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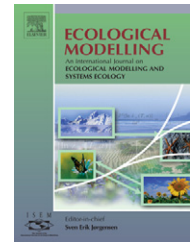

Soil water carrying capacity for vegetation: A hydrologic and biogeochemical process model solution

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ABSTRACT

The research for a maximum stand density that maintains sustainable development is necessary in arid and semi-arid areas where the conflict between limited soil water storage and the need for more plants in improving environmental quality almost always exists. However, the quantification of the research is not easy since it requires insight interpretations of the effects of plant density on soil water storage and soil water stress on plant growth. Such quantification is incomplete with current empirical methods or physical models because the dynamics effects of soil water stress and its feedbacks are not included. This paper presents a physically based model of soil water carrying capacity for vegetation (SWCCV). The model build on the concept of an equilibrium adjustment of vegetation growth to soil water dynamics, by iterative calculation between hydrologic and biogeochemical processes that account for the interactions between the limiting effects of soil moisture on photosynthesis and evaporative demand on soil water. It is capable to calculate the maximum plant density at any given initial conditions (site-specific data, vegetation, weather, and etc.) through hourly, daily and yearly cycles. Exploratory simulation to evaluate the model against results from previous studies for two sites indicated that the predictions by the model had good agreement with measured soil water contents in each layer, LAI and NPP for plants. Under the same initial conditions the predicted soil water carrying capacity captured well the soil water difference between two sites in terms of controlling vegetation density. Overall, the SWCCV model is capable in terms of predicting soil water carrying capacity, providing a new approach for understanding soil–vegetation interactions and making recommendations for better management of vegetation construction in arid and semi-arid areas.

1. Introduction

Deep insight understanding the relationship between soil water dynamics and vegetation density is helpful for making recommendations to soil erosion control and vegetation construction in semi-arid and arid areas (Braud et al., 2001; Yu et al., 2006; Zhou et al., 2006). On one hand, increasing vegetation density can significantly reduce sediment yield because of rapidly increasing land coverage, and resulting in an effective control of soil erosion (Bosch and Hewlett, 1982; Gardiol et al.,

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2003; Khanna et al., 1999; van Dijk and Bruijnzeel, 2003; Wang and Cai, 1999; Yu et al., 2006; Zhou et al., 2006). On the other hand, soil water should be prevented from excessive consume by vegetation since an increase in plant cover increases evapotranspiration (Kyushik et al., 2005). Soil water is the limiting factor in determining the vegetation density in the arid and semi-arid areas. Thus, the search for a maximum stand density as a basis for sustainable development is necessary in the areas where the conflict between limited soil water and much of required plant almost always exists.

The underlying concept and premises of carrying capacity, employed as tools for the operationalization of sustainable development (Schneider et al., 1978), is a very ambiguous term in ecology. It usually means to be the maximum number of individuals that can be supported in an environment without the area experiencing decreases in the ability to support future generations within that area (Guo and Shao, 2004). Moreover, planners usually define carrying capacity as the ability of a natural or artificial system to support the demands of current and future development without considerable degradation or damage (Zeide, 2004). Concern over rising planting in arid and semi-arid regions, and accompanying impacts on soil water, led the management to focus increasing attention on the concept of soil water carrying capacity (Guo and Shao, 2004). In particular, the concept may be useful in vegetation and range management as a general definition of carrying capacity does in ecosystem. Here soil water carrying capacity is defined as: a maximum vegetation density that an arid or semi-arid area will support without soil water experiencing decreases in the ability to support future generations during plant growth period, given the desired climatic condition, soil texture, and management program. "The desired climatic condition, soil texture, and management program" recognizes the need to be comprehensive, integrative, concurrent, and holistic in decision making. It is a useful concept for theoretical system modeling, but it is very problematic for practical application. In the real world, virtually no habitat is stable indefinitely. Seasonal variations occur throughout the year even the day; annual variations occur between years (e.g., weather); and disturbances, succession, ecological change are present over both short and long time scales. "Maximum vegetation density" can vary, depending on type and age composition desired or assumed, as well as expectations for biomass of the plant (e.g., "maximum sustained yield").

In practical application, carrying capacity is best determined empirically, after carefully defining exactly what is meant about location, climatic condition, reasonable limits of natural variation (e.g., are droughts or innutrition included?), and physiological characteristics of vegetation. It requires much empirical experience with the vegetation and the site-specific condition. Yet, extrapolation to other location than those specific lands studied involves much uncertainty. As for quantifying optimization vegetation for each position for anytime in catchment, empirical determination of carrying capacity is almost impossible.

Until recently, relatively little work has been done on theoretical calculation or estimation model of carrying capacity for vegetation. Zeide (2004) developed a simple model that accounted for each main growth predictor individually which allows one to calculate the density that maximizes volume growth at a given time. However, in the model soil moisture is not modified by plant density and does not restrict plant growth. Thus, the model is not in tune with the water and heat transfer character of soil-plant-atmosphere continuum. Based on the interaction between soil water supply and planting density, the empirical model derived from field trials did not consider soil moisture availability and the processes happened in soil–plant system, therefore, interactions between soil and plant are static and fixed, and consequently the model is difficult to model or predict (Guo and Shao, 2004). As these models do not ensure physical consistency of system solutions, Devonec and Barros (2002) has suggested materials process analysis to ensure such a consistency.

Physically based process model, which provide a dynamic way of determining soil water carrying capacity for vegetation, is confounded by two major problems: (1) hydrological and biogeochemical process are not on balance one another, and (2) biomass was used as a parameter inputted into the model by the trial and error method, it is really difficult to obtain the optimization vegetation density. As examples of biogeochemical models, such as FOREST-BGC (Aber and Federer, 1992), BIOME-BGC (Parton et al., 1996), PnET (Farquhar et al., 1980), and CENTURY (Garcia-Quijano and Barros, 2005) utilize variations of a photosynthesis model proposed by Farquhar et al. (Vörösmarty et al., 1989), which calculates CO_2 assimilation as a function of the carboxylation and oxygenation velocities, photosynthetic electron transport and dark respiration. However, moisture availability controls in the atmosphere (water vapor pressure) and soil (soil water content) are not taken into account, and therefore soil water stress to photosynthesis (Parton et al., 1996; Vörösmarty et al., 1989). In spite of the degree of biogeochemical detail present in this model, the physically based hydrological process is described in a relatively simple way, using of empirical formulas which are restricted to specific environment, or the hydrological model is run separately (Devonec and Barros, 2002). Therefore, the predicted soil water dynamics is not accurate because it is not affected by vegetation growth and the feedbacks of evapotranspiration and runoff (Devonec and Barros, 2002; Garcia-Quijano and Barros, 2005). With regard to hydrological models, in which each hydrologic process is described by semi-empirical function based on field data in great detail (Running et al., 1987), but are based on the assumption that the vegetation is static, neglecting feedbacks involving photosynthesis, soil moisture, and transpiration (White et al., 2000). Furthermore, most hydrological models rely on point measurements of LAI and assume that transpiration is uniform within the canopy independent of the height of each foliage layer. In our efforts to understand the interactions between soil water dynamics and vegetation growth, it has been increasingly recognized that hydrological and biogeochemical cycles need to be modeled in details coequally.

In order to take an effective approach to resolve this dilemma, we here present a quantifying model of Soil Water Carrying Capacity for Vegetation (SWCCV) that integrates hydrological and biogeochemical process and to examine the results that are obtained from field data. The model was built