Ecological Modelling 337 (2016) 211–220

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Climate change impacts on regenerating shrubland productivity

Arjun Adhikari[a,*,1], Joseph D. White[a,b]

[a] The Department of Biology, Baylor University, One Bear Place, Waco, TX 76798, USA
[b] The Institute of Ecological, Earth, and Environmental Sciences, Baylor University, One Bear Place, Waco, TX 76798, USA

ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 27 May 2016
Accepted 7 July 2016

Keywords:
3-PG model
Aboveground biomass
Rio grande valley
Spatial data

ABSTRACT

Over the past century, intensive agricultural activity in the Lower Rio Grande Valley, TX, USA, resulted in loss of more than 95% shrub cover. Restoration efforts in these shrublands have resulted in successful reestablishment of native shrubs communities important for carbon sequestration and related wildlife habitat conservation. To examine future climate change effects on restored shrublands, we used the Physiological Principles in Predicting Growth (3-PG) to predict impacts on shrub growth compared to current production. Simulations were performed with 30 m^2 grid cells using monthly incident solar radiation, temperature, precipitation, available soil water holding capacity, and soil fertility within a national wildlife refuge located in the valley. The model was calibrated and confirmed by comparing remote sensing derived aboveground biomass to simulation under current climate conditions with overall good correlation ($r^2 = 0.78$). The model parameter values were derived from experimental and literatures appropriate for shrub species commonly found in the study area. We assessed climate change effects on simulated shrub biomass by using monthly temperature and precipitation projections for three emissions scenarios for 2050. Predicted aboveground biomass for the current climate (30.78 Mg/ha) was higher compared to that of B1 (29.77 Mg/ha), A1B (27.54 Mg/ha), and A2 (28.01 Mg/ha) emission scenarios. We found that productivity in this shrubland was controlled by VPD and soil fertility. We conclude that restoration efforts within the study area have shown potential for increased carbon sequestration in shrub vegetation under current climate, but future climate change is likely to reduce its carbon uptake efficiency.

1. Introduction

Shrubland ecosystems are important for their role in global carbon dynamics because approximately 30% of terrestrial carbon is stored in tissue biomass and soil of these systems (Melillo et al., 1993; UNDP/UNSO, 1997; Lal, 2004; Bechtold and Inouye, 2007; Luo et al., 2007; Piao et al., 2009). Recent studies on climate change effects identified temperature, precipitation, vapor pressure deficit (VPD), and potential evapotranspiration (PET) as important drivers potentially altering structure and function of shrublands including carbon sequestration, species composition, and localized sustainability for the wildlife management (Archer et al., 1995; White et al., 2008; Adhikari and White, 2014). This leads to considerable uncertainty in the future carbon storage capacity of active replanting and naturally regenerating shrublands. This has increased interest in accurately predicting shrub growth and biomass accumulation in response to changing climate associated with management (Goodale and Davidson, 2002; Jackson et al., 2002; Wessel et al., 2004; Paul et al., 2013, 2015). Ecosystem process models are essential for predicting shrub growth with continued changing climate that provide insight on future carbon sequestration potential.

Process-based models have been used to estimate plant biomass under climate change and management scenarios (White et al., 2000, 2006; Coops and Waring, 2001; Coops et al., 2005; Almeida et al., 2010; Paul et al., 2015). Spatially explicit process-based models provide continuous estimates of plant growth for larger areas compared to conventional field approaches (White et al., 2008; Coops et al., 2001). Mechanistic models also offer opportunity to estimate carbon budget and investigate interacting sensitivities of plant growth to environmental factors such as temperature, precipitation, soil water availability, and soil nutrients (Battaglia and Sands, 1997; Landsberg and Waring, 1997; Berger and Hildenbrandth, 2000; White et al., 2000; Xenakis et al., 2008; Almeida et al., 2010; Ouyang et al., 2010).

* Corresponding author.
E-mail addresses: arjun.adhikari@montana.edu, aadhikari@gmail.com (A. Adhikari).
[1] Current address: North Central Climate Sciences Center (NC CSC), Department of Ecology, Montana State University, Bozeman, MT 59717, USA.

http://dx.doi.org/10.1016/j.ecolmodel.2016.07.003
0304-3800/

The Physiological Principles in Predicting Growth (3-PG) model was developed by Landsberg and Waring (1997), and has been widely applied in predicting forest growth rate and biomass accumulation using small number of parameterized variables from direct measurements and literature values (White et al., 2000, 2006). The 3-PG model is based on an established photosynthetically active radiation energy conversion principle related to carbon allocation constrained by meteorological and soil characteristics (Landsberg and Waring, 1997). The model has been adapted to incorporate spatial data and has been previously calibrated and tested successfully to predict plant biomass in primarily forested ecosystems (Coops, 1999; White et al., 2000; Coops et al., 2005; Almeida et al., 2010; Waring et al., 2010).

In this study, we assess the effects of climate change on growth of managed shrublands using the 3-PG model. Our study shows that the 3-PG model can be used in predicting response of shrub vegetation to the changing climate, as it was originally developed to predict growth in forests. For this study, we first calibrated the model by comparing simulated and remote sensing-derived aboveground shrub biomass from a previous study (Adhikari et al. in review). The calibrated model was then used to assess aboveground carbon storage potential of shrublands that are being restored and managed through active replanting under current and future climate change scenarios. Findings of this study are important for tempering future management expectations of shrubland restoration and expected carbon sequestration gains.

2. Methods

2.1. Study site

Our study area was the Lower Rio Grande Valley (LRGV) located in Lower Rio Grande Valley Wildlife National Refuge, Texas, USA, which we chose because of its current management objective as an endangered species refuge and as part of the U.S. portfolio of federal lands used for carbon sequestration (Zhu, 2010). Jahrsdoerfer and Leslie (1988) estimated over 95% of wildlife habitat of LRGV has been altered either into agricultural or urban lands since the 1930's. Currently, the LRGV encompasses 23000 ha conserved area at the northern edge of the Tamaulipan Biotic province (Blair, 1950; LRGV revegetation database, 2009; Fig. 1) and has been managed by US Fish and Wildlife Service (USFWS) since its establishment in 1979. Since 1982, a 5560 ha of this land has been actively replanted with native shrub species as part of agency's ecosystem restoration program. Westward from the Gulf of Mexico coast, the vegetation of LRGV thins with declining site water availability (Jahrsdoerfer and Leslie, 1988) as a result of low precipitation and high potential evapotranspiration (Fig. 2). The LRGV primarily serves as important habitat for many endangered species such as ocelots (*Leopardus pardalis*) and jaguarondis (*Puma yagouaroundi*), which utilize the contiguous shrub, cover as their habitat. Along with wildlife habitat, these shrublands are also potentially important as terrestrial carbon sinks (Navar-Chaidez, 2008).

Because the area of LRGV is extensive and crosses a gradient of precipitation, the study area was divided into four climatic zones longitudinally for subsequent analyses (Fig. 1; Table 1). For each climate zone, 30-year average temperature, precipitation, and vapor pressure deficit were calculated and are shown in Table 1 for reference. Significantly lower PET in Zone 1 should be due to higher rainfall and adjoining land to the coast (Williamson, 1998).

2.2. Description of the model

The 3-PG model that estimates the stand growth based on absorption and utilization of incident solar radiation (Landsberg and Waring, 1997) where photosynthetically active radiation, (PAR; φ_p) is calculated from short wave radiation assuming that 50% of this radiation is in the PAR range (McCree, 1972). Absorbed photosynthetically active radiation (APAR; φ_{pa}) is estimated from global solar radiation and leaf area index (LAI; $m^2\,m^{-2}$) using the Beer-Lambert law. The LAI used in calculating APAR is derived from the total foliage biomass present at the end of each month and a new monthly LAI value is derived from updated leaf biomass values multiplied by specific leaf area (SLA, m^2 kg dry matter^{-1} Eq. (1)).

$$LAI = SLA \times Wf \times 0.1 \quad (1)$$

where Wf is stand level foliage biomass (Mg dry matter ha^{-1}) and 0.1 converts units from Mg to kg to tons and ha and m^2.

Dimensionless physiological and environmental modifiers that range from value 0.0 to 1.0 ($0.0 \le f_i \le 1.0$) in 3-PG are used to constrain the overall amount of APAR, physiologically available for gross primary productivity (GPP). First, the utilized portion of APAR (φ_{pau}) is obtained by reducing APAR by the minimum value of the available soil water (f_θ) and atmospheric vapor pressure deficit (f_{vpd}) modifiers. These modifiers represent the environmental water limits to canopy gas exchange with values range between 0 (system 'shut down') to 1 (no constraint) (McMurtrie et al., 1994; Runyon et al., 1994; White et al., 2006). The value of the soil modifier, $f_{\theta,}$ is calculated from Eq. (2).

$$f_\theta = \pm\frac{1}{1+\left[\frac{1-r_\theta}{m}\right]^n} \quad (2)$$

where, m and n are coefficients representing the soil water potential change to different textural classes and r_θ is volumetric soil water content balance calculated as the difference between total monthly rainfall and evapotranspiration losses plus storage (Landsberg and Waring, 1997). The climatic modifier, VPD, is calculated as a negative exponential function, i.e. $f_{vpd} = exp^{-k*VPD}$ (where VPD is current vapor pressure deficit and k is strength of VPD response). The curvilinear relationship between these two modifiers is due to non-linear relationship effect of both atmospheric and soil water deficits on guard cell turgor pressure affecting stomatal opening and closure (Jones, 2014). For vapor pressure deficit, we used the method by Kimball et al. (1997) based on daily average and minimum temperatures because of the aridity of this area. Next, modifiers representing the effect environmental conditions affecting the physiological capacity of the plant to photosynthesize including air temperature (f_T), frost days per month (f_F), site nutrition (f_N), stand age (f_{age}) are multiplied by a specified maximum quantum efficiency of the canopy ($_{\alpha c}$) and φ_{pau} to calculate gross primary productivity (GPP = $_{\alpha c}\, f_T\, f_F\, f_N\, f_{age}\, \varphi_{pau}$). For these simulations, the effect of age on plant growth was assumed to be small given the small stature of the plants represented in the model therefore f_{age} was set to a constant value of 1.0. Also, no days in the current and future meteorological data were found to have minimum temperatures $\le$0 °C, therefore f_F was also set to 1.0.

Net primary productivity (NPP) is calculated as constant fraction of GPP with NPP allocated to different plant components as root and aboveground foliage, and stem mass. Allocation is determined based on the ratio of $\varphi_{pau}/\varphi_{pa}$ where decreases from 1.0 to 0.2 in the value of this ratio lead to a higher fraction of biomass allocated to roots (W_r). However, this allocation value varies with environmental conditions (see Navar et al., 2013). The NPP allocation to root increases soil fertility shown in Eq. (3).

$$f_N = f_{N_0} + \left(1 - f_{N_0}\right) W_r \quad (3)$$

where f_{N0} is the baseline soil fertility rating at the beginning of the simulation that ranges from 0.0 to 1.0, which we have derived here from soil organic matter. The change in f_N due to increased W_r reflects potential higher exposure of root surface area to available