Subsurface Soil Moisture (corrected with SMAP imagery)

Surface and **subsurface soil moisture** are calculated by the modified Palmer two-layer soil moisture model which accounts for the daily amount of water withdrawn by evapotranspiration and replenished by precipitation. **Sub-surface soil moisture levels** are best used to monitor an established crop because it estimates the available water within the plant's root zone of one meter or less. In general, the **subsurface soil moisture** may hold 0-275 mm/m of water depending on available water and the total soil′s water-holding capacity. Correspondingly, **subsurface soil moisture** values of:

- >100-mm indicates an abundance or at least favorable amount of moisture in the subsoil.
- <100-mm indicates the sub-surface soil moisture storage is short but can still support a well-established crop.
- <25-mm has very little sub-surface soil moisture and the crop could be severely stressed and reduce yields, especially if it occurs when the top-layer has little or no significant soil moisture and the crop is at a critical stage of growth.

Figure 1 (from AgRISTARS, 1981) illustrates percent soil moisture stresses during different corn growth stages, where percent soil moisture is the available water in both the surface and subsurface soil layers divided by the total soil's water holding capacity.

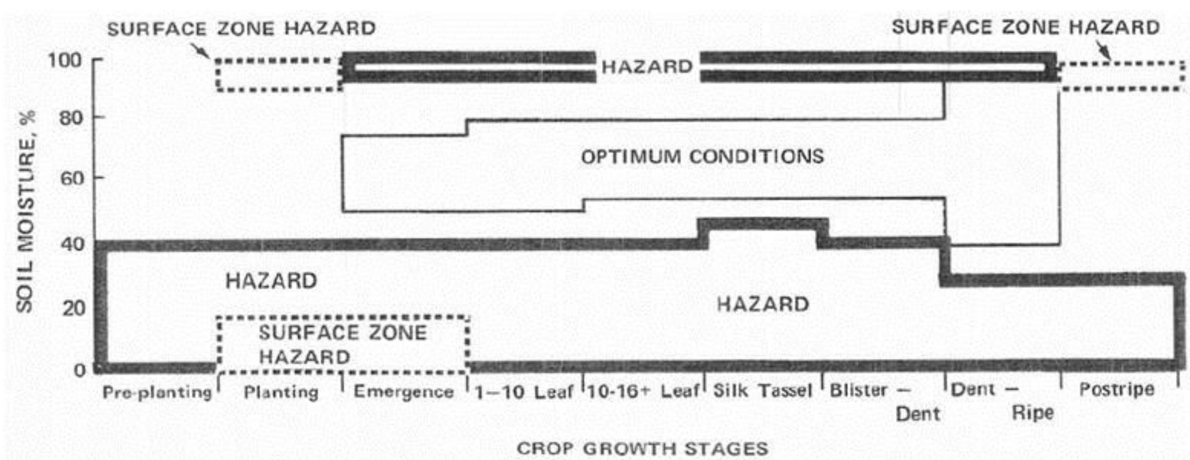

Figure 1. Soil moisture stress is 40 percent or less for most corn growth stages (from AgRISTARS, 1981).

Subsurface Soil Moisture corrected with SMAP imagery and assimilated by the Ensemble Kalman Filter (EnKF)

The **subsurface soil moisture** product is corrected by integrating satellite-derived Soil Moisture Active Passive (SMAP) mission surface soil moisture retrievals into the modified Palmer two-layer soil moisture model. The SMAP imagery helps to correct the modified Palmer soil moisture model by using an Ensemble Kalman Filter (EnKF) data assimilation approach. The assimilation of SMAP surface soil moisture estimates is designed specifically to correct the modified Palmer two-layer soil moisture predictions for the deleterious impact of rainfall forcing errors - particularly in regions of the world lacking extensive rain-gauge instrumentation (Bolten, et al, 2010).

The National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive (SMAP) mission is a satellite-based, L-band radar and radiometer instrument launched in January 2015. The SMAP was designed to provide global high-resolution soil moisture data with an accuracy of 0.04 m3/m3 that covers the globe on every three days. The SMAP Level 3 descending soil moisture products are gridded into daily composites with a spatial resolution of 25 km and then assimilated into the modified Palmer two-layer soil moisture model by using an Ensemble Kalman filter approach which dynamically updates all model-based soil moisture predictions to reflect information contained in the SMAP imagery.

In addition, SMAP imagery updates are made to both the (observable) surface soil layer and the (non-directly observable) subsurface soil layer via the use of error covariance information sampled from an ensemble of Monte Carlo model forecasts. The assimilation of SMAP surface soil moisture estimates is designed specifically to correct model-based soil moisture predictions for the deleterious impact of rainfall forcing errors - particularly in regions of the world lacking extensive rain-gauge instrumentation.

Palmer (1965) Two-layer Soil Moisture Model in General

The Palmer **two-layer soil moisture model** is a bookkeeping method that accounts for the water gained or lost in the soil profile by recording the amount of water withdrawn by evapotranspiration and replenished by precipitation. The final aim of the soil moisture model is to estimate if soil moisture storage between dry spells was adequate for maximum plant growth.

The soil moisture within two soil layers is calculated in daily time increments (mm/day of precipitation or evapotranspiration). The surface soil moisture is assumed to hold a maximum of one inch (or 25-mm) of available water, and the sub-layer soil moisture may hold 0-400 mm/m of water depending on the soil′s water-holding capacity (based on soil texture and soil depth) for the grid cell.

The soil moisture model assumes precipitation enters the two soil layers by first filling the surface soil layer and then filling the lower soil layer. Moisture is extracted from the two soil layers by evapotranspiration, whereby water is first depleted from the top layer and then extracted from the sub-surface layer. When the water-holding capacity of both soil layers is reached, excess precipitation is lost from the model and treated as runoff or deep percolation.

Daily evapotranspiration for the two-layer soil moisture model is calculated by the FAO 56 Penman-Monteith equation (Allen, et al, 1998) and daily precipitation is estimated from both surface observations and satellite data. The water-holding capacities for both soil layers were derived from the FAO (1996) Digital Soil Map of the World.

Modified Palmer Two-Layer Soil Moisture Model

The modified Palmer two layer soil model by FAS/IPAD is similar to the Palmer's (1965) two-layer soil moisture model, but Palmer's two-layer soil moisture model was modified by FAS/IPAD to:

1. Allow more gradual and realistic depletion of the surface layer.
2. Allow moisture to be depleted from the lower layer before the surface layer is completely dry.
3. Better estimate potential evapotranspiration with the modified FAO Penman-Monteith equation described by Allen, et al, (1998) and not using the Thornthwaite (1948) equation proposed by Palmer.
4. Assume soil type for each LIS grid cell from FAO's (1996) Digital Soil Map of the World (DSMW).
5. Assume maximum root depth for each LIS grid cell is one meter or less, depending on impermeable soil layers, when calculating the total soil water-holding capacity.

Both the original Palmer and modified-Palmer models assume the top first inch of available water is held in the top layer, and remaining soil water is held in the lower layer. Precipitation enters the model by first completely filling the surface layer and then filling the lower layer. When the soil water holding capacity of both layers is reached, excess precipitation is treated as runoff and is lost from the model.

The original Palmer model assumed moisture was removed from the surface layer at rate equal to the potential evapotranspiration calculated by the Thornthwaite (1948) method, and moisture was removed from the lower layer at fraction of the potential rate. It also assumed that moisture could not be removed from the lower layer until the surface layer was completely dry, but FAS/IPAD later found these assumptions did not adequately describe water extraction by plants. Therefore, FAS/IPAD slightly modified the extraction function to allow gradual and more realistic depletion in the surface layer and to allow moisture to be depleted from the lower layer before the surface is completely dry.

The modified extraction function allows moisture to be depletion from the surface at the potential evapotranspiration rate to 75 percent of the surface capacity (or 75% of 1 inch of water). When the surface layer is below 75 percent capacity, moisture is extracted from the surface at a reduced rate with the lower layer making up the remaining requirement. Moisture is extracted from the lower layer at a fraction of the potential, where this fraction is calculated as a ratio of actual water held to the total water-holding capacity.

Total Water Holding Capacity (WHC) Derived from the Modified FAO Digital Soil Map of the World (DSMW)

The total water holding capacity (WHC) of a soil is defined as the difference between the soil's field capacity less the permanent wilting point, with the total soil water holding capacity dependent on soil texture and soil depth. The global spatial distribution of soil texture and soil depth is defined by the FAO Digital Soil Map of the World (DSMW), and the DSMW was modified to estimate the total water holding capacity for each LIS (Land Information System, 2006) grid cell by assuming a maximum soil depth of 1-meter or less (Reynolds, et al, 2000). From the 1-meter or less soil depth assumption, the soil water holding capacity within each LIS grid cell normally ranges from 5 to 8 inches/meter of water depending on soil texture (ranging from sand to clay) and soil depth (ranging from one meter or less).

The daily available water (AW) within the plant's one meter (or less) root zone is calculated by the modified Palmer two-layer soil moisture model which accounts for the daily amount of water withdrawn by evapotranspiration and replenished by precipitation. The available water is expressed in millimeters per day, with percent soil moisture calculated as the daily available water (AW) divided by the total soil water holding capacity (WHC) for each LIS grid cell.

Refer to "Data Sources" for additional Crop Explorer metadata

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