Using Soil Moisture Information to Better Understand and Predict Wildfire Danger: A Review of Recent Developments and Outstanding Questions

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- remote sensing
- meteorology
- forestry
- geography

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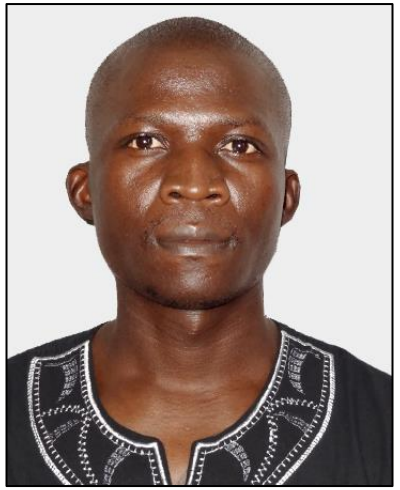

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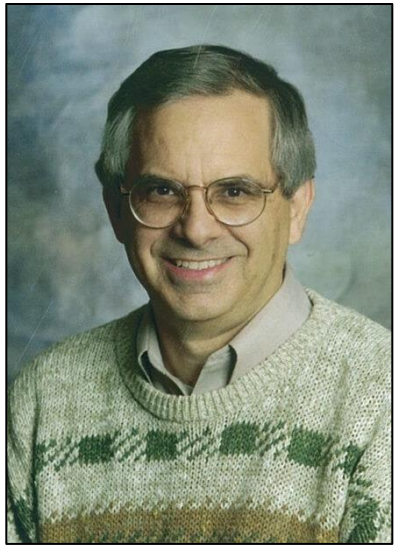

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Our motivating question:

How can increasingly available soil moisture information be used to better manage the impacts of fire on people and ecosystems?

A decade-long journey of discovery:

- Soil moisture affects growing-season wildfire size in the southern Great Plains. (Krueger et al., 2015)
- Concurrent and antecedent soil moisture related differently to wildfire in different seasons. (Krueger et al., 2016)
- Soil moisture is a better growing-season wildfire predictor than KBDI, a widely used drought index. (Krueger et al., 2017)
- Grassland fuel moisture and curing are strongly linked to soil moisture. (Sharma et al., 2020)
- Soil moisture information can help improve predictions of grassland fuel loads. (Krueger et al., 2021)

Figure caption: Andres Patrignani installing sensors to investigate the effects of soil moisture on grassland fuel bed conditions. Oklahoma State University Range Research Station, 2012.

Model for grassland fuel load

- First step – estimate evapotranspiration (ET_c)
  - FAO-56 dual crop coefficient method
  - Scaling of reference ET (ET_0)
- Second step – estimate biomass
  - Transpiration normalized by ET_0
  - Cumulative normalized T_c linearly related to biomass production
- Model cal/val for MOISST site
  - Evapotranspiration measurements (ET_c)
  - Grassland productivity measurements
  - With and without direct insertion of soil moisture data
- Statewide testing
  - Predict grassland productivity/fuel load
  - 25 counties, 3 years each

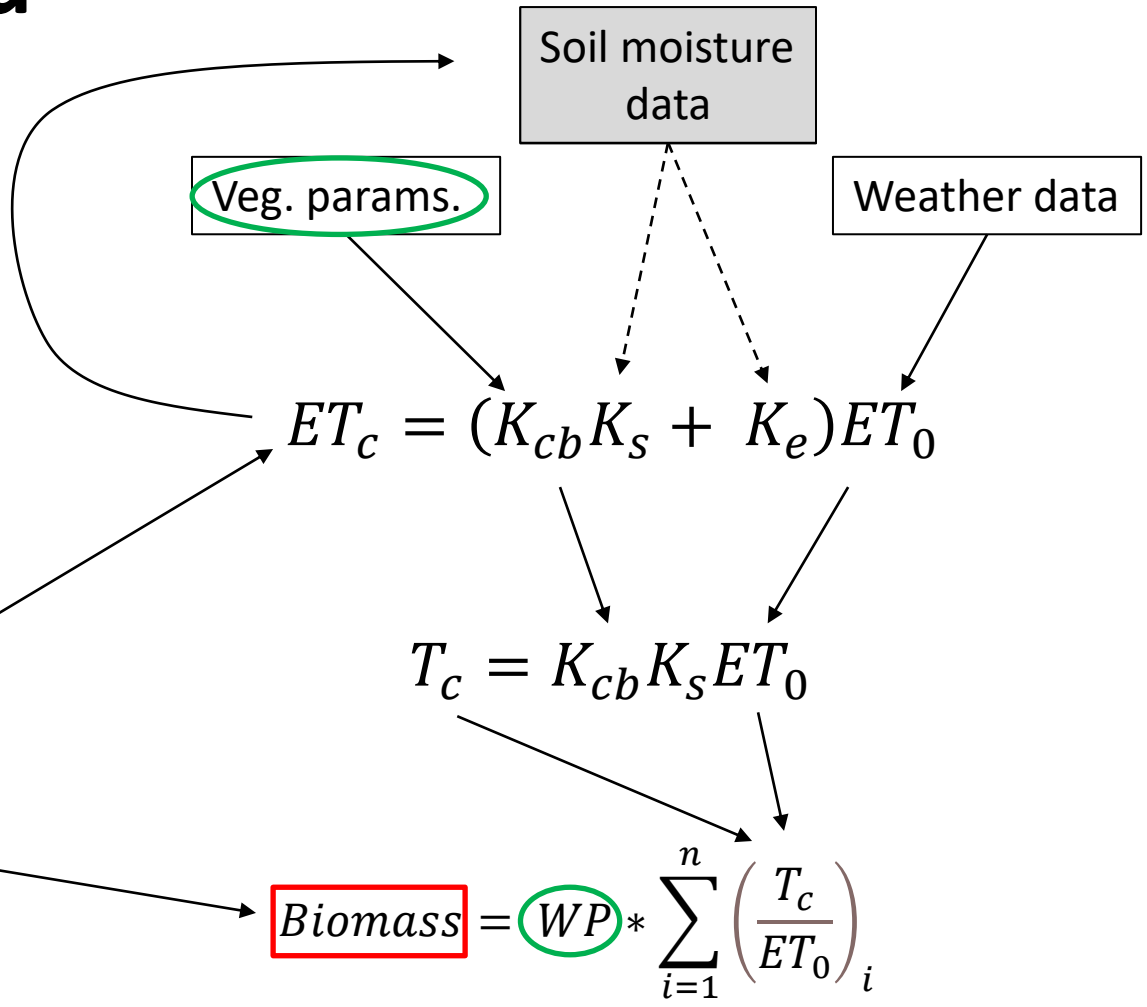

Figure caption: Flow-chart for grassland productivity/fuel load model.

ET calibration/validation

- Calibration period
  - 2013 – 2015
  - NSE = 0.79 w/o FAW
  - NSE = 0.87 w/ FAW
- Validation period
  - 2016 – 2017
  - NSE = 0.84 w/o FAW
  - NSE = 0.81 w/ FAW

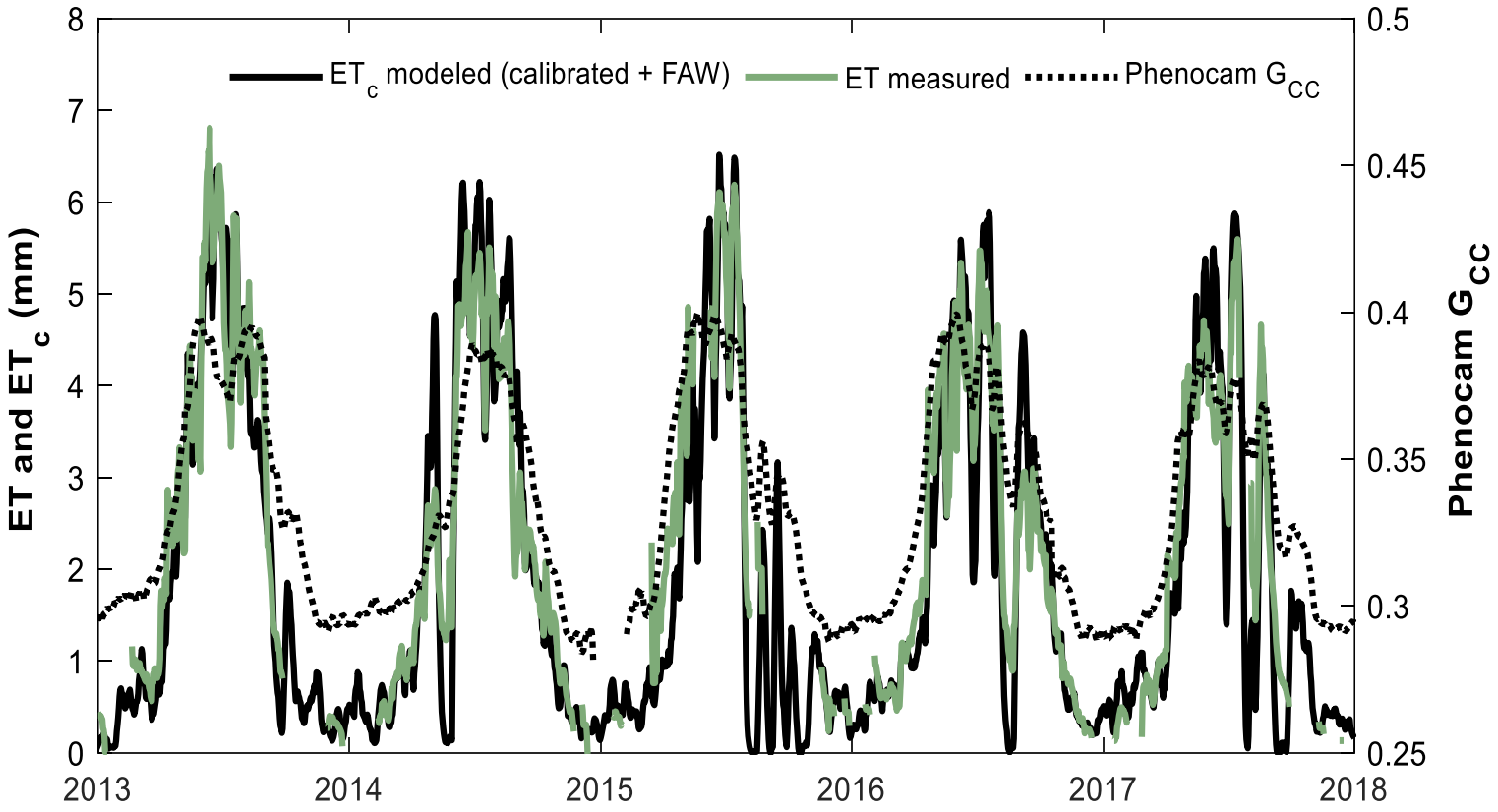

Figure caption: One-week average modeled ET_c, measured ET, and PhenoCam green chromatic coordinate (GCC) at the Marena, Oklahoma, In Situ Sensor Testbed (MOISST) 2013-2017. Modeled ET_c values used measured soil moisture instead of a simulated water balance (calibrated + FAW).

Biomass calibration

- Water productivity constant
  - 45 kg ha^{-1}
  - no literature comparisons
  - further testing warranted

- Biomass/fuel production
  - model reflects within season dynamics

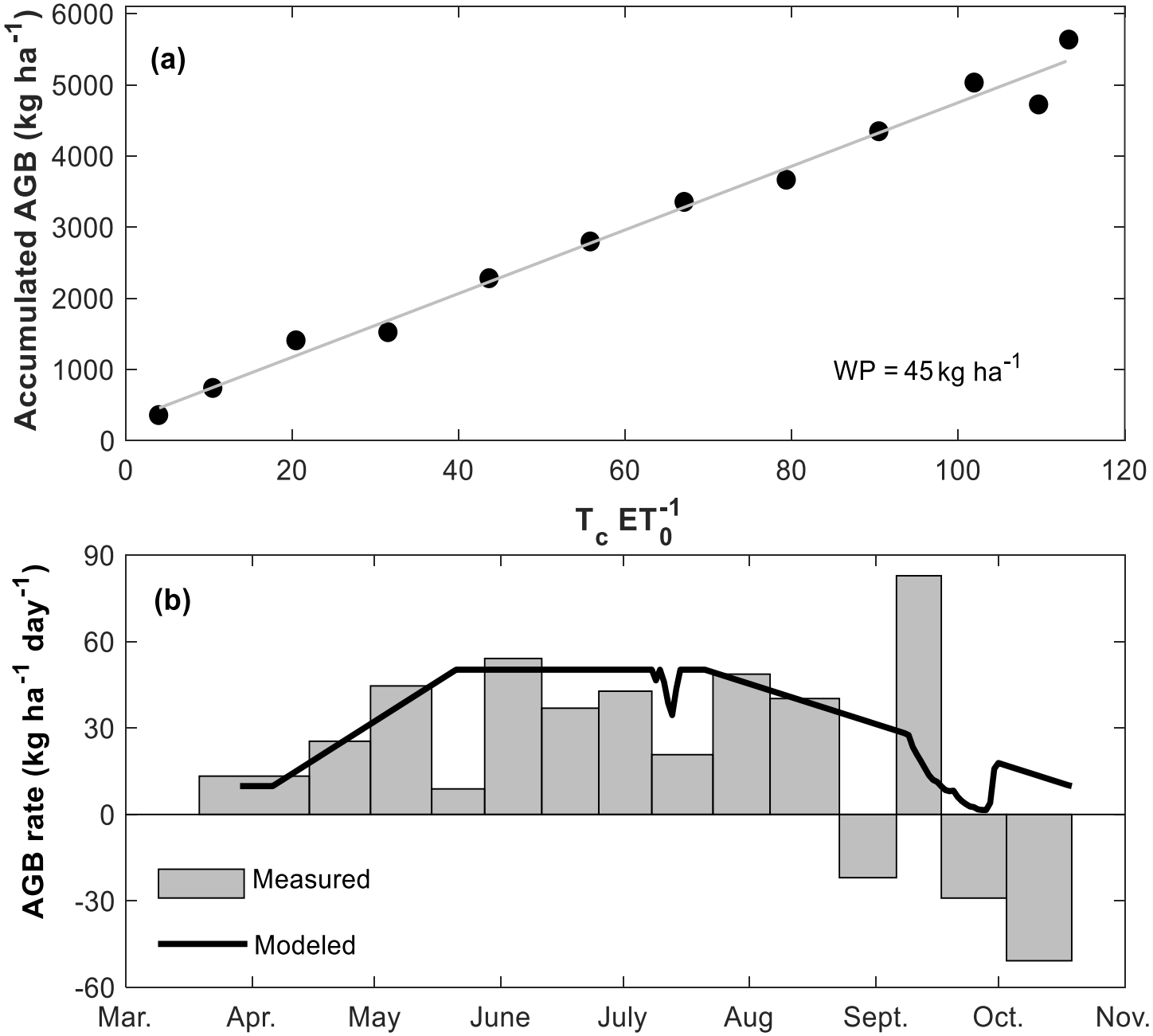

Figure caption: Accumulated above ground biomass (AGB) as a function of the sum of the daily ratio of modeled (calibrated + FAW) crop Transpiration (T_c) and reference evapotranspiration ET_0 from the mechanistic model, with the slope of regression line representing water productivity (WP) for the grass crop (panel a). Modeled and measured AGB accumulation rate at the MOISST site in 2013 (panel b).

Statewide model validation

- With soil moisture data insertion, model effectively predicted hay yield/grassland productivity/fuel load
  - NSE = 0.65
  - MAE = 270 kg ha^{-1}
- Without soil moisture data insertion, poorer predictions
  - NSE = 0.10
  - MAE = 475 kg ha^{-1}
- A step towards dynamic herbaceous fuel load models

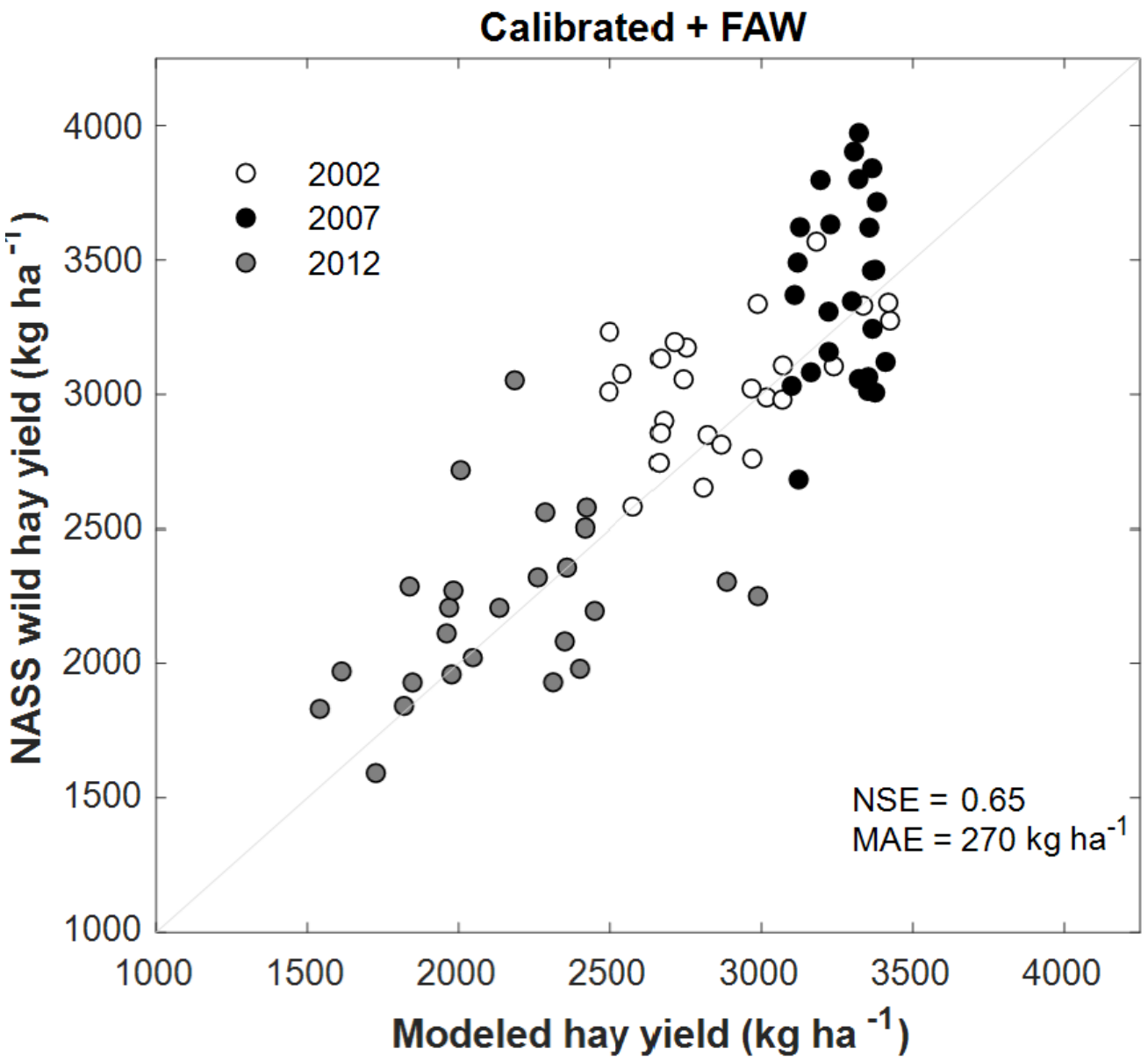

Figure caption: Measured vs. modeled county level wild hay yield in Oklahoma in 2002, 2007, and 2012 for the calibrated model with direct insertion of soil moisture data (calibrated + FAW).

Grassland fuel moisture strongly linked to soil moisture

- Declining FAW, Jun-Aug 2012
- Wildfire outbreak 3 Aug, 2012, when FAW = 0.24, burned >34,600 ha
- GFM and MFM declined with FAW, minimums coincident with wildfire
- Generally higher FAW and fuel moisture values in 2013
- Rapid declines in September 2013

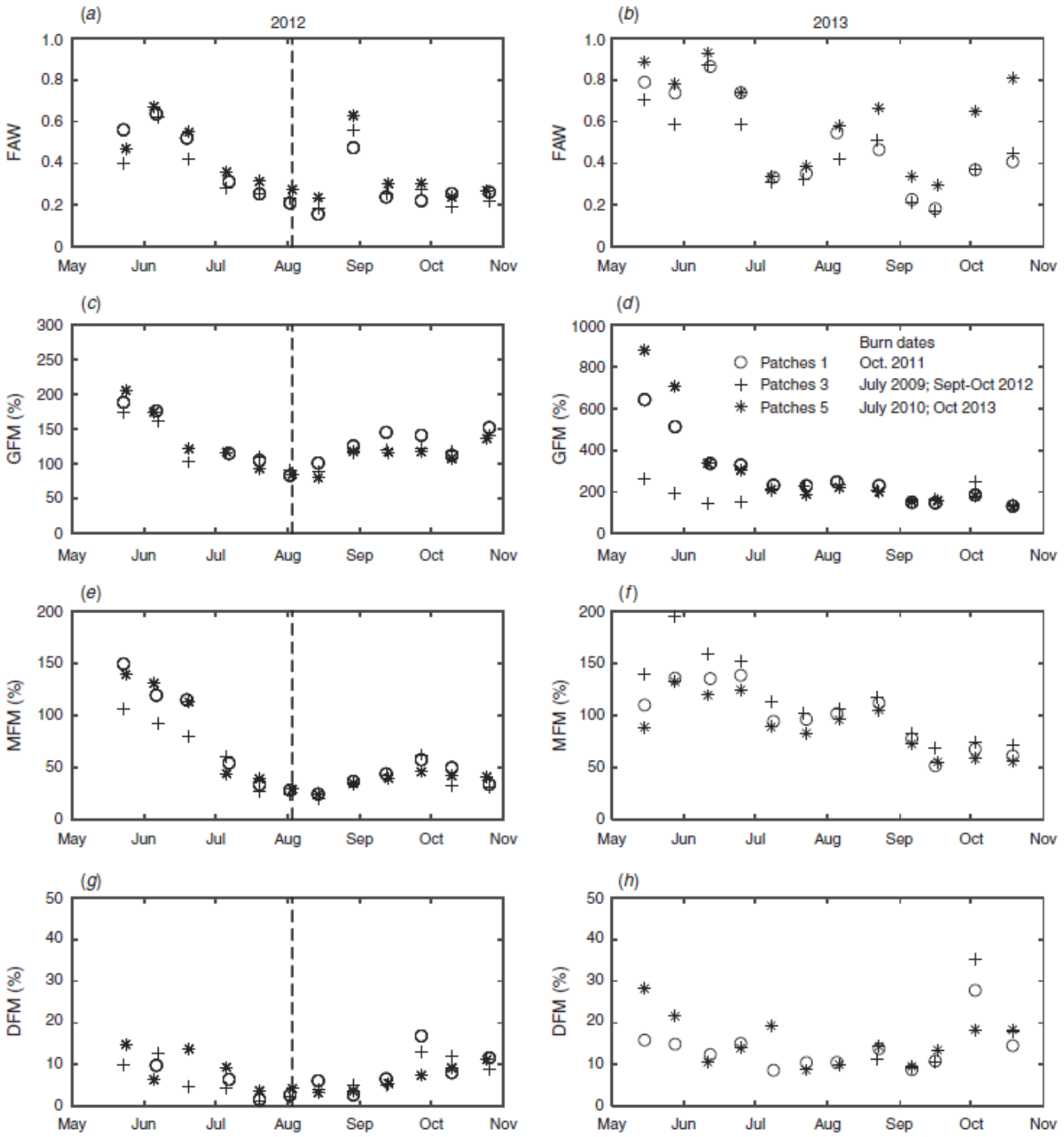

Figure caption: Time series of fraction of available water capacity (FAW) for the 0–40-cm layer, green fuel moisture (GFM), fuel moisture of the mixed live and dead herbaceous fuels (MFM), and dead fuel moisture (DFM), grouped by burn date (the date the sampled patch was burned).

Relationship of FAW to MFM and curing rate

- Strong linear relationship between MFM and FAW, when FAW < 0.59 and declining
- Strong inverse linear relationship between curing rate and FAW, when FAW < 0.3
- Maximum curing rate 12.6 g m^{-2} d^{-1} from 6–16 September 2013, when FAW averaged 0.21. Grassland dead fuel loads of 70 g m^{-2} can propagate fire.

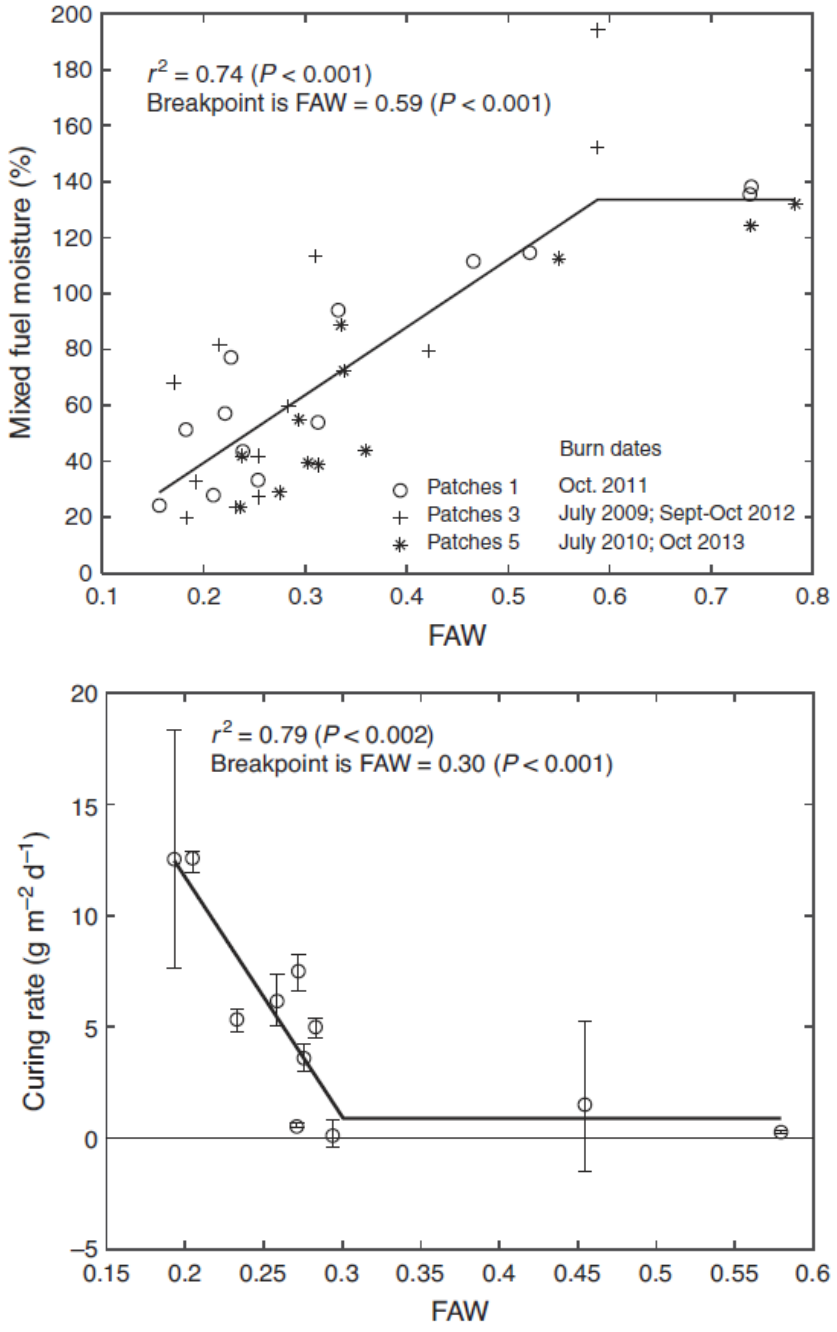

Figure caption: *Top panel* - Mixed-fuel moisture vs. fraction of available water capacity (FAW) for the 0–40-cm soil layer for sampling intervals when the soil moisture was declining. *Bottom panel* - Estimated curing rate (CR), i.e. rate at which herbaceous fuels transition from live to dead, vs. FAW. Error bars indicate the uncertainty in the CR estimate due to uncertainty in the true value of live fuel moisture.

How declining soil moisture leads to wildfire:

- Grassland fuel moisture declines when FAW < 0.60
- Grassland fuel production declines when FAW < 0.40
- Grassland fuel curing accelerates when FAW < 0.30
- Large growing season wildfires (in Oklahoma) occur primarily when FAW < 0.20

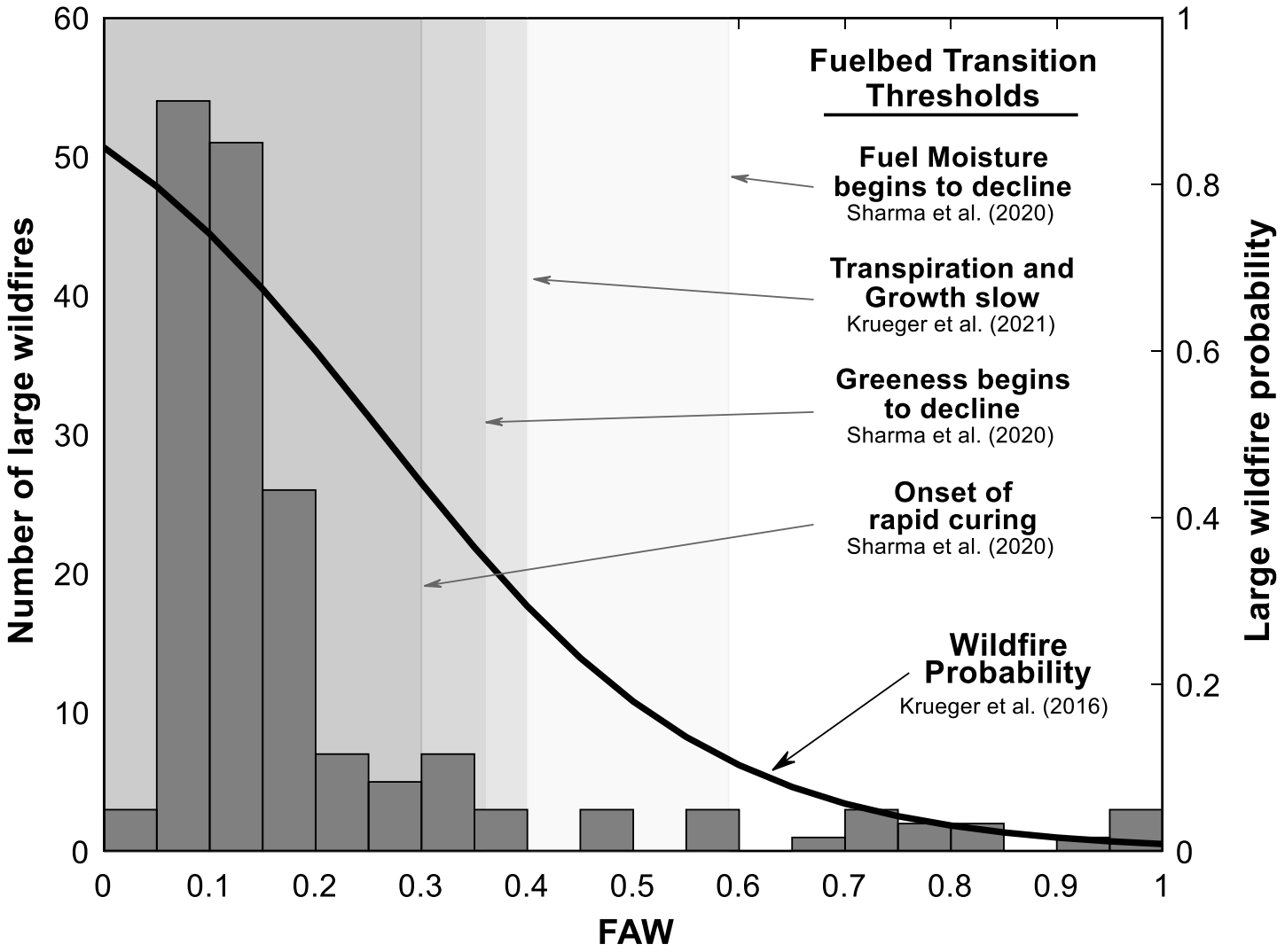

Figure caption: Frequency distribution and probabilistic relationship between fraction of available soil water capacity (FAW) and large growing-season wildfires in Oklahoma from 2000–2012. Live grassland fuels transition to dead fuels as soil moisture declines, beginning with a drop in live fuel moisture (FAW = 0.59) followed by decreased transpiration and growth (FAW = 0.40). Next, vegetative greenness declines (FAW = 0.36), which culminates in rapid fuel curing as soil moisture conditions continue to deteriorate (FAW = 0.30). Reproduced from Krueger et al. manuscript (under review at IJWF).

The current situation:

A growing body of research provides strong evidence that soil moisture is a key predictor of wildfire danger that *has not yet been effectively integrated into fire danger rating systems*.

Selected discoveries from other groups/other regions:

- Soil moisture (in situ) was strongly correlated with live fuel moisture for shrubs in Italy (Pellizzaro et al., 2007).
- High soil moisture conditions (remotely sensed) limit the extent of forest fires in Siberia (Bartsch et al., 2009).
- Low soil moisture conditions (modeled) are strongly associated with large wildfires in Florida (Slocum et al., 2010).
- Remotely sensed soil moisture can be used to estimate live fuel moisture within ~20% across the US (Lu and Wei, 2021)
- Soil moisture influences dead fuel moisture and fire risks in forests (e.g., Rakhmatulina et al., 2021 and others).

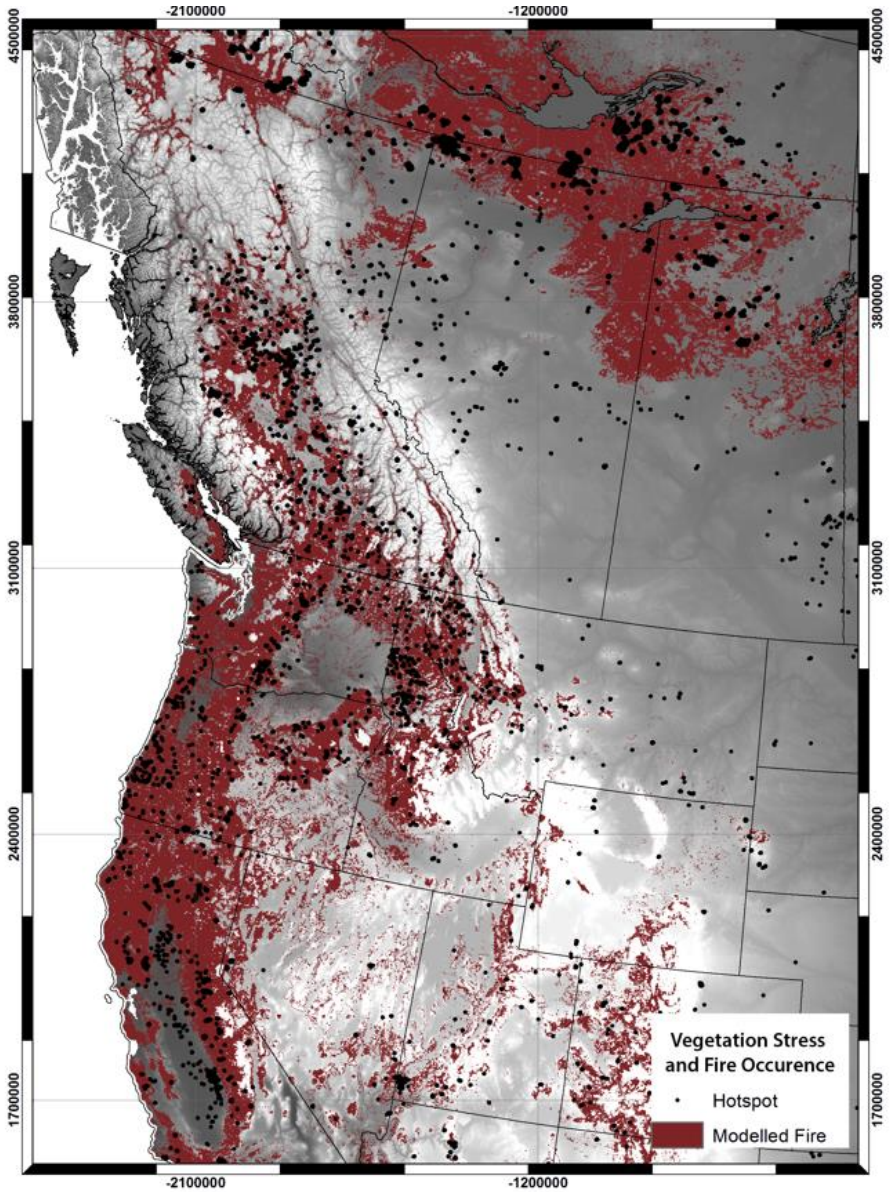

Figure caption: Predictions of wildfires (red) based on available soil water for forested portions of western North America in 2004, along with the locations of MODIS active fire hotspots (black dots) for the same period. (Waring and Coops, 2016).

Some key remaining questions:

- How can we best represent soil moisture (absolute values, FAW, anomalies, percentiles, etc.)?
- What are the most relevant soil depths to consider?
- How can in situ, remotely sensed, and modeled soil moisture data best be utilized?
- How can soil moisture conditions predict burning of organic soils?
- How do soil moisture conditions influence prescribed fires?
- ***<u>How can wildfire professionals be convinced and enabled to use soil moisture information?</u>***

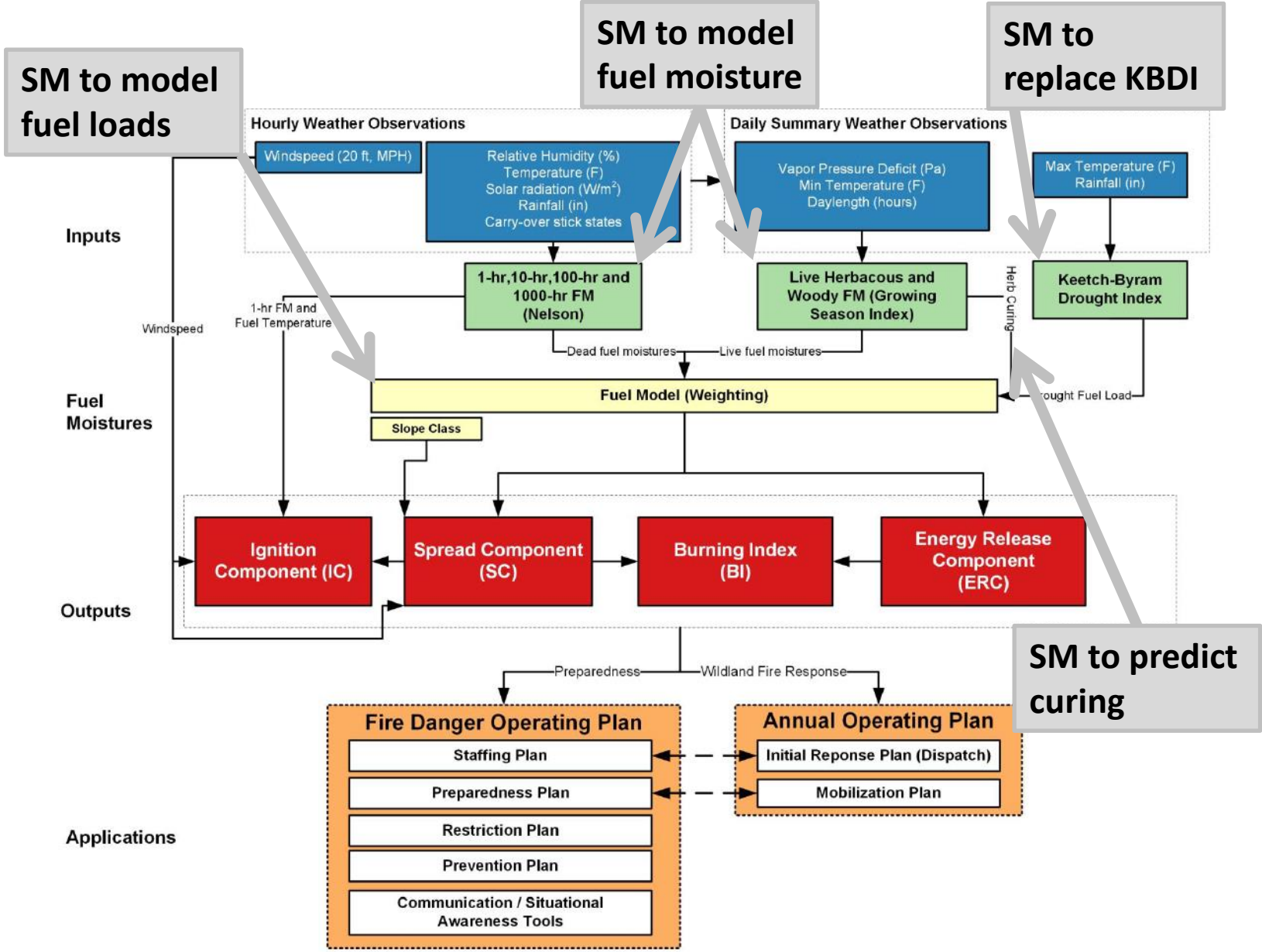

Figure caption: Flow chart representing the 2016 version of the US National Fire Danger Rating System (Jolly, 2018). Possible uses of soil moisture information for improved wildfire danger rating are presented in gray boxes.

Acknowledgments and invitations

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JOINT FIRE SCIENCE PROGRAM

USDA

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