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To: Mark Xu, Director, Resource Inventory & Assessment Division, USDA-NRCS
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Loretta J. Metz, CEAP-Grazing Land Component Leader, USDA-NRCS
Katherine Kraft, Director of Product Strategy, Teren Inc.

From: Mitch McClaran, Professor, University of Arizona

Subject: Request NRCS field soil scientists and rangeland specialists to field-test the **Climate-Enhanced Topographic Wetness Index** being developed collaboratively with University of Arizona, Teren Inc., and CEAP-Grazing Lands

The Grazing Lands component of the CEAP National Assessment (CEAP-Grazing Lands, CEAP-GL) quantifies the environmental effects of conservation practices at national and regional scales on privately-owned rangeland and pastureland and assesses conservation impacts on selected ecosystem services provided by managed grazing lands. The ecology and use of rangelands in the West are often intertwined with non-private lands (Federal, State and/or Local government ownerships) regarding wildlife habitat, grazing operations, water quality, water quantity issues, and other ecosystem services. CEAP-GL uses National Resources Inventory (NRI) Grazing Land Onsite Studies data, as well as Bureau of Land Management (BLM) data, to populate models such as RHEM (Rangeland Hydrology and Erosion Model), WEPP/SPUR (Water Erosion Prediction Project/Simulation, Production, and Utilization of Rangeland), APEX (Agricultural Policy/Environmental eXtender) model, and AERO (Aeolian EROsion) model to estimate effects of conservation practices on these private lands.

As the key modeling partner with CEAP-GL, both the University of Arizona and CEAP-GL require whole-scale landscape layers to conduct regional and national assessments. To make assessments and predictions of the effects of conservation practices, sometimes CEAP-GL and partners must impute data from measured areas to areas with no measurements. One need is to fill in vegetation data gaps for areas with similar hydrology and landscape features. The Climate-Enhanced Topographic Wetness Index (CETWI) was created to meet that need. CETWI facilitates imputation of field data values from NRI rangeland and pastureland on-site data, BLM data, and other data sources, to areas with little to no field data. The CETWI values and associated covariate values will be used to determine similar hydrology and landscape features, then join those identified landscapes to the soils data and field-measured data, as input data in models (RHEM, AERO, others) to estimate soil sediment yield, soil loss, water runoff, wind erosion, and particulate matter losses related to conservation practice implementation. CETWI will be used to aid in developing other CEAP-Grazing Land layers and tools, including the rangeland Ecological Vulnerability Index (rEVI) and the pastureland Ecological Vulnerability Index (pEVI), which will serve as the vegetated “SVI-cultivated cropland equivalents” that have repeatedly been requested by states for rangeland and pastureland.

CETWI was initially developed in 2017 to help assess practice impacts in Colorado for an EQIP initiative on carbon sequestration and GHG emissions. One assessment challenge was the lack of complete plot data –

SSURGO did not have full soil coverage on forestland, and U.S. Forest Service (USFS) data were at a different scale that could not be matched to SSURGO. Existing U.S. Geological Survey Topographic Wetness lndex (TWI) layers were inadequate because they capture runoff flow due to gravity only and disregard other environmental characteristics. Existing TWI layers are limited in scale of prediction and in their inability to model movement of water flow across multiple watersheds. With the support of Clint Evans (CO STC), CEAP-GL and Colorado NRCS staff helped develop this precursor to CETWI, which demonstrated how areas with similar hydrology and landscape features could be used to help impute data to fill gaps and run well-calibrated model scenarios. This enabled large landscape assessment and modeling of wildfire risk, erosion, water runoff, carbon sequestration, and biodiversity attributes. Results have been published,[i] and this Colorado forest project was presented to the agency and partners during the July 2020 *Conservation Outcomes* Webinar.

CETWI is a new TWI model (of which there are several) being developed for CEAP-GL use by Teren Inc and the University of Arizona; it is not a merger of old and new TWI factors. Neither existing TWI layers nor CETWI use soil properties; they are purely terrain-based models. Table 1 contrasts key model functions between CETWI and the two main TWI models (TWI and Enhanced D-infinity TWI).

Table 1. Key model functions between two existing topographic wetness index models (TWI and Enhanced D-infinity TWI), and the new Climate-Enhanced TWI model under development for CEAP-Grazing Lands.

Key Model Functions	TWI	Enhanced D-INF TWI	CETWI	Is this function an improvement?
Extracted from DEM 30m	X	X	X	
Extracted from DEM 10m			X	Yes
Analysis at very small and small catchment areas	X	X	X	
Analysis in User-defined multiple catchments			X	Yes
Analysis currently at 2-digit HUC scale, by 10m pixel			X	Yes
Incorporates climate			X	Yes
Adjusts for effective precipitation			X	Yes
Uses local slope angle	X	X		
Uses dynamic (micro-topographic) slope angles			X	Yes
Captures runoff flowing by gravity ONLY	X	X		
Captures runoff by gravity, PLUS effects of covariates*			X	Yes
Offers continuous flow past landscape obstructions			X	Yes
Incorporates multiple covariates*			X	Yes
Allows for weighting of individual covariates*			X	Yes
Allows for weighting of effective precipitation			X	Yes

* Covariates include: Aspect; Curvature; Flatness; Solar Insolation; Inundation; micro-topographic Slopes; Evapotranspiration.

CETWI is not the same as an updated TWI or Enhanced D-Infinity TWI, but instead is a new model using accepted engineering methods to determine flow hydraulics. CETWI requires heavy background processing of each covariate, precipitation, slope, hydraulic gradients, etc., which requires considerable computer processing ability. The result is an indexed map showing surface moisture decay over 10m pixels using the following equation that can be modified by weighting one or more of the covariates.

$$CETWI = P_w + H_w + O_w + Sl_w + A_w + I_w + C_w + So_w$$

Where P = relative precipitation, H = hydrologic influence, O = openness or flatness, Sl = slope (in degrees), A = aspect, I = inundation, C = curvature, So = solar insolation and w is a weight of influence, summing to 100, determined by local climate and ecological processes.

The final index displays spatial 10m pixel values ranging from 0 to 100, where 100 represents water undergoing no losing processes to 0 representing dry with no gaining processes occurring. The final CETWI model integrates these complex drivers of hydrologic condition into a single surface with values independent of anthropogenic bias representing ecological site potential driven by hydrologic processes. The final output values of the model do not account for land use or management activities and solely account for natural processes that would occur based on the current (past 30 years) climatic and terrain conditions.

Climatic covariates (*P*) include:

- Precipitation: Annual average values for precipitation for the last 30 years (1991-2021) from the PRISM datasets at 800m resolution. The 800m PRISM data does not include additional measured rainfall gage data compared to the 4km PRISM; it merely interpolates the 4km data to an 800m resolution.
- Vapor pressure: Annual average values for vapor pressure for the last 30 years (1991-2021) from the PRISM datasets at 800m resolution representing evaporation.
- Relative Precipitation: The net precipitation where average precipitation represents gaining moisture and average vapor pressure represents a loss of moisture.
- Effective Precipitation: The net precipitation minus the net evapotranspiration as determined from PRISM products and calculated based on the work of Sanford and Selnick (2012), where they created the evapotranspiration weighted precip index that is multiplied against precip.

Terrain-derived covariates include:

- Hillslope solar insolation (*So*): represents the amount of solar radiation and heat an area receives, parameters adjusted based on the topographic profile and the azimuth and zenith of the sun in relation to location. Low CETWI values represent higher solar inputs (less shaded), while high CETWI values represent lower solar inputs (more shaded).
- Slope (*Sl*): influences multiple hydrologic processes as well as heat loading factors, a percent-rise surface was calculated using the 10-meter DEM, where the rate of change was determined between a cell and its neighbors. Lower index values represent steeper slopes, while higher values represent lower slopes.
- Aspect (*A*): influences multiple hydrologic processes as well as heat loading factors, a surface representing the downhill slope was created by calculating maximum rate of change between a cell and its neighbors. The effect of aspect is assumed to diminish at slopes less than 5 degrees (9%). The lower CETWI values represent less shaded aspects (south-facing aspects in the northern hemisphere) to higher values representing more shaded aspects (north-facing aspects in the northern hemisphere).
- Flatness/Openness (*O*): Influences hydrologic processes; a flatness index was derived from the 10-meter DEM using the standard deviation of elevations based on a moving window analysis based on

10, 20, 30, 50 meter radiuses. A low standard deviation suggests a high degree of flatness. This occurs when values within the sample radius are tightly clustered around the mean and have minimal variability in elevation.

- <u>Curvature (*C*)</u>: Curvature is derived from the 10-meter DEM in the direction of slope gradient (profile curvature) and perpendicular to the gradient (plan curvature). Curvature is calculated at 10, 20, 30, and 50 meter resolution bumps. Profile curvature affects the acceleration and deceleration of flow, while the plan curvature affects the convergence and divergence of the flow. Lower CETWI values represent convex curvature profiles where runoff occurs, and higher values represent more concave curvature where moisture accumulates.

- <u>Inundation (*I*)</u>: Representing low lying areas where water is likely to collect/pool or have higher water tables. Inundation is derived using a multi-resolution approach that gets at inundation zones that may span across large geographical spaces. Low CETWI values represent areas not subjected to inundation (ridge lines or elevated areas across the landscape), and high values represent areas that are most subject to inundation of water (reservoirs, playas).

Hydrologic Influence (*H*):

Hydrologic influence is created in a two-phase approach and represents the influence of local hydrology on the surrounding area, determined using the results from a dynamic flow network and determining the least vertical and horizontal differences between each digital elevation model cell and its nearest stream cell. The flow network is created, using a 10-meter DEM, by dynamically changing stream initiation thresholds based on the local precipitation regime and slope, where high average relative precipitation values (greater than 400 cm relative precipitation) with moderate slopes require less area (2000ha) for stream initiation, and low relative precipitation and low slope require more area (35000ha). **A novel facet of this model is that accumulation can transition between growing or decaying as slope flattens or steepens and as the network passes through different precipitation regimes.** A decay function was added to the flow accumulation algorithm and was applied where slopes are less than 5 degrees and moisture is assumed to be lost to groundwater or evaporation. In these areas negative values are accumulated and represent the loss of moisture. These two-phase outputs are then combined into the Hydrologic Influence covariate.

TWI models use derivatives of DEM properties (e.g., slope, curvature, aspect, etc.) to model surface water flow. Each TWI variant model performs a bit differently, depending on the covariates that were included for the intended use of the particular model. However, many TWI models are used to infer potential soil properties and are therefore assistive in initial soil and ecological site mapping concepts.

Flow patterns or hydrologic analysis is an important element in natural resource sciences – soils, geomorphology, or ecosystems. Understanding how the water flows is an important constituent in natural resources modeling. Understanding areas with similar moisture retention capacities aids CEAP-GL in grouping large landscapes into representative units for modeling conservation practice effects. We also use soil and vegetation data in the modeling, but those layers are independent of the CETWI layer.

The decision to produce a new model, CETWI, was made because **existing TWI models do not offer**:

a. Covariate analysis or weighting
b. Large or small areas of analysis (eg, CETWI operates at very small to very large watershed areas; we are currently processing 2-digit HUCs with CETWI)
c. Continuous flow path analysis and decay beyond landscape obstructions (eg, roadways, dams, culverts, etc)
d. Integration and use of 4k (resampled/interpolated to 800m) PRISM climate data
e. Surface moisture values that are yielding high initial correlation to vegetation communities across landscapes

Each of these unique facets of CETWI will contribute significantly to the ability of CEAP-GL and partners to prepare data for model inputs, explain and interpret model outputs, and have the potential to add value to the effective targeting analyses that are characteristic outputs of the Resource Assessment Branch.

Validation:

With regard to how the precursor to CETWI was validated in the 2017-2019 CEAP-GL Colorado forest study with the Colorado Forest Restoration Institute, Jonas Feinstein confirmed that he performed an internal, informal assessment of the model outputs against NRCS and USFS vegetation datasets and conducted some limited field reconnaissance in areas lacking NRCS and USFS data. His analysis was never published beyond what was contained in this USFS General Technical Report (GTR-373, 2018), Principles and Practices for the Restoration of Ponderosa Pine and Dry Mixed-Conifer Forests of the Colorado Front Range.

Teren Inc., the University of Arizona subcontractor on CETWI, performed initial analysis of the CETWI layer in the following manner (excerpted from draft peer manuscript under development):

> "Both the TWI and CETWI raster surfaces were rescaled by reclassifying the values from 1-10 based on percentiles for statistical analysis. Jaccard's similarity coefficient and a principal component analysis were performed to investigate indices deviation and areas with a high degree of variance. Jaccard's coefficient is a measure of similarity between two sets of data, with a range from 0% to 100%. The higher the percentage, the more similar the two populations. A principal component analysis (PCA) was used to test variance between each dataset as well as covariate. A PCA is calculated from a covariance matrix and fits an n-dimensional ellipsoid to the data. The eigenvalues of each eigenvector are proportional to the amount of variance captured in that axis, the amount of variance in that axis is calculated by comparing the eigenvectors eigenvalue to the sum of all eigenvalues the amount of variance in that axis. The areas with high variance represent deviation between the indices. Finally, a Kolmogorov–Smirnov test (K-S Test) which is a test of the equality of two distributions and quantifies the distance between cumulative distribution functions was conducted using R statistical software. A K-S Test was performed first to test if there was a significant difference in the cumulative distributions of the CETWI and TWI. A K-S test was also conducted to compare CETWI values and vegetation distribution data for several species representative of specific habitats that included: spruce fir, lodgepole pine, aspen, mountain big sagebrush, Wyoming big sage, gamble oak, and greasewood. Vegetation distribution data from the LANDFIRE program from Colorado was used for this component of the study. Lastly, the CETWI cumulative distribution function was compared against the Normalized Difference Vegetation Index (NDVI) cumulative distribution function to further test the correlation with vegetation. The NDVI was calculated for June 2020 using LANDSAT 8 data at 30 m resolution."
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> "A second portion of the study testing the validity of the model and comparing it against traditional topographic indices was completed using three comparative analyses, Jaccard's Coefficient, PCA, and a K-S Test. A K-S Test was also used to examine the relationship between the cumulative distribution of CETWI values, cumulative distribution of vegetation indices values, and vegetation composition. The resulting CETWI output deviated significantly from other topographic indices which was in agreement with our original hypothesis that inclusion of the enhanced topographic covariates as well as climatic covariates would add a significant amount of explanatory information for variability at local and regional scales."

The University of Arizona and CEAP-GL Request the Following Field Verification Steps:

1. **NRCS field review and ground-truthing.** NRCS expertise would help ground-truth CETWI as part of the standard development process. This would benefit from having local soils expertise and this is what RAB requested in December 2021. CETWI, and CETWI methodology, is not a final product currently – we are attempting to validate it for various geographies.

2. We plan to validate using ARS watershed data and possibly NEON site data. The Walnut Gulch Experimental Watershed in southeastern Arizona is managed and instrumented by the ARS and is a Long-Term Agroecosystem Research (LTAR) site, with excellent storm event and flow data available to calibrate and validate CETWI. The University of Arizona is a partner with NEON and there is a network instrumentation site on the UA's Santa Rita Experimental Range with data available for CETWI calibration and validation. Other potential calibration and validation datasets are being explored, including additional LTAR and NEON sites, the USFS Terrestrial Ecosystem Unit Inventory (TEUI), the BLM AIM and LMF data, and other ARS locations.

   Prior to validation with those data, it is our goal to work with NRCS experts to "dial-in" the CETWI values within each HUC-2 watershed by adjusting the covariate weight(s) within the model. Once we have a CETWI that functions as expected for a given HUC-2, we will undergo calibration and validation to selected available data.

Your prompt reply is appreciated so that the project may proceed.

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Project Investigator for USDA-NRCS CEAP-Grazing Lands Component modeling
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[i] Addington, Robert N.; Aplet, Gregory H.; Battaglia, Mike A.; Briggs, Jennifer S.; Brown, Peter M.; Cheng, Antony S.; Dickinson, Yvette; Feinstein, Jonas A.; Pelz, Kristen A.; Regan, Claudia M.; Thinnes, Jim; Truex, Rick; Fornwalt, Paula J.; Gannon, Benjamin; Julian, Chad W.; Underhill, Jeffrey L.; Wolk, Brett. 2018. **Principles and practices for the restoration of ponderosa pine and dry mixed-conifer forests of the Colorado Front Range.** RMRS-GTR-373. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 121 p.