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Accounting for "hot spots" and "hot moments" in soil carbon models for water-limited ecosystems

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Soil organic carbon (SOC) dynamics in water-limited ecosystems are complicated by the stochastic nature of rainfall and patchy structure of vegetation, which can lead to “hot spots” and “hot moments” of high biological activity. Non-linear models that use spatial and temporal averages of forcing variables are unable to account for these phenomena and are likely to produce biased results. In this study we present a model of SOC abundance that accounts for spatial heterogeneity at the plant scale and temporal variability in soil moisture content at the daily scale. We approximated an existing simulation-based model of SOC dynamics as a stochastic differential equation driven by multiplicative noise that can be solved numerically for steady-state sizes of three SOC pools. We coupled this to a model of water balance and SOC input rate at a point for a given cover type, defined by the number of shrub and perennial grass root systems and canopies overlapping the point. Using a probabilistic description of vegetation structure based on a two dimensional Poisson process, we derived analytical expressions for the distribution of cover types across a landscape and produced weighted averages of SOC stocks. An application of the model to a shortgrass steppe ecosystem in Colorado, USA, replicated empirical data on spatial patterns and average abundance of SOC, whereas a version of the model using spatially averaged forcing variables overestimated SOC stocks by 12%. The model also successfully replicated data from paired desert grassland sites in New Mexico, USA, that had and had not been affected by woody plant encroachment, indicating that the model could be a useful tool for understanding and predicting the effect of woody plant encroachment on regional carbon budgets. We performed a theoretical analysis of a simplified version of the model to estimate the bias introduced by using spatial averages of forcing variables to model SOC stocks across a range of climatic conditions and vegetation types. Our analysis predicted that bias will be highest at very dry sites where the contrast between “hot spots” and their surroundings is strongest, resulting in high covariance between forcing variables, and at intermediate sites where the diversity of cover types leads to high variance in the forcing variables.