Agroseismology and the impact of farming practices on soil hydrodynamics

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Authors: Qibin Shi (*,[1,2]), David R. Montgomery[1], Abigail L.S. Swann[3,4], Nicoleta C. Cristea[5,6], Ethan Williams[1,7], Nan You[8], Simon Jeffery[9,10], Joe Collins[9,10], Ana Prada Barrio[9], Paula A. Misiewicz[9], Tarje Nissen-Meyer[10,11], and Marine A. Denolle (*,[1])

Affiliations:

[1] Department of Earth and Space Sciences, University of Washington; Seattle, USA.

[2] Department of Earth, Environmental and Planetary Sciences, Rice University; Houston, USA.

[3] Department of Atmospheric and Climate Science, University of Washington; Seattle, USA.

[4] Department of Biology, University of Washington; Seattle, USA.

[5] Department of Civil & Environmental Engineering, University of Washington; Seattle, USA.

[6] eScience Institute, University of Washington, Seattle, WA, USA.

[7] Department of Earth and Planetary Sciences, University of California; Santa Cruz, USA.

[8] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University; West Lafayette, USA.

[9] Agriculture and Environment Department, Harper Adams University; Newport, UK.

[10] Earth Rover Program; London, UK.

[11] Department of Mathematics and Statistics, University of Exeter; Exeter, UK.

*Corresponding author. Email: qshi@rice.edu, mdenolle@uw.edu

Abstract:

Impacts of farming practices on soil hydrodynamics are central to understanding agricultural landscapes covering almost half of the world's habitable land. Combining observations from distributed acoustic sensing with physics-based hydromechanical modeling, we tracked minute-resolution, meter-scale seismic and hydrological changes across agricultural fields with controlled histories of tillage and compaction. We show that dynamic capillary effects in soil govern transient stiffness and moisture redistribution in disturbed soils, producing sharp post-rain velocity drops from near-surface saturation and large hysteretic velocity rebounds driven by evapotranspiration. Our seismically inverted estimates of saturation reveal how disturbance alters flux partitioning and storage, establishing agroseismology and distributed acoustic sensing as scalable, non-invasive probes of soil hydromechanics with the potential to improve Earth system models, land management, and hazard resilience.

Main Text:

Soils form our planet's thin yet vital skin—a dynamic interface where the atmosphere meets solid Earth, governing the exchange of water, carbon, and energy while underpinning agricultural productivity, climate regulation, and landscape stability. At the heart of these functions lies the porous architecture of soil, which controls water retention and movement, thereby shaping surface and subsurface hydrological responses (*1*). Natural structures that develop over decades through intertwined biological and geomorphological processes can be disrupted by land management with far-reaching consequences for subsurface water dynamics central to soil ecosystems (*2*), evapotranspiration and energy fluxes essential for land surface modeling and climate dynamics (*3*), mechanical properties relevant to geotechnical and earthquake engineering (*4*), and moisture availability and resilience in agriculture (*5*). Nevertheless, most land surface and hydrological models treat soil as a static medium, overlooking its time-varying properties (*6*) and the effects of repeated mechanical disturbance.

Current approaches of measuring soil hydrological response and properties include both ground-based methods using point measurements with *in-situ* sensors (e.g., pressure transducers, tensiometers, time-domain reflectometry, capacitance, impedance sensors, thermal probes (*6*)) and non-invasive sensing (e.g., cosmic-ray neutron sensing, global navigation satellite systems reflectometry, gamma-ray monitoring, ground-penetrating radar (*7*)). However, spatial heterogeneity complicates the scaling of ground-based measurements across large areas. Satellite and airborne sensing provide coarse (tens of kilometers) regional and global coverage (*8*), while higher-resolution products from synthetic aperture radar carry sub-kilometer spatial resolution (*9*, *10*) but suffer from low temporal resolution (days to months) and are sensitive to vegetation, surface roughness, and atmospheric noise, limiting their ability to resolve fine-scale and short-term soil moisture dynamics. Each approach trades spatial coverage for temporal resolution.

As structural changes in soils significantly influence stiffness and seismic wave speeds (*11*), seismological methods have recently emerged as a powerful tool for continuous, spatially distributed monitoring of subsurface hydromechanical properties from changes in seismic velocities (dv/v) that have been shown to vary with groundwater and soil moisture levels (*12*–*16*). Modeled as responses to pore pressure changes driven by rainfall diffusion (*12*, *14*) under the assumption of nonlinear elasticity in saturated media (*17*, *18*), such correlations have enabled empirical assessments of droughts (*13*, *16*, *19*, *20*). Yet, to date, the approach remains site-specific and requires local tuning to explain observations (e.g., (*18*)).

Distributed acoustic sensing (DAS) transforms standard fiber-optic cables into dense seismic arrays with meter-scale spatial resolution, sub-minute temporal resolution, and broad frequency sensitivity, allowing detection of shear-wave velocity changes linked to near-surface moisture variability and soil stiffness (*21*). The utilization of fiber-optic cables enables continuous monitoring of soil hydrodynamics over kilometers at meter-scale resolution, addressing the scale gap between traditional point sensors and remote sensing. Here, we leveraged DAS and hydromechanical modeling to characterize the seismic signature of soil in an experimental farm

where long-term tillage and compaction treatments have consistently altered soil structure. This experimental farm provides a rare opportunity to test how controlled disturbance regimes impact soil hydromechanics. By integrating DAS with physically grounded models, we unravel how dynamic soil properties mediate the coupling between water fluxes and mechanical stability, with fundamental implications for agriculture, land surface modeling, and geotechnical risk analysis.

Turning fiber-optic cables into soil-health sensor networks

From March 17 to 19, 2023, we conducted a DAS experiment at Harper Adams University, UK (52.782°N, 2.428°W) across 27 ~4-meter-wide plots, each receiving consistent combinations of tillage and compaction since 2011 (Fig. 1). Tillage had been applied at three depths commonly used in farming—no tillage, 10 cm, and 25 cm—while compaction had been imposed using two tire pressure levels—70 kPa for both front and rear tires, and 120 kPa for front and 150 kPa for rear tires. Soil porosity measurements confirmed significant spatial variability across the plots (Fig. 1B). We deployed a fiber-optic cable perpendicular to plot boundaries in a finger-wide trench, directly into the bare soil at ~2 cm depth to ensure good soil coupling (Fig. 1E). Using a Sintela Onyx 1.0 DAS interrogator, we recorded 40 hours of continuous ambient seismic data at 2 kHz sampling and 3.19 m channel spacing. Spectral analysis revealed one or two peaks: typically, a fundamental mode around 15–25 Hz and an overtone near 25–50 Hz (fig. S1), consistent with resonance from soft topsoil overlying stiff subsoil. These peak frequencies depend on topsoil thickness and depth-integrated shear-wave velocity (v_S) (*22*). Episodes of broadband seismic energy, including signals above 80 Hz, corresponded with rainfall and were consistent with precipitation rate as the dominant control at these frequencies (*23–25*), with additional influences from raindrop velocity (*25*) and droplet size (*23*). Simultaneously, we collected meteorological data from a weather station ~500 m from the farm, including air temperature, humidity, and hourly precipitation. Using the precipitation record, we calibrated DAS power spectral density in the 80–140 Hz band as a 1-minute resolution proxy rain gauge (Fig. 1F and fig. S2). Additional variables (cloud cover and wind speed) were obtained from another station ~700 m from the farm ((*22*) and fig. S3). Overall, daily rainfall ranged from 5–10 mm, temperature from 5–15°C, humidity from 60–95% and wind speed (10-meter height) from 1–10 m/s.

We detected temporal changes in seismic velocity (dv/v), primarily reflecting changes in v_S (*26*), using ambient noise auto-correlation functions (ACF; (*27*)) derived from DAS. ACFs were stable over 15-second windows and showed coherent evolution between 15–60 Hz across plots (Fig. 1G, figs. S4 and S5). A three-pass denoising and polynomial-fitting routine improved robustness, especially during rapid dv/v fluctuations (e.g., after rainfall; fig. S6). The resulting dv/v time series (e.g., Channel 18, hereafter as Ch 18; Fig.1G) showed clear negative correlation with soil water content: precipitation events (P1-P4) triggered sharp dv/v decreases, followed by gradual recovery during drying. The dv/v response varied spatially, with some plots showing up to 60% dv/v increase during drying (e.g., Ch 18; Fig. 1G), whereas others exhibited considerably lower

variability (e.g., Ch 33; fig. S5). We considered *precipitation*, *evapotranspiration*, and *drainage* as the primary processes driving soil moisture dynamics (*28*).

Physical models

To interpret the observed seismic velocity changes, we built models that link soil water saturation to shear-wave velocity by incorporating hysteretic, capillarity-controlled effective stress into Hertz-Mindlin contact theory (*29*). Soil water saturation, S_w, is defined as the volumetric fraction of water in pore space (*11*, *21*). Our framework combined two elements: (i) a hydrological model ***H(.)*** that captures how precipitation, evapotranspiration, and drainage control S_w, and (ii) a lithological model ***L(.)*** that translates saturation changes into stiffness and seismic velocity.

The lithological model ***L(.)*** accounts for the impact of varying S_w on v_S. We started with $v_S = \sqrt{\mu_{eff}/\rho}$, where both effective shear modulus μ_{eff} and density ρ depend on S_w. μ_{eff} derives from Hertz-Mindlin theory (*29*), incorporating grain contact mechanics and S_w -dependent effective pressure P_e (*22*). P_e includes a capillary suction, counteracted by gravity, enhancing soil frame rigidity. Static suction stiffens soils during drying, but only dynamic capillarity—stresses that depend on wetting or drying rates (*30*)—explains the observed short-term hysteresis in seismic responses of some channels (fig. S7). Following (*31*), the dynamic capillary effect arises from finite water redistribution times in the pore networks and is thus dependent on hydraulic conductivity and meteorological forcing.

The hydrological model ***H(.)*** tracks the balance between precipitation, drainage, and evapotranspiration, following (*28*): $S_w(t) = P(t) - Q(t) - ET(t)$, where P is precipitation, Q is vertical drainage, and ET is evapotranspiration. We parameterized the drainage with an exponential decay (~70-hour timescale) of the precipitation input, similar to a baseflow model (*32*), and estimated ET from weather data (Fig. 1F) using the Penman-Monteith equation (*33*), adjusted for treatment effects (*22*).

We tested the combined model $v_S = L[H(P, Q, ET)]$ against observed velocities $v^{obs} = v_{S,ref} * (1 + dv/v)$ taking $v_{S,ref}$ immediately after the P4 rainfall event. Clay- and sand-type soil textures represent endmember grain contacts: with more cohesive grain-to-grain contacts, clay defines the upper bound of stiffness, while sand defines the lower bound. In addition, we tested capillary models (their absence, or whether they are static or dynamic) across channels. The parameter space for dynamic capillary coefficients is shown in Table S1. We illustrate two contrasting responses to ET (March 18, 12:00; Fig. 2), which either exhibit strong temporal fluctuations at Ch 18 or do not show any at Ch 33. The substantial v_S rise of 60% at Ch 18 was reproduced by dynamic capillary pressure and a rapid decrease in S_w (as much as 50% in a single afternoon) driven by ET (Fig. 2B), whereas static capillary effects explained only about half. In contrast, Ch 33 showed low temporal variability (Fig. 2C) despite identical meteorological forcing. Other channels (e.g., Ch 44; fig. S8) showed intermediate variability, consistent with static capillary effects under high

hydrological variability. These stark differences, despite spatial proximity, indicate that structure shaped by tillage and compaction is a dominant control, motivating a direct analysis of hydrological variability across soil treatments.

Connecting hydrodynamics with soil structure

Based on our lithological model, moisture perturbations from a given hydrological process (e.g., drainage or evapotranspiration) are proportional to relative changes in v_S. This proportionality reflects variability in pore-fluid pressure, with additional contributions from capillary effects (*22*); Section 6: *Lithological Model* and fig. S9). The hydromechanical response is strongly modulated by structural alterations from tillage and compaction. In the seismic analysis, we identified four distinct styles of lithological responses that correspond to different combinations of tillage depth and compaction pressure (Fig. 3A). All styles exhibit varying degrees of evaporation and drainage shaped by specific near-surface regimes.

The primary contrast is between responses with negligible saturation changes over two days (Fig. 3A; green) and those exhibiting pronounced perturbations (Fig. 3A; red, orange, yellow). The former corresponds to little or no tillage and reflects an unsaturated flow regime in which precipitation or irrigation rapidly infiltrates into the vadose zone through well-connected pore and micropore networks. The latter is associated with deep tillage, high compaction, or both, conditions that disrupt pore connectivity, impede drainage, and promote transient near-surface saturation. Common causes of such disruption include a compacted “plow-pan” layer at tillage depth, which impedes vertical flow, and matrix collapse and macropore closure from mechanical disturbance and high compaction (*34*). Evidence from the correlation between air humidity and soil saturation beneath Ch 18 (Fig. 2A) indicates that moisture remained near the surface, without penetrating to depth, and provides a clear demonstration of impaired hydraulic connectivity. These alterations reduce permeability, limit infiltration depth, heighten sensitivity to surface evaporation, and promote runoff and consequently erosion. In undisturbed soils, pore networks enable infiltration to the root zone. In highly disturbed soils, reduced infiltration promotes near-surface saturation, increasing runoff and evaporation, and thus delivering less moisture to the root zone (Fig. 4).

Three different styles of saturated response reflected treatment intensity. First, deep tillage and high compaction both produced pronounced 5-hour evaporation and prolonged drainage, while the combination of moderate tillage and compaction showed little evaporation (Fig. 3B), shorter drainage durations, and slightly faster post-rain drainage (Fig. 3C). Insensitivity to evaporation may result in persistently high saturation, suppressing capillary effects (Fig. 2C). Second, evaporation rates also differed between extreme tillage and extreme compaction due to their distinct impacts on pore structure. High surface loading pressure from traffic (Fig. 3A, dotted contours) compacts near-surface soil, altering the vertical distribution of permeability and aggregate connectivity. Hence, under shallow tillage and high compaction, micropores dominate water flow, promoting prolonged “Stage I” evaporation supported by capillary rise and

maintaining hydraulic continuity to the surface. In contrast, deep tillage and low compaction may disrupt near-surface pore networks and produce less efficient "Stage II" evaporation, which is dominated by vapor diffusion from a receding drying front (*35*). In other words, seismic velocity changes are governed by capillary contributions, particularly dynamic, rate-dependent effects, which depend on how water is partitioned between micropores and macropores, features that are highly sensitive to mechanical disturbance and thus motivate a quantitative measure of disturbance across plots.

To quantify mechanical disturbance across plots, we parameterized tillage depth, T (cm), and compaction expressed as tire pressure, C (kPa), into a disturbance index (DI). We chose a product and power-law functional form $DI = T^n C^m$, normalized DI to between 0–1 and fit the cumulative drainage $\delta(dv/v)$ for the exponents via grid search. We found the best-fitting values of n = 0.22 and m = 0.96 (fig. S10) and show the spatial variation of these correlations in Fig. 3D. Our results confirm a strong impact of mechanical disturbance (Fig. 3A) on hydrological and hydromechanical variability, consistent with previous reports (*34*). We modeled v_S across DAS channels based on DI, which aligned with observed patterns in space and time (Fig. S11), demonstrating the compounding effects of tillage and compaction on soil structure.

High-DI soils (Fig. 3A; red, orange, yellow) have decreased pore connectivity, heightened capillary suction, and prolonged water redistribution. These dynamic capillary effects amplified the soil's response to atmospheric forcing, driving greater fluctuations in inter-particle stress and in shallow moisture content during cycles of rainfall and evaporation. Over time, these effects can contribute to pore-scale mechanical fatigue, likely weakening soil aggregates (*36*). Low-DI soils (Fig. 3A; green) maintain well-connected pores, promoting deep infiltration and capillary buffering, thereby stabilizing shallow moisture.

These hydraulic and hydromechanical effects are rooted in mechanical disturbances to the soil structure. The sensitivity of seismic velocity to water saturation enables us to observe, in situ and in real time, the coupling between pore connectivity, moisture retention, and hydrological redistribution. By capturing both rapid hydrological fluxes and slow mechanical recovery, our approach bridges the physical models proposed by hydrologists with the dynamic behavior observed in the field, revealing how soil structures profoundly influence hydrological function. These insights carry significant implications for guiding sustainable agriculture and water management, as well as for improving models of land surface fluxes, carbon cycling, greenhouse gas fluxes, and geotechnical risk across disturbed and undisturbed landscapes.

Implications for agriculture and soil health

This mechanistic insight is independent of sensing approaches, but its broader relevance depends on resolving how mechanical disturbance shapes plant–soil interactions over full growing seasons and across the root zone (~30–150 cm; (*37*)). Nonetheless, our results show that tillage-related disturbance impairs moisture retention and thus drought resilience, an effect pertinent to

agricultural sustainability. Hence, adopting low-disturbance practices (e.g., no- or low-till farming) can serve as a potential climate adaptation to preserve the soil's structural capacity to buffer against drought and seasonal water stress. Continuous DAS monitoring can provide seasonal and longer measures of hydrologic flux, though evolving surface conditions, variable coupling, and interruptions from farming operations remain practical challenges. DAS enables battery-free, permanent sensing with kilometer-scale reach from a single interrogator. In agricultural settings, fibers can be installed alongside and between planting rows, enabling minimally intrusive, repeated monitoring of hydromechanical processes and facilitating the implementation of precision irrigation. Advances in DAS edge computing now allow on-site extraction of low-volume, process-level data products without retaining raw waveforms (*38*), supporting real-time integration with in-situ moisture probes and remote sensing. Benchmarked across multiple channels, this framework provides a scalable model that can be calibrated across diverse settings and establishes a quantitative baseline for future integration with direct soil moisture observations. Once validated across soil types and farming systems, such hybrid deployments could offer a low-labor, dense, and durable means of observing the subsurface moisture dynamics that govern agricultural resilience.

Implications for Earth system modelling

Beyond the farm scale, soil–water interactions carry implications for how land–atmosphere exchanges are represented in climate models. Although soil structure and pore connectivity exert first-order controls on these exchanges (*39*), the evolution of soil pore structure is largely omitted by current hydrologic and land-surface models (*40*), even though the omission is recognized as a major unresolved problem in hydrology and groundwater recharge (*41*). Our results outline a pathway to address this gap by tracking soil structure through time and with land-management changes, and by incorporating rate-dependent capillarity to refine estimates of *ET*, runoff, and groundwater recharge (e.g., Fig S12). This would add process-level constraints to complement traditional energy-based *ET* schemes. While model tuning in our framework parallels existing land-surface calibration (*42*), our approach anchors estimates to pore-scale hydromechanical behavior.

At kilometer scales, Earth system models rely on aggregated soil–atmosphere flux parameterizations (*43*) and sub-grid tiling (*40*). Because soil structure governs moisture availability and energy exchange, these parameterizations require finer constraints. DAS helps bridge this gap by delivering meter-scale, continuous measurements over tens of kilometers, enabling translation of plot-scale hydromechanical processes into landscape- and watershed-scale flux estimates. Our results show that fiber-optic sensing can sharpen land-surface flux parameterizations and support more robust climate-relevant land-surface modeling.

Implications for geotechnical engineering

Moisture-dependent stiffness also impacts seismic hazard and infrastructure stability. Although near-surface v_S is a standard input to seismic site response models (*44*), our results show that moisture-driven, capillary-induced changes challenge the assumption of a static geotechnical layer. This aligns with growing evidence that groundwater fluctuations and seasonal variability can modify site response and promote ground failure (*45*, *46*). Earthquake-triggered liquefaction, traditionally considered limited to fully saturated soil, may also occur in partially saturated soil (*47*) once a percolation threshold is exceeded (~70% saturation), and water levels remain a key control on failure potential (*48*). As climate variability and urbanization alter near-surface hydrology, incorporating the effects of hydrological processes on soil stability becomes essential for assessing ground failure and designing resilient infrastructure. Our fiber-optic sensing approach could enable in-situ monitoring of geostructures and real-time feedback on evolving stiffness as part of long-term infrastructure surveillance.

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Conceptualization: MD, TN, SJ, QS, DM, NC

Methodology: QS, NY, MD

Investigation: QS, MD, NY, AS, EW, NC

Data curation: QS, EW, APB, JC, PM

Visualization: QS

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Supplementary Materials

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The zenodo link (50) should work.

528 Materials and Methods
529 Figs. S1 to S15
530 Table S1
531 Data S1
532 References (*51–69*)
533

Fig. 1. Spatiotemporal variations of soil properties, treatments, and hydrological forcing.

(**A**) Predicted shear-wave velocity (v_S) assuming saturated soil, shown at different depths and locations along the cable. (**B**) Soil porosity at different depths and locations. (**C**) Degree of compaction from tire pressure (C_{tire}) applied during traffic, interpolated onto DAS channels. (**D**) Tilling depth (T_{till}) interpolated onto DAS channels. (**E**) Map of the research farm with the fiber-optic cable indicated in light blue. (**F**) Precipitation rate highlighting four main rainfall events (P1-P4), denoted by high-frequency DAS power spectral density, aligned with reference evapotranspiration (ET_0) from net radiation and hourly weather conditions (symbols). (**G**) Temporal changes in velocity over 40 hours at Channel 18 showing a sharp drop after rainfall, together with the stretched auto-correlation functions (ACF).

Fig. 2. Hydrological and lithological responses.

(**A**) Water saturation (S_w) at Ch. 18 and Ch. 33 defined as the volumetric fraction of water in pore space compared with air relative humidity. (**B**) Observed and modeled shear-wave velocity (v_S) in response to lithological changes near the Ch. 18. (**C**) Same as (B), but for Ch. 33.

Fig. 3. Spatial variability of mechanical disturbance.

(**A**) Spatial variation of hydromechanical responses in relation to tillage depth and degree of compaction measured by tire pressure. Four groups of dv/v curves (thin lines for individual channels), each negatively correlated with water saturation, are located using their first data point and color-coded in a traffic-light sequence according to relative hydrological response levels. The average dv/v curves are shown in thick lines. Contour lines represent the disturbance index (DI) and the relative impact of surface compaction on the tillage depth (stress ratio). (**B**) Velocity changes governed by evapotranspiration (ET) during Period 1 in (A). (**C**) Velocity changes governed by saturated versus unsaturated drainage during Period 2 in (A). (**D**) Disturbance Index (dashed) and total velocity change (solid) along the cable during the drainage-dominated Period 2 in (A).

559 **Fig. 4. Conceptual model of effects of physical disturbance on soil hydrological response.**

560 (**A**) In undisturbed (untilled, uncompacted) soil, unsaturated drainage can retain more moisture at
561 the field capacity, enabling root water uptake. (**B**) In highly disturbed (tilled) soil, disrupted soil
562 structure leads to near-surface saturation, enhanced evaporation, and less moisture retained below
563 the tillage depth.