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Process-based simulation of prairie growth

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ABSTRACT

When field research is cost- or time-prohibitive, models can inform decision-makers regarding the impact of agricultural policy on production and the environment, but process-based models that simulate animal-plant-soil interaction and ecosystem services in grazing lands are rare. In the U.S.A., APEX (Agricultural Policy/Environmental eXtender) is a model commonly used to inform policy on cropland, but its ability to simulate grazinglands was less robust. Therefore, we enhanced the APEX model's plant growth module to improve its utility on grazing lands. Improvements addressed allocation of new biomass, response to water stress, competition for soil water, and regrowth of herbaceous perennials. Sensitivity analysis demonstrated that simulated biomass responded to changes in precipitation through adjustments to both total biomass and distribution of biomass aboveground and belowground. A deep-rooted species generally outperformed a shallow-rooted species but the relative advantage was greatest when precipitation was historically low. A 10-year dataset of peak biomass collected in central Kansas, U.S.A., was divided among 5 species and species groups and was used for calibration and validation. When the mass of all species was combined in the validation dataset, the percent bias was −2%, Willmott's D_r was 0.79, and r^2 was 0.84. When biomass production of individual species was analyzed, the model did not perform as well, with the percent bias ranging from −36 to 29%, Willmott's D_r ranging from 0.58 to 0.71, and r^2 from 0.25 to 0.67. Because grazing lands often have a rich species diversity, the improvements made APEX better-suited to modeling such heterogeneous landscapes. However, simulating biomass of individual species, rather than the sum of all species, is an area that still needs improvement. Further testing at additional sites to calibrate single- and multiple-species growth and identify any spatial trends in model performance will also be beneficial.

1. Introduction

Grazinglands cover approximately 40% of the global terrestrial landmass (FAO, 2005) and store approximately 10% of its soil carbon (Nosberger et al., 2000). Conservative management of grazinglands can maintain or improve soil health and productive capacity while supplying numerous ecosystem services and agricultural products. In contrast, poor management can alter or eliminate grazingland vegetation, resulting in provision of fewer and poorer ecosystem services and less agricultural output. For instance, increasing stocking rates shifted North American midgrass communities, composed of a mixture of C3 and C4 grasses, to shortgrass communities dominated by C4 grasses (Launchbaugh, 1967; Hanson et al., 1978; Porensky et al., 2016). Concurrently, changing climates promise to impact grazinglands in novel ways.

Simulation models are useful for providing answers to alternative management and climate scenarios over long periods of time because it may be impossible or infeasible to conduct the large-scale research required to answer the same questions through field research. Many ecosystem models are capable of simulating grasslands, each with strengths and weaknesses. A few examples include: 1) the PHYGROW model (Stuth et al., 2003b), which has been used to anticipate forage shortages in grazinglands for over a decade (Stuth et al., 2003a; Stuth et al., 2005; Angerer, 2012); 2) GPFARM-Range, which has been used to simulate forage and cow-

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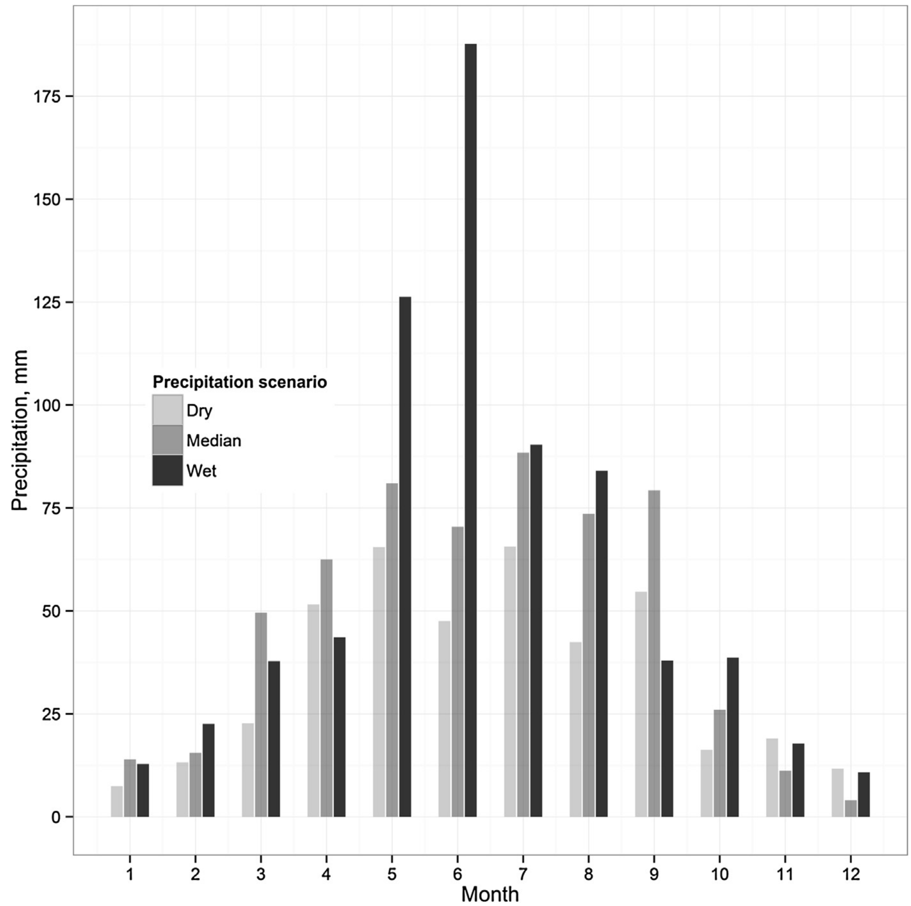

Fig. 1. Mean monthly precipitation at Hays, Kansas for the three scenarios: 1) median 5-year precipitation period since 1900 (1999–2003), 2) driest 5-year period since 1900 (1952–1956), and 3) wettest 5-year period since 1900 (1947–1951).

calf production in the Great Plains (Andales et al., 2005, 2006); SAVANNA (Coughenor, 1993), which includes spatial representation of ecosystem components; 4) the Sustainable Grazing Systems model (Johnson et al., 2003) which has been used to simulate forage production and steer liveweight gain in Australia (Doran-Browne et al., 2014); and 5) the APEX model (Gassman et al., 2010), a farm-scale version of EPIC (Williams et al., 1984). APEX has been in development for decades, has been extensively tested, and simulates production of a wide variety of crops and environmental variables. APEX and its related models (EPIC, ALMANAC, and SWAT) have been used to simulate perennial grass production (e.g., Kiniry et al., 2008; Wang et al., 2014; Santhi et al., 2001) but their development in this area is less mature than for annual crops.

Since 2003, APEX has been used by the Conservation Effects Assessment Project (CEAP) within the United States Department of Agriculture's Natural Resources Conservation Service to model the yield and environmental impacts of alternative farm conservation practices on croplands. In this capacity, the model helps to identify those conservation practices and suites of practices which are most effective at achieving desired environmental goals and the associated gain or loss of agricultural yield. To extend the use of APEX to rangeland and pastureland for the purposes of CEAP, it was necessary to enhance the model's ability to simulate grazing land dynamics. Specifically, the model required an improved ability to simulate perennial plant production throughout the entire year, improved competitive dynamics among plant species growing in mixture, and improved interaction between plant and animals. This study focuses on the first two requirements. Plant-animal interactions will be addressed by future work.

Therefore, we modified the APEX model (0806 version) to improve its ability to simulate perennial grassland vegetation. In the following sections, we: 1) describe the modifications made to the plant growth module, 2) conduct a sensitivity analysis and, 3) provide examples of the new model's performance with a historic dataset and hypothetical scenarios.

2. Methods

2.1. Plant growth module modifications

2.1.1. The APEX model

The APEX (Agricultural Policy/Environmental eXtender) model is a process-based model for simulating impacts of land management on whole farms and small watersheds. APEX is written in FORTRAN and uses a daily time step. Gassman et al. (2010) described the model's 12 major components, which include climate, hydrology, crop growth, pesticide fate, nutrient cycling, erosion-sedimentation, carbon cycling, management practices, soil temperature, plant environment control, economic budgets, and routing between land units. Climate inputs, including precipitation, daily maximum and minimum temperatures, relative humidity, and wind speed can be input from daily records or generated from monthly descriptive statistics. APEX is capable of simulating multiple species growing together in competition. Although species are defined by 60–70 different parameters, depending on the version of APEX, only a small subset of these (e.g., radiation use efficiency, maximum leaf area index) need to be adjusted for most model applications. Plant species compete for light, water, and nutrients.