Research review

Geophysical subsurface imaging for ecological applications

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Summary

Ecologists, ecohydrologists, and biogeochemists need detailed insights into belowground properties and processes, including changes in water, salts, and other elements that can influence ecosystem productivity and functioning. Relying on traditional sampling and observation techniques for such insights can be costly, time consuming, and infeasible, especially if the spatial scales involved are large. Geophysical imaging provides an alternative or complement to traditional methods to gather subsurface variables across time and space. In this paper, we review aspects of geophysical imaging, particularly electrical and electromagnetic imaging, that may benefit ecologists seeking clearer understanding of the shallow subsurface. Using electrical resistivity imaging, for example, we have been able to successfully show the effect of land-use conversions to agriculture on salt mobilization and leaching across kilometer-long transects and to depths of tens of meters. Recent advances in ground-penetrating radar and other geophysical imaging methods currently provide opportunities for subsurface imaging with sufficient detail to locate small (≥5 cm diameter) animal burrows and plant roots, observe soil-water and vegetation spatial correlations in small watersheds, estuaries, and marshes, and quantify changes in groundwater storage at local to regional scales using geophysical data from ground- and space-based platforms. Ecologists should benefit from adopting these minimally invasive, scalable imaging technologies to explore the subsurface and advance our collective research.

Introduction

Life is strongly tied to the Earth's thin outer zone from the top of the pedosphere to the depth of groundwater. Interactions and feedbacks between soil, water, rocks, and biological organisms influence biomass production, water resources, weather and climate, and numerous biogeochemical processes that sustain life (Jackson *et al.*, 2000; Amundson *et al.*, 2007). Consequently, our ability to produce crops for an expanding global population, to sustainably use soil and water resources, and to develop reliable climate and watershed models that accurately represent important land–atmosphere interactions and feedbacks is tied to how well we understand the properties and processes of the shallow subsurface.

Belowground observations at any scale remain challenging. Traditional techniques such as the use of soil pits and cores provide insights into structures, composition, constituents, and other variables. However, they can be impractical and inefficient when observations over large areas or depths are required because the heterogeneity of the shallow subsurface makes it difficult to deduce spatial properties and processes from scattered observations. Limitations of point observations become even more apparent with efforts to monitor transient processes. Dynamic plant root distributions and water uptake patterns, combined with the pulsed nature of water inputs, create highly heterogeneous arrays that can be difficult to capture even with dense networks of point sensors. Additionally, physical sampling often disturbs the natural state of the system, affecting the processes being monitored and influencing experimental outcomes.

The potential that geophysical methods have for studying the subsurface has been long recognized, first with their early applications in investigating the Earth's internal structure and functioning, and subsequently following their extensive use by the oil industry starting in the early 1900s. The fundamentals of various geophysical methods are described in widely available texts (i.e. Telford *et al.*, 1990; Reynolds, 1997; and others). Because geophysical methods provide a convenient way to examine the nature and properties of the subsurface in a minimally invasive manner, they can also ease the challenges faced by researchers interested in the shallow subsurface (*c.* < 10 m). Until about two decades ago, geophysical methods and tools remained difficult to access for more routine uses because of high equipment and survey costs and a dearth of instruments that were suited for detailed shallow subsurface measurements. Recent advances in electronics and equipment, data acquisition and processing, and data visualization and interpretation have reduced many of the earlier constraints of geophysical imaging. They are now broadly adopted by engineers and environmental scientists, and in the process have led to new specializations such as engineering geophysics, the science of applying and advancing geophysical imaging to solve engineering problems (Pellerin, 2002). Among these specializations, hydrogeophysics, which focuses on utilizing geophysical data to derive properties and observe hydrological processes, is particularly relevant for ecologists (Rubin & Hubbard, 2005; Hubbard & Linde, 2011). Despite the need for shallow subsurface data, the ecological community has remained mostly unaware of recent advances in geophysical imaging that can greatly benefit their research. Our aim in this paper is to highlight some opportunities in geophysical imaging, especially using electrical resistivity, electromagnetic induction, and ground-penetrating radar methods for ecological research, and to identify ways in which these methods can identify relationships among soil, water, vegetation, and other ecosystem components.

Electrical resistivity and electromagnetic induction imaging

Electrical and electromagnetic methods, including electrical resistivity imaging (ERI) and electromagnetic induction (EMI) imaging techniques, constitute a subset of geophysical methods especially suited for ecological and ecohydrological applications. Electrical resistivity (ρ), or its inverse, conductivity (σ), which can be estimated with ERI or EMI techniques, indicates the ease with which electricity is conducted through soil or other subsurface constituents. Strongly dependent on porosity, pore-water saturation, and the conductivity of the pore-water, ρ and σ have been successfully used in groundwater and agricultural investigations for assessing soil water availability and salinity (Corwin & Lesch, 2005).

Acquiring ground resistivity data with ERI involves introducing a low-frequency electrical current (I) into the subsurface through a pair of metal electrodes buried in the ground, then measuring the strength of the resulting potential field between a separate pair of electrodes. The ground resistivity is computed following Ohm's law using the measured potential difference, injected current, and a geometric factor that is a function of the electrode positions or configuration (Samouelian *et al.*, 2005). Modern ERI equipment allows for tens to hundreds of electrodes to be connected to execute complex data acquisition sequences for 2D and 3D profiling. Many aspects of the data acquisition process can be also automated to improve the efficiency and reliability of the process. Before these data can be used for subsurface interpretations, they also have to be inverted, which is an iterative calibration process that leads to a model of the subsurface that best fits the acquired data.

The EMI method examines the response of the ground to a propagating electromagnetic field to estimate its resistivity or conductivity (Reynolds, 1997). For shallow subsurface measurements, the electromagnetic field is typically generated by passing an alternating current through a small electrical coil (transmitter) loop that need not be physically connected to the ground. In response to this transmitter-generated electromagnetic field, soils and sediments in the ground produce a secondary electromagnetic field whose characteristics can be measured with a separate receiver coil loop. Conductivity or resistivity of the ground is subsequently estimated by comparing the attributes of the primary and secondary electromagnetic fields. EMI equipment used in shallow subsurface imaging has the advantage of being fairly lightweight and is often hand-held. The depth imaged by EMI can be controlled either by changing the separation length between transmitter and receiver coils or by adjusting the transmitter frequency (generally between 1 and 15 kHz). Because the transmitter and receiver coils need not be in contact with the ground, data acquisition with EMI can be fast, and can take place over any type of surface, including shallow ponds or lakes (Moore *et al.*, 2011).

In our research, we have used the sensitivity of soil electrical resistivity to water and salts to understand several ecohydrological processes. In the semi-arid dry woodlands of the Argentine Pampas, we used ERI to assess potential soil salinity changes accompanying the region's fast-expanding agriculture footprint, and to describe subsurface spatial relationships between vegetation, soil water, soil salinity, and groundwater. Several challenges limited our ability to rely on conventional field methods alone. These included woody field sites that were inaccessible by vehicle, a vadose zone too deep (> 30 m) and difficult (unconsolidated sand and sandy loam) to core, extensive spatial scales that needed to be assessed for understanding land-use-driven changes belowground, and the likelihood of deep water and salinity changes in the thick vadose zone. Without geophysical imaging, we were limited to auger depths of *c.* 10 m, but more often failed to penetrate below 3–6 m in the unconsolidated material because of collapsing bore walls or the presence of occasional hard caliche fragments. As evident from Fig. 1, which shows a 1-km-long resistivity transect from a woodland to a 70-yr-old crop field and back to another woodland, ERI helped us overcome many of these challenges and provided convincing evidence of broad-scale impacts of land-use change on salinity and hydrology in the region (see also Jayawickreme *et al.*, 2011). The thin, electrically conductive horizon beneath the woodlands (0–350, 900–1100 m lateral distances) is a salty soil zone that we further confirmed with solute analyses in soil cores. By contrast, the same high-conductivity horizon was clearly absent beneath the *c.* 70-yr-old crop field (Fig. 1; lateral distance of *c.* 350–900 m), where soil cores also confirmed higher soil-water contents and much lower salt concentrations compared with the woodlands. Furthermore, the resistivity image showed no evidence of a conductive horizon beneath the crops at any depth above the groundwater table located *c.* 35 m below the land surface, suggesting that leached salts had time to reach groundwater since the conversion to agriculture. Based on this evidence, we were able to conclude that land-use change is a significant concern for water resources in the region because of its rapid influence on deep

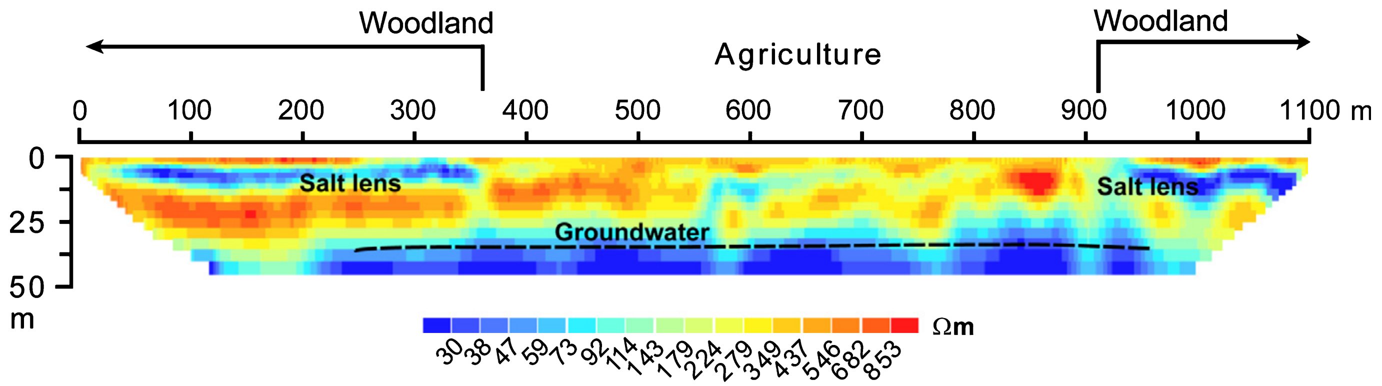

Fig. 1 Salt leaching triggered by land-use change captured with an electrical resistivity image spanning a 1.1-km woodland–agriculture–woodland transect in the semi-arid, sandy loessic plain of Central Argentina (adapted, with permission, from Jayawickreme *et al.*, 2011). The thin, but continuous, low-resistivity layer (*c.* 3–13 m) beneath the woodlands (0–360, 900–1100 m) shows areas with high soil salt concentrations. Increased soil water drainage with woodland-to-agriculture conversions in the region has led to significant salt leaching from the soil, as evidenced by the absence of the salt lens under the crop field (360–900 m), which is *c.* 70 yr old.

soil-water infiltration and salt leaching from the vadose zone. Coring and other forms of destructive sampling are often difficult, even impossible to use to obtain such clear insights belowground, and spatial links to the vegetation above. As complementary approaches, traditional coring and geophysical imaging can lead to a wealth of ecological and eco-hydrological knowledge.

The sensitivity of electrical resistivity or conductivity to water content and salinity of a soil can be exploited to explore many other ecological phenomena. Davidson *et al.* (2009) highlight the complementary use of ERI to substantiate deep (> 11 m) rooting and soil-water uptake in Amazonian woodlands during drought, and Jackson *et al.* (2005) show how ERI was instrumental to obtaining evidence of groundwater salinization by recently introduced eucalyptus (*Eucalyptus camaldulensis*) plantations in shallow groundwater regions of the Argentinean Pampas. Other examples of resistivity applications for soil-water, texture, and salinity mapping can be found in the recent geophysics and ecological literature (Reedy & Scanlon, 2003; Jayawickreme *et al.*, 2008; Nosetto *et al.*, 2013; Triantafilis & Monteiro Santos, 2013). Applications of ERI have not been limited to soil and salinity investigations alone. Hagrey (2007), for instance, discussed the potential of using ERI for imaging inside tree trunks for structure and fluid assessments, and Amato *et al.* (2009) for quantifying root biomass in experimental alfalfa (*Medicago sativa*) plots.

Time-lapse application of ERI and EMI, where ground resistivity is repeatedly monitored through time, can be equally useful for ecologists. Differences in resistivity through time can provide insights into transient soil-water dynamics when other major variables influencing resistivity remain relatively constant. Measurements can be established across vegetation gradients or ecotones to image soil-water changes driven by transpiration and plant-water uptake (Srayeddin & Doussan, 2009), or to study hydraulic redistribution and other ecological phenomena (Robinson *et al.*, 2012a). EMI is a particularly versatile method for time-lapse observations of large field plots or small watershed because data can be collected quickly while walking with a hand-held instrument coupled to a GPS unit (Moore *et al.*, 2011; Robinson *et al.*, 2012b) (Fig. 2). Although still not widely explored, the spatial mapping capabilities of EMI can also be exploited to capture canopy throughfall and ground-level soil moisture relationships and other spatial processes. Such application areas are likely to emerge as the awareness of using geophysical imaging for ecological research grows.

Ecological insights from ground-penetrating radar

Since the introduction of the first commercial ground-penetrating radar (GPR) system in the 1980s (Annan, 2002), the use of GPR for subsurface investigations has been growing rapidly. With GPR, subsurface features and properties are investigated by pulsing electromagnetic energy belowground (Reynolds, 1997). Common GPR equipment constitutes a pair of antennae, one for transmitting the electromagnetic waves and the other for intercepting the transmitted energy that is reflected by interfaces separating contrasting materials (i.e. soil and rock, soil and roots, etc). Transmitter frequency (*c.* 0.01–1 GHz) can be set depending on the desired imaging depth and degree of detail sought. With lower frequencies, greater depths can be imaged, though typically with less detail. GPR data are commonly collected by moving the transmitter and receiver antennae along the surface while maintaining a constant separation between the antennae. This can be done by a person or vehicle in open terrain to collect data along transects or grids. Newer GPR equipment is often packaged in self-contained units with integrated GPS and real-time data visualization capabilities, allowing for better mobility and field use.

GPR typically performs best in sandy environments with a low content of conductive materials (i.e. clay or saline pore-water). In such settings, high-resolution data that are suitable for extracting a range of ecologically relevant variables can be acquired. One common use of GPR in hydrology has been to quantify soil water content (Huisman *et al.*, 2003), but the ability to detect boundaries between contrasting materials could be particularly useful in ecology. Using advanced 3D techniques, Kinlaw & Grasmueck (2012) show how GPR can be deployed to image the morphology of animal burrows belowground (Fig. 3). Such applications can provide new insights into environments that are typically difficult to access. Similarly, GPR has been used for mapping diverse ecosystem attributes and processes, including soil depth in forests

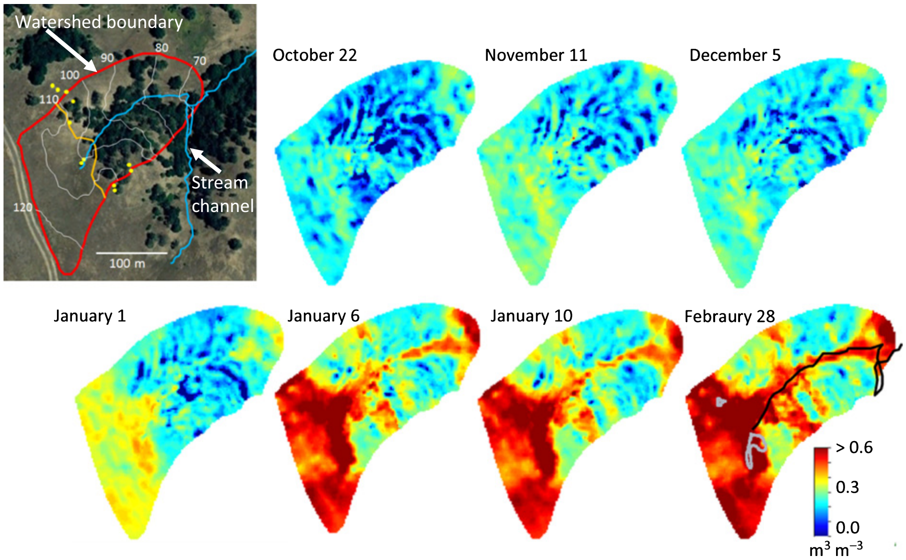

Fig. 2 Development of near-surface soil moisture patterns over a small watershed imaged with time-lapsed electromagnetic induction (EMI) and statistical methods (adapted, with permission, from Robinson *et al.*, 2012b). White lines on the top left image are 10-m contours, yellow dots are rock outcrops, and the orange line separates areas with two different rock types within the watershed. The strong contrast in soil moisture that developed following a large precipitation event between 1 January and 6 January shows how strongly soil moisture contents can vary spatially even within a relatively small watershed such as this as a result of topography, vegetation, and soil texture differences.

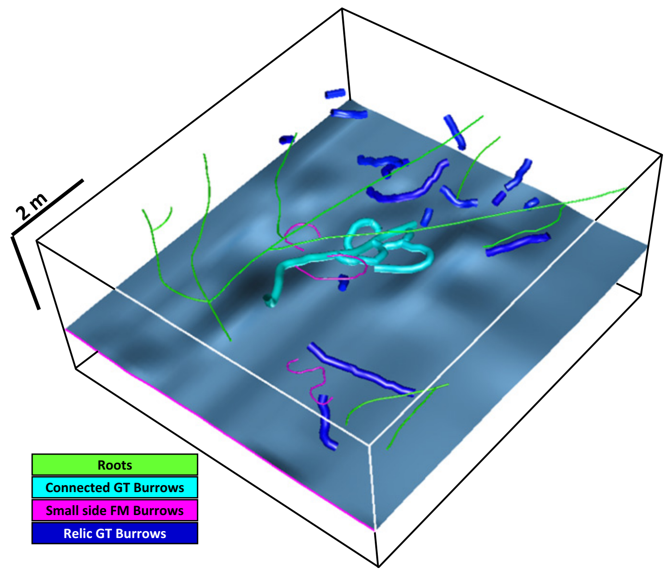

Fig. 3 Organization of subterranean gopher tortoise (GT) burrows (turquoise-colored tubes, width *c.* 30 cm and height *c.* 15 cm) in the Ocala National Forest, Florida, imaged with high-resolution ground-penetrating radar (adapted, with permission, from Kinlaw & Grasmueck, 2012). Tree roots and field mouse (FM) burrows mapped with ground-penetrating radar (GPR) reflections are *c.* 5 cm in diameter. Mapping such intricately detailed subsurface features with GPR requires high-precision equipment and advanced data-processing skills.

(Sucre *et al.*, 2011), biomass and biogenic gas monitoring in peatlands (Comas *et al.*, 2008), wood quality in tree trunks (Lorenzo *et al.*, 2010), and soil freeze–thaw patterns (Steelman *et al.*, 2010). Based on increasing success in mapping large buried roots (Butnor *et al.*, 2003; Stover *et al.*, 2007), researchers are improving GPR for more comprehensive root mapping, with these ideas potentially extending to broader soil carbon and water-related research.

Deriving environmental variables from geophysical data

Qualitative information about the subsurface can be readily derived from geophysical images. However, these images can be more meaningful when they are expressed in terms of soil water, salinity, or other variables commonly used by ecologists. Over the years, geophysicists have observed various correlations between geophysical responses and environmental variables and, based on these, have developed models to derive quantitative estimates of subsurface variables from geophysical data. Archie's model (Archie, 1942) is one example that is widely used to express electrical resistivity (ρ) in terms of porosity (Ø), pore-water saturation (S), and electrical resistivity of the pore-water (ρ_w);

$$\rho = \varnothing^{-m} S^{-n} \rho_w \qquad \text{Eqn 1}$$

where m is typically assigned a value between 1.3 and 2.5 and is known as the cementation exponent and n (*c.* 2) is the saturation exponent. Developed for clay-free soils, Archie's model may produce erroneous estimates when clay mineral fraction is substantial. For such clayey soils, other models have been proposed (e.g. Waxman & Smits, 1968). Similarly, with GPR, Topp's model (Topp *et al.*, 1980) is widely used for extracting soil moisture estimates from GPR travel velocities in soils (Alumbaugh *et al.*, 2002; Huisman *et al.*, 2003). From an ecological perspective, GPR is perhaps most suitable for locating and mapping subsurface discontinuities or heterogeneities defined by the position of tree roots, animal burrows, soil-to-regolith or bedrock transitions, and water table depths, among others. Deriving such useful information from raw GPR field data requires some data processing in the field or laboratory. The most basic steps are fairly simple using GPR software, recognizing that ground-truthing is necessary (Cassidy,

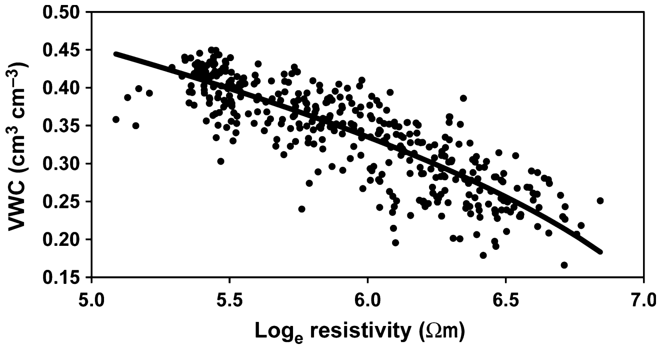

Fig. 4 Calibration of electrical resistivity data to estimate volumetric soil water contents (VWC) with time domain reflectometry (TDR) measurements in an Amazonian woodland. Calibration curve, $VWC = \sqrt{[(-0.0935 \times \log_e R) + 0.6733]}$ (adapted, with permission, from Davidson *et al.*, 2009). Soil moisture derived from resistivity data often compares well with moisture estimates from soil samples or other point sensors because of the strong dependence between electrical conductivity and soil water saturation. However, resistivity-derived moisture values should be used with caution and understanding that they can be affected by data acquisition and data processing (i.e. inversion) decisions, environmental conditions, and other factors.

2009). More advanced uses (e.g. detailed 3D volume scans for hydraulic properties) may require supplementary software tools and specialized data-processing skills. In place of generalized models such as the above-mentioned Archie's model, site-specific models can be tailored to conditions at a specific field site. Such models are typically developed and calibrated in a controlled laboratory or field setting and involve systematic manipulation of moisture or other variables of interest while recording the resulting change in conductivity or resistivity (Davidson *et al.*, 2009; Hadzick *et al.*, 2011) (Fig. 4).

Opportunities and challenges in integrating geophysical data with ecological research

We have illustrated a number of applications that we believe can spark interest in geophysical imaging among ecologists. The ability to obtain subsurface data across vegetation gradients, to monitor transient processes driven by soil-water, and to construct the subsurface architecture and arrangement of ecologically relevant entities, without the need for extensive destructive sampling, is potentially valuable for ecologists. Beyond the plot- or field-scale imaging shown here, geophysical data can be collected from sensors on airborne platforms for large field- or biome-scale studies (Cresswell *et al.*, 2007; Burrage *et al.*, 2008), or inside boreholes for finer-scale applications (Coscia *et al.*, 2011). Because the cost of adopting imaging methods is decreasing, and the reliability of the data and the models produced is increasing, now is an opportune time to integrate geophysical imaging more fully into ecological research through collaborations between ecologists, geophysicists, and hydrologists. Belowground insights gained through such efforts could greatly increase understanding of the links between above- and belowground processes in ecosystems.

As with all research tools, some basic conditions need to be met in order to apply geophysical imaging to ecological studies. These include compatible ranges of field conditions, a good match between the imaging method and the subsurface information sought, the ability to obtain high quality geophysical data, availability of suitable data processing and inversion schemes, and the potential to link geophysical responses to subsurface variables of ecological interest. For instance, GPR imaging can be hampered by interference from power lines generating electromagnetic noise in urban areas and by clayey or salty soils because of rapid dissipation of electromagnetic energy in electrically conductive materials. Similarly, time-lapse imaging may be impractical for monitoring fast ($<$ few hours) changing environments because of the required measurement speeds, or required instrument sensitivities to detect subtle changes. Awareness of such limitations is important because outcomes depend on the quality of the data acquired. It is also important to remember that a geophysical image is a model of the subsurface constructed by inverting the data. Such inverse reconstructions are nonunique, meaning that multiple subsurface realizations may fit the same data and may be influenced by constraints applied during the inversion process. As a result, interpreting images can sometimes be challenging or inconclusive. Nevertheless, progress has been made to minimize ambiguous interpretations and improve the reliability of the geophysical data by using complementary data sets (e.g. GPR and ERI) (Hirsch *et al.*, 2008), integrating other types of field data (i.e. soil boundaries or water-table depth observed in boreholes or trenches; Hickin *et al.*, 2009), and improving inversion codes (Auken & Christiansen, 2004). An additional caveat with geophysical images is that they can be over-interpreted to draw incorrect or unrealistic conclusions. Given these considerations, efforts to integrate geophysical imaging for ecological observation should be made collaboratively between ecologists and geophysicists with adequate cross-disciplinary experience and exposure.

Although we have restricted our review to a few techniques, there are other promising methods available for ecological and ecohydrological applications. Gravity data collected onboard GRACE (Gravity Recovery and Climate Experiment) satellites or on the ground using microgravity meters are proving increasingly useful for monitoring groundwater storage changes in response to prolonged weather extremes (i.e. drought) or groundwater extraction for irrigation (Rodell *et al.*, 2009; Jacob *et al.*, 2010). As geophysical technologies continue to advance, we believe they will become frontline tools for ecological and ecohydrological research, similar to the way that satellite-based sensors contributed to aboveground ecosystem observations in recent decades. Combined with the minimally invasive nature of these methods, scalability of measurements to image across multiple spatial domains, and repeatability of measurements to capture transient processes, the future for geophysical subsurface imaging is bright; ecologists will benefit from adopting these technologies and contributing to their development to advance our collective research.

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