left	1.52
Kerr7	Sandhill	6.1	N	10 °	230 °	turned right	2.24

(a) Unable to manipulate camera past this point in burrow

(b) Gopher tortoise at length indicated, unable to manipulate camera past tortoise, burrow continues unknown length

(c) Burrow extends beyond length of camera; gopher tortoise probably residing in burrow based on recent tracks and sign

sualization of burrows. Like any good scientific method, GPR mapping is repeatable. A major advantage is its non-destructive abilities. Although the environmental impact of mowing a small amount of vegetation at the surface immediately above a burrow is not known, none of the burrows or entrances was physically impacted in any way using this technique. The method is non-invasive to the interior of the burrow; all the work is done at the surface. Finally, the digital format allows the data to be analyzed using a variety of approaches.

Presently the only other method available to obtain an image of a burrow is to fill a burrow with some type of material that hardens into a three-dimensional mold of the burrow shape, then excavate the mold. Although excavations are normally conducted to relocate gopher tortoises, it can be part of a process to map burrows, as in our Clermont foam study mentioned above. Although the time spent in the field with each activity was roughly comparable, mapping by excavation is an inefficient and crude technique compared to GPR. With GPR, we tested 14 sites in 8 field days, spending three to four hours at each site, including set-up time. Practically any burrow could be selected; with the excavation method only burrows listed on a State-issued permit could be imaged.

There are some limitations to the GPR method as well. Stott (1996) found that his GPR system exaggerated vertical tunnel height by a factor of 1.43. In our studies tunnel height could not be determined as the reflection derived from the top of the burrow in most cases was so high in amplitude that it effectively interfered with any reflections that might have occurred from the burrow base. In addition, the suitability of GPR to survey animal burrows in media other than dry sand can not be predicted. Although sand is well known as excellent for radar transmission, silty and clay-rich soils would likely attenuate energy prior to reaching the depth of burrows. For most intermediate-sized burrowing vertebrates that inhabit dry upland sandy regions of Florida, however, this would not be a problem. There have also been no tests of this technique with smaller (e.g., rodent) sized burrows. Burrows we surveyed were ca. 25–35 cm in width and 11–18 cm high. Our burrow camera showed the existence of smaller Florida Mice (*Podomys floridanus*) burrows intersecting the main tortoise tunnels, but our GPR profiles did not discern these smaller tunnels. It is possible that antennae with very high frequencies (greater than 900 MHz) could potentially be used to image smaller burrows, following techniques discussed in this paper. Higher frequency antennae have a greater resolution, but a shallower depth of total energy penetration. Finally, we were unable to confirm the presence of tortoises in two burrows where our camera showed that they were in fact there.

In our study, a catalog of the shape, depth, and orientation of burrows was produced for 14 Gopher Tortoise burrows in central Florida. Data were collected in dense grids of reflection profiles over 8 field days, which were then interpreted to show their orientation in three-dimensions. We demonstrated that the GPR method can be accurately and cost-effectively used in these types of studies for not only burrowing reptiles such as gopher tortoises, but potentially many other burrowing organisms. This imaging technique potentially has worldwide conservation implications for the study of these structures and the medium to large-sized vertebrates that dig and use them.

Ground-penetrating radar is one of the more complex near-surface geophysical methods and there is usually a learning curve involved for all who would like to use the technique. As with most tools, manuals are only partially helpful in standard set-up and data collection methods, which must usually be adjusted for each area studied. This is because ground conditions (soil type and moisture) as well as the nature of the targets usually vary at different geographic sites. Some systems record directly to a laptop, but most record data internally within the radar control system for later downloading. Software to process received reflected data into profiles and three-dimensional images is available for each system, written by the manufacturer. A number of competing software packages are available, some for free on the internet, and some that necessitate yearly subscription expenses of about US $1500 or so. A complete GPR system costs about US $30,000 to purchase, but can be rented from a number of companies in the U.S. and around the world for about US $250 per day. If one wished to write a grant to use this technology in a study, perhaps US $2500 should be allocated for initial training, along with US $3000 for system rental for a few weeks. One should then plan on spending at least four weeks to learn the intricacies of this system in the field. The SlicerDicer program costs about US $600 (academic version US $450) and the FormZ program costs US $400. About one or two weeks is a reasonable time period required for one to effectively learn each program.

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