Final Technical Report for Department of Energy Award DE-SC0010857, "Towards parameterization of root-rock hydrologic interactions in the Earth System Model".

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The goal of the project is to understand how plants survive droughts, as the decimation of transpiration could shift the surface energy balance from latent heat to sensible heat, leading to warming of the lower atmosphere and amplification of drought. The hypothesis we investigated is that there is a store of moisture in the weathered bedrock below the organic soil mantle, so that plants that have roots deep enough to access this moisture reservoir could survive drought.

Our study takes advantage of a multi-year high-resolution dataset of water table and sapflow velocities in a research site in the Eel River watershed in Northern California. The climate is Mediterranean, with distinct winter rain and summer dry seasons. The data show that the water table some 20 m below the surface undergoes rapid rise and slow decline after each winter storm. The data also show that the transpiration seasonality of evergreen tree varies from species to species, with Pacific madrones having maximal transpiration in the dry summer.

We developed a new stochastic parameterization of hydraulic conductivity that introduces heterogeneity into the traditional formulation and captures the preferential flow through the weathered bedrock (Vrettas and Fung, 2015). The parameterization is designed for implementation in global climate models. With the new parameterization in the Richards equation, we succeeded in reproducing the fluctuations of the water table in seven well locations over six years. Our results show that "rock moisture", the moisture in the weathered bedrock below the soil mantle and above the water table, is estimated to comprise 30% of the moisture because of the great depth of the weathered bedrock layer.

In a follow-on study (Vrettas and Fung, 2016), we extended Vrettas and Fung (2015), and carried out a series of model experiments that explore how subsurface properties impact evapotranspiration (ET) in a Mediterranean climate where a significant portion of ET is observed to take place in the dry and sunny summer when the precipitation is insufficient to meet the demand. In the experiments, we specified the annual maximum ET demand, the seasonality of the demand, and the rooting depths of the vegetation. We also included or excluded hydraulic redistribution by roots, and included a special case when we investigated the sensitivity of ET to a less conductive subsurface.

For the three years we investigated with annual precipitation ranging between 900 and 2,100 mm, both ET and 'runoff' increase with increasing precipitation. Annual

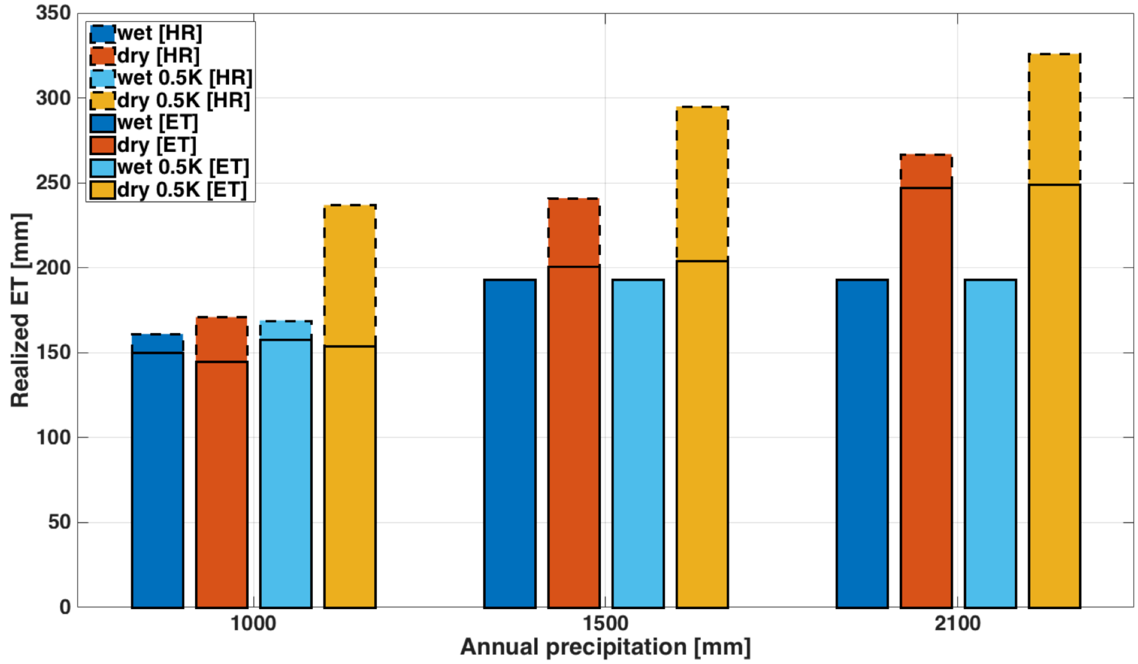

Figure 1. Impact of hydraulic redistribution on wet and dry season ET for annual precipitation amounts of 1,000, 1,500 and 2,100 mm/a, from the experiments with 10m roots, ET demand of 675 mm/a, partitioned 30:70 between the wet and dry seasons.

precipitation is mainly balanced by ET and runoff. Consistent with field observations, (e.g. Brooks et al., 2006), our results show that hydraulic redistribution is important for sustaining ET in the dry seasons when the vertical gradient in water potential is large. The maximum annual ET realized for our experiments is ~460 mm/a, for the case where the prescribed demand is 675 mm/a, partitioned 30:70 between wet:dry seasons, with 10 m roots and hydraulic redistribution operating. This estimate is comparable to the value of 500 mm/a we infer from the intercept of the discharge-rainfall relationship for the entire Eel River watershed with an area of ~9,500 km^2 (Syvitski and Morehead, 1999).

The results highlight the importance of lithology, species composition and root function for ET, especially under dry conditions. Where there are fractures in the weathered bedrock and likely soil and rock moisture, we would expect roots deep enough to access the moisture, and hydraulic redistribution to be most effective. The species composition and associated plant traits are manifested in the seasonality of ET: our observations show that proximate evergreen trees have very different sap velocity response to precipitation. The maximum ET realized for a region thus depends on the optimal combination of precipitation, plant traits and subsurface conditions: too much precipitation in a region with a highly fractured subsurface would promote infiltration and runoff at the expense of storage, and greater wet-season ET would deplete the moisture store for the summer.

We thus hypothesize that lithology, in addition to climate, is an important factor in the distribution of vegetation. Indeed, in Northern California, the demarcation between evergreen and deciduous vegetation follows the boundary between the Coastal Belt (which stores water) and the mélange (which sheds water). Trees that survive prolonged droughts have deep roots and are found in regions with weathered bedrock.

The study presented here is a first step, and prototypes an approach toward understanding resilience of vegetation to droughts. A dynamic root model may be coupled to carbon allocation models already implemented in CESMs. Implementation of the framework presented here into global climate models is encouraged by recent progress in several directions. These include: (1) a global gridded dataset of the thicknesses (up to 50 m) of soil, weathered bedrock (intact regolith), and sedimentary deposits (Pelletier et al., 2016); (2) inference of effective hydraulic conductivity and fracture density in the weathered bedrock from high-frequency observations of the water table (Vrettas and Fung, 2015); and (3) inference of ecosystems that utilize ground water (e.g., Thompson et al., 2011; Pérez Hoyos et al., 2016). Also, model results can be cross-checked by satellite observations, such as skin (top 5 cm) moisture from the SMAP satellite in areas other than dense forests where vegetation water content exceeds 5 kg/m^2 (Entekhabi et al., 2010), or the column-integral of water loading from GRACE (Tapley et al., 2004). Advancing the modeling and constraining model results will require characterization of decreasing exponentials for porosity, wilting point, and field capacity, as well as high-frequency vertical profiles of subsurface moisture, extending to a depth of 10 m or more.

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