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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 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.

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26

27 1. INTRODUCTION

28

29 Rangeland grasses in the arid western U.S. grow quickly, set seed, and
30 senesce in a relatively short timeframe enabling them to survive and
31 reproduce when the limited soil moisture is available. Previous attempts at
32 simulating plant growth on rangelands [11, 12, 14, 15] allowed the grasses to
33 have a growing season for the entire period when temperatures were
34 adequately high. However, reality is that such grasses have a relatively short
35 growth cycle, maybe 4 to 6 weeks in the spring. They can then have another
36 similar growth period if adequate rains occur later in the season.

37

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

51

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

62

63 The ALMANAC model (Agricultural Land Management Alternatives with
64 Numerical Assessment Criteria) [7,8] is a process-based simulation model
65 designed to evaluate impacts of various management strategies such as
66 grazing management, invasive species, and revegetation. Plant cover, soil
67 stabilization by plants, and nutrient cycling by plants represent the major
68 aspects varying within each season and between years in response to these

69 management strategies. As such, realistic simulation of plant development is
70 necessary for effective simulation evaluations.

71

72 Work with ALMANAC continues to explore the potential to identify,
73 parameterize, and simulate trait-based functional groups using
74 representative species within these groups [14,15]. Model output will be
75 applied to assessing ecosystem impacts and services associated with shifts
76 in both species composition and management practices. For example, the
77 ALMANAC model could be implemented to interpret site monitoring and
78 adaptive management approaches such that it could be a valuable tool for
79 conservation practice planning.

80

81 The parameters for two of these grasses, needle and thread and green
82 needlegrass, were then used along with previously derived parameters for
83 bottlebrush squirreltail (*Elymus elymoides*) and western wheatgrass
84 (*Pascopyrum smithii*) [15] to test the ALMANAC model's ability to replicate
85 reported USDA-NRCS range productivity values. This was done for three
86 typical ecological sites near Miles City. Using long-term simulations, the
87 model's simulated grass yields were compared to the NRCS values for
88 normal years, low yielding (dry) years, and high yielding (wet) years. These
89 results are designed to provide a valuable technology transfer tool to assess
90 environmental and management impacts on ecological site productivity under
91 such conditions.

2. MATERIAL AND METHODS

2.1 Field Measurements

Plant measurements for parameter derivation were described previously [10]. 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 [5, 6, 16].

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 m	Field capacity mean vol.	Wilting point mean vol.	Pot. PAW stored at FC cm	Organic C % 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

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

125 (*Pseudoroegneria spicata* (Pursh) Á. Löve), green needlegrass, western
126 wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve) and thickspike wheatgrass
127 (*Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould), and a diverse group of
128 short grasses, such as Sandberg bluegrass (*Poa secunda* J. Presl), blue
129 grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths), and prairie
130 junegrass (*Koeleria macrantha* (Ledeb.) Schult.). While there are a diversity
131 of forbs (purple prairie clover (*Dalea purpurea* Vent.) and white prairie clover
132 (*Dalea candida* Michx. ex Willd.), prairie coneflower (*Ratibida columnifera*
133 (Nutt.) Woot. & Standl.), dotted gayfeather (*Liatris punctata* Hook.)) at this
134 ecological site, they comprised almost none of the dry matter in the samples.
135 Thus they were not included in the analyses. Shrubs such as Wyoming big
136 sagebrush (*Artemisia tridentata* Nuttall) and winterfat (*Krascheninnikovia*
137 *lanata* (Pursh) A. Meeuse & Smit) are common.

138
139 The Sandy/Silty ecological site's plant community contains a high diversity of
140 tall and medium height grasses (prairie sandreed, little bluestem
141 (*Schizachyrium scoparium* (Michx.) Nash), big bluestem (*Andropogon*
142 *gerardii* Vitman), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á.
143 Löve), needle and thread, and Indian ricegrass (*Achnatherum hymenoides*
144 (Roem. & Schult.) Barkworth), and short grasses and sedges (sand dropseed
145 (*Sporobolus cryptandrus* (Torr.) A. Gray), plains muhly (*Muhlenbergia*
146 *cuspidata* (Torr. ex Hook.) Rydb.), sun sedge (*Carex inops* L.H. Bailey ssp.
147 *heliophila* (Mack.) Crins.), prairie junegrass (*Koeleria macrantha* (Ledeb.)
148 J.A. Schultes), threadleaf sedge, and blue grama). There are a diversity of
149 forbs, shrubs, and half-shrubs which occur, but they comprise a very small
150 percentage of the total biomass.

151
152 Measurements included taking series of at least five photosynthetically active
153 radiation (PAR) measurements below the plant canopy concurrently with
154 above plant canopy PAR measurements. Fraction of intercepted PAR
155 (FIPAR) values were collected with the AccuPAR LP-80 ceptometer and
156 external sensor (Decagon Devices, Inc., Pullman, WA) by synchronous
157 measures of PAR above and below the plant canopy. Plants were harvested,
158 weighed fresh, and a subsample was weighed. Value of FIPAR was the
159 average of
160
$$\text{FIPAR} = 1.0 (\text{below PAR}/\text{above PAR}) \quad (1)$$

161
162 Clippings of all the plant material in a 1 m by 1 m area (5 cm from the
163 ground) were taken in the same locations as the PAR measurements. All the
164 material was weighed fresh, subsampled, and the subsample weighed fresh.
165 The subsamples were then overnight-mailed to USDA-ARS, Temple, TX.
166 There the leaf area was measured with a LI-3100 Area Meter (LI-COR
167 Biosciences, Lincoln, NE) and dried to constant weight in an 80°C forced air
168 oven. Total leaf area of each original sample and its dry weight were

169 calculated using the fresh weight ratio of the subsample to total sample.
170 Thus the leaf area index (LAI) and dry plant weight (g per m² ground area)
171 were calculated.

172
173 The light extinction coefficient (k) for Beer's law [10, 18] was calculated for
174 each sample as

175
176
$$\text{FIPAR} = 1.0 - \exp(-k \cdot \text{LAI}) \quad (2)$$

177
178 Transposed to

179
180
$$k = -(\ln(1.0 - \text{FIPAR})) / \text{LAI} \quad (3)$$

181
182 Radiation use efficiency (RUE) requires measurements of cumulative dry
183 weight (g of plant biomass per m² of ground area) and summed intercepted
184 PAR (SIPAR) (MJ per m² of ground area). Value of SIPAR requires daily
185 values for FIPAR and incident PAR (assuming 45% of incident total solar
186 radiation is PAR, [17]). Mean values of FIPAR for each grass species on the
187 different dates were used with linear interpolation to calculate daily FIPAR.

188

189 **2.2 Simulations of Ecological Sites with ALMANAC**

190

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

200

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

208

209 The Silty-Steep ecological site's plant communities contain a high diversity of
210 tall and medium height, cool and warm season grasses (bluebunch
211 wheatgrass, green needlegrass, little bluestem, western wheatgrass, and
212 plains muhly) with a diverse mix of other grasses and sedges (needle and

213 thread, threadleaf sedge, prairie junegrass, and Sandberg bluegrass).
214 Several forbs, shrubs, and half-shrubs also occur on this site, but in relatively
215 small percentages. Common shrubs are Wyoming big sagebrush, winterfat,
216 snowberry (*Symphoricarpos albus* (L.) S.F. Blake), prairie rose (*Rosa*
217 *arkansana* Porter), and creeping juniper (*Juniperus horizontalis* Moench).
218 Trees such as Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and
219 Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) occur occasionally.

220

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

225

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

232

233 These three sites included at least one of the grass species measured in this
234 study and sometimes also had either western wheatgrass or bottlebrush
235 squirreltail. The latter two grasses have previously been parameterized and
236 tested against NRCS ecological site yields [15]. The radiation use
237 efficiencies (whole plant) used for the simulations were 5.0 for needle and
238 thread, 4.8 for green needlegrass, 3.5 for western wheatgrass, and 1.64 for
239 bottlebrush squirreltail. Potential leaf area index for each site is dependent
240 on plant density. Thus shallower soils (that are more drought prone) have
241 lower potential LAI values (see Tables 3-5).

242

243 The duration of the growth cycle was set similarly short as in the
244 measurement periods. We assumed 700 degree days (base temperature
245 6°C, optimum temperature 25°C) to complete a growth cycle. We assumed
246 there were two cycles per year. Simulated harvests to determine biomass
247 were on July 1 and September 1 each year.

248

249 All grasses were simulated with the same optimum nitrogen and phosphorus
250 concentrations. These were: 0.03 for N in seedlings, 0.013 N for plants near
251 anthesis, and 0.007 N for mature plants. These three values for P were
252 0.0084, 0.0032, and 0.0019, respectively.

253

254 The weather data (daily precipitation, maximum temperature, and minimum
255 temperature) for these simulations were years 1937 to 2015 for the airport
256 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 prairie 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

300 June for winterfat. Flowering for prairie sandreed ranged from 12 August to
301 26 August. Seed fill was complete by 3-4 weeks following flowering in each
302 case.

303

304 **3.2 Leaf Area Index (LAI) and Extinction Coefficient (k)**

305

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

308

309 Maximum LAI (LAI_{mx}) values were generally less than 1.0, as expected
310 (Table 2). Only threadleaf sedge in the third year had a maximum LAI value
311 greater than 1.0. Many of the other grasses by year combinations had
312 maximum LAI values less than 0.5.

313

314 The extinction coefficient quantifies how efficiently the leaf canopy intercepts
315 light (PAR). As described in equations 1 and 2 above, more upright leafed
316 plants such as switchgrass have k values near -0.3 [10, 13]. More horizontal
317 leafed plants such as cocklebur or sunflower have k values near -1.0 [8, 9].
318 Common crop values are near -0.5 to -0.6 [3].

319

320 Complicating these general ideas is the within plant canopy phenomenon of
321 leaves shading leaves as the LAI exceeds 1.0. Leaves positioned above
322 other leaves and leaf clumping makes their efficiency of light interception
323 lower and thus decreases k [3].

324

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

334 **Table 2. Field measured parameters for four grasses in Miles City, MT.**
 335

	k means	LAI _{mx}	RUE $\pm$ SE
<u>2013</u>			
threadleaf sedge	-0.19	0.40	3.22 $\pm$ 1.99
needle and thread green	-0.48	0.64	--
needlegrass	-1.30	0.07	5.62 $\pm$ 3.68
prairie sandreed	-1.26	0.43	0.27 $\pm$ 0.29
<u>2014</u>			
threadleaf sedge	-0.19	0.45	3.78 $\pm$ 1.51
needle and thread green	-0.21	0.26	5.01 $\pm$ 2.44
needlegrass	-1.13	0.18	2.04 $\pm$ 0.61
prairie sandreed	-1.14	0.20	--
<u>2015</u>			
threadleaf sedge	-0.09	2.16	--
needle and thread green	-1.54	0.14	2.96 $\pm$ 0.26
needlegrass	-0.45	0.48	--
prairie sandreed	-1.28	0.61	0.45 $\pm$ 0.06

336

337

338 **Table 3. Recommended values based on three years of data.**

	k	LAI _{mx}	RUE
threadleaf sedge	-0.16	1.00	(4.37) ¹
needle and thread green	-0.74	0.35	4.02 (5.02) ¹
needlegrass	-0.96	0.24	3.83 (4.79) ¹
prairie sandreed	-1.23	0.41	0.36 (0.45) ¹

348 parenteses were calculated for entire plants,
 349 assuming 20% of the total plant growth was partitioned to roots
 350 by the end of the growing seasons.

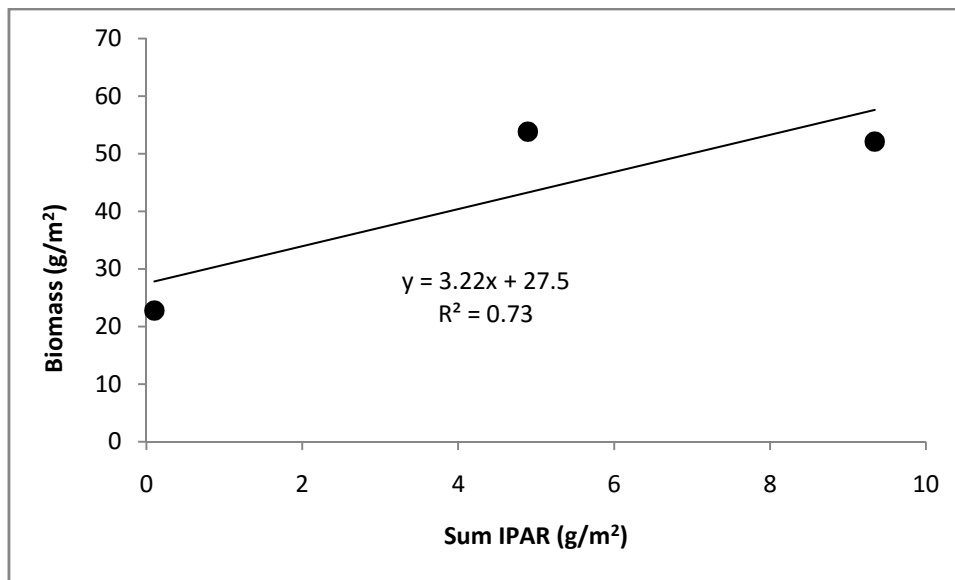
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352

353 **3.3 Radiation Use Efficiency (RUE)**

354 As discussed above, the challenge in this study was to schedule sampling
355 dates with adequate frequency to capture the active growth (increasing
356 biomass) of these grasses. Plots of cumulative dry matter and cumulative
357 summed IPAR (Figures 1 to 3 and Tables 2 and 3) had repeated
358 measurements showing increases in biomass. Thus these are the
359 cumulative plant dry matter in units of g per m² ground area and the
360 cumulative intercepted photosynthetically active radiation in units of MJ per
361 m² ground area. The slopes of these figures are the RUE values, in g of
362 biomass per MJ of IPAR.
363

364

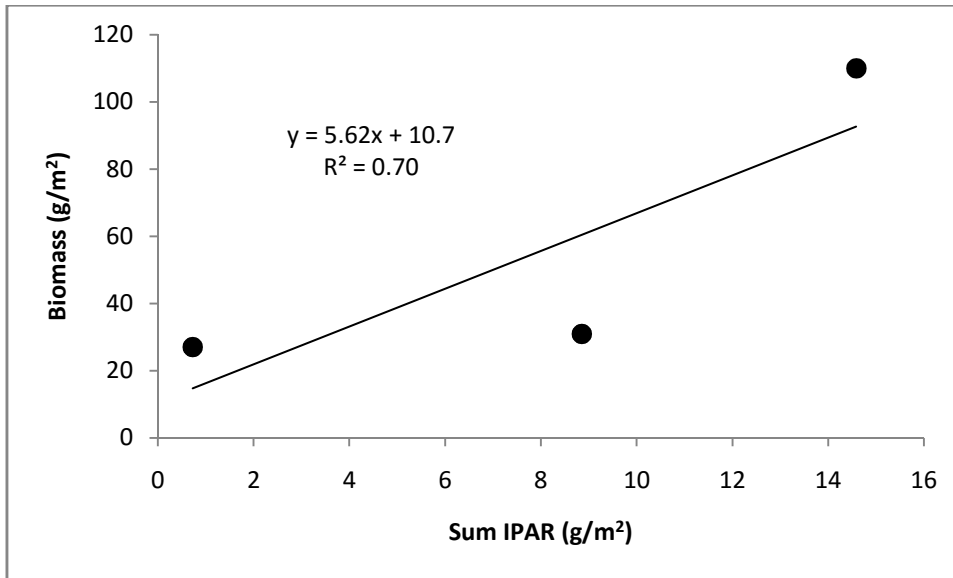


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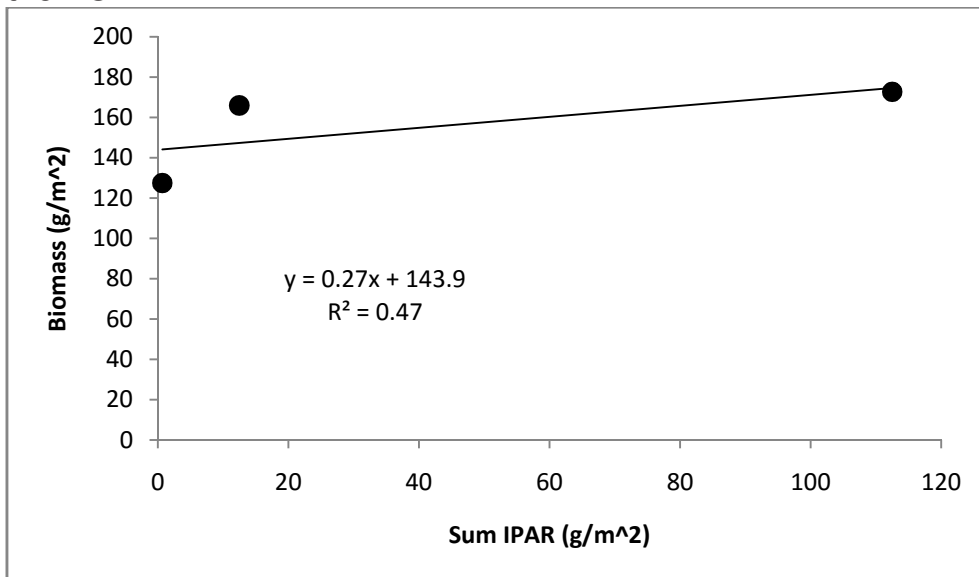
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367 **Fig. 1a. Calculation of radiation use efficiency (RUE) for threadleaf**
368 **sedge in 2013. The aboveground dry biomass as a function of summed**
369 **intercepted photosynthetically active radiation (IPAR). The slope is the**
370 **RUE.**

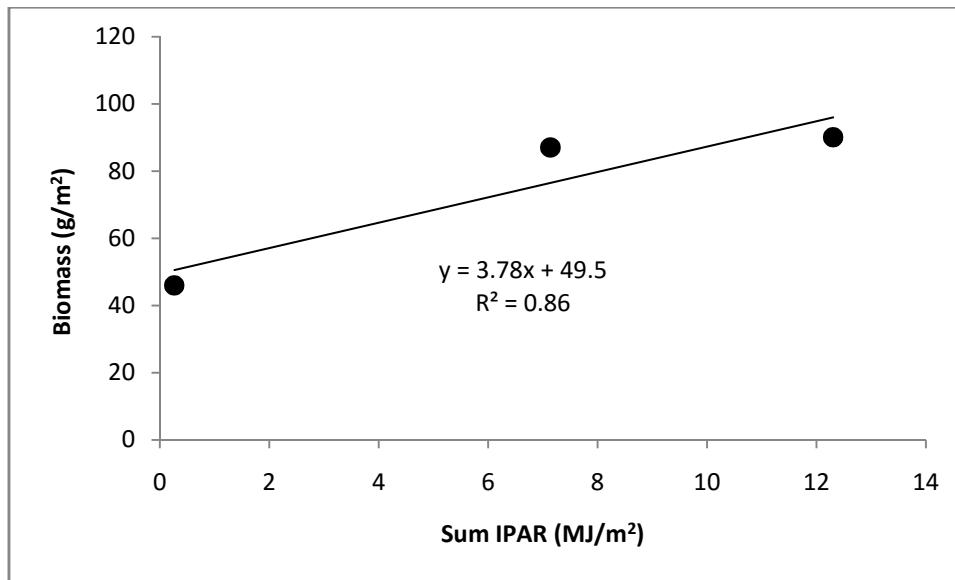
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373
374 **Fig. 1b. Calculation of RUE for green needlegrass in 2013. The**
375 **aboveground dry biomass as a function of summed IPAR. The slope is**
376 **the RUE.**



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378
379 **Fig. 1c. Calculation of RUE for prairie sandreed in 2013. The**
380 **aboveground dry biomass as a function of summed IPAR. The slope is**
381 **the RUE.**
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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.

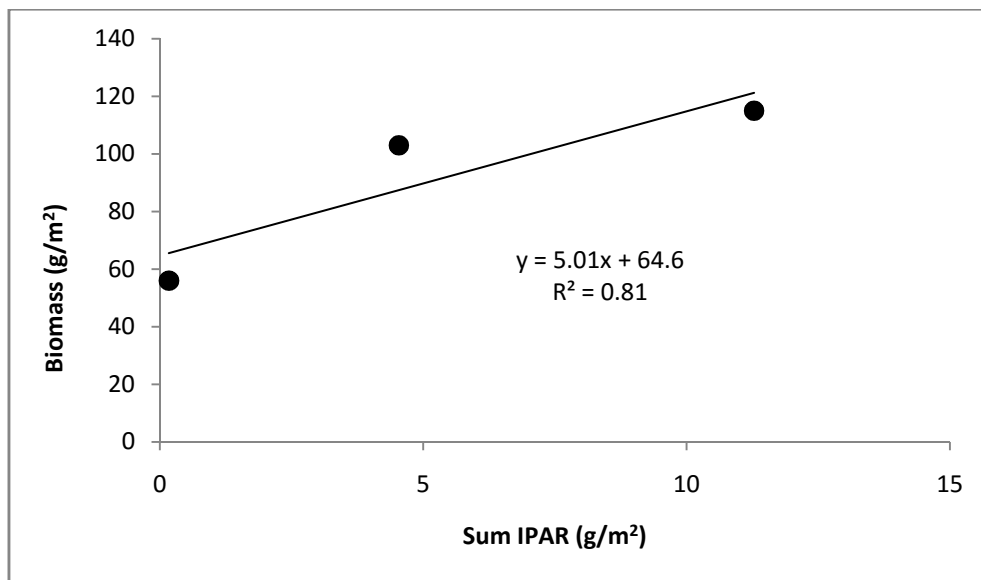


Fig. 2b. Calculation of RUE for needle and thread in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.

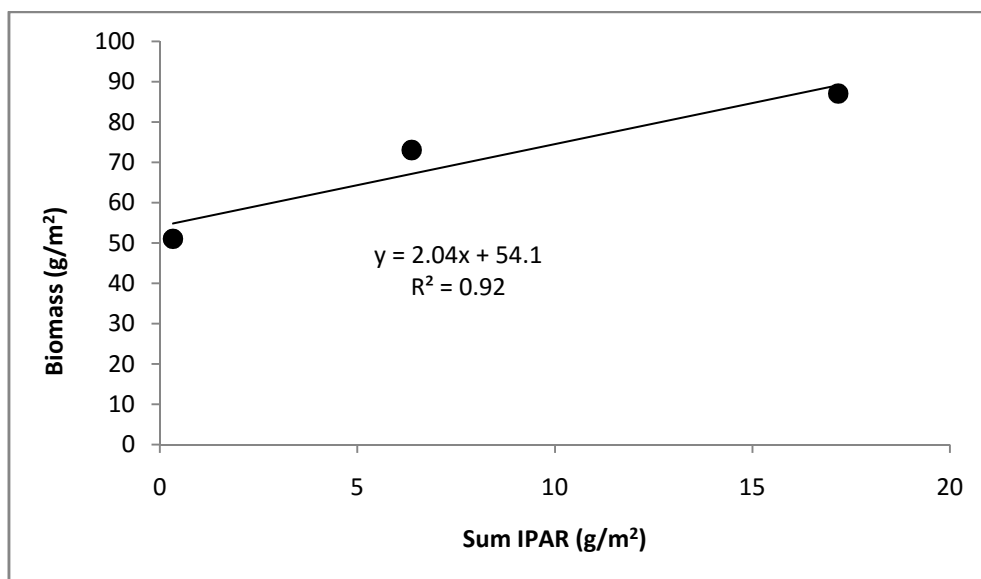
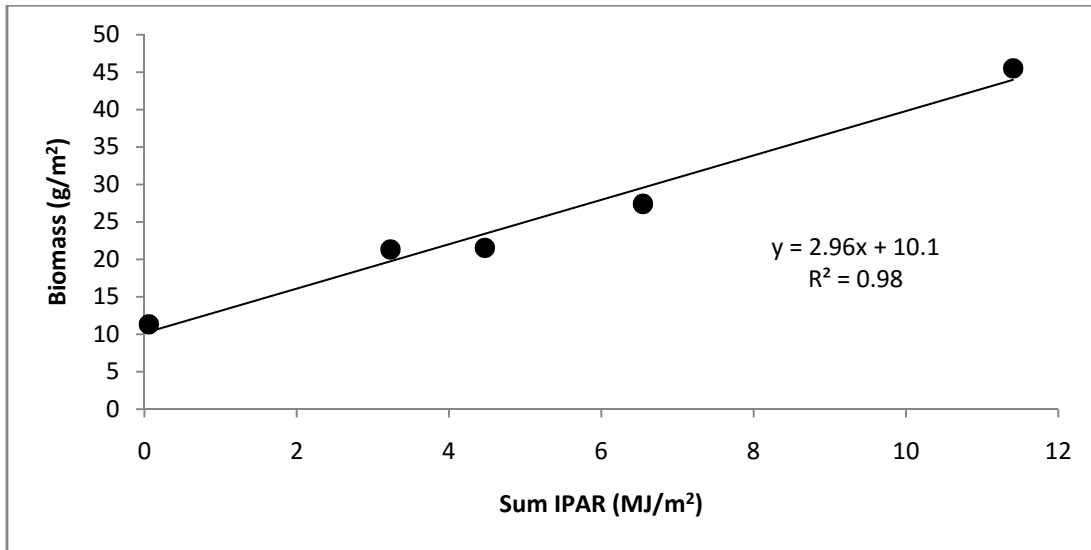
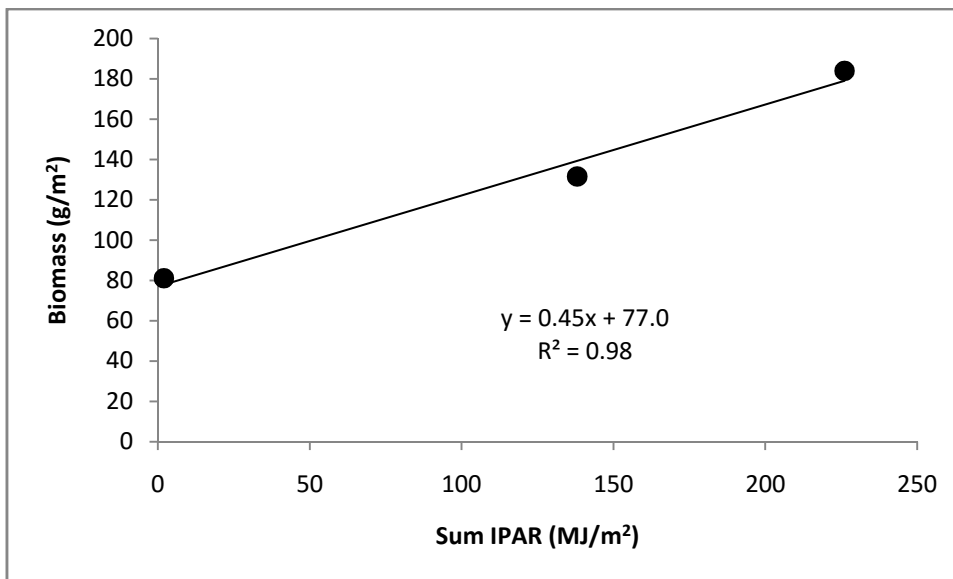


Fig. 2c. Calculation of RUE for green needlegrass in 2014. The aboveground dry biomass as a function of summed IPAR. The slope is the RUE.



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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.



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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.

417 Mean values of RUE showed a relatively narrow range, 3.5 to 4.0 g per MJ
418 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.

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. [10] 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 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.

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	high frac. of Norm

	20% of years	
	<u>1.28 (1.45)¹</u>	<u>1.25</u>
452	¹ Values in parentheses are the means divided by the average value,	
453	for comparison with NRCS fractions shown.	
454		
455	For the Claypan ecological site on Creed soil series (Table 5), the mean yield	
456	is 99% of the norm reported by NRCS. The mean of the low simulated yields	
457	is 77% of the mean simulated while the corresponding NRCS value is 63%.	
458	The mean of the high simulated yields is 137% of the mean, close to the	
459	NRCS value of 137%.	

460 **Table 5. Creed ecological site yields (Mg/ha). Simulated potential LAI**
 461 **values were 0.1 green needlegrass and 0.2 for western wheatgrass.**
 462 **Avg. of mid years simulations was 99% of NRCS norm.**
 463

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

465 ¹Values in parentheses are the means divided by the average
 466 value, for comparison with NRCS fractions shown.
 467
 468

469 Finally, for the higher yielding Silty-Steep ecological site on Cambeth soil
 470 series (Table 6), the mean simulated yield is 102% of the norm reported by
 471 NRCS. The mean of the low simulated yields is 76%, similar to the 77% for
 472 NRCS. The mean of the high simulated yields is 140% of the average,
 473 somewhat higher than the 123% for the NRCS values.
 474

475 **Table 6. Cambeth ecological site yields (Mg/ha). Simulated**
 476 **potential LAI values were 0.1 for green needlegrass,**
 477 **0.3 for western wheatgrass, and 0.3 for bottlebrush**
 478 **squirreltail. Avg. of mid years simulations was 102%**
 479 **of NRCS norm.**
 480

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
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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 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 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 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

4. DISCUSSION

Previously published values for western grasses [15] 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.

518

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

541 Finally, the use of plant functional groups represented by species in this
542 study shares some common features with the modeling studies discussed
543 above that used functional groups. Boer and Smith [1] simulated Australian
544 rangeland vegetation with three plant functional groups: annual herbaceous,
545 perennial herbaceous, and woody. Grigulis et al. [4] simulated an introduced
546 grass and shrubs as different plant functional groups. Cousins et al. [2]
547 simulated grassland in Sweden with five plant functional groups based on
548 responses to grazing. Functional groups based on the parameters described
549 herein could be based on general plant type and morphology. Thus such
550 groups will be complementary to some of the approaches in the published
551 simulation studies.

552

553 5. CONCLUSION

554

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

561

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