Satellite-Based Assessment of Depth-Dependent Soil Moisture Drought Dynamics in the State of Iowa

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Keywords: drought; Iowa; remote sensing; SMAP L4; soil moisture memory; vertical propagation

Introduction

Soil moisture drought develops differently across the soil profile. Near-surface moisture responds quickly to rainfall, evaporative demand, and surface energy exchange, while moisture stored within the root zone generally changes more slowly and can remain depleted after the surface has begun to recover. This distinction matters in agricultural regions because surface wetness does not necessarily represent the water available to crops at depth. Soil moisture memory adds another layer to this problem: antecedent wet or dry conditions can influence later states for days to weeks, and the characteristic persistence can differ substantially with depth (Rahmati et al., 2024; Seneviratne et al., 2010).

NASA's Soil Moisture Active Passive (SMAP) mission provides a useful framework for examining these differences consistently over large areas. The SMAP Level-4 product combines L-band satellite information with the NASA Catchment land surface model to provide spatially continuous estimates of surface and root-zone soil moisture (Entekhabi et al., 2010; Reichle et al., 2019). The surface product represents near-surface moisture, whereas the root-zone product represents an integrated model-assimilated state over the upper soil profile. Considering these two products together makes it possible to examine drought development, persistence, and surface-to-root-zone transition without assuming that a single moisture layer represents the full soil profile.

This work presents a preliminary depth-explicit assessment of soil moisture drought across Iowa. The objectives are to compare drought behavior between the surface and root-zone states, evaluate differences in soil moisture persistence, examine whether surface drought conditions are subsequently expressed in the root zone, and explore the atmospheric conditions associated with these responses. The broader aim is to clarify how much information about subsurface drought can reasonably be inferred from surface soil moisture alone.

Method

SMAP Level-4 soil moisture was analyzed across Iowa for 2020-2025. The product provides three-hourly estimates of surface soil moisture at approximately 0-5 cm and an integrated root-zone estimate at approximately 0-100 cm. The root-zone variable is a land-surface-model data-assimilation estimate rather than a direct satellite measurement at a discrete depth and is therefore interpreted as an integrated root-zone state. Three-hourly observations were aggregated to daily conditions and spatially summarized across Iowa.

Seasonal standardized anomalies were calculated independently for the surface and root-zone series to reduce the influence of the annual cycle. Drought events were identified using a dual-threshold framework with a separate onset and recovery criterion and a minimum-duration requirement to exclude brief excursions. Events were then compared in terms of occurrence, persistence, and relative intensity. Soil moisture persistence was assessed from the autocorrelation structure of the standardized anomaly series. Characteristic memory was defined using the e-folding criterion, providing a common measure of how long antecedent moisture conditions remain reflected in later states.

Surface-to-root-zone transition was evaluated by matching root-zone drought onsets with preceding surface drought events. Positive-lag, one-to-one matching was used so that each root-zone event was associated with the nearest plausible surface precursor, and alternative lag windows were examined as a sensitivity check. This analysis is interpreted as transition between two related SMAP states rather than literal tracking of a moisture parcel through independent soil layers.

Atmospheric controls were evaluated using ERA5-Land daily fields (Muñoz-Sabater et al., 2021). The preliminary analysis considered precipitation, vapor pressure deficit, net solar radiation, air temperature, and wind speed. Seasonal anomalies and short antecedent periods were examined to compare moisture supply with atmospheric evaporative demand and surface-energy forcing. These relationships are interpreted as associations and are not used to infer direct causality.

Results

The preliminary analysis shows a consistent separation between surface and root-zone drought behavior. Surface soil moisture varies more rapidly, with drought conditions developing and recovering on shorter timescales. Root-zone drought occurs less frequently but tends to persist longer once established. This contrast indicates that short-term changes at the surface do not necessarily represent equivalent changes in subsurface water availability.

The persistence analysis supports the same interpretation. The surface signal loses memory of antecedent conditions relatively quickly, whereas the root-zone signal retains a stronger influence from earlier moisture states. This longer subsurface memory provides a physical explanation for the slower development and recovery of root-zone drought and for periods when near-surface conditions improve while the integrated root zone remains dry.

The event-based comparison suggests that surface and root-zone drought are coupled only under some conditions. A meaningful subset of surface drought episodes is followed by drought development in the root-zone signal after a positive delay, while other surface events remain confined to the upper layer. Surface drying can therefore provide useful information about developing subsurface stress, but it should not be treated as automatic evidence of root-zone drought.

Atmospheric relationships are strongest for the surface layer. Precipitation is positively associated with soil moisture conditions, while higher vapor pressure deficit is associated with drying. Net solar radiation also shows a clearer relationship with surface moisture than with the root-zone signal. Air temperature and wind speed show comparatively weak independent relationships in the present statewide analysis. Overall, the atmospheric signal becomes less direct at depth, consistent with the buffering effect of soil-water storage.

Discussion and Conclusion

The preliminary findings show that soil moisture drought across Iowa has a clear vertical structure. Surface soil moisture is a sensitive indicator of recent atmospheric forcing, but this sensitivity also produces rapid fluctuations that may not reflect conditions throughout the root zone. The root-zone signal responds more slowly and retains the influence of antecedent moisture conditions for longer. Apparent surface recovery therefore does not necessarily mean that subsurface drought has ended, while some short-lived surface deficits may disappear without developing into persistent root-zone stress.

The atmospheric analysis provides a physically consistent context for these differences. Precipitation replenishes soil-water storage, whereas elevated atmospheric moisture demand promotes drying, especially near the surface. The weaker relationships at depth suggest that root-zone conditions integrate forcing over longer periods rather than responding directly to individual weather fluctuations. This depth-dependent buffering is important when satellite soil moisture products are used for agricultural drought assessment, early warning, or interpretation of crop water stress.

The propagation analysis further indicates that surface drought can contain useful information about subsequent root-zone conditions, but the relationship is conditional rather than deterministic. Monitoring systems based only on the surface layer may identify rapid drought development effectively, yet they can overstate short-lived surface stress or imply recovery before subsurface storage has fully recovered. Joint consideration of surface and root-zone conditions provides a more complete description of drought evolution.

Several limitations remain important at this stage. SMAP Level-4 represents regional-scale conditions and cannot resolve field-level differences in soil texture, crop management, rooting depth, or artificial drainage. The root-zone product is model assimilated rather than a direct measurement, and the present statewide analysis reduces spatial heterogeneity within Iowa. The relatively short study period also represents recent drought behavior rather than a long-term climatology. Continued work will therefore evaluate the analysis at the grid-cell level, compare the results with depth-matched ground observations, examine spatial variation in drought transition, and test the sensitivity of the event and memory definitions.

Overall, the analysis indicates that surface and root-zone soil moisture provide complementary rather than interchangeable information. Surface conditions capture rapid atmospheric responses, while the root zone better represents persistent subsurface moisture deficits. Retaining this depth distinction provides a stronger basis for interpreting satellite-based drought conditions and for understanding how agricultural drought develops and persists across Iowa.

Acknowledgements:

The authors acknowledge NASA for providing the SMAP Level-4 soil moisture product and the European Centre for Medium-Range Weather Forecasts and Copernicus Climate Change Service for ERA5-Land data. The authors also acknowledge the University of Iowa for computational and research support.

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