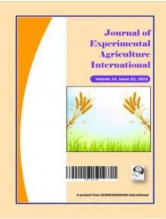

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Short Duration, Perennial Grasses in Low Rainfall Sites in Montana: Deriving Growth Parameters and Simulating with a Process-Based Model

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Authors' contributions

This work was carried out in collaboration between all authors. Author JRK designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors JMM, MKP and RWK collected the plant samples and selected the study sites. Author LJM initiated the study and organized the collaboration. All authors read and approved the final manuscript.

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ABSTRACT

Rangeland grasses in the arid western U.S. grow quickly, set seed, and senesce in a relatively short timeframe enabling them to survive and reproduce when the limited soil moisture is available. In addition, rangeland management in arid sites can benefit from process-based simulation tools to optimize grazing timing, intensity and duration and for assessing impacts of invasive species and of climate change. In this study, over three growing seasons, we derived the needed growth parameters for the ALMANAC model to simulate three common cool season grasses and one warm season grass in Montana. The parameters were then used with the model to simulate plant growth

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on three typical ecological sites near Miles City. Model parameters such as radiation use efficiency and potential leaf area index showed expected trends with the four grasses. Once the parameters were used with the ALMANAC model, simulations showed reasonable agreement with published NRCS grass yields for normal years, wet years, and dry years. Thus this process-based model and parameters such as those described herein will be valuable for assessing various management scenarios and climate variables in these types of low rainfall, western U.S. ecological sites.

Keywords: Simulation modeling; western U.S. native grasses; rangeland management; plant parameters.

1. INTRODUCTION

Rangeland grasses in the arid western U.S. grow quickly, set seed, and senesce in a relatively short timeframe enabling them to survive and reproduce when the limited soil moisture is available. Previous attempts at simulating plant growth on rangelands [1-4] allowed the grasses to have a growing season for the entire period when temperatures were adequately high. However, reality is that such grasses have a relatively short growth cycle, maybe 4 to 6 weeks in the spring. They can then have another similar growth period if adequate rains occur later in the season.

Rangeland management in arid sites can benefit from process-based simulation tools to optimize grazing timing, intensity and duration, and for assessing impacts of invasive species and climate change. Grazing contributes to changes in plant community composition, changes in long term productivity, and the ability of ecological sites to respond to changes in climate including temperature and rainfall. Such models require realistic algorithms that describe plant growth and realistic plant parameters for the primary plant species or plant functional groups. With such appropriate model functions and parameters, process-based models should be able to not only realistically simulate scenarios similar to those in measurement years, but also should be able to simulate conditions not previously experienced. This is a major advantage over simple statistical regressions for grass yields as a function of weather variables such as rainfall.

In this study, we derived the needed growth parameters for the ALMANAC model for three common cool season grasses: threadleaf sedge *(Carex filifolia* Nutt.); needle and thread *(Hesperostipa comata* (Trin. & Rupr.) Barkworth); and green needlegrass (*Nassella viridula* (Trin.) Barkworth); and one common warm season grass: prairie sandreed (*Calamovilfa longifolia* (Hook.) Scribn.). These were derived in the field in a 31.5 cm rainfall, 74 cm snowfall area on the ARS Fort Keogh Range and Livestock Research Station near Miles City, MT. As part of this effort, the duration of leaf area development was determined to allow realistic simulation of their growth patterns.

The ALMANAC model (Agricultural Land Management Alternatives with Numerical Assessment Criteria) [5-6] is a process-based simulation model designed to evaluate impacts of various management strategies such as grazing management, invasive species, and revegetation. Plant cover, soil stabilization by plants, and nutrient cycling by plants represent the major aspects varying within each season and between years in response to these management strategies. As such, realistic simulation of plant development is necessary for effective simulation evaluations.

Work with ALMANAC continues to explore the potential to identify, parameterize, and simulate trait-based functional groups using representative species within these groups [3-4]. Model output will be applied to assessing ecosystem impacts and services associated with shifts in both species composition and management practices. For example, the ALMANAC model could be implemented to interpret site monitoring and adaptive management approaches such that it could be a valuable tool for conservation practice planning.

The parameters for two of these grasses, needle and thread and green needlegrass, were then used along with previously derived parameters for bottlebrush squirreltail (*Elymus elymoides*) and western wheatgrass (*Pascopyrum smithii*) [4] to test the ALMANAC model's ability to replicate reported USDA-NRCS range productivity values. This was done for three typical ecological sites near Miles City. Using long-term simulations, the model's simulated grass yields were compared to the NRCS values for normal years, low yielding (dry) years, and high yielding (wet) years. These results are designed to provide a valuable technology transfer tool to assess environmental and management impacts on ecological site productivity under such conditions.

2. MATERIALS AND METHODS

2.1 Field Measurements

Plant measurements for parameter derivation were described previously [7]. Measurements were taken on relatively uniform established stands of the four grass species on ecological sites near Miles City, MT. Soil types and ecological sites were a Kobase-Gerdrum silty clay loam ("Clayey" ecological site (Cy) RRU 58A-E 10-14" p.z.R058AE002MT) for green needlegrass and a Chinook-Twilight-Eapa complex ("Sandy" ecological site (Sy) RRU 58A-E 10-14" p.z. R058AE003MT) for the other grasses. Values related to water holding capacity and organic carbon varied among the soils (Table 1).

Regional topography ranges from rolling hills to broken badlands with small intersecting streams that seasonally drain into large permanent rivers meandering through broad, nearly level valleys. The potential natural vegetation on the experimental station is a grama-needlegrass-wheatgrass (Bouteloua-Stipa-Agropyron) mixed grass dominant [8-10].

The Clayey ecological sites, according to the Web Soil Survey ((United States Department of Agriculture, Natural Resource Conservation Service, USDA-NRCS Web Soil Survey) (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm)), are level to undulating grasslands dominated by cool season grasses, with forbs and shrubs occurring in smaller percentages. Approximately 85-90% of the annual production by weight is grasses and sedges, 1-5% is forbs, and 5-10% is shrubs and cacti. Canopy cover of shrubs is typically 1-5%. Trees are not significant on this site. Dominant species include bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve), green needlegrass, western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve) and thickspike wheatgrass (*Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould), and a diverse group of short grasses, such as Sandberg bluegrass (*Poa secunda* J. Presl), blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths), and prairie junegrass (*Koeleria macrantha* (Ledeb.) Schult.). While there are a diversity of forbs (purple prairie clover (*Dalea purpurea* Vent.) and white prairie clover (*Dalea candida* Michx. ex Willd.), prairie coneflower (*Ratibida columnifera* (Nutt.) Woot. & Standl.), dotted gayfeather (*Liatris punctata* Hook.)) at this ecological site, they comprised almost none of the dry matter in the samples. Thus they were not included in the analyses. Shrubs such as Wyoming big sagebrush (*Artemisia tridentata* Nuttall) and winterfat (*Krascheninnikovia lanata* (Pursh) A. Meeuse & Smit) are common.

The Sandy/Silty ecological site’s plant community contains a high diversity of tall and medium height grasses (prairie sandreed, little bluestem (*Schizachyrium scoparium* (Michx.) Nash), big bluestem (*Andropogon gerardii* Vitman), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve), needle and thread, and Indian ricegrass (*Achnatherum hymenoides* (Roem. & Schult.) Barkworth), and short grasses and sedges (sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray), plains muhly (*Muhlenbergia cuspidata* (Torr. ex Hook.) Rydb.), sun sedge (*Carex inops* L.H. Bailey ssp. *heliophila* (Mack.) Crins.), prairie junegrass (*Koeleria macrantha* (Ledeb.) J.A. Schultes), threadleaf sedge, and blue grama). There are a diversity of forbs, shrubs, and half-shrubs which occur, but they comprise a very small percentage of the total biomass.

Table 1. Soil values related to water holding capacity and organic carbon. PAW is the plant available water at field capacity

Soil name	Soil depth	Field capacity	Wilting point	Pot. PAW stored at FC	Organic C
	m	mean vol.	mean vol.	cm	% in top 8 cm
Kobasse-Gerdrum	1.52	0.336	0.224	17.0	0.88
Chinook-Twilight-Eapa	1.52	0.155	0.066	13.5	0.88
Cabbart	0.30	0.280	0.140	4.2	0.88
Cambeth	0.36	0.298	0.150	9.8	1.18
Creed	0.30	0.286	0.162	3.7	1.18

Measurements included taking series of at least five photosynthetically active radiation (PAR) measurements below the plant canopy concurrently with above plant canopy PAR measurements. Fraction of intercepted PAR (FIPAR) values were collected with the AccuPAR LP-80 ceptometer and external sensor (Decagon Devices, Inc., Pullman, WA) by synchronous measures of PAR above and below the plant canopy. Plants were harvested, weighed fresh, and a subsample was weighed. Value of FIPAR was the average of

$$\text{FIPAR} = 1.0\ (\text{below PAR}/\text{above PAR}) \qquad (1)$$

Clippings of all the plant material in a 1 m by 1 m area (5 cm from the ground) were taken in the same locations as the PAR measurements. All the material was weighed fresh, subsampled, and the subsample weighed fresh. The subsamples were then overnight-mailed to USDA-ARS, Temple, TX. There the leaf area was measured with a LI-3100 Area Meter (LI-COR Biosciences, Lincoln, NE) and dried to constant weight in an 80℃ forced air oven. Total leaf area of each original sample and its dry weight were calculated using the fresh weight ratio of the subsample to total sample. Thus the leaf area index (LAI) and dry plant weight (g per m^2 ground area) were calculated.

The light extinction coefficient (k) for Beer's law [7,11] was calculated for each sample as

$$\text{FIPAR} = 1.0 - \exp(-k*\text{LAI}) \qquad (2)$$

Transposed to

$$k = -(\text{logn}\ (1.0 - \text{FIPAR}))\ /\ \text{LAI} \qquad (3)$$

Radiation use efficiency (RUE) requires measurements of cumulative dry weight (g of plant biomass per m^2 of ground area) and summed intercepted PAR (SIPAR) (MJ per m^2 of ground area). Value of SIPAR requires daily values for FIPAR and incident PAR (assuming 45% of incident total solar radiation is PAR, [12]). Mean values of FIPAR for each grass species on the different dates were used with linear interpolation to calculate daily FIPAR.

2.2 Simulations of Ecological Sites with ALMANAC

Three ecological sites were chosen that covered large areas near Miles City. These were chosen to be different from the soil where the plant measurements were taken to test the parameters' and model's ability to simulate diverse sites and soils. The simulated sites were a "Shallow" ecological site with a Cabbart soil (Loamy, mixed, superactive, calcareous, frigid, shallow Aridic Ustorthents); a "Silty-Steep" ecological site with a Cambeth soil (Fine-silty, mixed, superactive, frigid Aridic Calciustepts); and a "Claypan" ecological site with a Creed soil (Fine, smectitic, frigid Aridic Natrustalfs).

The Shallow ecological site's plant communities (according to the USDA-NRCS Web Soil Survey) contain a high diversity of tall grasses (prairie sandreed, little bluestem, big bluestem, needle and thread, Indian ricegrass, and bluebunch wheatgrass), short grasses and sedges (sand dropseed, plains muhly, prairie junegrass, threadleaf sedge and blue grama), and shrubs (skunkbush sumac (*Rhus trilobata* Nutt.) and winterfat). There are also a diversity of forbs, and half-shrubs which occur in small percentages.

The Silty-Steep ecological site's plant communities contain a high diversity of tall and medium height, cool and warm season grasses (bluebunch wheatgrass, green needlegrass, little bluestem, western wheatgrass, and plains muhly) with a diverse mix of other grasses and sedges (needle and thread, threadleaf sedge, prairie junegrass, and Sandberg bluegrass). Several forbs, shrubs, and half-shrubs also occur on this site, but in relatively small percentages. Common shrubs are Wyoming big sagebrush, winterfat, snowberry (*Symphoricarpos albus* (L.) S.F. Blake), prairie rose (*Rosa arkansana* Porter), and creeping juniper (*Juniperus horizontalis* Moench). Trees such as Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) occur occasionally.

The Claypan ecological site's plant community contains a variety of medium cool season grasses (western wheatgrass, green needlegrass), and shrubs that include Nuttall's saltbush (*Atriplex nuttallii* S. Watson), winterfat, silver sagebrush (*Artemisia cana* Pursh), and Wyoming big sagebrush.

Values related to water holding capacity and organic carbon varied among sites and differed from the two sites where the plant data were collected (Table 1). Runoff curve number was set to 84 for all three sites to standardize runoff across the three sites. The Penman-Monteith equation was used to calculate potential evapotranspiration. It was chosen to standardize the evapotranspiration calculation method across sites.

These three sites included at least one of the grass species measured in this study and sometimes also had either western wheatgrass or bottlebrush squirreltail. The latter two grasses have previously been parameterized and tested against NRCS ecological site yields [4]. The radiation use efficiencies (whole plant) used for the simulations were 5.0 for needle and thread, 4.8 for green needlegrass, 3.5 for western wheatgrass, and 1.64 for bottlebrush squirreltail. Potential leaf area index for each site is dependent on plant density. Thus shallower soils (that are more drought prone) have lower potential LAI values (see Tables 3-5).

The duration of the growth cycle was set similarly short as in the measurement periods. We assumed 700 degree days (base temperature 6℃, optimum temperature 25℃) to complete a growth cycle. We assumed there were two cycles per year. Simulated harvests to determine biomass were on July 1 and September 1 each year.

All grasses were simulated with the same optimum nitrogen and phosphorus concentrations. These were: 0.03 for N in seedlings, 0.013 N for plants near anthesis, and 0.007 N for mature plants. These three values for P were 0.0084, 0.0032, and 0.0019, respectively.

The weather data (daily precipitation, maximum temperature, and minimum temperature) for these simulations were years 1937 to 2015 for the airport weather station in Miles City (Miles City, Frank Wiley Field Airport (KMLS), Lat. 46.42806°N, Long. 105.88639°W, Elev. 2628ft.). Solar radiation data were generated within the ALMANAC model from these other weather inputs: latitude and longitude, and day of the year.

The first eight years of simulations we used to allow the model to stabilize, with the actual analyses done on the subsequent years. The mean and standard deviation were calculated for these subsequent years. Then the yields were put into three groups: Those with yields in the lowest 20% of years (lowest 14 yielding years), those in the highest 20% of years (highest 14 years), and in the middle 60% of years (the middle 43 years). The means of these three groups were then compared to the NRCS published values for dry years, wet years, and normal years.

3. RESULTS

The climate values during the three years of plant measurements (2013-2015) were similar to previously recorded values from 1937 to 2012. The means and standard deviation values for the cold season (Oct. through April) in 1937 to 2012 were maximum daily temperature (Tmax) of 6.5±2.5 C, minimum daily temperature (Tmin) of -6.1±1.8 C, and precipitation sum (Precip) of 115±42 mm. Cold season values for 2013 to 2015 were 6.6±1.6 C for Tmax, -6.2±1.0 C for Tmin, and 73±14 mm for Precip. For the active growing season (May to June), from 1937 to 2012, values were 22.3±2.9 C for Tmax, 8.3±2.4 C for Tmin, and 120±55 mm for Precip. For the active growing season from 2013 to 2015, values were 23.0±0.8 C for Tmax, 9.4±0.6 C for Tmin, and 182±50 mm for Precip.

A challenge when dealing with grasses in this type of arid area is sampling frequently enough to capture the growth during its short duration. This required sampling at least every two weeks. The previously applied sampling scheme was adapted to handle the short growth cycle grasses in this study.

3.1 Phenology

Phenological stages followed the expected trend of the warm season praire sandreed lagging behind the other plant species. First leaf greenup occurred from 8 May to 22 May for the the first four plant species (green needlegrass, threadleaf sedge, needle and thread, and winterfat). First greenup occurred from 3 June to 6 June for prairie sandreed. Flowering dates ranged from 4 June to 22 June for green needlegrass, from 8 May to 22 May for threadleaf sedge, from 4 June to 29 June for needle and thread, and from 3 June to 23 June for winterfat. Flowering for prairie sandreed ranged from 12 August to 26 August. Seed fill was complete by 3-4 weeks following flowering in each case.

3.2 Leaf Area Index (LAI) and Extinction Coefficient (k)

Leaf area index increases generally occurred over four to six weeks (data not shown). These durations ranged from about 2 weeks to nearly 7 weeks.

Maximum LAI (LAImx) values were generally less than 1.0, as expected (Table 2). Only threadleaf sedge in the third year had a maximum LAI value greater than 1.0. Many of the other grasses by year combinations had maximum LAI values less than 0.5.

The extinction coefficient quantifies how efficiently the leaf canopy intercepts light (PAR). As described in equations 1 and 2 above, more upright leafed plants such as switchgrass have k values near -0.3 [7,13]. More horizontal leafed plants such as cocklebur or sunflower have k values near -1.0 [6,14]. Common crop values are near -0.5 to -0.6 [15].

Complicating these general ideas is the within plant canopy phenomenon of leaves shading leaves as the LAI exceeds 1.0. Leaves positioned above other leaves and leaf clumping makes their efficiency of light interception lower and thus decreases k [15].

The four grasses in this study showed a wide range of k values (Tables 2 and 3). Threadleaf sedge had the highest maximum LAI values in two of the three years and the lowest mean k value each year. Needle and thread and green needlegrass had intermediate k values (near -0.7 and -1.0, respectively). Their maximum LAI values were near 0.25 and 0.35. If using a plant functional group approach, values of -0.85 for k and 0.3 for maximum LAI could be used for these two grasses. Finally, prairie sandreed showed the highest magnitude k, greater than -1.0. Its average maximum LAI value was near that of needle and thread.

3.3 Radiation Use Efficiency (RUE)

As discussed above, the challenge in this study was to schedule sampling dates with adequate frequency to capture the active growth (increasing biomass) of these grasses. Plots of cumulative dry matter and cumulative summed IPAR (Figs. 1 to 3 and Tables 2 and 3) had repeated measurements showing increases in biomass. Thus these are the cumulative plant dry matter in units of g per m^2 ground area and the cumulative intercepted photosynthetically active radiation in units of MJ per m^2 ground area. The slopes of these figures are the RUE values, in g of biomass per MJ of IPAR.

Mean values of RUE showed a relatively narrow range, 3.5 to 4.0 g per MJ IPAR for the top three grasses and a much lower mean for prairie sandreed (Tables 2 and 3). For the top three grasses with all the data, RUE values ranged from about 3.0 to 5.0. For means across years the range was narrower. Prairie sandreed was much lower, below 0.5 g per MJ IPAR each time. Thus, if using a plant functional group approach, a mean RUE of 3.78 could be used for the top three grasses. Prairie sandreed would obviously have to have a much lower value.

Table 2. Field measured parameters for four grasses in miles city, MT

	k means	LAImx	RUE±SE
2013			
Threadleaf sedge	-0.19	0.40	3.22±1.99
Needle and thread	-0.48	0.64	--
Green needlegrass	-1.30	0.07	5.62±3.68
Prairie sandreed	-1.26	0.43	0.27±0.29
2014			
Threadleaf sedge	-0.19	0.45	3.78±1.51
Needle and thread	-0.21	0.26	5.01±2.44
Green needlegrass	-1.13	0.18	2.04±0.61
Prairie sandreed	-1.14	0.20	--
2015			
Threadleaf sedge	-0.09	2.16	--
Needle and thread	-1.54	0.14	2.96±0.26
Green needlegrass	-0.45	0.48	--
Prairie sandreed	-1.28	0.61	0.45±0.06

Table 3. Recommended values based on three years of data

	k	LAImx	RUE
Threadleaf sedge	-0.16	1.00	3.50(4.37)[1]
Needle and thread	-0.74	0.35	4.02(5.02)[1]
Green needlegrass	-0.96	0.24	3.83(4.79)[1]
Prairie sandreed	-1.23	0.41	0.36(0.45)[1]

[1] *RUE values in parentheses were calculated for entire plants, assuming 20% of the total plant growth was partitioned to roots by the end of the growing seasons*

Assuming 20% of the total plant growth was into roots by the end of each growing season, values for simulation would range from 4.4 to 5.0 for the top three grasses. Kiniry et al. [7] found roots to total biomass to be 33 to 35% the second year after establishment for sideoats grama (*Bouteloua curtipendula* (Michaux) Torrey) and switchgrass (*Panicum virgatum* L.). By the third year these percentages had climbed to 60 to 66%. So 20% for an individual year's growth appears to be reasonable. The mean total plant RUE calculated like this for these three grasses is 4.73 g per MJ IPAR. For prairie sandreed, this value is 0.45.

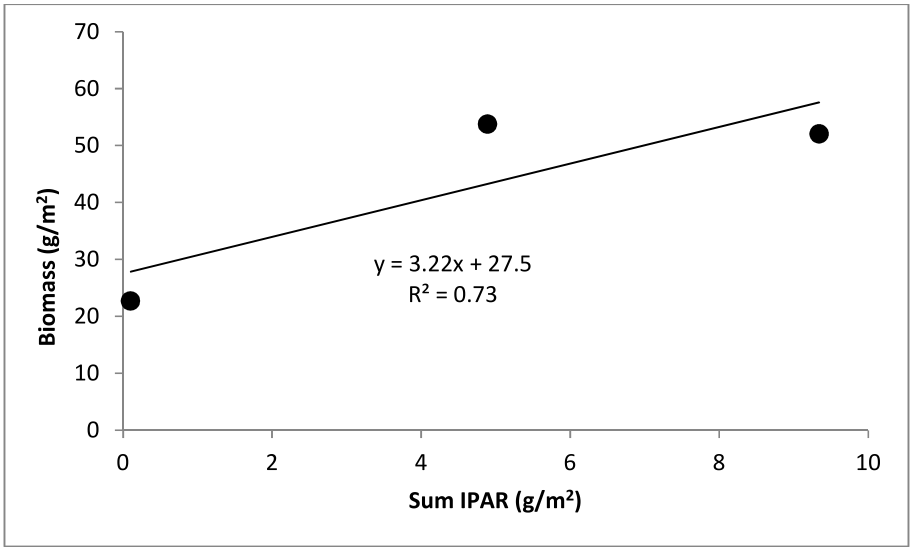

Fig. 1a. Calculation of radiation use efficiency (RUE) for threadleaf sedge in 2013. The aboveground dry biomass as a function of summed intercepted photosynthetically active radiation (IPAR). The slope is the RUE

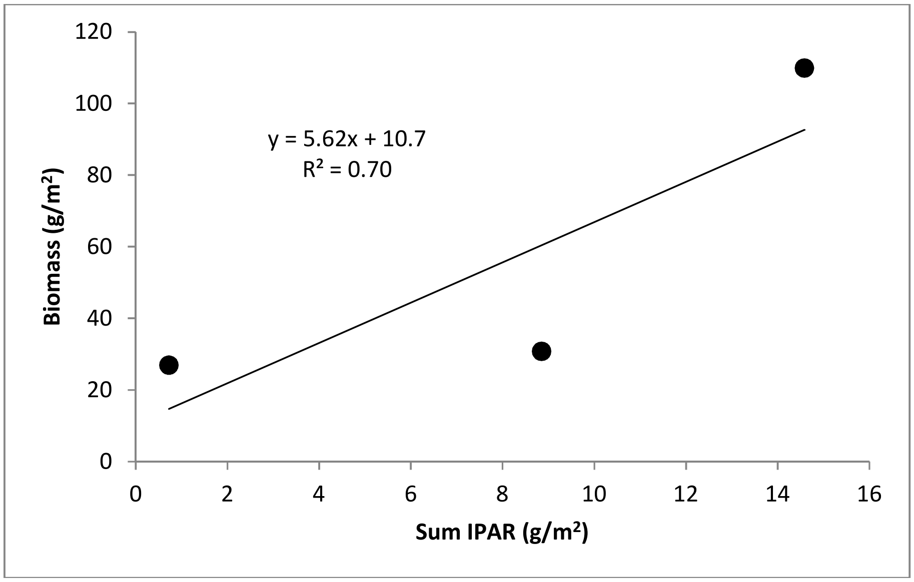

Fig. 1b. Calculation of RUE for green needlegrass in 2013. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE

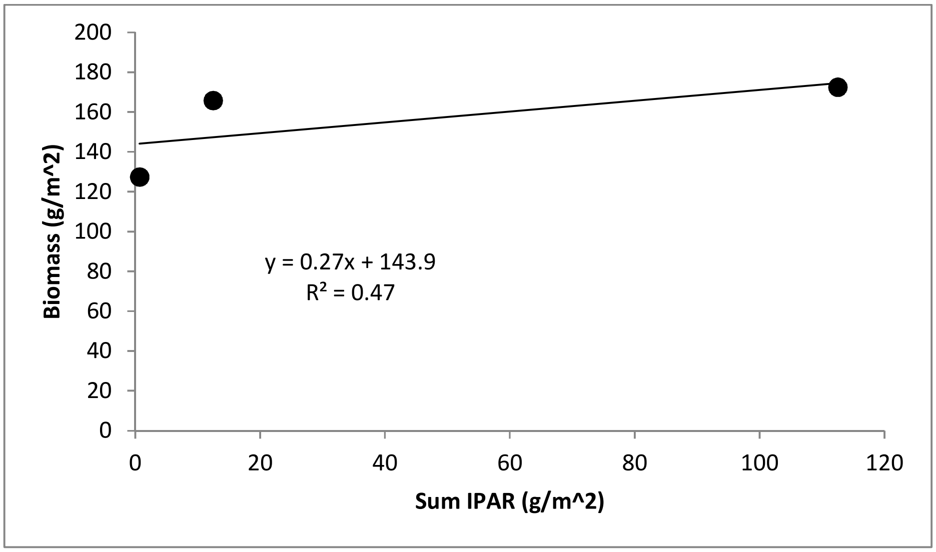

Fig. 1c. Calculation of RUE for prairie sandreed in 2013. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE

3.4 Simulations of Ecological Sites with ALMANAC

The ALMANAC model realistically simulates the average yielding and low yielding (dry) years for all three sites, while showing some overprediction in high (wet) years in two of the three sites. For the Shallow ecological site on Cabbart soil series (Table 4), the mean simulated yield is 100% of the norm reported by NRCS. The mean of the low simulated yields is 76% of the mean simulated yield as compared to 75% for the low NRCS reported yield. The mean of the high simulated yield is 145% of the mean simulated. This is somewhat greater than the 125% value for NRCS high yield as a fraction of the normal.

For the Claypan ecological site on Creed soil series (Table 5), the mean yield is 99% of the norm reported by NRCS. The mean of the low simulated yields is 77% of the mean simulated

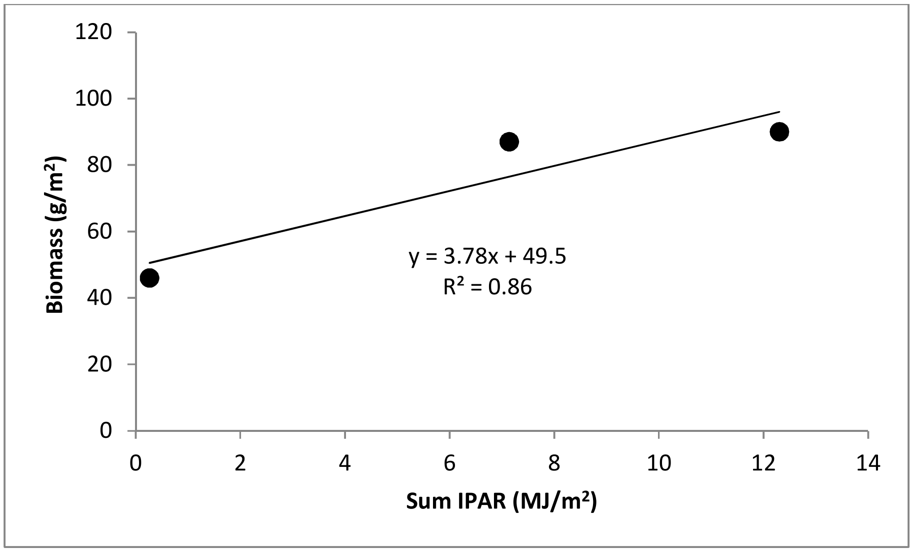

Fig. 2a. Calculation of RUE for threadleaf sedge in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE

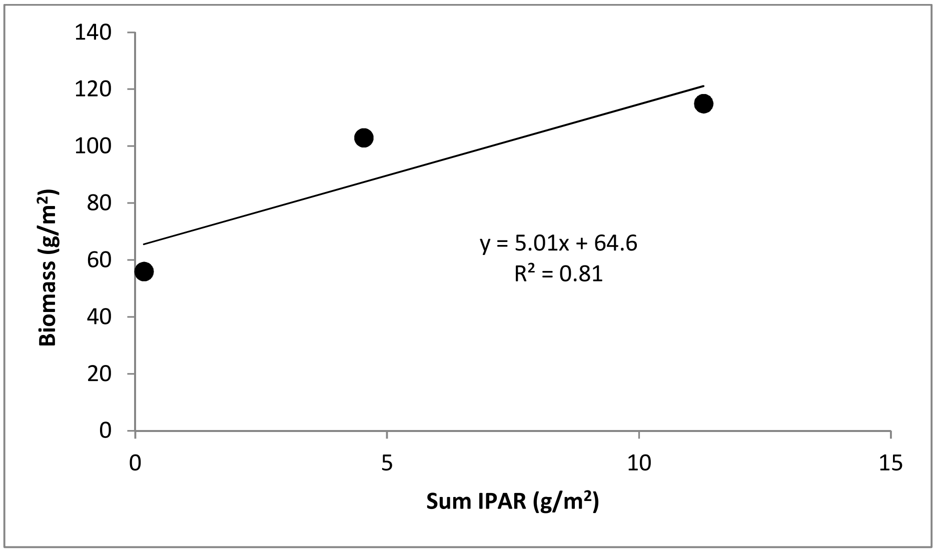

Fig. 2b. Calculation of RUE for needle and thread in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE

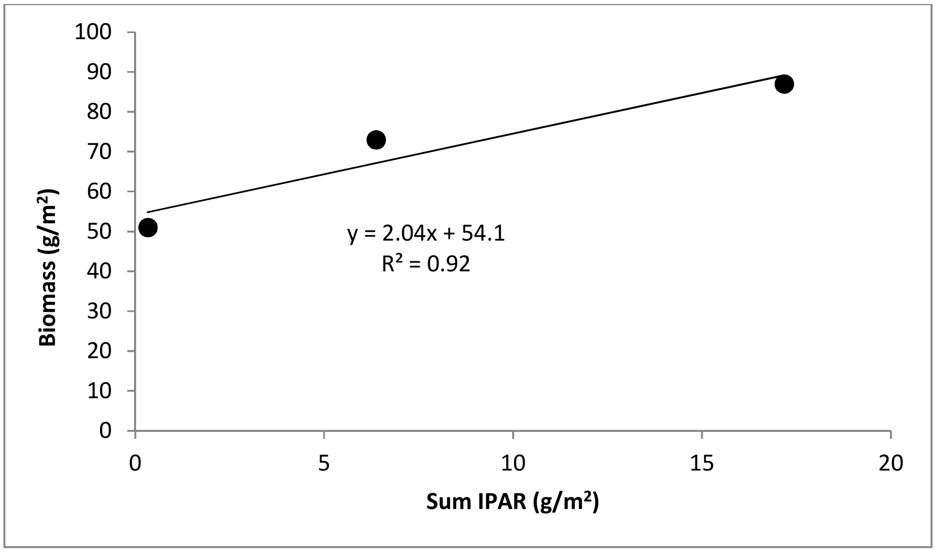

Fig. 2c. Calculation of RUE for green needlegrass in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE

while the corresponding NRCS value is 63%. The mean of the high simulated yields is 137% of the mean, close to the NRCS value of 137%.

Finally, for the higher yielding Silty-Steep ecological site on Cambeth soil series (Table 6), the mean simulated yield is 102% of the norm reported by NRCS. The mean of the low simulated yields is 76%, similar to the 77% for NRCS. The mean of the high simulated yields is 140% of the average, somewhat higher than the 123% for the NRCS values.

Over all three ecological sites, means show similar trends (Table 7). The overall mean simulated is 100% of the NRCS norm. The mean of the low simulated yields is 76% of the mean and the NRCS mean value is 725%. The mean of the simulated high yields is 141% of the average, somewhat higher than the NRCS value of 1295%. Thus overall the model

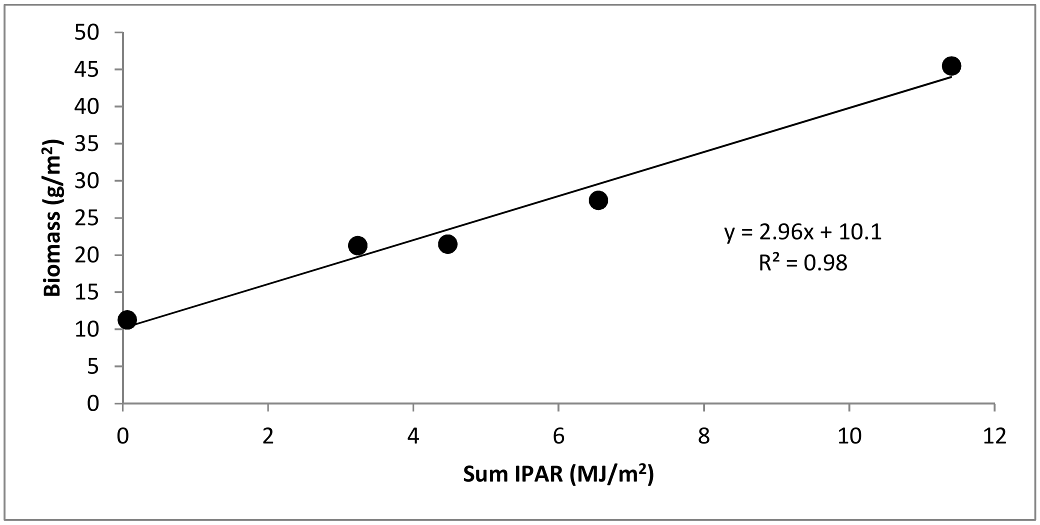

Fig. 3a. Calculation of RUE for needle and thread in 2015. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE

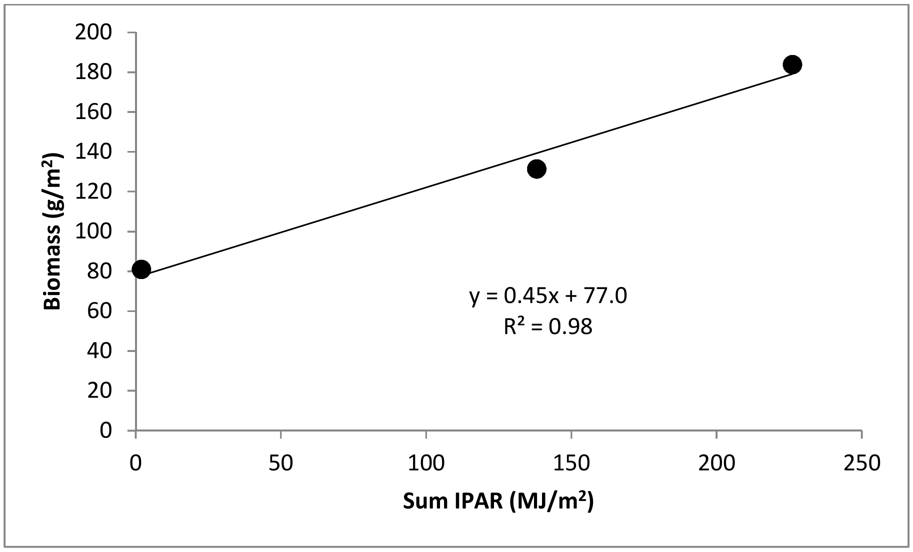

Fig. 3b. Calculation of RUE for prairie sandreed in 2015. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE

did a reasonable job simulating these representative ecological sites in normal and dry years with the grass parameters described herein. Causes of the general overprediction in wet years at two of the three sites warrant further study.

4. DISCUSSION

Previously published values for western grasses [4] generally showed lower values for RUE and greater values for maximum LAI than the values presented above. Grass maximum LAI values described herein were generally between 0.24 and 1.0. The values described herein should be useful for applications of a plant functional group approach for similar western U.S. grasses in similar rainfall sites.

The results of this study demonstrated that assessments with process-based models such as ALMANAC are feasible with realistic estimates of plant parameters for the grass species in their plant functional groups in similar rainfall regions. Realistic simulation of plant development makes such simulation evaluations effective and scientifically defensible. These evaluations should be possible to achieve in a timely manner with such plant functional group parameters. Measurements of individual species within these groups provide estimates for the needed parameters for groups for these assessments.

Table 4. Cabbart ecological site yields (Mg/ha). Simulated potential LAI values were 0.1 for needle and thread and 0.3 for bottlebrush squirreltail. Avg. of mid years simulations was 100% of NRCS norm

Simulation avgs.	NRCS values
Mean of lowest 20% of years	Low frac. of Norm
0.67 (0.76)[1]	0.75
Mean of middle 60% of years	Norm
0.88	0.88
Mean of highest 20% of years	High frac. of Norm
1.28 (1.45)[1]	1.25

[1] *Values in parentheses are the means divided by the average value, for comparison with NRCS fractions shown*

Table 5. Creed ecological site yields (Mg/ha). Simulated potential LAI values were 0.1 green needlegrass and 0.2 for western wheatgrass. Avg. of mid years simulations was 99% of NRCS norm

Simulation avgs.	NRCS values
Mean of lowest 20% of years	low frac. of Norm
0.68 (0.78)[1]	0.625
Mean of middle 60% of years	Norm
0.88	0.88
Mean of highest 20% of years	high frac. of Norm
1.20 (1.37)[1]	1.37

[1] *Values in parentheses are the means divided by the average value, for comparison with NRCS fractions shown*

The numerous contexts in which it is useful to simulate plant functional groups or communities rather than individual species will be greatly improved by the results of this study. Large-scale regional assessments, such as those used to predict plant response to climate change or to applications of conservation practices, will benefit from this approach. Similar work on grasses in these and other functional groups should be expanded towards a workable plant functional group system that can be simulated by ALMANAC and similar process-based models. Thus, model output can be applied to assessing ecosystem impacts and services associated with shifts in both species composition and management practices. The ALMANAC model can be readily implemented to interpret site monitoring and guide adaptive management approaches. The model should prove a valuable and critical tool for conservation practice planning. The overprediction of yields in wet years for two of the three sites needs to be investigated in light of the high values for RUE calculated in this study (5.0 g per MJ IPAR for needle and thread and 4.8 for green needlegrass; the two new species simulated) as well as the high k values (-0.74 and -0.96, respectively). The mixtures with these species showed reasonable growth in the normal and low rainfall years, as compared with expected NRCS values, but appeared to have too large a potential production in those years when rainfall was above average. Future work to characterize their growth with adequate soil water, possibly with irrigation, could shed light on this issue.

Table 6. Cambeth ecological site yields (Mg/ha). Simulated potential LAI values were 0.1 for green needlegrass, 0.3 for western wheatgrass, and 0.3 for bottlebrush squirreltail. Avg. of mid years simulations was 102% of NRCS norm

Simulation avgs.	NRCS values
Mean of lowest 20% of years	Low frac. of Norm
1.10 (0.76)[1]	0.77
Mean of middle 60% of years	Norm
1.46	1.43
Mean of highest 20% of years	High frac. of Norm
2.04 (1.40)[1]	1.23

[1] *Values in parentheses are the means divided by The average value, for comparison with NRCS fractions shown*

Finally, the use of plant functional groups represented by species in this study shares some common features with the modeling studies discussed above that used functional groups. Boer and Smith [16] simulated Australian rangeland vegetation with three plant functional groups: annual herbaceous, perennial herbaceous, and woody. Grigulis et al. [17] simulated an introduced grass and shrubs as different plant functional groups. Cousins et al. [18] simulated grassland in Sweden with five plant functional groups based on responses to grazing. Functional groups based on the parameters described herein could be based on general plant type and morphology. Thus such groups will be complementary to some of the approaches in the published simulation studies.

Table 7. Means of the simulations' yields and of the NRCS yields over all three ecological sites. Avg. of mid years simulations for all three ecological sites was 100% of average for the three NRCS norms

Simulated low values / mid. avg.	**NRCS low as frac of norm**
0.76	0.72
Simulated high / mid. avg.	**NRCS high as frac of norm**
1.41	1.29

5. CONCLUSION

The parameters described in this study will be useful for the actual species measured and for plant functional groups they could represent. Such values, additionally, will be valuable in applying Beer's law with measured FIPAR as a nondestructive method of calculating LAI. FIPAR could be measured on the ground with linear PAR sensors (as in this study) or remotely with cameras estimating fraction of plant cover, as a surrogate for FIPAR.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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