

Original Research Article

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

ABSTRACT

Rangeland grasses in the arid western U.S. must grow quickly, set seed, and senesce in a relatively short timeframe in order 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 project, 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 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. must grow quickly, set seed, and senesce in a relatively short timeframe in order to survive and reproduce when the limited soil moisture is available. Previous attempts at simulating plant growth on rangelands [8, 9, 11, 12] 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 project, 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 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*) [12] 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. MATERIAL 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 (ecological site Clayey (Cy) RRU 58A-E 10-14" p.z.R058AE002MT) for green needlegrass and a Chinook-Twilight-Eapa complex (sandy/silty ecological site, Sandy (Sy) RRU 58A-E 10-14" p.z. R058AE003MT) for the other grasses.

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

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

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°C 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 m² ground area) were calculated.

The light extinction coefficient (k) for Beer's law [7, 14] was calculated for each sample as

$$\text{FIPAR} = 1.0 - \exp(-k \cdot \text{LAI}) \quad (2)$$

Transposed to

$$k = -(\ln(1.0 - \text{FIPAR})) / \text{LAI} \quad (3)$$

Radiation use efficiency (RUE) requires measurements of cumulative dry weight (g of plant biomass per m² of ground area) and summed intercepted PAR (SIPAR) (MJ per m² of ground area). Value of SIPAR requires daily values for FIPAR and incident PAR (assuming 45% of incident total solar radiation is PAR, [13]). 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 based prevalence over the range 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 Calcistepes); and a “Claypan” ecological site with a Creed soil (Fine, smectitic, frigid Aridic Natrustals). The Cabbart soil was simulated with a 0.3 m total depth, an average field capacity of 0.277, and average wilting point of 0.129, for a total plant available water of 4.14 cm. These values for the simulated Creed soils were 0.3 m, 0.286 cm, 0.162 cm, and 3.72 cm. These values for Cambeth were 0.36 m, 0.298 cm, 0.150 cm, and 5.33 cm. 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 [12]. 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°C, optimum temperature 25°C) 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

3.1 General

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 results described below are based on adaptation of the sampling scheme which was developed for plants with longer duration growth cycles.

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 values were generally less than 1.0, as expected (Table 1). 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). More upright leafed plants such as switchgrass have k values near -0.3 [7, 10]. More horizontal leafed plants such as cocklebur or sunflower have k values near -1.0 [5, 6]. Common crop values are near -0.5 to -0.6 [3].

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 [3].

The four grasses in this study showed a wide range of k values (Tables 1 and 2). 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.

Table 1. Field measured parameters for four grasses in Miles City, MT.

	k means	LAI _{mx}	RUE ± SE
<u>2013</u>			
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
<u>2014</u>			
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	--
<u>2015</u>			
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 2. Recommended values based on three years of data.

	k	LAI _{mx}	RUE
threadleaf sedge	-0.16	1.00	3.50 (4.375) ¹
needle and thread	-0.74	0.35	4.02 (5.025) 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.

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 (Figures 1 to 3 and Tables 1 and 2) had repeated measurements showing increases in biomass. Slopes of these figures are the RUE values, in g of biomass per MJ of IPAR.

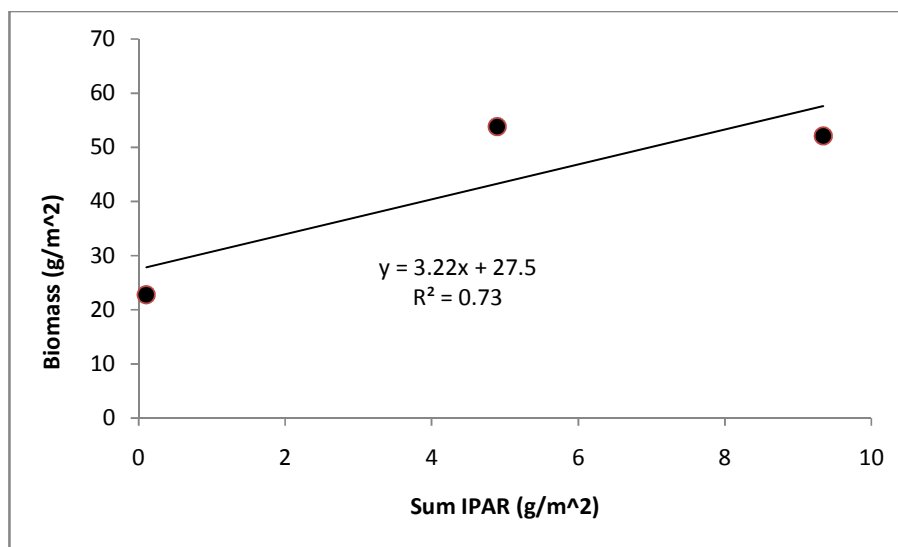


Fig. 1a. Calculation of radiation use efficiency (RUE) for threadleaf sedge in 2013. The aboveground dry biomass as a function of summed intercepted photosynthetically active radiation (IPAR). The slope is the RUE.

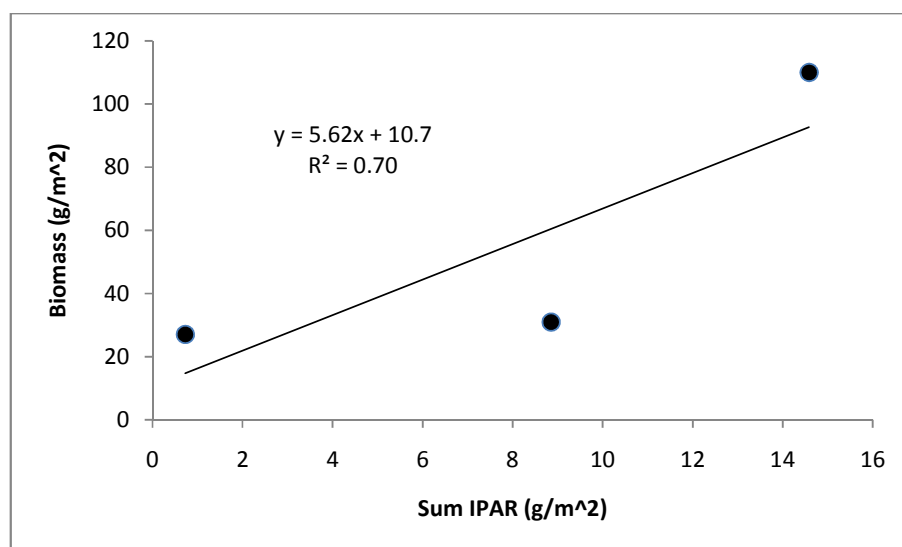


Fig. 1b. Calculation of RUE for green needlegrass in 2013. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

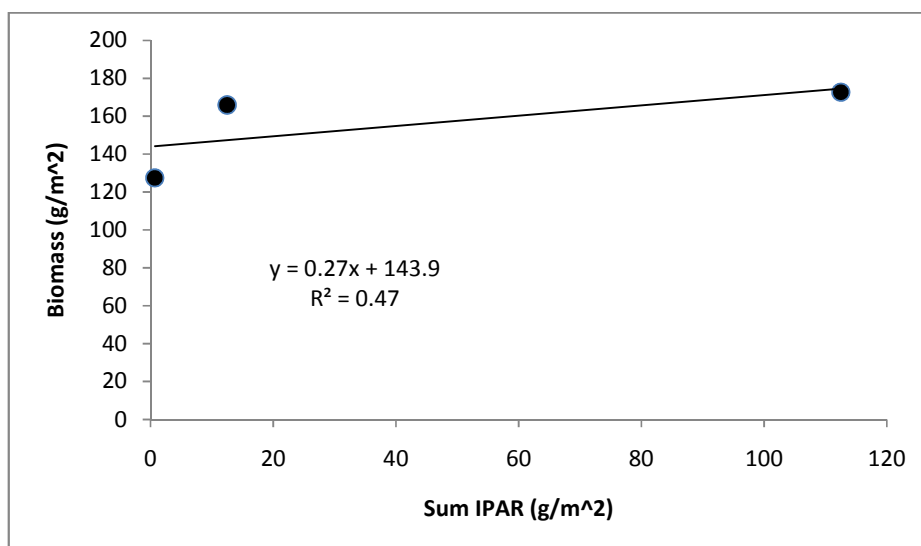


Fig. 1c. Calculation of RUE for prairie sandreed in 2013. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

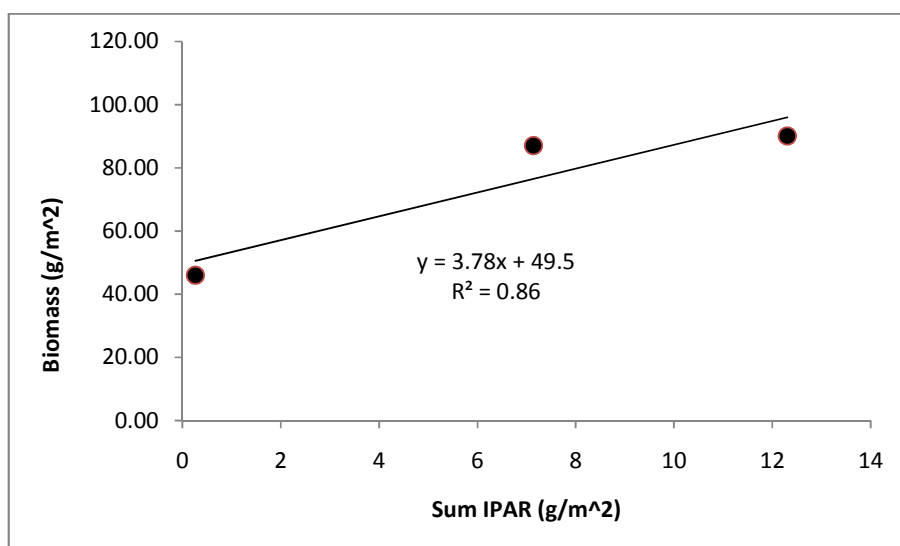


Fig. 2a. Calculation of RUE for threadleaf sedge in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

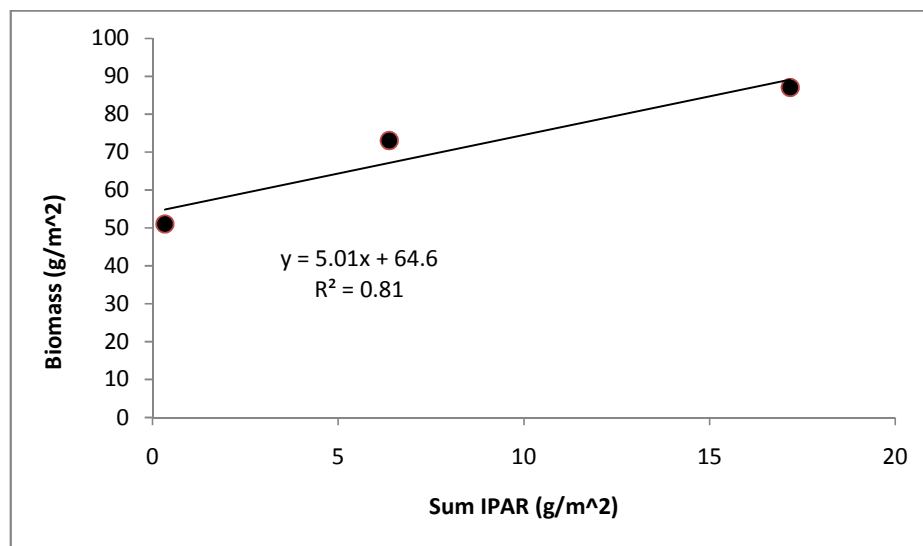


Fig. 2b. Calculation of RUE for needle and thread in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

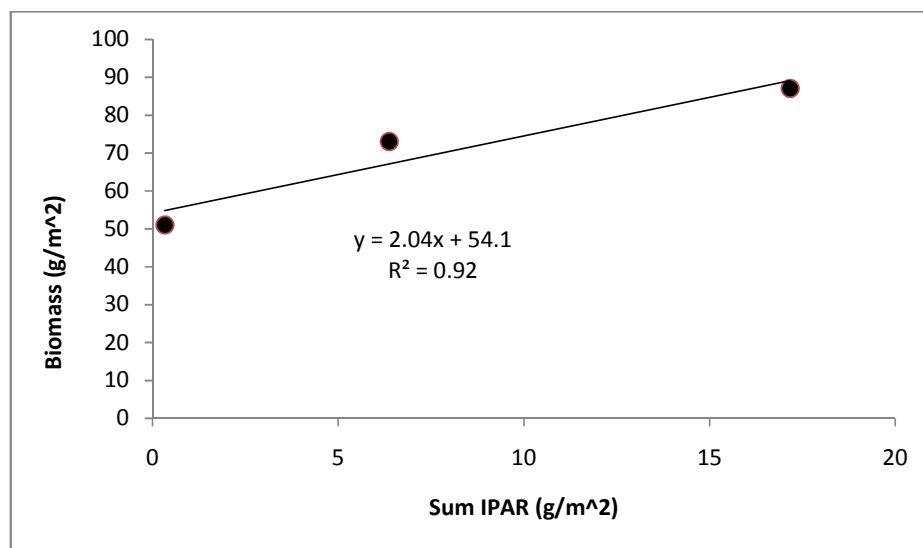


Fig. 2c. Calculation of RUE for green needlegrass in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

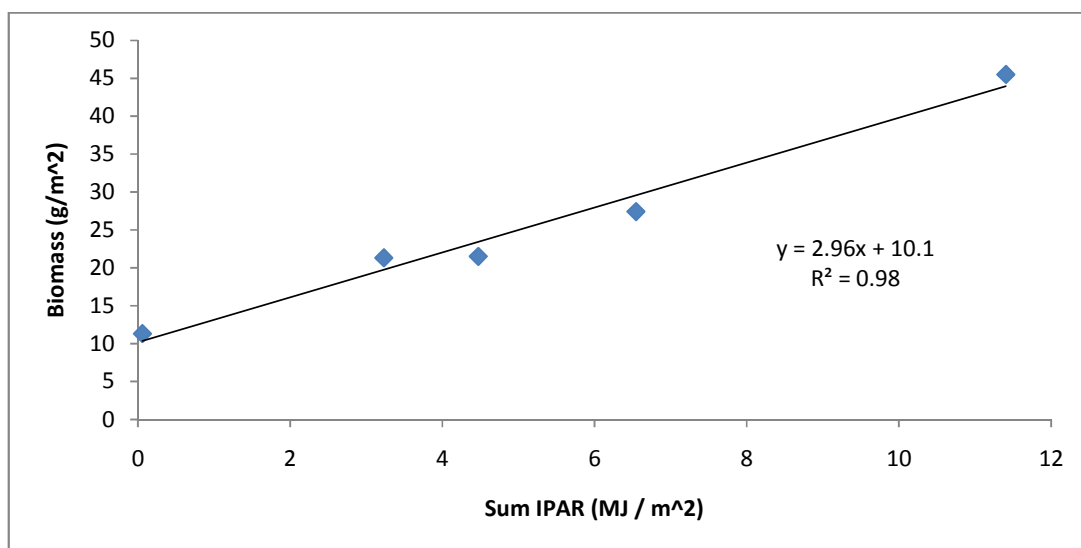


Fig. 3a. Calculation of RUE for needle and thread in 2015. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

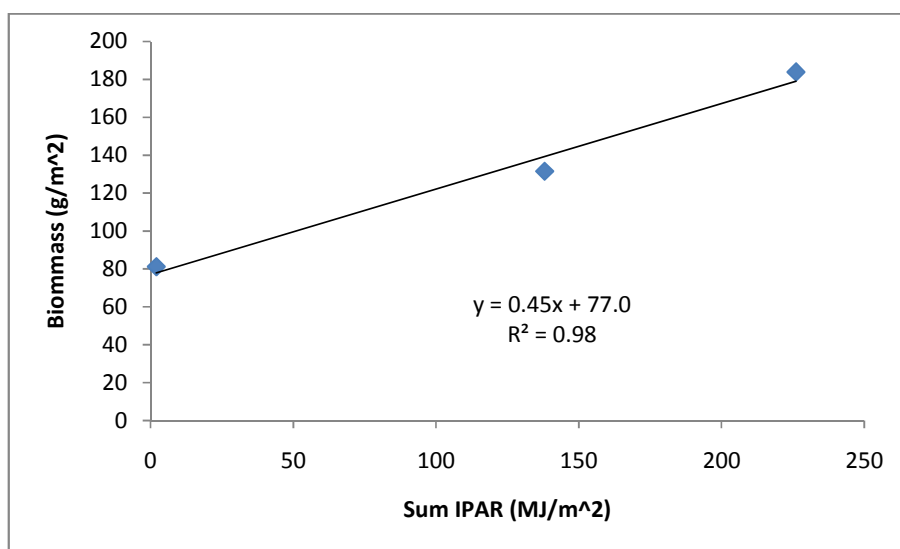


Fig. 3b. Calculation of RUE for prairie sandreed in 2015. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

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 1 and 2). 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.

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.

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 3), 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.

Table 3. 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 were 100.0% of NRCS norm.

Simulation avgs.	NRCS values
Mean of lowest 20% of years	low frac. of Norm
0.665 (0.756) ¹	0.75
Mean of middle 60% of years	Norm
0.880	0.88
Mean of highest 20% of years	high frac. of Norm
1.278 (1.453) ¹	1.25

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

For the Claypan ecological site on Creed soil series (Table 4), the mean yield is 99% of the norm reported by NRCS. The mean of the low simulated yields is 77% of the mean simulated while the corresponding NRCS value is 62.5%. The mean of the high simulated yields is 137.4% of the mean, close to the NRCS value of 137.5%.

Table 4. 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 were 99.4% of NRCS norm.

Simulation avgs.	NRCS values
Mean of lowest 20% of years	low frac. of Norm
0.680 (0.777) ¹	0.625
Mean of middle 60% of years	Norm
0.875	0.88
Mean of highest 20% of years	high frac. of Norm
1.203 (1.374) ¹	1.375

¹Values in parentheses are the means divided by the average

value, for comparison with NRCS fractions shown.

Finally, for the higher yielding Silty-Steep ecological site on Cambeth soil series (Table 5), 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.

Table 5. 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 101.8% of NRCS norm.

Simulation avgs.	NRCS values
Mean of lowest 20% of years	low frac. of Norm
1.105 (0.758) ¹	0.77
Mean of middle 60% of years	<u>Norm</u>
1.456	1.43
Mean of highest 20% of years	high frac. of Norm
2.042 (1.402) ¹	1.23

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

Over all three ecological sites, means show similar trends (Table 6). 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 71.5%. The mean of the simulated high yields is 141% of the average, somewhat higher than the NRCS value of 128.5%. Thus overall the model 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.

Table 6. 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 100.4% of average for the three NRCS norms.

Simulated low values / mid. avg.	<u>NRCS low as frac of norm</u>
0.764	0.715
Simulated high / mid. avg.	<u>NRCS high as frac of norm</u>
1.410	1.285

4. DISCUSSION

Previously published values for western grasses [12] 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 project 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.

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.

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 [1] simulated Australian rangeland vegetation with three plant functional groups: annual herbaceous, perennial herbaceous, and woody. Grigulis et al. [4] simulated an introduced grass and shrubs as different plant functional groups. Cousins et al. [2] 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.

5. CONCLUSION

The parameters described in this project 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.

REFERENCES

1. Boer M, Smith S. MA plant functional approach to the prediction of changes in Australian rangeland vegetation under grazing and fire. *J. Veg. Sci.* 2003;14:333-344.
2. Cousins SAO, Lavorel S, Davies I. Modelling the effects of landscape pattern and grazing regimes on the persistence of plant species with high conservation value in grasslands in south-eastern Sweden. *Lands. Ecol.* 2003;18:315-332.
3. Flenet F, Kiniry JR, Board JE, Westgate ME, Reicosky DC. Row spacing effects on light extinction coefficients of corn, sorghum, soybean, and sunflower. *Agron. J.* 1996;88:185-190.
4. Grigulis K, Lavorel S, Davies ID, Dossantos A, Lloret F, Montserrat V. Landscape scale positive feedbacks between fire and expansion of the large tussock grass, *Ampelodesmos mauritanica* in Catalan shrublands. *Glob. Change Biol.* 2005;11:1042-1053.
5. Kiniry JR, Williams JR, Gassman PW, Debaeke P. A general, process-oriented model for two competing plant species. *Trans ASAE.* 1992a;35: 801-810.

- 379 6. Kiniry JR, Blancheet R, Williams JR, Texier V, Jones CA, Cabelguenne M. Sunflower
380 simulation using the EPIC and ALMANAC models. *Field Crops Res.* 1992b;30:403-423.
- 381 7. Kiniry JR, Tischler CR, Van Esbroeck GA. Radiation use efficiency and leaf CO₂ exchange for
382 diverse C₄ grasses. *Biomass Bioenergy.* 1999;17:95-112.
- 383 8. Kiniry JR, Sanchez H, Greenwade J, Seidensticker E, Bell JR, Pringle F, Peacock G. Jr.,
384 Rives J. Simulating grass productivity on diverse range sites in Texas. *J. Soil Water Conserv.*
385 2002;57:144-150.
- 386 9. Kiniry JR, Burson BL, Evers GW, Williams JR, Sanchez H, Wade C, Featherston JW,
387 Greenwade J. Coastal bermudagrass, bahiagrass, and native range simulation at diverse
388 sites in Texas. *Agron. J.* 2007;99:450-461.
- 389 10. Kiniry JR, Johnson M-V, Mitchell R, Vogel K, Kaiser J, Bruckerhoff S, Cordsiemon R.
390 Switchgrass leaf area index and light extinction coefficients. *Agron. J.* 2011;103:119-122.
- 391 11. Kiniry JR, Johnson M-V, Venuto BC, Burson BL. Novel application of ALMANAC: Modelling a
392 functional group, "exotic warm-season perennial grasses". *Am. J. Exper. Agric.* 2013;3:631-
393 50.
- 394 12. Kiniry JR, Briggs J, Englert J, Weltz M, Jensen K, Tilley D, Stannard M, Young-Matthews A,
395 Blanke T, Smither-Kopperl M, Winslow S, Goodson D. Plant parameters for plant functional
396 groups of western rangelands to enable process-based simulation modeling. *Am. J. Exper.*
397 *Agric.* 2014;47:746-766.
- 398 13. Meek DW, Hatfield JL, Howell TA, Idso SB, Reginato RJ. A generalized relationship between
399 photosynthetically active radiation and solar radiation. *Agron. J.* 1984;76:939-945.
- 400 14. Monsi M, Saeki T. Über den lichtfaktor in den pflanzengesellschaften und seine bedeutung für
401 die stoffproduktion. *Jpn. J. Bot.* 1953;14:22-52.