Herbaceous Biomass Estimation from SPOT 5 Imagery in Semiarid Rangelands of Idaho

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Abstract: Eight vegetation indices (VI) commonly used for above-ground biomass (AGB) estimation were derived from Satellite Pour l'Observation de la Terre 5 (SPOT 5) imagery and used to predict herbaceous AGB at a semiarid rangeland study site in southeastern Idaho. The relationship between herbaceous AGB and vegetation water content was also evaluated and as a result, a suite of water-sensitive vegetation indices (WSVI) were developed. Correlation coefficients between herbaceous AGB, VIs, and WSVIs were calculated, demonstrating that WSVIs were correlated ($r^2 \geq 0.51$) with vegetation water content and performed better than standard VIs in herbaceous AGB estimates within the semiarid rangelands of Idaho.

INTRODUCTION

Rangelands cover approximately 40% of the earth's terrestrial surface and are important areas for livestock production and wildlife habitat (Breman and de Wit, 1983; Huntsinger and Hopkinson, 1996). To effectively manage rangelands it is important to assess ecosystem productivity and biomass production (Running et al., 2004). Biomass estimates represent the quantity of matter in a given area and are expressed either as the weight of organisms per unit area or as the volume of organisms per unit volume. Previous total above-ground biomass (AGB) research has demonstrated that vegetation indices (VI) are sensitive to the biophysical and biochemical variations in vegetation, and as a result are the most common parameters used to estimate AGB (Davidson and Csillag, 2001; Kawamura et al., 2005; Numata et al., 2008). A remote sensing–derived VI is a quantitative optical measure of canopy greenness (Tucker, 1979; Weiser et al., 1986). Various VIs, such as the normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and soil adjusted vegetation index (SAVI), have been correlated with AGB, and applied to predict AGB within a variety of biomes (Davidson and Csillag, 2001; Kogan et al., 2004; Mirik et al., 2005; Wessels et al., 2006; Numata et al., 2008; Cho and Skidmore, 2009) (Table 1). Recently, ground-based and satellite-based spectral measurement methods have been developed to better quantify AGB. For instance, many ground-based methods use portable field spectroradiometers or digital cameras (e.g., ASD spectrometers, ASD Inc., Boulder, CO, USA; Dycam Agricultural Digital Camera (ADC), Dycam Inc., Chatworth, CA, USA) to collect canopy radiance and predict AGB through an

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Table 1. Correlation of Vegetation Indices with Total Above-Ground Biomass (AGB) Reported in Different Studies

Study area	Sensor	Index	R^2	Sources
Kentucky, USA	Greenseeker RT500	NDVI	0.68	Flynn et al., 2008
Southern Africa	Landsat7 -ETM+	Green/blue	0.85	Samimi and Kraus, 2004
Inner Mongolia, China	MODIS	NDVI	0.75	Kawamura et al., 2005
Italy	HyMap	NDVI	0.32–0.58	Cho and Skidmore, 2009
		NDWI	0.49–0.55	
Czech Republic	ADC	NDVI	0.83 (managed)	Mašková et al., 2008
			0.52 (unmanaged)	
Namibia	AVHRR	NDVI	0.76	Sannier et al., 2002
Northern Alaska	UniSpec-DC	NDVI	0.84	Boelman et al., 2003
Italy		NDVI	0.32	Schino et al., 2003
Brazilian Amazon	Analytical Spectral Device	NDVI	0.03	Numata et al., 2008
		NDWI	0.13	

empirical relationship between spectral values and biomass samples (Boelman et al., 2003; Flynn et al., 2008; Mašková et al., 2008). These methods are straightforward and accurate for small-area studies (e.g., approximately 1–10 ha); however, they are also labor intensive and difficult to apply over broad spatial scales or long-term temporal scales.

The increasing availability of satellite-based remote sensing data extends the assessment of AGB to a broader spatiotemporal scale. For example, remotely sensed data acquired from various sensors have been used to assess AGB, including NOAA's AVHRR (Box et al., 1989; Sannier et al., 2002; Kogan et al., 2004; Wessels et al., 2006), MODIS (Kawamura et al., 2005; Xu et al., 2008), Landsat-5 TM and Landsat-7 ETM+ (Friedl et al., 1994; Schino et al., 2003; Samimi and Kraus, 2004), SPOT VEGETATION (Verbesselt et al., 2006b), and hyperspectral sensors such as PROBE-1, Hyperion, and the HyMap system (Mutanga and Skidmore, 2004; Mirik et al., 2005; Numata et al., 2008; Cho and Skidmore, 2009).

Although many studies have investigated the ability to assess AGB from VIs, many problems have been found. One problem is that an empirical relationship derived by a VI for the accurate prediction of AGB at one site or time period may not apply to other sites or even the same site at another time (Foody et al., 2003). This problem is primarily due to variations in the natural environment (e.g., variable precipitation, soil-water content, and temperature conditions), viewing season (e.g., phenology during the growing season), and the sensor used in the study (e.g., differences in spatial resolution and other sensor characteristics) (Davidson and Csillag, 2001; Schino et al., 2003; Flynn et al., 2008). In addition, because VIs have differing abilities to provide accurate estimates of AGB, it is difficult to determine an optimal VI for a specific study. For example, the same VI (e.g., NDVI) may have different prediction accuracies within various regions, yet different types of VIs (e.g., NDVI vs NDWI) may perform quite differently within the same region (Table 1). These problems limit the transferability of predictive relationships and the effectiveness of VIs to estimate AGB.

Approximately 48% of Idaho is considered rangeland, and many of these areas are categorized as a semiarid sagebrush-steppe ecosystem (http://www.idrange.org). AGB estimation in the semiarid rangelands of the Intermountain West plays an important role in rangeland ecosystem assessment. In the semiarid rangelands of Idaho, high temperatures hasten the desiccation of plants, and many grass species senesce during the summer. The relationship between herbaceous AGB and VIs is most accurately estimated when the proportion of green or growing material is high (Hill, 2004; Numata et al., 2008) relative to the proportion of bare ground and/or litter. While important, determining an optimal VI for the accurate estimation of seasonal herbaceous AGB in semiarid rangelands may be difficult.

Most VIs used for AGB estimation are based on radiance or reflectance from a red band (RED) around 0.66 μm and a near infrared band (NIR) around 0.86 μm (Huete et al., 2002; Chuvieco et al., 2004). The RED band characteristically shows a strong chlorophyll absorption region for vegetation and strong reflectance for soils, while the NIR band is located in the high reflectance plateau of vegetation canopies. Because absorption by liquid water near 0.86 μm is negligible, NIR reflectance is affected primarily by internal leaf structure and cellulose content (Gao, 1996). In contrast, the short-wave infrared band (SWIR) (around 1.24 μm) is located in the high reflectance plateau of vegetation reflectance with weak liquid absorption (canopy scattering enhances the water absorption) (Jacquemoud et al., 1996; Jackson et al., 2004). The SWIR band reflects changes in both the vegetation water content and the spongy mesophyll structure of vegetation. The combination of the NIR band with the SWIR band can remove variation induced by internal leaf structure and leaf dry matter content (Gao, 1996; Ceccato et al., 2001). This combination of these bands (NIR and SWIR) is also sensitive to changes in liquid water content within the vegetation canopy (Serrano et al., 2000; Zarco-Tejada et al., 2003).

In this study, a suite of water-sensitive vegetation indices (WSVI) were developed, incorporating the NIR and SWIR portions of the electromagnetic spectrum, to help characterize plant water content and better estimate herbaceous AGB in semiarid rangeland ecosystems. The study was designed to investigate the applicability of various VIs for the assessment of herbaceous AGB in the semiarid rangelands of Idaho, USA. To accomplish this, eight VIs—including the difference vegetation index (DVI; Richardson and Everitt, 1992), ratio vegetation index (RVI; Jordan, 1969), normalized difference vegetation index (NDVI; Rouse et al., 1973), re-normalized difference vegetation index (RDVI; Roujean and Breon, 1995), soil adjusted vegetation index

(SAVI; Huete 1988), the second modified soil adjusted vegetation index (MSAVI2; Qi et al. 1994), infrared percentage vegetation index (IPVI; Crippen, 1990), and modified simple ratio (MSR; Chen, 1996)—were derived from Satellite Pour l'Observation de la Terre 5 (SPOT 5) imagery. In addition, the relationship between herbaceous AGB and total water content was determined. Finally, correlation estimates between herbaceous AGB, VIs, and WSVIs were calculated, and the performance of herbaceous AGB predictions from both VIs and WSVIs were evaluated using field-based measurements of herbaceous AGB.

MATERIALS AND METHODS

Study Area

The study area, known as the Big Desert, lies in southeastern Idaho, USA, approximately 71 km northwest of Pocatello. The center of the study area was located at 113° 4' 18.68" W and 43° 14' 27.88" N (Fig. 1). This area is managed by the U.S. Bureau of Land Management (BLM) and exhibits a large variety of native as well as invasive plant species. The area is a semiarid sagebrush-steppe ecosystem with a high proportion of bare ground ($\bar{x}$ bare ground > 17%; Studley et al., 2009). The area is sagebrush steppe, consisting primarily of native and non-native grasses, forbs, and many shrub species, including sagebrush (*Artemisia tridentata*) and rabbit brush (*Chrysothamnus nauseosus*). Annual precipitation is 23 cm, with 40% of the precipitation falling from April through June. The area is bordered by geologically young lava formations to the south and west and irrigated agricultural lands to the north and east. Sheep grazing is the primary anthropogenic disturbance to the study area, with semi-extensive continuous/seasonal grazing systems used on allotments ranging in size from 1100 to over 125,000 ha. Wildfire is a common disturbance and nearly 40% of the study area has burned in the past 10 years.

Field Data Collection

This study presents results using total herbaceous AGB measurements only, and does not include any measurements of shrub biomass production. Twenty-nine sample locations were selected for the collection of herbaceous AGB, which has been defined for the purposes of this study as all grasses, forbs, and standing litter. Site selection criteria included the site being a homogeneous area at least 20 m × 20 m in size (cf., spatial resolution of SPOT satellite imagery = 10 m × 10 m in size, thus helping to assure the sample pixel was also homogeneous), with still larger areas being preferred. The dominant plants in each site are herbaceous vegetation, with the plot center ≥ 70 m from any "edges," including roads, fences, or power lines, and plot perimeters ≥100 m from all other plots. Preference was given to sites with perimeters located >250 m apart. The location of each sample plot center was recorded using a Trimble Geo XH GPS receiver using latitude-longitude (WGS 84). All GPS data were post-process differentially corrected (±0.10 m after post-processing with a 95% CI using reference stations located <80 km from the study area) to ensure the sample location was registered with the correct and representative pixel within the satellite imagery (Weber, 2006; Weber et al., 2008).

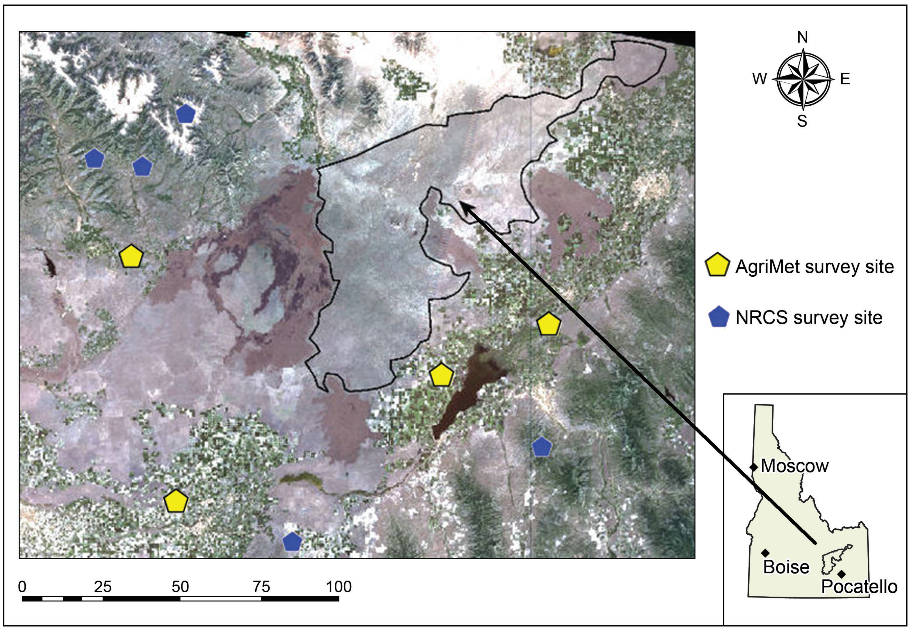

Fig. 1. Location and general characteristics of the Big Desert in southeastern, Idaho. No weather station survey site was available within the Big Desert study area; however, nine sites were located that bound the study area. Although some sites are in the mountains, the weather there exhibits a similar trend compared to that of the Snake River Plain.

Available herbaceous AGB was measured using a plastic-coated cable hoop 2.36 m in circumference. The hoop was randomly tossed into each of four quadrants (NW, NE, SE, and SW) centered over the sample point. All herbaceous vegetation within the hoop was clipped as close to the ground as allowed by the clipper (approximately 5 mm from the ground surface) and weighed immediately (±1 g) using a Pesola scale tared to the weight of an ordinary paper bag. The samples were taken to the laboratory, and dried in 75°C ovens for 48 hours. After drying, the samples were re-weighed to determine vegetation water content. Biomass was estimated following Sheley (1999) and expressed in kilograms per hectare.

Vegetation Indices Derived from SPOT 5-Imagery

Satellite Pour l'Observation de la Terre 5 (SPOT 5) multispectral imagery (10 m × 10 m pixels) was acquired for the Big Desert study area on June 27, 2009. The imagery was georectified against 2004 National Agriculture Imagery Program (NAIP) natural color aerial imagery (1 m ×1 m pixels). Atmospheric correction was performed with Idrisi Taiga (v16.03) using the ATMOSC module (Clark Labs, Worcester, MA). All imagery was corrected for atmospheric effects using the Cos(t) model (Chavez, 1996) and input parameters reported in the metadata supplied by SPOT Image Corporation. The imagery was then projected into Idaho Transverse Mercator (NAD 83). The eight VIs used in this study were derived from the SPOT 5 imagery.

Table 2. Water-Sensitive Vegetation Indices Used to Estimate Herbaceous Total Above-Ground Biomass[a]

Index	Formula
DWI	$NIR - SWIR$
RWI	$NIR/SWIR$
NDWI	$\frac{NIR - SWIR}{NIR + SWIR}$
RDWI	$\frac{NIR - SWIR}{\sqrt{NIR + SWIR}}$
SAWI	$\frac{(NIR - SWIR)(1 + L)}{NIR + SWIR + L}$, where $L = 0.5$
MSAWI2	$\frac{2NIR + 1 - \sqrt{(2NIR + 1)^2 - 8(NIR - SWIR)}}{2}$
IPWI	$\frac{NIR}{NIR + SWIR}$
MWSR	$\frac{\frac{NIR}{SWIR} - 1}{\sqrt{\frac{NIR}{SWIR} + 1}}$

[a]Note the substitution of the SWIR band for the RED band (cf. Table 3).

Water Sensitive Vegetation Indices

Using the same SPOT 5 imagery, eight WSVIs were developed by directly substituting the SWIR band for the RED band within the eight VIs described above (Table 2). The "Sample" tool within ESRI's ArcGIS 10 was then used to extract VI and WSVI values at each sample site (n = 29). The resulting data were exported to SPSS (V17.0) for further analysis. Correlations between VI/WSVI values and measured herbaceous AGB were used to determine the applicability and efficacy of each.

RESULTS AND DISCUSSION

Field-based herbaceous AGB estimates ranged from 518 kg/ha to 8075 kg/ha ($\bar{x}$ = 2982 kg/ha) based on vegetation samples collected at 29 field locations. Using linear regression analysis between each VI and herbaceous AGB measurements, the relationship between these variables was described (Table 3). Based upon these results, it was noted that the relationships varied greatly and the strength of all correlations were relatively weak ($0.28 \leq r^2 \leq 0.40$). This was likely attributable to the mixture of photosynthetic and non-photosynthetic plant material found in the field, and correspondingly in the herbaceous AGB samples used in this study. As a result, the VIs provided poor estimates of herbaceous AGB. Furthermore, the prediction of

Table 3. Correlation between Herbaceous Total Above-Ground Biomass and the VIs and WSVIs Used in This Study

Standard VIs using RED and NIR bands				Water-sensitive VIs using NIR and SWIR bands			
Index	r^2	F-value	p	Index	r^2	F-value	p
DVI	0.40	17.9	<0.001	DWI	0.53	30.1	<0.001
RVI	0.35	14.3	0.001	RWI	0.54	31.2	<0.001
NDVI	0.28	10.6	0.003	NDWI	0.52	29.0	<0.001
RDVI	0.35	14.3	0.001	RDWI	0.52	29.8	<0.001
SAVI	0.37	15.8	<0.001	SAWI	0.53	29.8	<0.001
MSAVI2	0.39	17.0	<0.001	MSAWI2	0.53	30.3	<0.001
IPVI	0.28	10.6	0.003	IPWI	0.52	29.0	<0.001
MSR	0.32	12.6	0.001	MWSR	0.53	30.3	<0.001

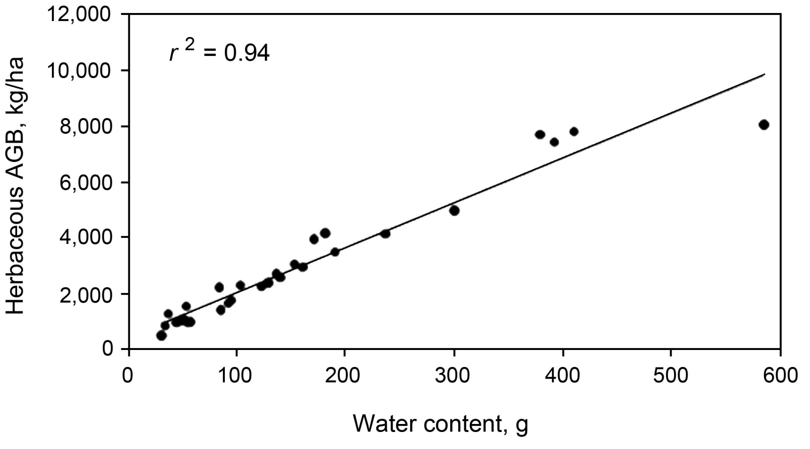

Fig. 2. Relationship between herbaceous total above-ground biomass (AGB) and vegetation water content.

herbaceous AGB was least well explained using NDVI ($r^2 = 0.28$, $p = 0.003$); as a result, NDVI was not considered a reliable predictor of herbaceous AGB in this study area, although it remains one of most widely used VIs for AGB prediction and many other vegetation studies.

Based on field survey data, the relationship between herbaceous AGB and vegetation water content (Fig. 2) revealed a significant correlation ($r^2 = 0.94$, $p < 0.001$). Related studies have shown that grass biophysical parameters such as leaf area index are related to liquid water content (Hunt and Rock, 1989; Roberts et al., 1997, 2004). Numata et al. (2008) indicated water absorption spectra between 1100 and 1250 nm had a significant correlation with canopy water content and suggested that the use of water absorption features (i.e., water absorption depth and water absorption area) may improve the accuracy of biomass estimation. Therefore, the hypothesis that an index

Table 4. Coefficients of Determination (r2) Calculated for the Relationships between Vegetation Water Content and Vegetation Indices

Standard VIs using RED and NIR bands				Water sensitive VIs using NIR and SWIR bands			
Index	r^2	*F*-value	*p*	Index	r^2	*F*-value	*p*
DVI	0.40	17.9	<0.001	DWI	0.52	29.4	<0.001
RVI	0.35	14.8	0.001	RWI	0.52	29.7	<0.001
NDVI	0.30	11.6	0.002	NDWI	0.52	28.5	<0.001
RDVI	0.36	15.0	0.001	RDWI	0.52	29.1	<0.001
SAVI	0.38	16.2	<0.001	SAWI	0.52	29.2	<0.001
MSAVI2	0.39	17.2	<0.001	MSAWI2	0.52	29.5	<0.001
IPVI	0.30	11.6	0.002	IPWI	0.51	28.5	<0.001
MSR	0.33	13.4	0.001	MWSR	0.52	29.2	<0.001

that closely correlates to water content may also exhibit strong correlation with herbaceous AGB was tested.

In order to validate this hypothesis, the eight VIs used in this study along with eight WSVIs were correlated against vegetation water content (Table 4). The observed correlation between the VIs and vegetation water content were relatively weak ($0.30 \leq r^2 \leq 0.40$), while the WSVIs were more highly correlated ($r^2 \geq 0.51$) with vegetation water content. These results suggest the combination of NIR and SWIR bands are more sensitive to changes in liquid water content within vegetation, and that WSVIs exhibit a better response to water content of herbaceous vegetation in semiarid rangeland ecosystems.

Linear relationships were determined between eight WSVIs and herbaceous AGB (Table 3). In comparison to the more traditional VIs ($r^2 \leq 0.40$), the WSVIs exhibited much stronger relationships with herbaceous AGB ($r^2 \geq 0.52$). In addition, it should be noted that the NDWI (based on the same simple band ratio structure NDVI [NDVI = $(NIR - R)/(NIR + R)$]) better explained the variation in herbaceous AGB relative to NDVI (i.e., the coefficient of determination increased from 0.28 to 0.52). This result is similar to previous research reporting that NDWI performed better in drought conditions than NDVI (Verbesselt et al., 2006a; Gu et al., 2007). These results further suggest that herbaceous AGB is highly correlated with vegetation water content and that WSVIs can more accurately predict herbaceous AGB for semiarid rangeland sites.

This study was designed for herbaceous AGB estimation in the semiarid rangelands of Idaho. The relationships revealed by the study are still condition-specific and should not be directly extrapolated to other regions. However, the specific approach developed in this study can be used across other rangeland areas.

Assessment of Error and Bias

It is difficult to collect a large amount of field-measured AGB data, and we used a relatively small sample size ($n = 29$) in this study. Because the limitation on sample size may influence the strength of each index, the robustness of the correlation

Table 5. Robustness of Correlation between WSVIs and AGB Tested by Jackknife Method

Index	Mean r^2	RMSE
DWI	0.52	0.032
RWI	0.54	0.026
NDWI	0.51	0.038
RDWI	0.52	0.031
SAWI	0.51	0.036
MSAWI2	0.51	0.038
IPWI	0.52	0.019
MWSR	0.53	0.037

between WSVIs and AGB were tested using the jackknife method (Table 5) (Efron and Gong, 1983; Buermann et al., 2008). Small RMSE values were computed and the mean r^2 values calculated by the jackknife method were similar to the r^2 values given in Table 3. We conclude that the observed correlation between WSVIs and AGB were not highly influenced by a few individual samples and the regression and correlation results presented herein are robust.

Previous studies have demonstrated varied results with VIs and each reveal different strengths of correlations with AGB under specific conditions dependent upon the phenology of plants within a given growing season (Reeves et al., 2001). Cho and Skidmore (2009) indicated that VIs are highly correlated ($r^2 \geq 0.50$) with AGB when vegetation was in the early stages of senescence. In semiarid rangeland ecosystems, high summer temperatures hasten the desiccation of plants, and many plants begin senescence in mid- to late June. In this study, all herbaceous AGB data were collected between July 1 and July 9, 2009. Based on monthly precipitation data provided by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (http://www.id.nrcs.usda.gov/snow/data/historic.html) and the United States Bureau of Reclamation (USBR) AgriMet Program (http://www.usbr.gov/pn/agrimet/), it is noted that mean monthly precipitation between April and July 2009 (260 mm) was greater than the mean monthly precipitation during the same time period in either 2007 (140 mm) or 2008 (92 mm), and that precipitation in June substantially increased in 2009 (48 mm for 2007, 21mm for 2008, and 141 mm for 2009) (Fig. 1; Tables 6 and 7). These statistics, along with cooler than average temperatures, suggest that senescence may have been delayed in 2009, with the experimental time period of this study falling within the early stages of senescence. Numata et al. (2008) achieved very poor correlation between NDWI/NDVI and herbaceous AGB (Table 1) because their field sampling occurred much later in the season (beginning of August) and during a time of the year when most herbaceous plant materials were already senesced.

NDVI physically responds to chlorophyll absorption and is not directly related to the quantity of water in the vegetation (Ceccato et al., 2002). Cheng et al. (2008)

Table 6. Natural Resources Conservation Service (NRCS) and AgriMet Survey Site List along with Monthly Precipitation and Monthly Mean Temperature

Site name	Lat.	Long.	Year	Precipitation, mm					Mean temperature, ° C		
				April	May	June	July	Total	April	May	June
Garfield R.S.	43°36′	–113°55′	2007	43	8	25	28	104	9	13	19
			2008	23	43	13	23	102	16	19	20
			2009	30	71	203	20	324	8	10	16
Swede Peak	43°37′	–113°58′	2007	56	15	30	38	139	8	13	19
			2008	25	28	3	0	56	7	12	18
			2009	28	43	201	23	295	7	9	15
Smiley Mountain	43°43′	–113°50′	2007	89	33	89	15	226	6	10	17
			2008	30	94	48	13	185	3	8	15
			2009	89	91	180	43	403	5	7	13
Howell Canyon	42°19′	–113°36′	2007	150	30	117	25	322	8	12	18
			2008	56	76	58	15	205	5	10	17
			2009	124	66	170	3	363	7	9	16
Wildhorse Divide	42°45′	–112°28′	2007	86	25	74	13	198	10	13	18
			2008	36	66	33	0	135	7	12	17
			2009	107	58	163	36	364	9	11	16
Fort Hall	43°04′	–112°25′	2007	30	5	39	5	79	13	17	23
			2008	3	37	9	4	53	11	16	20
			2009	31	29	97	15	172	12	15	20
Rupert	42°35′	–113°52′	2007	19	9	20	8	56	14	17	23
			2008	3	17	12	7	39	12	17	21
			2009	26	18	53	6	103	13	15	21
Picabo	43°18′	–114°09′	2007	23	3	10	3	39	13	18	24
			2008	7	22	7	0	36	11	16	21
			2009	20	41	98	8	167	12	14	20
Aberdeen	42°57′	–112°49′	2007	36	3	30	14	83	14	18	23
			2008	4	23	6	1	34	12	16	21
			2009	23	22	102	17	164	13	15	20

Table 7. Analysis of Precipitation and Temperature on 2007, 2008, and 2009

Year	Average precipitation, mm				Average temperature, ° C			Total precipitation	Standard deviation
	April	May	June	July	May	June	July		
2007	59	15	48	17	11	15	20	140	56[a]
2008	20	45	21	7	9	14	19	92	69[b]
2009	53	49	141	19	10	12	17	260	

[a]Standard deviation of precipitation for 2007 and 2008.
[b]Standard deviation of precipitation for 2008 and 2009.

indicate that NDVI's correlation with water content was probably due to a correlation with green leaf density. Because of the sparse vegetation and dry plant matter (litter) found in semiarid regions, NDVI was not a reliable indicator of water content or herbaceous AGB in this study. However, some AGB estimates have shown strong NDVI correlations to biomass ($r^2 \geq 0.50$), but this may be because these study areas were more homogeneous and/or contained a higher proportion of green grass cover (Mašková et al. 2008). The accuracy of herbaceous AGB predictions based upon remotely sensed data is strongly influenced by the presence and abundance of grass species as well as the presence and abundance of bare ground and other spectral distraction features. A more homogeneous surface always provides higher correlations between remotely sensed measures and herbaceous AGB estimates compared to more heterogeneous surfaces (Numata et al., 2008). In addition, as opposed to the traditional VI, the WSVIs have the advantage of leveraging liquid water absorption regions to more accurately predict water content even in areas without contiguous spectral coverage (Serrano et al., 2000). This is possibly one reason why the WSVIs performed better in the semiarid rangelands of Idaho.

CONCLUSION

This study has focused on estimation of herbaceous AGB in the semiarid rangelands of Idaho. Based on a survey of herbaceous AGB, a significant correlation ($p < 0.001$) between herbaceous AGB and vegetation water content was found. In addition, a suite of WSVIs were developed that describe water content and herbaceous AGB in semiarid rangeland ecosystems. Correlation estimates between herbaceous AGB, VIs, and WSVIs were calculated, and the performance of herbaceous AGB predictions for both the VIs and WSVIs were evaluated using field-based measurements of herbaceous AGB. Results demonstrate that the WSVIs were correlated ($r^2 \geq 0.51$) with vegetation water content and performed better in herbaceous AGB estimation for the semiarid rangelands of Idaho relative to VIs. Furthermore, it was noticed that not only did vegetation water content influence the accuracy of herbaceous AGB estimates, but based on findings reported in other studies, phenological stage and plant community structure also influence the accuracy of herbaceous AGB estimates derived from remotely sensed data. Numerous factors influence the successful use of remote sensing data for the estimation of herbaceous AGB, and water content, described using WSVIs, explained approximately 50% of the variance in herbaceous AGB measurements collected as part of this study. Other factors that likely play a role include sun angle, shadow, georegistration, and the varying affect of soils. Future work will seek to assess a more comprehensive characterization of the influence of these factors on herbaceous AGB estimations in semiarid rangelands.

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