

Original Research Article

Plant Parameters for Plant Functional Groups of Western Rangelands to Enable Process-based Simulation Modeling

ABSTRACT

Regional environmental assessments with process-based models require realistic estimates of plant parameters for the primary plant functional groups in the region. "Functional group" in this context is an operational term, based on similarities in plant type and in plant parameter values. Plant Materials Centers of the Natural Resource Conservation Service of USDA are valuable resources, often overlooked and underutilized for plant evaluations in the different regions of the U.S. With this in mind, the objectives of this study were to quantify leaf area index, light extinction coefficient for Beer's law, radiation use efficiency, and nitrogen and phosphorus concentrations in well-managed stands of representative plant species for some major plant functional groups in the western U.S. We measured fraction of intercepted photosynthetically active radiation, leaf area index, and dry matter during the growing season in established field plots. These plant parameters for the ALMANAC model were then used to simulate five representative ecological sites in the region. These plant parameters are valuable for simulating individual plant species and plant functional groups. Using these plant parameters, the ALMANAC model and similar process-based models such as SWAT and APEX, will be readily implemented to interpret site monitoring and guide adaptive management approaches related to soil and water conservation.

Aims:

Study design:

Place and Duration of Study:

Methodology:

Results:

Conclusion:

Keywords: *Plant Parameters; Western Rangelands.*

1. INTRODUCTION

Regional assessments with process-based models such as Soil and Water Assessment Tool (SWAT) [1,2]; Agricultural Policy/Environmental eXtender (APEX) [3], or Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) [4] require realistic estimates of plant parameters for the primary plant functional groups in the region. Assessments such as Rangeland-CEAP

(Conservation Effects Assessment Project) are 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. Likewise, to proceed with these evaluations in a timely manner, the primary plant species within a region need to be characterized into plant functional groups. "Functional group" in this context is an operational term, based on similarities in plant type and in plant parameter values. Measurement of a representative species within each group will provide estimates for the needed growth parameters. Errors in applying such plant group parameters can be evaluated by comparing model simulation outputs to those using parameters for individual plant species contained in the group.

Process-based models such as ALMANAC are capable of realistically predicting production potentials of multiple species of exotic perennial warm-season grasses. The ability of ALMANAC to simulate the old world bluestem (OWB) group (*Bothriochloa ischaemum* (L.) Keng) and buffelgrass (*Pennisetum ciliare* [L.] Link) [5] suggest that it may be possible to apply ALMANAC to the simulation of plant functional groups. This possibility is bolstered by previous successes with ALMANAC realistically simulating communities of grasses and forbs in the arid western U.S. with a generic set of community-based parameters [6].

There are a number of contexts in which it might be useful to simulate functional groups or communities rather than individual species. For example, large scale regional assessments, such as those predicting a plant community's response to climate change or to conservation practices, may benefit from a coarser, functional group approach rather than a fine-scale species approach to simulation. Work with ALMANAC continues to explore the potential to identify, parameterize, and simulate trait-based functional groups with this process-based plant growth model. It is intended that this concept be expanded towards development of a workable plant functional group system that could be simulated by ALMANAC. Thereby 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 as such that it could prove a valuable and critical tool for conservation practice planning.

Plant Materials Centers (PMC's) of the Natural Resources Conservation Service of USDA are valuable resources, often overlooked and underutilized for plant evaluations in the different regions of the U.S. Their efforts over the last several decades have led to identification of important ecotypes of promising native plants in the different regions [7]. They have relatively large plots of such plants that can readily be measured for parameter derivation for process-based models. Consequently, the objective of this project was to work with PMC's in the western states, along with USDA-ARS researchers at Logan, UT and Temple, TX, to develop plant parameters for representative species from some of the primary plant functional groups in these regions. These were developed for the ALMANAC model for the Rangeland-CEAP project, with the idea that these parameters can also be readily applied in the SWAT, APEX, and similar process-based models.

The parameters developed for the ALMANAC model will be useful for the actual species measured and for the plant functional groups they represent. Thus specific objectives of this study were to quantify leaf area index (LAI), light extinction coefficient (k) for Beer's law, radiation use efficiency (RUE), and plant nitrogen and phosphorus concentrations in well-managed stands of representative plant species for some major plant functional groups in the western U.S. Such values, additionally, will be valuable in applying Beer's law with measured fraction of intercepted photosynthetically active radiation (FIPAR) as a nondestructive method of calculating LAI. Values for FIPAR could be measured on the ground with linear photosynthetically active radiation (PAR) sensors (as in this study) or remotely with cameras estimating fraction of plant cover, as a surrogate for FIPAR. In addition, model simulation output using mean values for a group of species was compared to output for some individual species. This was intended to quantify potential simulation errors when using a functional group for plant parameters.

2. MATERIALS AND METHODS

2.1 Site Specific Descriptions and Management

All measurements were taken on well-established plots of each plant type. Sites varied in soil type, atitude, longitude, and elevation (Figure 1 and Table 1). The study involved on-the-ground measurements of FIPAR (nondestructive), LAI (destructive), and dry matter (destructive). Plant species measured varied among sites and years (Table 2).

Beaver, UT: Average annual precip. is 300 mm and elev. is 1799mm. Plots were planted November 2006; fall dormant planting at 2.5 seeds per cm of row; spacing between rows is 20 cm; plots are 1.25 m x 5 m; Each year the forage was removed to a stubble height of 15 cm; dryland; no fertilization.

Fillmore, UT: Average annual precip. is 380 mm and elev. is 365m. Plots were planted November 2004; fall dormant planting at 2.5 seeds per cm of row; spacing between rows was 20 cm; plots were 1.25 m x 5 m; each year the forage was removed to a stubble height of 15 cm; dryland; no fertilization.

Stone, ID (Curlew National Grassland): Average annual precip. is 250 mm and elev. is 1392m. Plots were planted November 2002; fall dormant planting at 2.5 seeds per cm of row; spacing between rows is 20 cm; plots are 1.25 m x 5 m; each year the forage was removed to a stubble height of 15 cm; dryland; no fertilization.

Logan, UT: Average annual precip. is 450 mm and elev. is 1392m. These sites are stock seed fields and are distributed around Cache Valley all similar in elevation and annual precipitation. They were irrigated twice a year to field capacity near flowering and in August to initiate new growth. They were planted in 91 cm row spacings. Within a row they were solid seeded at 3 to 4 seeds per cm of row.



Fig. 1. _____

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Table 1. Experimental locations

Location	Latitude (N)	Longitude (W)	Elevation (m)	Soil Type
Lockeford, CA	38°10'20"	121°10'3"	20	Columbia fine sandy loam, drained, 0 to 2 percent slopes
Meeker, CO	40°0'17'121"	107°50'17"	1971	Zoltay clay loam, 3 to 8 percent slopes
Aberdeen, ID	42°59'6"	112°54'29"	1364	Declo loam, 0 to 2 percent slopes
Pullman, WA	46°43'57"	117°0'1"	786	Latahco silt loam, 0 to 3 percent slopes
Bridger, MT	45°16'1"	108°53'3"	1135	Haverson silty clay loam, 0 to 2 percent slopes
Los Lunas, NM	34°46'20"	106°45'32"	1472	Bluepoint loamy fine sand, 1 to 3 percent slopes
Beaver, UT	38°20'52"	112°35'21"	1971	Murdock silt loam, 1 to 3 percent slopes
Logan, UT	41°48'48"	111°49'27"	1382	Nibley Silty Clay Loam, 0 to 3 percent slopes
Fillmore, UT	39°12'11"	112°14'14"	1772	Spager gravelly very fine sandy loam, 5 to 15 percent slopes
Stone, ID	42° 02'25"	112°40'18"	1408	Mellor-Freedom complex, 0 to 2 percent slopes

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112 **Table 2. Plant species measured. Nomenclature follows USDA-NRCS (2012) [8]**

Plant Species	Common Name 'Variety'	Location
<i>Cleome isomeris</i> Greene	bladderpod spiderflower 'Dorado'	Lockeford, CA
<i>Distichlis spicata</i> (L.) Greene	saltgrass LK517f Germplasm	Lockeford, CA
<i>Elymus elymoides</i> (Raf.) Swezey	Squirreltail	Lockeford, CA
<i>Sporobolus airoides</i> (Torr.) Torr.	alkali sacaton	Lockeford, CA
<i>Festuca arizonica</i> Vasey	Arizona fescue 'Redondo'	Meeker, CO
<i>Hedysarum boreale</i> Nutt.	Utah sweetvetch	Meeker, CO
<i>Pascopyrum smithii</i> (Rydb.) Á. Löve	western wheatgrass 'Arriba'	Meeker, CO
<i>Penstemon strictus</i> Benth.	Rocky Mountain penstemon 'Bandera'	Meeker, CO
<i>Prunus virginiana</i> L.	Chokecherry	Meeker, CO
<i>Elymus elymoides</i>	bottlebrush squirreltail 'Wapiti'	Meeker, CO
<i>Bromus marginatus</i> Nees ex. Steud.	mountain brome "Garnet"	Meeker, CO
<i>Achnatherum hymenoides</i> (Roem. & Schult.) Barkworth	indian ricegrass '739'	Meeker, CO
<i>Elymus wawawaiensis</i> J. Carlson & Barkworth	Snake River wheatgrass	Aberdeen, ID
<i>Elymus lanceolatus</i> (Scribn. & J.G. Sm.) Gould	thickspike wheatgrass	Aberdeen, ID
<i>Elymus trachycaulus</i> (Link) Gould ex Shinnars	slender wheatgrass	Aberdeen, ID
<i>Pascopyrum smithii</i>	western wheatgrass	Aberdeen, ID
<i>Pseudoroegneria spicata</i> (Pursh) Á. Löve	bluebunch wheatgrass	Aberdeen, ID
<i>Pseudoroegneria spicata</i>	bluebunch wheatgrass	Pullman, WA
<i>Achnatherum hymenoides</i>	indian ricegrass 'Rimrock'	Bridger, MT
<i>Elymus lanceolatus</i>	thickspike wheatgrass 'Critana'	Bridger, MT
<i>Leymus cinereus</i> (Scribn. & Merr.) Á. Löve	basin wildrye 'Trailhead'	Bridger, MT
<i>Pascopyrum smithii</i>	western wheatgrass 'Rosana'	Bridger, MT
<i>Gaillardia aristata</i> Pursh	blanketflower Meriwether germplasm	Bridger, MT
<i>Ratibida columnifera</i> (Nutt.) Woot. & Standl.	upright prairie coneflower Stillwater Germplasm	Bridger, MT
<i>Dalea candida</i> Michx. Ex Wild.	white prairie clover Antelope germplasm	Bridger, MT
<i>Pleuraphis jamesii</i> Torr.	galleta grass 'Viva'	Los Lunas, NM
<i>Bouteloua curtipendula</i> (Michx.) Torr.	sideoats grama 'Vaughn'	Los Lunas, NM
<i>Agropyron cristatum</i> (L.) Gaertn.	crested wheatgrass 'Hycrest'	Beaver, UT
<i>Thinopyrum intermedium</i> (Host) Barkworth & D.R. Dewey	intermediate wheatgrass 'Oahe'	Beaver, UT
<i>Psathyrostachys juncea</i> (Fisch.) Nevski		Beaver, UT
<i>Agropyron fragile</i> (Roth.) P. Candargy	Russian wildrye 'Bozoisky'	Beaver, UT
<i>Bromus inermis</i> Leyss.	Siberian wheatgrass 'Vavilov II'	Beaver, UT
<i>Achnatherum hymenoides</i>	smooth brome 'Manchar'	Beaver, UT
<i>Elumus wawawaiensis</i>	indian ricegrass 'Rimrock'	Beaver, UT
<i>Elymus elymoides</i>	Snake River wheatgrass 'Secar'	Beaver, UT
	bottlebrush squirreltail 'Sand Hollow'	Beaver, UT

<i>Elymus lanceolatus</i>	thickspike wheatgrass 'Bannock'	Beaver, UT
<i>Elymus lanceolatus</i>	thickspike wheatgrass 'Critana'	Beaver, UT
<i>Elymus trachycaulus</i>	slender wheatgrass 'Firststike'	Beaver, UT
<i>Leymus cinereus</i>	basin wildrye 'Trailhead'	Beaver, UT
<i>Pascopyrum smithii</i>	western wheatgrass 'Rosana'	Beaver, UT
<i>Pseudoroegneria spicata</i>	bluebunch wheatgrass 'Goldar'	Beaver, UT
<i>Bromus biebersteinii</i>	meadow brome 'Cache'	Fillmore, UT
<i>Agropyron cristatus</i>	crested wheatgrass 'Hycrest'	Fillmore, UT; Stone, ID
<i>Psathyrostachys juncea</i>	Russian wildrye 'Bozoisky'	Fillmore, UT; Stone, ID
<i>Pascopyrum smithii</i>	western wheatgrass 'Rosana'	Fillmore, UT; Stone, ID
<i>Pseudoroegneria spicata</i>	bluebunch wheatgrass 'Goldar'	Fillmore, UT; Stone, ID
<i>Agropyron fragile</i>	Siberian wheatgrass 'Vavilov II'	Stone, ID
<i>Agropyron cristatum</i>	crested wheatgrass 'Hycrest II'	Logan, UT
<i>Thinopyrum intermedium</i>	intermediate wheatgrass 'experimental'	Logan, UT
<i>Psathyrostachys juncea</i>	Russian wildrye 'Bozoisky II'	Logan, UT
<i>Agropyron fragile</i>	Siberian wheatgrass 'Vavilov II2'	Logan, UT
<i>Elymus wawawaiensis</i>	Snake River wheatgrass 'Discovery'	Logan, UT
<i>Elymus trachycaulus</i>	slender wheatgrass 'Firststike'	Logan, UT
<i>Leymus cinereus</i>	basin wildrye 'Continental'	Logan, UT

Bridger, MT (Billings, MT PMC): Average annual precip. is 292 mm and elev. is 1117m. Establishment date varied among plant species, with indian ricegrass being Nov. 2009, western wheatgrass being April 2007, thickspike wheatgrass being April 2005, and basin wildrye being April 1995. Irrigation consisted of 10 cm of flood irrigation in late June or early July. All plots were fertilized with 12 kg ha⁻¹ N and 58 kg ha⁻¹ P on 2 Nov 2010 and with 112 kg ha⁻¹ N and 42 kg ha⁻¹ P on 1 June 2011.

Aberdeen, ID PMC: Average annual precip. is 250 mm and elev. is 1342m. Plots were all planted in 2007. They received 41 cm of total water (rainfall plus irrigation) each growing season. Plots were mowed each summer near anthesis date to prevent seed spread. They were fertilized each year with 264 kg ha⁻¹ of 16-20-0 and 73 kg ha⁻¹ of 46-0-0. Bunchgrasses at this location had 20 plants m⁻².

Lockeford, CA PMC: Average annual precip. is 480mm. and elev. is 31m. Bladderpod plots were mature 18-year-old shrubs planted on about 3-m spacing. The saltgrass plot was a 19-year-old solid stand that was mowed once per year and disked every few years to maintain vigor. Neither received fertilizer or irrigation during the previous 5 years. Sacaton was 7 years old with 4 plants m⁻² and squirreltail was 1 year old with 20 plants m⁻². Sacaton plots were fertilized each spring with 112 kg ha⁻¹ of 16-20-0, surface irrigated 2-3 times per year during seed ripening, and mowed each fall. Squirreltail plot did not receive any supplemental irrigation, fertilizer or mowing.

Meeker, CO PMC: Average annual precip. is 410 mm and elev. is 1981 m. Annual fertilizer applications consisted of 90 kg ha⁻¹ N, 11 kg ha⁻¹ P and 5.6 kg ha⁻¹ S for all plots except chockcherry and indian ricegrass. These two species had no fertilizer applied.

Overhead sprinklers were used to irrigate sufficiently to avoid drought stress three times each growing season for Utah sweetvetch, Arizona fescue and Bottlebrush squirreltail. Similarly, gated pipe was used to irrigate three times each growing season for Western wheatgrass, Rocky Mountain penstemon, and mountain brome. Indian ricegrass and chokecherry were not irrigated. Weeds were controlled by mechanical weeding, hand weeding, and herbicides. Harvesting and mowing is completed by hand/combine or swather. Prior to measurements, chokecherry had been established 6 years, Utah

sweetvetch 2 years, Arizona fescue 8 years, western wheatgrass 5 years, Rocky Mountain penstemon 8 years, mountain brome 19 years, bottlebrush squirreltail 7 years, and indian ricegrass 7 years.

Los Lunas, NM PMC: Average annual precip. is 251 mm and elev. is 1480 m. Foundation seed field of sideoats grama grass “Vaughn” was planted in 2004. Plots were clipped to 10 cm. in March. Plots were fertilized with 45 kg ha⁻¹ N and 45 kg ha⁻¹ P on 26 March 2012. Pre-emergence herbicide was applied on 6 April 2012. Plots were irrigated on 12 April, 24 May, 15 June, 5 July, and 3 August 2012 in sufficient amounts to prevent any drought stress. Initial green-up occurred on 22 April 2012 and full green-up on 1 May 2012.

Foundation seed field of galleta grass cultivar “Viva” was planted in 2003. Plots were burned 13 March 2012. Plots were fertilized with 45 kg ha⁻¹ N on 26 March and 9 Sept 2012 and 45 kg ha⁻¹ phosphorus on 12 April and 9 Sept 2012. Pre-emergence herbicide was applied on 6 April 2012. Plots were irrigated sufficiently to avoid drought stress on 16 April, 22 May, 14 June, and 10 August 2012. Initial green-up occurred on 20 April 2012 and full green-up on 1 May.

2.2 Field Measurements

Values for FIPAR were determined by repeated measurements of PAR below the plant canopy with an AccuPAR LP-80 ceptometer (Decagon Devices, Inc., Pullman, WA), with concurrent measurements above the canopy with a PAR sensor. Plant samples were harvested from a 0.5 x 0.5-m ground area at 0.05 m height, weighed fresh, and a subsample weighed fresh. This subsample was measured for leaf area with a LI-3100 Area Meter (LI-COR Biosciences, Lincoln, NE), dried in a forced air oven at 65°C until constant weight was reached, then weighed. The nitrogen concentration was determined using a Leco FP-528 nitrogen/protein analyzer (LECO Corp., St. Joseph, MI) with Dumas combustion [9,10]. Phosphorus concentration was determined using a microwave assisted acid digestion and analyzed through a Thermo IRIS Advantage HX analyzer (Thermo Fisher Scientific Inc., Waltham, MA).

LAI was calculated as:

$$\text{LAI} = \text{Total fresh wt./subsample fresh wt.} \times \text{leaf area of subsample (cm}^2\text{)/(50 cm} \times \text{50 cm)} [1]$$

Radiation use efficiency (RUE) was calculated as the rate of increase in above-ground dry matter (g per m² ground area) per unit of intercepted photosynthetically active radiation (IPAR) (MJ per m² ground area). Ideally this was calculated as a slope of the line for dry matter = f(IPAR). However, sometimes only two harvest dates were usable; in those cases RUE was calculated from differences. Only data from dates showing increases in dry matter were included. This constrained RUE values for time periods when plants were growing and not static, as can occur on range sites especially with drought stress. Values for FIPAR were calculated on a daily basis, with values for dates between measurement dates calculated by linear interpolation.

2.3 ALMANAC Simulations

USDA-NRCS Ecological site description (ESD) data were used to demonstrate the validity of the derived plant parameters. The simulation sites were constrained by availability of ESD data. Only two of the states considered had such data available for testing the application of plant parameters to nearby sites. These were in Utah and New Mexico (Table 8a). Thus, these serve as examples of applications of a small number of our derived parameters, with the idea that these model demonstrations will be expanded in the future as more extensive ESD data becomes available.

Initially each of these sites was simulated with the parameters for the represented individual plant species. Next, only one or two of these species were simulated, with the potential leaf area index values adjusted to match the total for the site in the previous runs. Finally, simulations were repeated with the mean parameters for each plant functional group represented. Similarly for this last set of simulations, the total potential leaf area index was set to the same value as the sum of all species simulated in their

group. This was accomplished in each case by adjusting plant density. The difference in plant biomass yields were compared to the reported NRCS biomass yields for each of these three approaches for each site.

3. RESULTS

3.1 Field Measurements

Results below are described by plant genera (Table 3). Values for individual plant species are in Appendix A.

Maximum LAI (LAI_{max}), light extinction coefficient for Beer's law (k), and RUE are the three main driving parameters defining potential leaf canopy development and potential dry matter production in the absence of environmental stress (Table 3). Grass LAI_{max} ranged from 1.0 to 2.1 with a few exceptions. The bromes, indian ricegrass, and Arizona fescue had LAI_{max} below 1.0, and basin wildrye and galleta grass had LAI_{max} of 2.9 and 3.3, respectively. Values for k ranged from -0.50 to -0.85 with a few exceptions. The mean k value of brome, crested/Siberian wheatgrasses, and intermediate wheatgrass had k values lower than -0.5. High mean k values of -0.90 and -1.06 were measured for Arizona fescue and sideoats grama, respectively.

Radiation use efficiency (RUE) values ranged from 0.70 to 1.3 g MJ⁻¹ with some exceptions. Saltgrass mean RUE was low, at 0.35, as was Russian wildrye at 0.47 g MJ⁻¹. Arizona fescue had a high mean RUE value of 2.07 g MJ⁻¹.

For forbs, the three parameters varied widely among the few genera represented. Values for LAI_{max} of the two leguminous forbs were 0.6 and nearly 3.0. Values for LAI_{max} for the non-leguminous forbs ranged from 0.5 to about 1.1. Correspondingly, among the five genera, k varied from -0.3 to -0.6 and RUE varied from near 1.1 to 4.4 g MJ⁻¹.

Shrubs had an even more limited set of values, with measurements only on *Prunus* and *Cleome*. Values of LAI_{max} were 0.2 and 1.5; values for k were -0.5 and -1.65, respectively. We did not have values for RUE for these due to the slower, more long-term nature of their growth. However due to drastically different values for LAI_{max} and k , it appeared that these two genera will require different parameters to simulate each.

3.1.1 Groupings into functional groups by plant type and maximum LAI

We grouped the grasses into four groups (Table 4) and the forbs into two groups (Tables 3 and 5). We split the cool season bunchgrasses into those with LAI_{max} values less than 1.0 and those between 1.0 and 2.0. The two higher LAI, warm season grasses, saltgrass and sacaton, were pooled together. The last group consisted of two warm season grasses: galleta grass and sideoats grama. Consistency in each of these four groups makes their simulations with one set of plant parameters very feasible. The one exception may be with the saltgrass/sacaton group where LAI_{max} values differed two-fold. The forbs similarly had a mean LAI_{max} near 1.0 and a mean RUE value greater than for most of the grasses. The two shrubs (Tables 3 and 5) differed greatly in LAI_{max} values and will likely need to be simulated with separate parameters for many applications.

Table 3. Functional group summary split by genera. WR stands for wildrye, WG stands for wheatgrass, and SQT stands for squirreltail. “k” is the extinction coefficient for Beer’s law. Max LAI is the mean across data sets for maximum LAI during each season. RUE (radiation use efficiency) is the above ground biomass (g) per MJ intercepted photosynthetically active radiation.

	Genus	Max LAI	Avg k	RUE	Number of Site Years
Grasses					
bromes	<i>Bromus</i>	0.76	-0.48	1.15	5
indian ricegrass	<i>Achnatherum</i>	0.64	-0.85	1.32	6
Russian WR	<i>Psathyrostachys</i>	1.44	-0.66	0.72	6
basin WR	<i>Leymus</i>	2.88	-0.73	0.47	6
bluebunch WG	<i>Pseudoroegneria</i>	1.34	-0.82	1.31	8
crested/Siberian WG	<i>Agropyron</i>	1.44	-0.46	0.84	11
intermediate WG	<i>Thinopyrum</i>	2.07	-0.39	1.47	4
WG/SQT	<i>Elymus</i>	1.26	-0.71	0.78	25
western WG	<i>Pascopyrum</i>	1.84	-0.74	1.10	10
saltgrass	<i>Distichlis</i>	3.30	-0.52	0.35	2
galleta grass	<i>Pleuraphis</i>	1.14	-0.52	1.00	2
sideoats grama	<i>Bouteloua</i>	1.22	-1.06	1.22	1
Arizona fescue	<i>Festuca</i>	0.63	-0.90	2.07	2
alkali sacaton	<i>Sporobolus</i>	1.57	-0.77	0.40	1
Leguminous Forbs					
white prairie clover	<i>Dalea</i>	2.93	-0.31	2.99	1
Utah sweetvetch	<i>Hedysarum</i>	0.61	-0.63	1.13	2
Nonleguminous Forbs					
Rocky Mt. penstemon	<i>Penstemon</i>	0.99	-0.43	1.34	2
blanketflower	<i>Gaillardia</i>	1.07	-0.30	4.42	1
upright prairie coneflower	<i>Ratibida</i>	0.47	-0.57	2.16	1
Shrubs					
chokecherry	<i>Prunus</i>	0.21	-0.52		1
bladderspod spiderflower	<i>Cleome</i>	1.47	-1.65		1

Table 4. Grass functional group summary

	Max LAI	Avg k	RUE	Number of Site Years
Low LAI cool-season bunchgrasses	0.65	-0.75	1.66	
squirreltail	0.55	-0.78	2.09	5
brome	0.76	-0.48	1.15	5
indian ricegrass	0.64	-0.85	1.32	6
Arizona fescue	0.63	-0.90	2.07	2
Cool-season wildryes & wheatgrasses	1.37	-0.75	0.74	
wildrye*	1.52	-0.78	0.60	12
wheatgrass**	1.22	-0.71	0.87	53
Warm-season saltgrass & sacaton	2.44	-0.65	0.38	
saltgrass	3.30	-0.52	0.35	2
sacaton	1.57	-0.77	0.40	1
Warm-season galleta grass & sideoats grama	1.23	-0.71	0.96	
galleta grass	1.14	-0.52	1.00	2
sideoats grama	1.22	-1.06	1.22	1

*Two divergent sets based on LAI, one group with 2 datasets and LAI= 4.89, k= -0.40, and RUE= 0.72, and another group with 10 datasets with LAI= 0.93, k= -0.85, and RUE= 0.47.

**Two divergent sets based on LAI, one group with 6 datasets and LAI= 3.42, k= -0.27, and RUE= 1.15, and another group with 44 datasets with LAI= 0.59, k= -0.79, and RUE= 0.90.

Table 5. Functional group summary by plant growth type. Due to the slow growth of shrubs, RUE measurements were not reported for this relatively short-term project.

	Max LAI	Avg k	RUE	Number of Site Years
Shrubs	0.84	-1.09		2
Leguminous forbs	1.38	-0.52	1.68	3
Non leguminous forbs	0.91	-0.43	2.31	4
Rhizomatous grasses	1.26	-0.69	0.80	42
Bunchgrasses	1.14	-0.74	1.24	47

3.1.2 Groupings by five broad functional groups based solely on plant type

Finally, as shown in Table 5, we pooled all the rhizomatous grasses into one group and the bunchgrasses into another group. The forbs are in two groups as discussed in the previous section, depending on whether they are leguminous or not. The shrubs are in one group, as discussed above. These groupings give estimates for simulations where users simply want to look at the overall water use or soil erosion of a generic set of plants, with no interest in grazing management or other ecosystem services. The LAImax values averaged about 0.8 to 1.4. Values for k showed remarkable similarity among the groups, mostly near -0.5 to -0.7. The non-leguminous forbs had a lower mean k, near -0.4, while shrubs had a higher k, near -1.1. The RUE values likewise ranged from about 0.8 to 1.7 g per MJ intercepted PAR, with the one exception being the higher value for non-legume forbs.

Previously published values (Table 6) for LAImax, k, and RUE showed ranges similar to those in the present study. Grass LAImax values were generally between 1.5 and 4.0 with notable exceptions. Blue grama was much lower, and big bluestem and eastern gamagrass had LAImax values of 5.0 or more.

281

Table 6. Previously published values for comparison

Our published values	Max LAI	Mean k	RUE
blue grama ¹	0.26	-1.62	0.57
sideoats grama ²	1.50	-1.05	1.1
buffalograss ¹	2.13	-1.20	1.38
bahiagrass ¹	2.21	-1.00	1.25
coastal bermudagrass ¹	2.19	-1.10	1.50
big bluestem ²	8.00	-0.36	1.4
Johnsongrass ³			2.26
buffelgrass ⁴	4.04	-0.52	2.26
old world bluestem ⁴	3.57	-0.46	1.18
eastern gamagrass ²	5.00	-0.31	2.1
eastern red cedar ⁵			1.60
mesquite ⁵			1.61

282

¹ Kiniry et al., 2007 [11].

283

² Kiniry et al., 1999 [12].

284

³ Kiniry, 1994 [13].

285

⁴ Kiniry et al., in review [14].

286

⁵ Kiniry, 1998 [15].

287

288

289 Mean k values from these previous studies fell into two groups, those with k absolute values of 0.31 to
 290 0.52 and those with k absolute values of 1.0 to 1.62. It is interesting to note that the one species found in
 291 both tables, sideoats grama, had similar LAI and k values: LAImax values of 1.22 vs. 1.50 for the present
 292 study and Kiniry et al. [12], respectively and k values of -1.06 vs. -1.05. Likewise RUE values for this
 293 species were similar between the two studies: 1.22 g MJ⁻¹ in the present study and 1.10 in Kiniry et al.
 294 [10].

295

296 **3.1.2 Nitrogen and phosphorus concentrations**

297

298 For this portion of the study, we split the grasses into rhizomatous vs. bunchgrass and the forbs into
 299 leguminous vs. non-leguminous, and looked at each by the U.S. state where measurements were taken
 300 (Table 7). Concentrations of both N and P generally started high early in the season and gradually
 301 decreased, as expected. As we pooled the values over states, the means became more stable between
 302 the two grass groups. These means, either for each of the two grass groups or for all the grasses pooled,
 303 provide a reasonable guide for simulating these important plant nutrients.

304

305 **3.2 ALMANAC Simulations**

306

307 As discussed above, simulation sites were chosen based on proximity to measurement sites and
 308 availability of ecological site description (ESD) data (Table 8a). Simulated plant species were chosen
 309 based on their dominance in the ESD database for each site. Plant densities in each community were
 310 adjusted to simulate reasonable potential LAI for each site.

311

312 As such, simulated annual biomass values using all the species listed were close to reported values in all
 313 cases (Table 8b). The three ESD's in New Mexico had large differences among reported annual biomass
 314 yields. These were closely mirrored by the simulated yields for these sites. These yield differences among
 315 sites were due to differences in plant species composition, the potential LAI of each, and the soils. The
 316 same rainfall data was used for all three sites due to their proximity.

317

Table 7a. For 2011, representative values for 14 plant functional groups in 6 states. No. msrd. is the number of plant varieties measured. BN values are plant nitrogen concentrations for early in the season, mid-season, and late-season. BP values are for plant phosphorus concentrations for early, mid- and late-season. Rhiz. Grass is for rhizomatous grasses and Bunchgrass is for bunchgrasses.

Func. Group	State (No. msrd.)	BN1	BN2	BN3	BP1	BP2	BP3
Rhiz. Grass	ID (2)	2.36	---	1.12	0.228	---	0.154
Bunchgrass	ID (4)	2.64	---	1.21	0.261	---	0.180
Rhiz. Grass	CA (1)	3.35	1.34	0.87	0.378	0.165	0.204
Bunchgrass	CA (1)	2.32	1.74	1.28	0.188	0.183	0.135
Rhiz. Grass	CO (1)	3.46	1.70	1.61	0.285	0.214	0.178
Bunchgrass	CO (1)	2.67	1.85	1.88	0.244	0.203	0.228
Rhiz. Grass	MT (2)	1.92	1.75	1.32	0.235	0.191	0.166
Bunchgrass	MT (2)	2.06	1.56	1.06	0.240	0.203	0.123
Pooled Values							
Rhiz. Grass		2.77	1.60	1.23	0.282	0.19	0.176
Bunchgrass		2.42	1.72	1.36	0.233	0.196	0.167
All Grasses		2.59	1.66	1.29	0.258	0.193	0.171
Leguminous forb	CO (1) MT (1)	4.63	4.61	2.99	0.385	0.346	0.199
Non-leg. Forb	CO (1) MT(2)	3.60	1.43	1.66	0.469	0.252	0.262

Table 7b. For 2012, representative values for 14 plant functional groups in 6 states. No. msrd. is the number of plant varieties measured. BN values are plant nitrogen concentrations for early in the season, mid-season, and late-season. BP values are for plant phosphorus concentrations for early, mid- and late-season. Rhiz. is for rhizomatous grasses and Bunchgrass is for bunchgrasses.

Func. Group	State (No. msrd.)	BN1	BN2	BN3	BP1	BP2	BP3
Rhiz. Grass	NM (1)	---	---	0.93	---	---	0.195
Bunchgrass	NM (1)	---	---	0.82	---	---	0.158
Rhiz. Grass	ID (1)	2.78	---	---	0.273	---	---
Bunchgrass	CA (1)	3.82	---	---	0.297	---	---
Bunchgrass	CO (2)	3.38	2.03	1.47	0.280	0.230	0.193
Rhiz. Grass	MT (2)	1.92	1.75	1.32	0.235	0.191	0.166
Bunchgrass	MT (2)	2.06	1.56	1.06	0.240	0.203	0.123
Pooled Values							
Rhiz. Grass		2.35	1.75	1.13	0.254	0.191	0.181
Bunchgrass		3.09	1.80	1.12	0.272	0.217	0.158
All Grasses		2.79	1.78	1.12	0.265	0.208	0.167
Leguminous forb	MT (1)	3.02	1.28	---	0.255	0.115	---
Non-leg. Forb	ID (1) MT(2)	2.26	1.20	0.88	0.285	0.205	0.173

Table 8a. Simulation locations

Location	Latitude (N)	Longitude (W)	Soil	Mean annual rainfall (mm)	Weather Station
Los Lunas, NM	34°39'40.680"	106°50'6.000"	Caliza-Bluepoint complex, 1 to 2% slopes	242	Quemado
Los Lunas, NM	34°39'40.680"	106°50'6.000"	Wink-Madurez association, gently sloping	242	Quemado
Los Lunas, NM	34°39'40.680"	106°50'6.000"	Gila Loam	242	Quemado
Beaver, UT	38°20'52.440"	112°35'21.840"	Murdock Silt Loam 1-3% slopes	331	Blanding
Logan, UT	41°47'9.240"	111°49'3.720"	Millville Silt Loam 0-2% slopes	411	Bear River Refuge

Similar results are shown using all the species listed for the two ecological sites in Utah. The higher elevation site (Beaver, near Fillmore, elev. 1772 m) had much lower potential LAI and only about 0.57 Mg ha⁻¹ simulated and published dry matter yields. Thus both sites were simulated with the same three plant species parameters, only changing the potential LAI. Simulations with mean functional group simulations often had similar mean yields as with the more specific parameters, with the possible exception of the Logan UT site (Table 8b).

When we used only one or two plant species (shown in bold in Table 8b), simulated yields were generally reasonably close in the three New Mexico sites, but were too high in the two Utah sites. For the three sites in New Mexico, simulated yields were 68%, 90%, and 106% of published values. For the two New Mexico sites, simulated yields were 184% and 176% of published values.

When we used the mean functional group parameters (also Table 8b), simulated yields were reasonably close to published values in most cases. In three of the five sites, simulated yields for the functional group of the site were within 5% of published values. Exceptions were in the second site and the last site listed. Simulated yields were 119% and 130% of published values, respectively.

357

Table 8b. Simulation location results

Location	Ecological site name	Grasses simulated	Corresponding potential LAI values	Ecol. Site pub. Yields (Mg/ha)	Sim. Yields ¹ (Mg/ha)	Sim. Yields ² (Mg/ha)	Sim. Yields ³ (Mg/ha)
Los Lunas, NM	Gravelly sand	bush muhly	0.1	0.34	0.33	0.23	0.33
		blue grama	0.1				
		galleta grass	0.2(0.4)				
Los Lunas, NM	Loamy	galleta grass	0.2(0.5)	0.48	0.50	0.43	0.57
		bottlebrush squirreltail	0.05				
		bush muhly	0.1				
		indian ricegrass	0.1(0.15)				
		black grama	0.2				
Los Lunas, NM	Bottomland	galleta grass	0.2	2.11	2.12	2.15	2.10
		sacaton	7.3(7.3)				
		blue grama	0.2				
		vine mesquite	3.6(4.0)				
Beaver, UT	Upland loam	squirreltail	0.1(0.2)	0.58	0.57	1.07	0.61
		indian ricegrass	0.1				
		bluebunch	0.1(0.1)				
		wheatgrass					
Logan, UT	Upland loam	squirreltail	0.2(0.3)	0.71	0.69	1.25	0.92
		indian ricegrass	0.1				
		bluebunch	0.2(0.2)				
		wheatgrass					

358 ¹Simulated yields using derived parameters for each species.

359 ²Simulated yields using one or two represented species, with potential LAI adjusted to match total
360 potential LAI of the separate species. Bold grass names are the ones simulated, and the values in
361 parentheses are the adjusted potential LAI.

362 ³Simulated yields using mean derived parameters for the relevant plant functional group.

3634

3645 4. CONCLUSION

365
366 The results of this project demonstrated that assessments with process-based models such as
367 ALMANAC are feasible with realistic estimates of plant parameters for plant functional groups in a region.
368 Realistic simulation of plant development makes such simulation evaluations effective and scientifically
369 defensible. These evaluations should be possible to achieve in a timely manner with these plant
370 functional group parameters. Our measurements of individual species within these groups provide
371 estimates for the needed parameters for the group for these assessments.

372
373 The numerous contexts in which it is useful to simulate functional groups or communities rather than
374 individual species will be greatly improved by the results of this study. Large scale regional assessments,
375 such as those used to predict plant response to climate change or to conservation practices, will benefit
376 from this coarser, functional group approach. This work demonstrates the potential to identify,
377 parameterize, and simulate trait-based functional groups with this type of process-based plant growth
378 model. This work should be expanded towards a workable plant functional group system that can be
379 simulated by ALMANAC. Thus, model output will be applied to assessing ecosystem impacts and
380 services associated with shifts in both species composition and management practices. The ALMANAC
381 model can be readily implemented to interpret site monitoring and guide adaptive management
382 approaches. The model should prove a valuable and critical tool for Conservation Practice Planning.

383
384 The parameters described in this project will be useful for the actual species measured and for the plant
385 functional groups they represent. Such values, additionally, will be valuable in applying Beer's law with
386 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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Appendix A

Plant parameters for each species at each site.

CEAP Total Summary by Functional Groups												
Shrub	2010			2011			2012			Average across yrs		
	Max LAI	Avg K	RUE	Max LAI	Avg K	RUE	Max LAI	Avg K	RUE	Max LAI	Avg K	RUE
bladderspod spikerflower CA	1.47	-	1.65							1.47	-	1.65
choke cherry CO	0.21	-	0.52							0.21	-	0.52
Average by Year	0.84	1.09								0.84	1.09	
Legume Forb												
Utah sweet vetch CO	0.55	-	0.54	0.93	0.66	-	0.72	1.13		0.61	-	0.63
Antelope white prairie clover MT							2.93	0.31	2.99	2.93	0.31	2.99
Average by Year	0.55	0.54	0.93	0.66	0.72	1.13	2.93	0.31	2.99	1.38	0.52	1.68
Non Legume Forb												
Bandera Rocky Mt. Pennisetum CO	1.04	-	0.55	1.34	0.93	-	0.30			0.99	-	0.43
Meriwether Blanketflower MT							1.07	0.30	4.42	1.07	0.30	4.42
Stillwater Prairie Coneflower MT							0.47	0.57	2.16	0.47	0.57	2.16
Average by Year	1.04	0.55	1.34	0.93	0.30		0.77	0.43	3.29	0.91	0.43	2.31
Rhizomatous grass												
saltgrass CA	2.53	-	0.52	0.29	4.06	-	0.51	0.41		3.30	-	0.52
Viva galleta grass NM					1.43	-	0.74	0.61	0.84	0.30	1.14	0.52
Manchar smooth brome B.UT	0.89	-			0.72	-		0.18	-	0.60	-	1.00

		0.20			0.58			0.65		0.48		
		-			-			-		-		
Hycrest crested wheatgrass B.UT	0.31	0.43		0.28	0.80		0.18	0.44		0.26	0.55	
		-								-		
Hycrest crested wheatgrass F.UT	0.21	0.59								0.21	0.59	
Hycrest crested wheatgrass S.ID	0.90									0.90		
		-						-		-		
Hycrest II crested wheatgrass L.UT							3.91	0.21	1.11	3.91	0.21	1.11
		-			-			-		-		
Oahe Intermediate wheatgrass B.UT	0.56	0.60		0.48	0.74		0.13	0.52		0.39	0.62	
intermediate wheatgrass								-		-		
"experimental" L.UT							3.76	0.17	1.47	3.76	0.17	1.47
		-			-			-		-		
slender wheatgrass ID				2.07	0.74	0.41	1.98	0.85	0.76	2.02	0.79	0.59
		-			-			-		-		
First Strike slender wheatgrass B.UT	0.54	0.42		0.14	1.14		0.07	2.55		0.25	1.37	
		-			-			-		-		
First Strike slender wheatgrass L.UT							2.77	0.18	1.29	2.77	0.18	1.29
		-			-			-		-		
thickspike wheatgrass ID	4.74	0.29	0.10	1.10	1.58	0.49				2.92	0.94	0.30
		-			-			-		-		
Bannock thickspike wheatgrass B.UT	0.39	0.47		0.31	1.02		0.13	0.62	0.19	0.28	0.70	0.19
		-			-			-		-		
Critana thickspike wheatgrass MT	1.29	0.86	0.29	1.12	0.48	0.89				1.21	0.67	0.59
		-			-			-		-		
Critana thickspike wheatgrass B.UT				0.30	1.18		0.10	0.71	0.40	0.20	0.94	0.40
		-			-			-		-		
Arriba western wheatgrass CO	1.31	1.18	2.38	1.80	0.36	2.21				1.56	0.77	2.30
		-			-			-		-		
western wheatgrass ID	5.82	0.45	0.53							5.82	0.45	0.53
		-			-			-		-		
Rosana western wheatgrass MT	3.99	0.56	0.55	0.61	0.90	0.40				2.30	0.73	0.48
		-			-			-		-		
Rosana western wheatgrass B.UT	0.29	0.56		0.38	0.97		0.14	0.52		0.27	0.68	
		-			-			-		-		
Rosana western wheatgrass F.UT	0.37	1.06								0.37	1.06	
Rosana western wheatgrass S.ID	0.75									0.75		
		-			-			-		-		
Average by Year	1.56	0.59	0.69	1.06	0.84	0.77	1.18	0.64	0.94	1.26	0.69	0.80

Bunchgrass

Bottlebrush squirreltail CA	0.27	-	0.61							0.27	-	0.61					
Wapiti squirreltail CO								2.16	0.14	2.09			2.16	0.14	2.09		
Sand Hollow bottlebrush squirreltail B.UT	0.49	-	0.39		0.15	-	1.42	0.07	-	0.68			0.24	-	0.83		
alkali sacaton CA					1.57	-	0.77						1.57	-	0.77		0.40
Redondo AZ fescue CO	0.57	-	1.02	3.62	0.69	-	0.77						0.63	-	0.90		2.07
Garnet mt. brome CO								1.44	-	0.20	1.15		1.44	-	0.20		1.15
Cache meadow brome F.UT	0.61	-	0.65										0.61	-	0.65		
"739" indian ricegrass CO								1.51	-	0.17	3.07		1.51	-	0.17		3.07
Rimrock indian ricegrass MT	0.79	-	0.94	0.30	1.00	-	1.09						0.90	-	1.02		0.45
Rimrock indian ricegrass B.UT	0.28	-	0.74		0.19	-	1.39	0.08	-	0.80			0.18	-	0.98		
Snake River wheatgrass ID					1.61	-	0.97						1.61	-	0.97		
Secar Snake River wheatgrass B.Ut	0.31	-	0.44		0.22	-	1.44	0.14	-	0.59			0.22	-	0.82		
Discovery Snake River wheatgrass L.UT								2.20	-	0.23			2.20	-	0.23		
bluebunch wheatgrass ID	6.75	-	0.20	0.73	1.96	-	0.97						4.36	-	0.59		0.87
bluebunch wheatgrass M.ID					0.86	-	1.05						0.86	-	1.05		1.76
Goldar bluebunch wheatgrass S.ID	0.56												0.56				
Goldar bluebunch wheatgrass B.UT	0.58	-	0.35		0.78	-	0.99	0.47	-	0.32			0.61	-	0.55		
Goldar bluebunch wheatgrass F.UT	0.33	-	1.08										0.33	-	1.08		
Continental basin wildrye L.UT								6.02	-	0.42			6.02	-	0.42		

Trailhead basin wildrye MT	2.37	- 0.53		1.90	- 1.45	0.47				2.14	- 0.99	0.47
Trailhead basin wildrye B.UT	0.57	- 0.57		0.75	- 0.65		0.18	- 1.12		0.50	- 0.78	
Vaughn sideoats grama NM							1.22	- 1.06	1.22	1.22	- 1.06	1.22
Boziosky Russian wildrye F. UT	0.49	- 0.74								0.49	- 0.74	
Boziosky Russian wildrye S.ID	1.23									1.23		
Boziosky Russian wildrye B.UT	0.44	- 0.45		0.41	- 0.46		0.07	- 1.70		0.31	- 0.87	
Bozoisky II Russian wildrye L.UT							3.75	- 0.38	0.72	3.75	- 0.38	0.72
Vavilov II Siberian wheatgrass B.UT	0.45	- 0.34		0.24	- 1.15		0.14	- 0.51	0.07	0.28	- 0.67	0.07
Vavilov II Siberian wheatgrass S.ID	0.66									0.66		
Vavilov II Siberian wheatgrass L.UT							3.90	- 0.26	1.35	3.90	- 0.26	1.35
Average by Year	0.99	- 0.60	1.55	0.88	- 1.04	0.79	1.56	- 0.57	1.38	1.14	- 0.74	1.24