

Advancing soil hydrological monitoring: Innovations and challenges in distributed acoustic sensing

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The porous architecture of soil constitutes a dynamic spatial arrangement that is continuously modified by anthropogenic drivers, such as tillage and mechanical compaction. These disturbances modulate the soil's capacity for water retention, nutrient cycling, and energy flux regulation.¹ Quantifying these dynamic changes has remained challenging because conventional monitoring technologies have historically forced a compromise between spatial coverage and temporal resolution (Figure 1A).

THE PERSISTENT SPATIOTEMPORAL SCALE GAP IN HYDROLOGICAL MONITORING

Microscale imaging provides three-dimensional reconstructions of soil pore networks but commonly requires extracting samples, limiting observation of transient field dynamics. In-situ sensors provide frequent measurements under natural conditions but sample small volume may omit preferential flow pathways or compacted layers. Remote sensing supplies spatially continuous information on near-surface soil moisture, vegetation condition, land-surface temperature, and evapotranspiration over broad areas, but current products generally cannot resolve plot-scale subsurface hydromechanical processes. The methods are therefore complementary: imaging and point sensors provide local structure and validation, Distributed Acoustic Sensing (DAS) supplies dense field-scale seismic observations, and remote sensing places those observations in their landscape context. (Figures 1A-B).

AGROSEISMOLOGY VIA DISTRIBUTED ACOUSTIC SENSING

Shi et al.² demonstrated the potential of DAS within agroseismology, here defined as the use of seismic observations and model-based inference to investigate hydromechanical processes in agricultural soils. DAS interrogates Rayleigh backscatter in fiber-optic cables; optical phase changes are converted to axial strain or strain rate along the cable. Hydrological variables are inferred only through changes in seismic attributes, such as relative velocity, attenuation, or dispersion, together with forcing data and hydromechanical models.³

Conditional scale bridging

The farm data resolved sharp post-rain velocity drops and spatially variable recovery across management treatments. However, hydrological interpretation remained conditional on the rainfall proxy, water-balance assumptions, model class, parameter calibration, and independent checks.

Continuous multiscale sampling

Shi et al.'s raw strain-rate acquisition (2 kHz), rainfall proxy (one minute), and relative-velocity series (five minutes) operate at different temporal resolutions. The 3.19 m channels sampled one linear farm transect. Longer deployments are technically possible, but tested extent, channel spacing, derived-product cadence, source field, and coupling should be reported separately.

Model-constrained hydromechanical coupling

The shallow cable installation was minimally intrusive rather than strictly noninvasive. Ambient-noise autocorrelation and temporal stretching produced relative velocity change; a precipitation-drainage-evapotranspiration balance produced saturation; and a Hertz-Mindlin model with static or dynamic capillarity mapped saturation to stiffness (Figure 1C). Each arrow adds assumptions, so saturation and flux partitioning remain model-

constrained estimates.

METHODOLOGICAL AND TECHNICAL CHALLENGES OF AGROSEISMOLOGY

The central challenge is signal non-uniqueness: similar DAS responses can arise from water redistribution, temperature, structural change, biological activity, source variability, or cable coupling. Study-specific issues in Shi et al. include the absence of collocated soil moisture sensors, use of relative-humidity as proxy for a shallow-sensitivity interpretation,² fitted water balance and capillary parameters, and an empirical Disturbance Index (Figure 1C). Environmental confounding, coupling stability, and one-dimensional sampling are broader challenges for agricultural DAS.

Theoretical simplifications

In their framework, fluid saturation is isolated as the primary driver of effective elastic moduli changes while the solid matrix and soil porosity are assumed constant over short timescales. The Hertz-Mindlin contact theory idealizes soil as a granular medium. Surface-wave studies show that capillary forces affect dispersion in partially saturated soils,⁴ but mixed soils and disturbance-driven structural changes may violate these assumptions.

Depth and biological limits

The model assumes horizontally homogeneous and vertically averaged soil properties confined to the top 10 centimeters. This inherently neglects deeper root-zone dynamics and localized subsurface heterogeneity. It can therefore inform relative near-surface responses under comparable conditions, but it does not yet establish retrieval of absolute root-zone storage, plant water uptake, crop water stress, or irrigation demand.

Validation limitations

Relative air humidity in the original experiment captures atmospheric drying but is not an independent benchmark for soil water content, matric potential, or root-zone availability. Future field tests should pair DAS with collocated profile soil moisture and matric potential sensors, soil temperature, bulk density and structure observations, and coupling diagnostics. These data are needed to test whether changes attributed to hydrology are distinguishable from other causes.

Site-specific calibration

In Shi et al. study,² the empirical Disturbance Index parameterizes tillage depth and tire pressure at one farm but not an intrinsic property of DAS. Transferability should be evaluated with site-held-out tests spanning soil texture, management, installation, and source conditions, with uncertainty reported for each inferred variable.

General signal confounding

DAS captures complex signals reflecting strain, vibration, and temperature. In dynamic natural environments, it is challenging to completely decouple seismic velocity changes caused by water saturation and pore pressure from structural reconfigurations induced by root growth, bioturbation, or diurnal thermoelastic effects. Reliable hydrological interpretation therefore requires explicit confounder measurements, physical constraints, and uncertainty analysis rather than signal density alone.

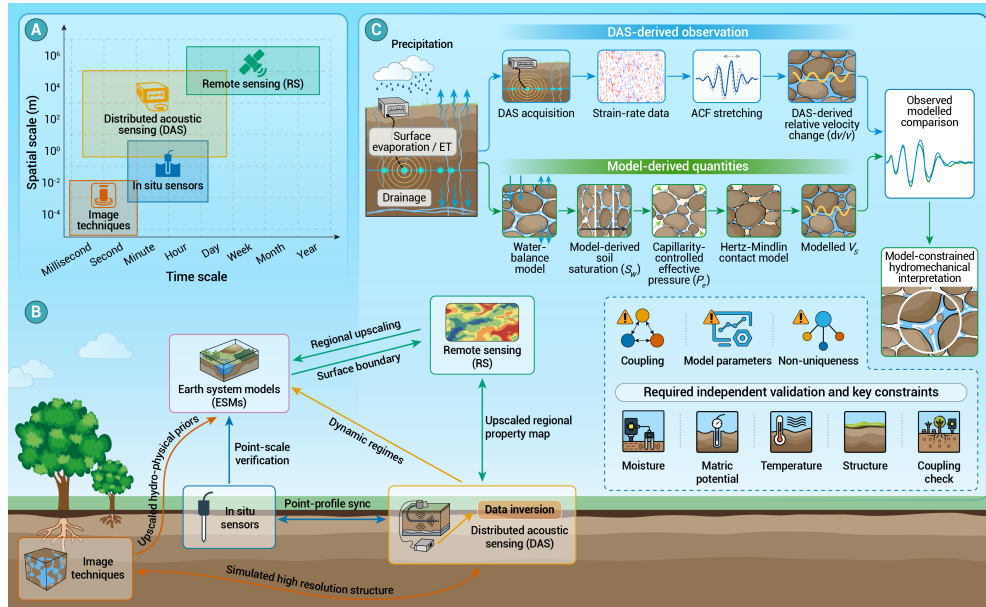


Figure 1. A multiscale framework for DAS-enabled soil hydrological monitoring and model-constrained inference.

tivity with improved load-impact resistance against heavy farming equipment. Combining these material advancements with low-disturbance implantation techniques may facilitate the construction of long-term, stable physical transmission channels, providing the critical durability needed for the widespread agricultural application of DAS.

Question-matched observation networks

A single transect may be sufficient to detect a rainfall or irrigation wetting front along one dimension. Crossed or multi-azimuth transects, with adequate source illumination, are needed to distinguish lateral redistribution from vertical change. Estimating root-zone storage would additionally require depth-resolved

Mechanical coupling vulnerabilities

The long-term success of this observational system relies on maintaining consistent mechanical contact between the fiber-optic cable and the soil matrix. Wetting-drying cycles, frost heaving, and routine machinery operations can easily compromise acoustic integrity and data quality over time. Long-term deployments therefore require protected installation, repeatable coupling diagnostics, and maintenance records.

One-dimensional sensing in three-dimensional anisotropic soils

While DAS excels in capturing linear, one-dimensional spatial data over vast distance, it struggles to capture the three-dimensional, anisotropic nature of soils. Current wavefield inversion algorithms often simplify volumetric dynamics, failing to completely distinguish vertical from horizontal feedback. Consequently, applying these inversions to shallow one-dimensional cables may risk misinterpreting highly localized near-surface artifacts as broader structural changes at depth.

POTENTIAL ADVANCEMENTS FOR DAS MONITORING

These limits call for targeted validation and deployment rather than a universal inversion workflow. Near-term progress is most likely from multi-sensor calibration, physically constrained learning, durable installation, and networks matched to specific hydrological questions.

Multi-sensor integrated frameworks

DAS should be integrated with in-situ sensors and remote sensing to assemble training and validation datasets across soil types, climates, installation methods, and management regimes. Fusing these diverse datasets can test transferability and robustness of inversion frameworks across different soils and management systems.

AI-assisted signal isolation and edge computing

Machine learning models could learn mappings between waveform attributes and independently measured hydromechanical states, or classify noise and coupling changes. Training labels must come from collocated measurements such as soil moisture, matric potential, temperature, and structural or coupling observations. Site-held-out validation and calibrated uncertainty are essential; without them, models remain site-specific signal filters rather than general hydrological inversions. Edge computing now allows for the on-site extraction of low-volume, process-level data products without retaining massive raw waveforms.⁵

Durable sensing materials and deployment technologies

Innovations such as specialized fibers with surface micro-textures could enhance coupling stability within complex, dynamic environments. Establishing differentiated protection design criteria will help balance acoustic sensi-

moisture or matric-potential profiles and data assimilation. These designs remain hypotheses for field testing, not established minimum specifications.

CONCLUSION

Shi et al.² showed that DAS can fill part of the observational gap between point sensors and remote sensing, but dense sampling alone does not yield hydrological information. The near-term opportunity is validated field-scale observation of relative near-surface wetting, drying, and management-induced hydromechanical change. Translating these responses into root-zone storage, crop-water status, or decision variables will require multi-sensor calibration, cross-site tests, and uncertainty-aware models. DAS may eventually provide benchmarks for Earth system models, but only after inferred variables are shown to transfer across soils, vegetation, management, and scale.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.