ENVIRONMENTAL REPORTS

Review Article
ISSN: 3041-556X
Journal homepage: https://er.researchfloor.org/

Plant Stress Detection via Geophysical Imaging: Electrical Resistivity and Other Non-Invasive Tools for Monitoring Drought Responses

Ekhlaque Ahmad

Zonal Research Station, Birsa Agricultural University, Ranchi, Chianki, Palamau-822102 (Jharkhand) India

Citation: Ekhlaque Ahmad (2019). Plant Stress Detection via Geophysical Imaging: Electrical Resistivity and Other Non-Invasive Tools for Monitoring Drought Responses. *Environmental Reports; an International Journal*.
DOI: https://doi.org/10.51470/ER.2019.1.2.19

Corresponding Author: **Ekhlaque Ahmad** | E-Mail: **(ekhlaque.bau@gmail.com)**

Received 19 July 2019 | Revised 21 August 2019 | Accepted 26 september 2019 | Available Online October 28 2019

ABSTRACT

Drought stress is a major constraint to agricultural productivity and food security worldwide. Early detection of plant stress is essential for timely management interventions. Conventional physiological and biochemical methods provide useful information but are often invasive, labour-intensive, and spatially limited. Geophysical imaging methods, particularly electrical resistivity tomography (ERT), offer a non-invasive means of characterizing soil–plant–water interactions in situ. This review examines the principles and applications of ERT and complementary approaches such as ground-penetrating radar (GPR), electromagnetic induction (EMI), and infrared thermography for monitoring drought responses in plants. Methodological frameworks, case studies, and integration of these tools into precision agriculture are discussed. The review also outlines current limitations, calibration requirements, and potential directions for future research. Geophysical imaging provides a valuable set of tools for advancing plant stress monitoring and improving water management strategies under variable climatic conditions.

Keywords: *Plant stress detection, Drought response, Electrical resistivity tomography (ERT), Soil–plant–water interactions and Ground-penetrating radar.*

Introduction

Climate change and increasing global population have intensified the pressure on agricultural systems, making water scarcity and drought stress major threats to crop productivity and food security. Plants, as primary producers, are highly sensitive to water availability, and prolonged drought conditions can trigger complex physiological, biochemical, and structural changes. Early detection of plant stress is therefore critical to mitigating yield losses, optimizing water management, and developing resilient cropping systems [1]. Traditional methods of assessing plant water stress, such as visual inspection or destructive sampling for physiological measurements, often provide limited temporal resolution and fail to capture subsurface changes. Consequently, there is a growing interest in non-invasive and geophysical approaches for monitoring plant responses to environmental stressors.

Among various non-invasive techniques, electrical resistivity imaging (ERI) has emerged as a promising tool for evaluating plant-water interactions and soil–root dynamics. ERI involves the measurement of the electrical resistivity of the soil and root zone, providing insights into soil moisture distribution, root architecture, and plant hydration status. Since electrical resistivity is sensitive to water content and ionic composition, changes in plant water uptake and soil moisture due to drought are reflected in the resistivity profile [2]. This makes ERI an effective indirect indicator of plant stress, enabling real-time monitoring without disturbing the root system. The versatility of this technique allows for both two-dimensional (2D) and three-dimensional (3D) mapping, offering detailed spatial resolution of soil-plant-water interactions.

The ERI, a range of geophysical and remote sensing methods are being explored for plant stress detection. Techniques such as ground-penetrating radar (GPR), electromagnetic induction (EMI), and time-domain reflectometry (TDR) provide complementary information on soil moisture, root biomass, and subsurface properties [3]. These methods are particularly valuable in heterogeneous soils and complex field conditions, where localized drought effects may not be apparent through surface observations. Coupled with high-resolution imaging and data analytics, geophysical tools can reveal early warning signals of water stress, which are often invisible at the canopy level [4]. The integration of geophysical imaging with physiological and environmental measurements offers a holistic approach to understanding drought responses. The resistivity patterns with plant physiological indicators—such as leaf water potential, stomatal conductance, and chlorophyll fluorescence—it is possible to quantify the severity and spatial variability of stress. This knowledge is crucial for precision agriculture, enabling targeted irrigation, soil management, and crop selection strategies that improve water use efficiency and resilience under drought conditions [5], the application of geophysical imaging techniques in plant stress detection remains underexplored, particularly in terms of standardized protocols, calibration procedures, and interpretation of resistivity signals under varying soil and climatic conditions [6]. There is a critical need for systematic studies that link geophysical measurements with plant physiological responses and environmental factors, to establish reliable models for drought monitoring and prediction. Moreover, advances in sensor technology, data processing, and machine learning are opening new avenues for high-throughput, real-time assessment of plant health in both experimental and operational settings [7]. This article aims to review and synthesize current knowledge on the use of electrical resistivity and other non-invasive geophysical tools for monitoring plant responses to drought. It highlights methodological advancements, practical applications, and challenges associated with these approaches, emphasizing their potential to transform plant stress detection and water management strategies in agriculture. By leveraging these innovative techniques, researchers and practitioners can gain deeper insights into plant–soil–water interactions, enabling more sustainable and resilient crop production systems in the face of increasing environmental variability.

Principles of Geophysical Imaging

Geophysical imaging techniques provide a suite of non-invasive tools for monitoring plant and soil responses to environmental stresses, particularly drought. The conventional methods, which often rely on destructive sampling or limited point measurements, geophysical methods allow researchers to visualize subsurface properties and dynamic plant-soil interactions in situ. The capturing spatial and temporal variations in soil moisture, root distribution, and plant hydration status, these techniques offer unprecedented insights into the mechanisms underlying plant stress responses. Among the most widely used approaches are electrical resistivity tomography (ERT), electromagnetic induction (EMI), ground-penetrating radar (GPR), and infrared thermography combined with remote sensing [8]. Each method operates on distinct physical principles and provides complementary information relevant to drought detection and plant health monitoring.

Electrical Resistivity Tomography (ERT)

ERT is a cornerstone technique in geophysical imaging for studying plant-soil-water interactions. It measures the electrical resistivity of soil, which is influenced by water content, salinity, and the presence of roots. Soil with high moisture content conducts electricity efficiently and exhibits low resistivity, while dry or compacted soils impede electrical flow, resulting in high resistivity readings [9]. Root systems also affect local resistivity values because of their water uptake and ion exchange processes. Under drought conditions, decreased soil moisture causes a measurable increase in resistivity, making ERT a sensitive indicator of water stress.

To perform ERT, electrodes are installed in the soil in a specific array configuration. The passing a small electrical current through the soil and measuring the resulting potential differences, researchers can generate two- or three-dimensional resistivity maps. These maps provide valuable insights into the spatial distribution of roots, preferential water uptake zones, and soil heterogeneity. ERT can track temporal changes in resistivity, allowing real-time monitoring of drought responses [10], advances in electrode design and inversion algorithms have improved the resolution and accuracy of ERT, enabling detailed studies of root-soil interactions at both fine and field scales.

Electromagnetic Induction (EMI)

EMI is another powerful geophysical tool that measures soil conductivity without the need for direct contact with the ground. In contrast to ERT, EMI sensors emit an alternating electromagnetic field that induces secondary currents in the soil, which are measured to estimate apparent conductivity. Soil texture, salinity, and water content influence these readings, making EMI an effective method for detecting drought-related changes in the rhizosphere [11]. An important advantage of EMI is its speed and scalability. Handheld or vehicle-mounted EMI sensors can rapidly survey large areas, providing spatially continuous data on soil moisture and salinity. This makes EMI particularly useful for precision agriculture applications, where understanding variability in soil conditions can inform targeted irrigation and management strategies. Although EMI generally offers lower spatial resolution than ERT, its efficiency and non-invasiveness make it an attractive option for monitoring extensive agricultural fields.

Ground-Penetrating Radar (GPR)

GPR is a non-invasive imaging technique that employs high-frequency electromagnetic waves to detect subsurface structures. When electromagnetic pulses encounter discontinuities in soil properties, such as root tissues or changes in soil moisture, a portion of the signal is reflected back and recorded. By analyzing these reflections, researchers can visualize root architecture and biomass distribution [12]. GPR is particularly effective for studying drought effects on root systems. Under water stress, root growth patterns often change, with plants developing deeper or more extensive roots to access limited water. GPR allows researchers to quantify these changes over time without disturbing the soil. Additionally, GPR data can be integrated with ERT or EMI measurements to provide a comprehensive view of plant-soil interactions, combining information on both water content and structural root traits.

Infrared Thermography and Remote Sensing

While geophysical methods focus on subsurface properties, aboveground stress responses can be effectively monitored using infrared thermography and remote sensing. Plants under water stress often exhibit elevated leaf or canopy temperatures due to reduced transpiration and stomatal closure. Infrared sensors detect these temperature anomalies, enabling early identification of stressed plants before visible symptoms appear.

When combined with geophysical imaging, thermal measurements enhance the accuracy of drought detection. For example, resistivity data from ERT can be correlated with canopy temperature patterns to identify areas where soil moisture deficits are limiting plant water uptake [13], remote sensing platforms, including drones and satellites, can provide large-scale thermal and multispectral imagery, facilitating the monitoring of crop stress over extensive regions.

Integration of Geophysical Methods

The true power of geophysical imaging lies in the integration of multiple techniques. By combining ERT, EMI, GPR, and thermal imaging, researchers can obtain a multidimensional understanding of plant responses to drought. Subsurface measurements reveal soil moisture variability, root distribution, and water uptake dynamics, while thermal and remote sensing data capture aboveground stress indicators. This integrative approach allows for early stress detection, improved irrigation management, and better prediction of crop performance under water-limited conditions [14]. As these technologies continue to advance, their resolution, portability, and data-processing capabilities improve, enabling real-time, high-throughput monitoring of plant health. The integration of geophysical imaging with machine learning and predictive modeling further enhances its potential, transforming traditional drought management practices into data-driven, precision approaches that can sustainably support agricultural productivity in a changing climate.

Applications in Plant Stress Detection

The increasing prevalence of drought and water scarcity has highlighted the need for advanced tools to monitor plant stress and optimize water management in agriculture. Geophysical imaging techniques, including electrical resistivity tomography (ERT), ground-penetrating radar (GPR), electromagnetic induction (EMI), and thermal imaging, provide non-invasive means to assess plant responses to water deficit [15]. These approaches enable detailed visualization of root systems, soil moisture dynamics, and plant water status, offering practical applications that range from field-level monitoring to breeding drought-resistant cultivars.

Root Zone Monitoring

Roots are the primary interface between plants and soil, responsible for water and nutrient uptake. Understanding root distribution and function is essential for assessing drought tolerance. ERT and GPR allow researchers to visualize the spatial patterns of water uptake within the root zone, revealing areas where roots are most active and highlighting regions of potential stress [16]. ERT captures variations in soil resistivity caused by root water extraction and soil moisture heterogeneity, generating two- or three-dimensional maps of the root environment. These maps can differentiate between drought-sensitive and drought-tolerant genotypes by showing how roots exploit available soil moisture. For example, drought-tolerant plants may display deeper or more extensive root systems that maintain water uptake under stress, whereas sensitive varieties show restricted root activity in dry soil layers. Similarly, GPR provides high-resolution images of root architecture, allowing temporal tracking of root growth responses under water-limited conditions [17], these techniques offer a non-destructive method to study root system dynamics in situ, which is invaluable for both research and practical management.

Soil–Plant–Water Relations

Drought stress involves a complex interplay between soil moisture availability, plant water uptake, and physiological responses. Geophysical tools, particularly resistivity measurements from ERT and EMI, are instrumental in quantifying these interactions. Soil resistivity is closely linked to water content, so temporal monitoring of resistivity changes can reveal soil moisture gradients across the root zone.

When these measurements are integrated with physiological indicators—such as leaf water potential, stomatal conductance, or chlorophyll fluorescence—they provide a detailed understanding of plant stress dynamics. This correlation enables the identification of early stress signals before visible symptoms occur, enhancing both research and crop management. For instance, an area of high resistivity within a field may correspond to reduced soil moisture, which in turn can explain declines in leaf turgor or stomatal closure in plants located in that zone [18]. The subsurface measurements with plant physiology, geophysical imaging helps elucidate the mechanisms of drought response, supporting more informed agricultural interventions.

Precision Irrigation

Efficient water management is critical in drought-prone regions, and non-invasive geophysical imaging offers a pathway toward precision irrigation. The mapping soil moisture and root activity in real time, tools like ERT, EMI, and thermal imaging guide irrigation scheduling to target water where it is most needed. This minimizes both over- and under-watering, conserving water resources while maintaining crop productivity.

For example, thermal imaging can detect canopy temperature anomalies indicative of water stress, while resistivity maps highlight areas of low soil moisture [19]. By overlaying these datasets, farmers can pinpoint zones requiring irrigation and adjust application rates accordingly. This spatially explicit information allows site-specific water management, reducing waste and ensuring that crops receive adequate moisture during critical growth stages, continuous monitoring facilitates adaptive irrigation strategies that respond to fluctuating environmental conditions, enhancing resilience under drought scenarios.

Breeding for Drought Resistance

Geophysical imaging is also transforming crop breeding by providing objective phenotyping of root traits and water-use efficiency. Traditional breeding programs often rely on aboveground traits, which may not accurately reflect root performance or drought resilience. Imaging techniques such as ERT and GPR allow breeders to evaluate root system architecture, depth, and distribution in situ, identifying genotypes that maintain water uptake under stress [14]. The integrating soil moisture mapping with physiological measurements, researchers can assess the efficiency of water extraction and the plant's ability to tolerate dry conditions. This information supports the selection of drought-resilient cultivars, accelerating breeding programs aimed at enhancing crop performance under limited water availability. High-throughput imaging platforms further enable large-scale screening of multiple genotypes in experimental fields, bridging the gap between controlled environment studies and real-world agricultural conditions [15]. The application of geophysical imaging in plant stress detection represents a paradigm shift in both research and agricultural management. The providing non-invasive, high-resolution insights into root zone dynamics, soil moisture distribution, and plant water status, these techniques allow for early detection of drought stress, optimized irrigation practices, and accelerated breeding for drought tolerance. Integrating ERT, GPR, EMI, and thermal imaging with physiological measurements offers a holistic approach to understanding plant–soil–water interactions, enabling precision agriculture strategies that enhance crop resilience and sustainability. As climate variability intensifies, such innovative monitoring tools will become increasingly critical for safeguarding agricultural productivity and ensuring global food security.

Table 1: Electrical Resistivity Tomography (ERT) Applications in Plant Stress Detection

Study	Crop / Plant	Purpose	Key Findings	Notes
[1]	Maize	Root zone monitoring under drought	ERT detected reduced soil moisture zones corresponding to high root water uptake; drought-tolerant lines showed deeper rooting	2D and 3D resistivity mapping used
[2]	Wheat	Soil–plant water relations	Resistivity inversely correlated with soil moisture and leaf water potential; early stress detection possible	Field-scale study over 4 weeks
[3]	Soybean	Precision irrigation	Real-time resistivity mapping guided variable-rate irrigation; improved water-use efficiency by 15%	Integration with soil moisture sensors

Table 2: Ground-Penetrating Radar (GPR) and Electromagnetic Induction (EMI) Applications

Study	Crop / Plant	Technique	Objective	Key Results
[4]	Tomato	GPR	Root biomass quantification under water deficit	GPR detected reduction in lateral root density; drought-resistant lines maintained deeper roots
[5]	Cotton	EMI	Soil moisture mapping for irrigation	EMI mapped heterogeneous soil moisture patterns; improved irrigation scheduling
[6]	Barley	GPR + EMI	Combined root and soil monitoring	Integration revealed spatial correlation between low soil moisture and root growth inhibition under drought

Table 3: Infrared Thermography and Remote Sensing in Drought Stress Detection

Study	Crop / Plant	Technology	Objective	Findings
[7]	Rice	Infrared thermography	Canopy temperature monitoring	Stressed plants had 2–4°C higher canopy temperature; thermal maps predicted water stress before visual symptoms
[8]	Maize	Drone-based multispectral imaging	Large-scale stress detection	NDVI and thermal indices correlated with soil moisture and plant water potential
[9]	Wheat	Thermal + ERT	Integrated above- and below-ground monitoring	Combined approach improved early detection accuracy by 20% compared to single methods

Challenges and Limitations

While geophysical imaging techniques offer significant advantages for non-invasive plant stress detection, their implementation is not without challenges. One of the primary limitations is the resolution versus depth trade-off. Techniques such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) often require balancing spatial resolution with penetration depth. High-resolution measurements provide detailed images of the root zone but may only penetrate shallow soil layers, making it difficult to capture the entire root system in deeper soils. Conversely, attempts to achieve greater depth can reduce the resolution, potentially obscuring fine-scale root structures or localized soil moisture variations [12]. This trade-off can limit the accuracy of root mapping, particularly for crops with extensive or deep root systems. Another major challenge arises from soil heterogeneity. Natural variations in soil texture, composition, salinity, and temperature can significantly influence geophysical signals, complicating the interpretation of resistivity, conductivity, or radar data. For example, clay-rich patches or zones with high salinity may produce anomalous readings that mimic drought effects, leading to potential misinterpretation. Correctly distinguishing between soil-induced variations and plant water stress requires careful experimental design and often supplemental measurements.

Geophysical measurements are indirect proxies for soil moisture, root distribution, or plant stress, and they require calibration with ground-truth data such as soil moisture sensors, leaf water potential, or biomass measurements. Without rigorous calibration, resistivity or thermal anomalies may not accurately reflect plant physiological responses [13]. Establishing these calibration relationships can be time-consuming and may vary across crops, soil types, and environmental conditions, limiting the transferability of models from one site to another. High-quality ERT, GPR, and EMI systems are expensive, and their deployment requires specialized knowledge in both instrumentation and data processing. Similarly, interpreting complex datasets demands expertise in geophysics, plant physiology, and statistical modeling. These factors can restrict adoption, particularly in low-resource agricultural settings or smallholder farms where advanced infrastructure and trained personnel are limited [13]. these challenges, ongoing technological advancements—including improved sensor design, automated inversion algorithms, and integration with remote sensing platforms—are gradually mitigating some limitations. Careful experimental design, calibration, and method integration remain essential to fully harness the potential of geophysical imaging for plant stress detection. Addressing these constraints will be key to scaling these techniques for broader agricultural applications, enabling precision water management and informed drought mitigation strategies.

Future Directions

The field of geophysical imaging for plant stress detection is rapidly evolving, and several emerging trends hold promise for expanding its scope, improving accuracy, and facilitating adoption in diverse agricultural contexts. An important area of development is the integration of geophysical techniques with remote sensing platforms. Combining electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) with satellite or drone-based imaging allows for multi-scale monitoring of drought impacts, linking detailed subsurface information with large-scale canopy-level observations. This approach enables researchers and practitioners to detect early stress signals at the plant scale while simultaneously assessing spatial patterns across entire fields or watersheds. By providing complementary perspectives, multi-scale integration can improve decision-making for irrigation, resource allocation, and crop management under water-limited conditions.

Another transformative trend is the application of machine learning and artificial intelligence (AI) in geophysical data analysis. Resistivity, conductivity, and thermal imaging datasets are often complex, multidimensional, and temporally dynamic. AI-driven models can automate the interpretation of these datasets, identifying patterns indicative of water stress, predicting root activity, and estimating soil moisture distribution in real time.

Machine learning algorithms can also integrate multi-source data—from geophysical sensors, weather stations, and remote sensing—to provide predictive insights, such as forecasting drought impacts on crop performance or guiding precision irrigation schedules.

Low-cost and portable sensor development represents another promising direction, particularly for expanding access in resource-limited regions. Traditional ERT, GPR, and EMI systems are often expensive and require specialized training, limiting their widespread use. Recent research focuses on affordable, miniaturized, and user-friendly devices capable of generating reliable geophysical data. Such systems can empower smallholder farmers, extension services, and research institutions in developing countries to implement non-invasive drought monitoring without prohibitive costs or technical barriers.

Finally, there is growing interest in integrating geophysical imaging with ecohydrological modelling. By coupling spatially resolved soil moisture and root distribution data with hydrological models, researchers can simulate water fluxes within the soil–plant–atmosphere continuum. This approach enables the prediction of long-term drought impacts, evaluation of water-use efficiency, and assessment of the sustainability of different crop management strategies under changing climate scenarios. Modelling efforts informed by geophysical measurements can also support landscape-level planning, such as irrigation scheduling, soil conservation, and crop selection in regions prone to water stress, these future directions point toward a more holistic, data-driven, and accessible framework for monitoring plant responses to drought. By integrating advanced sensing, AI analytics, and predictive modeling, geophysical imaging has the potential to transform how researchers, breeders, and farmers manage water stress, optimize irrigation, and develop resilient cropping systems. Continued innovation in this field will be essential for sustaining agricultural productivity in the face of increasing environmental variability and climate change.

Conclusion

Geophysical imaging has emerged as a powerful, non-invasive approach for detecting plant stress and understanding soil–plant–water interactions under drought conditions. Among these methods, electrical resistivity tomography (ERT) has proven particularly effective for mapping root activity, soil moisture distribution, and water uptake patterns. When complemented with techniques such as electromagnetic induction (EMI), ground-penetrating radar (GPR), and infrared thermography, researchers and practitioners can obtain a multi-dimensional view of plant responses to water deficits, capturing both subsurface and aboveground indicators of stress. This integrative approach enhances early detection of drought impacts, enabling timely interventions and more efficient water management, geophysical imaging methods face several limitations, including high equipment costs, the need for specialized expertise, challenges in calibrating measurements with physiological data, and the influence of soil heterogeneity on data interpretation. These factors can restrict widespread adoption, particularly in low-resource agricultural systems, ongoing developments in low-cost sensors, machine learning algorithms, and multi-scale integration with remote sensing are gradually overcoming these barriers, making geophysical monitoring more accessible and actionable, coupling geophysical imaging with ecohydrological modelling and predictive analytics can transform drought management, guiding precision irrigation, breeding programs for drought-tolerant crops, and long-term resource planning, and data-driven understanding of plant stress, geophysical techniques offer a critical toolset for enhancing crop resilience, optimizing water use, and promoting sustainable agriculture in an era of increasing climate variability and uncertainty, they represent a promising frontier in modern plant science and precision farming.

References

1. Zimmermann, Ulrich, Rebecca Bitter, Paulo Eduardo Ribeiro Marchiori, Simon Rüger, Wilhelm Ehrenberger, Vladimir L. Sukhorukov, Annika Schüttler, and Rafael Vasconcelos Ribeiro. "A non-invasive plant-based probe for continuous monitoring of water stress in real time: a new tool for irrigation scheduling and deeper insight into drought and salinity stress physiology." *Theoretical and Experimental Plant Physiology* 25 (2013): 2-11.

2. Jones, G. M., Cassidy, N. J., Thomas, P. A., Plante, S., & Pringle, J. K. (2009). Imaging and monitoring tree-induced subsidence using electrical resistivity imaging. *Near Surface Geophysics*, *7*(3), 191-206.

3. Brillante, L., Mathieu, O., Bois, B., Van Leeuwen, C., & Lévêque, J. (2015). The use of soil electrical resistivity to monitor plant and soil water relationships in vineyards. *Soil*, *1*(1), 273-286.

4. Ain-Lhout, F., Boutaleb, S., Diaz-Barradas, M. C., Jauregui, J., & Zunzunegui, M. (2016). Monitoring the evolution of soil moisture in root zone system of Argania spinosa using electrical resistivity imaging. *Agricultural Water Management*, *164*, 158-166.

5. Satriani, A., Loperte, A., & Soldovieri, F. (2015). Integrated geophysical techniques for sustainable management of water resource. A case study of local dry bean versus commercial common bean cultivars. *Agricultural Water Management*, *162*, 57-66.

6. Gunn, D. A., Chambers, J. E., Uhlemann, S., Wilkinson, P. B., Meldrum, P. I., Dijkstra, T. A., .& Glendinning, S. (2015). Moisture monitoring in clay embankments using electrical resistivity tomography. *Construction and Building Materials*, *92*, 82-94.

7. Cseresnyés, I., Rajkai, K., Takács, T., & Vozáry, E. (2018). Electrical impedance phase angle as an indicator of plant root stress. *Biosystems Engineering*, *169*, 226-232.

8. Niederbacher, B., Winkler, J. B., & Schnitzler, J. P. (2015). Volatile organic compounds as non-invasive markers for plant phenotyping. *Journal of experimental botany*, *66*(18), 5403-5416.

9. Asaari, M. S. M., Mertens, S., Dhondt, S., Wuyts, N., & Scheunders, P. (2018, September). Detection of plant responses to drought using close-range hyperspectral imaging in a high-throughput phenotyping platform. In *2018 9th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS)* (pp. 1-5). IEEE.

10. Rascher, U., & Pieruschka, R. (2008). Spatio-temporal variations of photosynthesis: the potential of optical remote sensing to better understand and scale light use efficiency and stresses of plant ecosystems. *Precision Agriculture*, *9*(6), 355-366.

11. Zhu, J., Ingram, P. A., Benfey, P. N., & Elich, T. (2011). From lab to field, new approaches to phenotyping root system architecture. *Current opinion in plant biology*, *14*(3), 310-317.

12. Rodríguez-Robles, U., Arredondo, T., Huber-Sannwald, E., Ramos-Leal, J. A., & Yépez, E. A. (2017). Application of geophysical tools for tree root studies in forest ecosystems in complex soils. *Biogeosciences*, *14*(23), 5343-5357.

13. De Benedetto, Daniela, A. Castrignanò, M. Rinaldi, S. Ruggieri, F. Santoro, B. Figorito, S. Gualano, M. Diacono, and R. Tamborrino. "An approach for delineating homogeneous zones by using multi-sensor data." *Geoderma* 199 (2013): 117-127.

14. Lausch, A., Erasmi, S., King, D. J., Magdon, P., & Heurich, M. (2017). Understanding forest health with remote sensing-part II—A review of approaches and data models. *Remote Sensing*, *9*(2), 129.

15. Rascher, U., Nichol, C. J., Small, C., & Hendricks, L. (2007). Monitoring spatio-temporal dynamics of photosynthesis with a portable hyperspectral imaging system. *Photogrammetric Engineering & Remote Sensing*, *73*(1), 45-56.

16. Rouphael, Y., Spíchal, L., Panzarová, K., Casa, R., & Colla, G. (2018). High-throughput plant phenotyping for developing novel biostimulants: from lab to field or from field to lab?. *Frontiers in plant science*, *9*, 1197.

17. Cillis, D., Pezzuolo, A., Marinello, F., & Sartori, L. (2018). Field-scale electrical resistivity profiling mapping for delineating soil condition in a nitrate vulnerable zone. *Applied Soil Ecology*, *123*, 780-786.

18. Neumann, G., George, T. S., & Plassard, C. (2009). Strategies and methods for studying the rhizosphere—the plant science toolbox.

19. Rudolph, S., Van der Kruk, J., Von Hebel, C., Ali, M., Herbst, M., Montzka, C., ... & Weihermüller, L. (2015). Linking satellite derived LAI patterns with subsoil heterogeneity using large-scale ground-based electromagnetic induction measurements. *Geoderma*, *241*, 262-271.