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Measuring Eastern Redcedar (*Juniperus virginiana* L.) Mass With the Use of Satellite Imagery

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Abstract

Eastern redcedar (*Juniperus virginiana* L.) is an aggressively spreading native species in Oklahoma grasslands. It decreases rangeland forage production, and has been implicated in reducing stream flow and groundwater recharge. Industrial-scale plans to use redcedar as a biofuel source are being considered. Optimal placement of redcedar-based industries requires determination of redcedar availability. Such large-area inventories of redcedar mass can be practically addressed via aircraft or satellite remote sensing. Therefore, we conducted a study in central and western Oklahoma to develop and test a remote-sensing–based allometric equation relating redcedar canopy area to aboveground dry mass (AGM). We used automated methods to measure tree canopy area from georectified, pan-sharpened, multispectral QuickBird images having a spatial resolution of 0.45 m^2 per pixel ground sample area. We also measured the canopy area and fresh and dry mass of these trees with the use of destructive sampling techniques. Regression analysis showed that satellite-derived measurements of canopy coverage explained about 85% of field-measured redcedar dry AGM in the study plots. The resulting allometric equation was applied to an independent data set, yielding dry AGM of 38.2 metric tons $\cdot$ ha^{-1}, which was well within the field-measured range of 36–43 metric tons $\cdot$ ha^{-1}. The allometric equation was then applied to Natural Resources Conservation Service measurements of redcedar canopy coverage for 17 counties in Oklahoma, to determine that the area of interest contains a median value of about 11.5 million metric tons of redcedar AGM. These results indicate that 0.45-m^2 spatial resolution multispectral imagery can be a useful tool for rapid and reliable measurement of redcedar dry AGM.

Resumen

El cedro rojo (*Juniperus virginiana* L.) es una especie nativa que se propaga agresivamente en los pastizales de Oklahoma. Disminuye la producción de forraje de pastizales y se le ha involucrado en la reducción del caudal y recarga del agua subterránea. Se han considerado planes a escala industrial para utilizar el cedro rojo como fuente de biocombustibles. La óptima ubicación de las industrias que utilizaran el cedro requiere conocer su disponibilidad. Dichos inventarios conducidos en grandes superficies para determinar la acumulación del cedro puede llevarse a cabo únicamente por medio de aeronaves o sensores remotos por medio de satélite. Por lo tanto conducimos un estudio en la parte central y el Oeste de Oklahoma para desarrollar y probar una ecuación alométrica basada en sensores remotos y relacionarla con la cobertura del cedro con la materia seca aérea (AGM). Utilizamos métodos automatizados para medir la cubierta de los arboles de imágenes multi-espectrales rectificadas de QuickBird. Las imágenes tenían una resolución espacial de 0.45 m^2 por pixel de las muestras en el terreno. También medimos la cubierta aérea y la masa fresca y seca de estos árboles utilizando una técnica destructiva. Análisis de regresión mostraron que las medidas derivadas de satélite del área de la cobertura explicaban aproximadamente el 85% de las medidas de campo de AGM del cedro rojo seco en las parcelas de estudio. La ecuación alométrica resultante se aplicó a un grupo de datos independientes dando como resultado una producción de materia seca de 38.2 toneladas métricas $\cdot$ ha^{-1} de AGM, lo cual estaba dentro del rango de las medidas de campo de 36 a 45 toneladas métricas $\cdot$ ha^{-1}. Después la ecuación alométrica se aplicó a una serie de medidas del Servicio de Conservación de Recursos Naturales de cobertura aérea del cedro rojo provenientes de 17 condados de Oklahoma, para determinar que el área de interés contiene un valor promedio de aproximadamente de 11.5 millones de toneladas métricas de AGM de cedro rojo. Estos resultados indican que imágenes de 0.45 m^2 de resolución multi-espectrales pueden ser una herramienta útil para una medición rápida y confiable de AGM del cedro seco.

Key Words: phytomass, invasive species, remote sensing

INTRODUCTION

Eastern redcedar (*Juniperus virginiana* L.), a native and aggressively encroaching tree species, caused an estimated $218 million of economic loss in 2001 in Oklahoma, with losses expected to rise to $447 million in 2013 (Natural Resources Conservation Service [NRCS] 2008). Eastern red-

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cedar (herein referred to as redcedar) decreases rangeland forage production, decreases land value, and has been implicated in reducing stream flow and groundwater recharge (Oklahoma Conservation Commission 2008). By 1950 redcedar had invaded 0.6 million hectares in Oklahoma (NRCS 2008) and that land area is estimated to exceed 3.5 million hectares by 2013.

Redcedar has many commercial uses, including furniture making, animal bedding, mulch, paneling, and lost circulation material for oil-well drilling. Regional companies are currently considering large investments in industrial-scale plans to produce redcedar wood pellets for home heating, or to use redcedar directly in gasification plants for the subsequent production of steam or electricity for small rural communities, and for use in ethanol production.

The optimal placement of redcedar-based industries requires determination of redcedar availability at landscape or larger scales. Large-area inventory of redcedar mass can only be practically addressed via aircraft or satellite remote sensing, because it is too costly, time consuming, and labor intensive to produce such inventories via ground-based sampling. Carneggie and Lauer (1966) were among the first to point out the applicability of multispectral remotely sensed data in the study of forests. Both remote sensing and forestry literature contain numerous examples of studies investigating the use of remotely sensed data to provide various measures of tree biophysical parameters (Nilsson 1996; Lefsky et al. 1999; Shugart et al. 2000; Mallinis et al. 2004), to identify and classify forest stands (Ranson and Sun 1994; Vauhkonen et al. 2009), to conduct inventories (Carneggie and Lauer 1966; Hyyppa and Hallikainen 1996), to monitor disease and pest infestations (Heller and Bega 1973; Rock et al. 1986; Ekstrand 1994), to assess carbon stocks (Kimes et al. 1996; Smith et al. 2008), and to assess encroachment of woody species into grasslands (Sankey and Germino 2008).

In terms of phytomass estimation via remote sensing, Sader et al. (1989) correlated the Normalized Vegetation Index (NDVI), the ratio of the difference of red and near-infrared reflectance to their sum (Tucker 1979), to mass of various forest types. These investigators found good correlation between NDVI and mass for a pine stand containing trees of similar ages. However, they found that NDVI was not a good predictor of mass for successional forests of ages > 15–20 yr, nor for uneven-aged, mixed broadleaf forests. Roy and Ravan (1996) correlated NDVI derived from Landsat Thematic Mapper (TM) data to mass of three different vegetation types: forest, shrub, and grasslands. These investigators found weak correlation between NDVI and mass in each of the three vegetation types, but stronger correlation was observed between mass and reflectance in all individual TM wavebands (except band 4; $0.60 \geq r^2 \leq 0.74$). More recently, Lu et al. (2004) found significant correlations between reflectance from Landsat TM wave bands and aboveground mass, basal area, average stand diameter, and average stand height. Saatchi et al. (2007) incorporated 19 sources of remotely sensed data and other ancillary data sets into a decision-tree approach for estimating forest mass and its distribution across the Amazon basin. Comparison of the remotely sensed mass estimates to field plot measurements suggested an accuracy of about 80%.

The above studies all related spectral response, either reflectance in individual wavebands or vegetation indices (combinations of reflectances such as NDVI), to mass. Greenberg et al. (2005), in an effort to quantify regional scale mass for trees in the Lake Tahoe basin, used hyperspatial IKONOS imagery to measure canopy area. Measured canopy area determined from the IKONOS imagery was then used in an allometric equation relating it to mass ($r^2 = 0.77$). Estimates of regional scale mass generated via this allometric equation were not validated by the authors. Suganuma et al. (2006) took structural attributes of trees directly observable by remote-sensing platforms and incorporated them into allometric equations to predict tree mass. These investigators found that canopy coverage—the ratio of the vertical projection area of the forest canopy to unit ground area—was highly correlated with mass ($r^2 > 0.94$) for wooded lands in Western Australia. Recently, Anaya et al. (2009) developed a prediction equation relating percent tree cover (i.e., canopy coverage) to mass for primary forest, secondary forest, and savanna conditions in Colombia, South America. Mass measurements were acquired from plot studies and percent tree cover was derived from the MODIS Vegetation Continuous Algorithm product (VCA; Hansen et al. 2002, 2003). The mass estimates derived from the equation were regressed against the measured data, and analysis of the residuals revealed a trend to underpredict mass in secondary forests as percent cover increased.

The VCA is a 500-m spatial-resolution product depicting proportional vegetation cover for woody vegetation, herbaceous vegetation, and bare ground. The 500-m spatial resolution produces pixels measuring 25 ha in size, and does not provide differentiation between various woody species. Because the spatial resolution is too low to differentiate species, the VCA was not appropriate for this study.

The NRCS conducted a remote-sensing–based assessment of redcedar encroachment across 17 Oklahoma counties. The assessment was conducted over the 2002–2005 time frame and predicted that about 393,000 ha of land had been affected. However, no attempt was made by the NRCS to determine redcedar mass from their assessment.

Given the potential for development of a redcedar-based industry in Oklahoma, and the paucity of literature describing the relationship between redcedar coverage and dry AGM, an accurate regional assessment of redcedar is needed. The general objective of this study was to develop and test a remote-sensing–based allometric equation relating tree canopy area to dry AGM. Specific objectives were 1) to evaluate the relationship between field measurements of tree canopy area and dry AGM, 2) to evaluate the relationship between canopy area measurements made from hyperspatial QuickBird satellite imagery and that measured in the field, 3) to develop and test a remote-sensing–based allometric equation that predicts dry AGM from canopy coverage, and 4) to produce county-level redcedar AGM estimates from the NRCS redcedar coverage maps and the allometric equation for 17 counties in Oklahoma.

METHODS AND MATERIALS

Study Sites

Three Oklahoma locations (two central and one western) with varying levels of redcedar were selected for this study (Table 1). Trees from Cherokee and Geary (central sites) were taken from

Table 1. Location designation, county, latitude, longitude, soil type, and description for three eastern redcedar harvest sites in western Oklahoma.

Location	County	Latitude	Longitude	Soil type	Soil description
Cherokee	Canadian	35°33′50″N	98°12′5″W	Dill-Ironmound complex 5–8% slope	Dill: Coarse–loamy, mixed, active, thermic Typic Haplustepts
					Ironmound: Loamy, mixed, active, thermic, shallow Udic Haplustepts
				Grant-Ironmound complex 5–8% slope	Grant: Fine–silty, mixed, superactive, thermic Udic Argiustolls
Geary	Blaine	35°41′1″N	98°28′31″W	Konawa 1–3% slope	Konawa: Fine–loamy, mixed, active, thermic Ultic Haplustaffs
Woodward	Woodward	36°27′2″N	99°24′6″W	Lincoln 0–3% slope	Lincoln: Sandy, mixed, thermic, Typic Ustifluvents

upland environments, and trees from the Woodward location (western site) were harvested from a riparian cottonwood bottomland along the North Canadian River. Native vegetation is tall grasses, with small a percentage of trees, primarily cottonwood (*Populus* spp.). The invasive saltcedar (*Tamarix* spp.) is also present. Normal annual precipitation and temperature are 870 mm and 14.9°C at Cherokee, 734 mm and 15.2°C at Geary, and 660 mm and 13.4°C at Woodward (National Oceanic and Atmospheric Administration 2002).

Within each location, four 900-m^2 plots (30 × 30 m) were randomly identified for destructive sampling. Trees at the Woodward location were commercially cut in early 2007 and left to dry within the plot area. The trees were weighed beginning 8 January 2008. Annual monthly precipitation and air temperature were 118% and 103% of normal values, respectively. It was assumed that weight measurements made at this site adequately represented dry mass. At the Cherokee and Geary locations, trees were harvested and weighed immediately. Harvest began on 4 December 2007 at Geary and on 3 February 2009 at the Cherokee location. All trees were cut at ground level, numbered, and weighed on a portable platform scale. A 3–5-cm-thick cross section of bole was cut from the base of each tree at the Cherokee and Geary sites ($n = 641$). Representative stems and branches were fed through a shredder and, along with the boles, were oven dried at 60°C to a constant mass to determine moisture content. Redcedar dry mass as a percentage of fresh weight is multiplied by fresh weight of each tree at Geary and Cherokee to obtain dry AGM. A total of 941 individual trees were harvested and weighed across the three locations. Plots 2 and 4 of the Woodward location, and plots 1 and 2 of the Cherokee location, had an abundance of sapling trees that did not contribute substantially to overall yield. Although not included in the individual tree measurements, these saplings were clipped at ground level, bundled together, and weighed for total mass calculations. None of these seedlings/saplings exceeded 500 g of mean dry weight and maximum number per any one plot was less than 100.

Sixty-four trees from the Geary location and 78 trees from the Cherokee location were measured for individual tree canopy area before tree harvest. Canopy area was measured by using the mean radius of the least and greatest diameter of drip line to calculate canopy area as a circle (Engle and Kulbeth 1992). It was not possible to measure individual tree canopy area at the Woodward site because of commercial precutting of trees.

Hyperspatial Remotely Sensed Data

Georectified, pan-sharpened, multispectral QuickBird images were obtained for each of the three study sites. The spatial resolution of the images was 0.45 m^2, with reflectance data collected in the blue (450–520 nm), green (520–600 nm), red (630–690 nm), and near-infrared (760–900 nm) wave bands. The capture date of the imagery and relevant view and illumination geometry for each site are given in Table 2.

The QuickBird archives were searched for images of the study sites that had minimal cloud cover (< 20%) and were acquired in winter or early spring to provide maximum contrasts between the evergreen redcedar canopies and dormant warm-season vegetation. The images were taken 2–4 yr before ground sampling. From the tree-canopy area and tree age data (not shown), it was estimated that individual tree canopy area increased approximately 0.26 $m^2 \cdot yr^{-1}$. Thus, the archived images were deemed suitable for the purposes of this investigation.

Hyperspatial data were necessary for the study because canopy area was quite variable across the study sites and some small trees would not be detected by coarse spatial resolution satellites. For example, the canopy areas for the largest redcedar trees at the Geary site were near 100 m^2, with most of the canopy areas less than 70 m^2. Landsat 5 and 7 TM multispectral pixels have a spatial resolution of 30 m, producing a pixel size of 900 m^2, too large for application to this study. SPOT multispectral imagery can be pan sharpened to produce a spatial resolution of about 100 m^2, again too large for the purposes of this study.

Image Processing

An unsupervised classification was conducted on each QuickBird image with the use of the self-organizing map (SOM) feature of IDRISI 15.01 (Clark Labs 2006). The SOM procedure was chosen because it does not require development of class signatures from the remotely sensed data prior to classification, makes no assumption concerning the probabilistic models of data, generalizes in noisy environments, and has the ability to learn complex patterns (Ji 2000). Like other unsupervised classification procedures, the SOM places each pixel in an image into one of a predetermined number of classes specified by the user. A maximum of 25 classes was set and all

Table 2. Date and location of QuickBird satellite imagery with view and solar geometry information.

Site ID	Image date	Nadir angle	Solar elevation	Solar azimuth
		degrees		
Geary	19 April 2006	13	63	150
Woodward	31 March 2004	9	53	145
Cherokee	22 December 2006	13	30	167

four bands of imagery were used in the classification process. After the initial classification step, the classes were compared to false color composites (developed from QuickBird bands 2, 3, and 4) of the area. Classes not related to redcedar (e.g., roads, bare soil, dormant grass, water, etc.) were manually reclassified as nonredcedar, resulting in a two-category map of each study site (redcedar, and nonredcedar). Boundary coordinates of each plot at each study site were obtained with the use of a handheld GPS unit (horizontal accuracy ≤ 10 m), and used to isolate each plot from the larger classified image. An aggregation routine was used whereby adjacent and touching redcedar pixels within a plot were grouped into distinct clusters representing either individual tree canopies or a group of trees with overlapping canopies, with each cluster automatically assigned a unique numerical identifier. A histogram routine was then used to provide pixel counts for each uniquely identified cluster. Canopy area was calculated by multiplying the number of pixels in each cluster by the pixel ground area (0.45 m^2).

It should be noted that because of tree canopy coalescence at the Cherokee and Woodward sites, only the Geary site provided the opportunity to correlate individual tree canopy area as measured from the QuickBird imagery to that measured in the field. At the Geary site the canopies of some adjacent trees were not separable in the QuickBird imagery, were considered to represent one tree, and were correlated to the sum of the field-measured canopy areas of those trees ($n = 49$).

Statistical Analysis

Descriptive and comparative statistics for the field-measured data were generated with the use of a least-squares mixed-model analysis of variance procedures (PROC MIXED; SAS Institute 2003). The SAS general linear models procedure (PROC GLM) was used in development of the allometric equation. Specifically, PROC GLM was used to determine the homogeneity of regression with the use of site, canopy area (as measured from satellite imagery), and canopy area by site as independent variables. Unless otherwise stated, all levels of significance are reported as $P \leq 0.05$.

Allometric Equation Validation

The allometric equation developed herein was tested on a 1.35-ha site near Curtis, Oklahoma (lat 36°26′17″N, long 99°06′23″W). We learned that this site had been selected for demonstration of commercial-scale removal of redcedars. Arrangements were made between the landowner, equipment dealer, and project leaders to gain access to the harvest weight of the redcedar. The area was cleared of redcedar on 26–27 March 2010 with the use of a feller-buncher, with felled trees gathered and wire-wrapped with a mechanical bundling system. A cab-mounted GPS system was used to obtain boundary coordinates of the harvest area. A total of 255 bundles were harvested. Ninety-five bundles were loaded onto a flatbed semitruck and weighed, yielding an average bundle weight (fresh) of 380.7 kg. Thus, the total fresh weight of redcedar harvested from the site was about 97 079 kg, or a yield of 71.9 metric tons ha^{-1}. We used our laboratory measurement of redcedar dry mass as percentage of the fresh weight to calculate the range of redcedar dry AGM for the area.

A November 2009 (preharvest) image of the area was obtained from the QuickBird image archive and was processed in the same manner described above for the equation development sites. The GPS boundary coordinates obtained during harvest were then used to extract the validation site from the larger classified image, and percent redcedar coverage calculated for the area.

NRCS County-Level Redcedar Maps

A description of the NRCS procedure for producing the redcedar maps is not in the open literature and is therefore described here. Personnel from the Oklahoma state NRCS office used Landsat 5 TM multispectral data to construct redcedar coverage maps for 16 contiguous counties located in central, north central, and western Oklahoma, and one county in south-central Oklahoma. The Landsat image dates used in the study ranged from 2002 to 2005. Ten 4-ha groundtruth sampling areas in each of five cover classes (no redcedar, 10–30% coverage, 30–70% coverage, > 70% coverage, and oak/redcedar mix) were located in each county. (Coverage classes were based on NRCS program needs.) Boundary coordinates for each sampling area were acquired with the use of handheld GPS devices, and used to locate the sampling areas on the Landsat imagery. An unsupervised classification scheme was used to categorize the various land cover units initially into 1 of 50 classes. A manual reclassification procedure was then used to place redcedar pixels into one of the five coverage categories. NRCS personnel evaluated the accuracy of the maps by randomly locating two 3.14-ha plots per section (one section = 259 ha) in each of the 17 counties on color aerial photographs (ground sampling distance = 1 m) obtained through the National Agricultural Imagery Program (2009). The aerial photographs were acquired for the years 2005 and 2008. The aerial photographs occurring nearest in time to the Landsat imagery were used in the verification process. Presence of redcedar and its percent coverage as determined from the aerial photograph was then matched to the proper location on the classified images (i.e., redcedar maps). Exact correspondence in both the presence and percent coverage between the classified image and the aerial photograph represented a "correct" classification for that point. However, lack of correspondence between the aerial photograph and classified image in either the presence of redcedar or percent coverage resulted in an "incorrect" classification for that point. With the use of this procedure, image classification accuracy was found to be ≥ 90% for each county. Figure 1 is an example of a finalized redcedar coverage map. (Maps available at http://www.ok.nrcs.usda.gov/technical/GIS/CountyBaseMaps/RedCedar.html).

RESULTS

Field Measurements

Figures 2a and 2b are QuickBird false color composites of the Geary and Woodward sites, respectively, which together depict the range of tree density encountered in the study. It is observed in Figure 2a that the hyperspatial images permit easy detection of individual and small trees. Tree density was much greater at the Cherokee and Woodward sites than at the Geary site

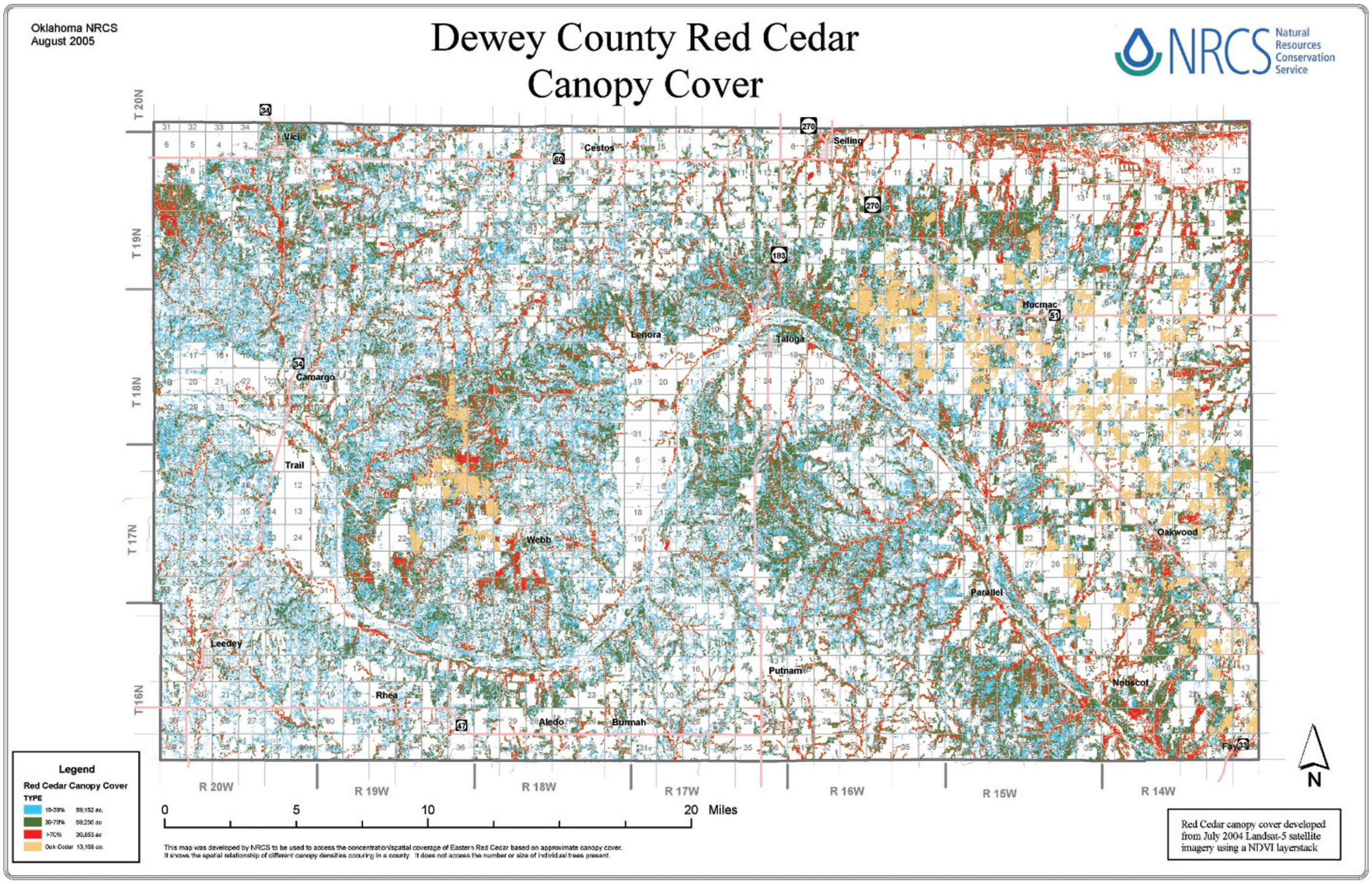


Figure 1. Natural Resources Conservation Service redcedar coverage map for Dewey County, Oklahoma. Areas in blue, green, and red represent the 10–30%, 30–70%, and $>70\%$ coverage categories, respectively. The oak/cedar mix category (tan color) was not used in this study. Land area in each category is also given in the legend, but difficult to read at the scale reproduced in the figure.

(Table 3), with coalescence of tree canopies at both Cherokee and Woodward (Fig. 2b).

Laboratory analysis of the sample branches, stems, and boles revealed that redcedar dry mass was $55.1 \pm 4.96\%$ of fresh weight ($n = 641$). Individual tree weights varied considerably across locations with mean tree weights ranging from 23 to 78 kg tree^{-1} (Table 3). Total dry AGM varied among and within locations but was greatest for the Woodward location. However, mean yields were not statistically different between Cherokee and Woodward (36 and 42 $t \cdot ha^{-1}$, respectively) but both locations exceeded Geary production (14 $t \cdot ha^{-1}$). Because the Cherokee location averaged 1 593 trees ha^{-1} compared to 866 trees $\cdot$ ha^{-1} at the Woodward location, the difference in dry biomass was not a direct function of tree numbers per hectare but a combination of tree number and tree weight. Trees at the Woodward location averaged 50 kg $\cdot$ tree^{-1}, amd those at Cherokee averaged 23 kg $\cdot$ tree^{-1}.

Individual tree canopy area, measured for 142 trees at Cherokee and Geary, varied greatly among and between the study sites, and averaged 6.3 ± 12.4 m^2 (data not shown). Across locations, tree canopy area was highly correlated with tree dry AGM ($r = 0.97$; $P < 0.0001$), indicating that canopy area explains about 94% of the variability in dry AGM.

Satellite Measurements

From Figure 3 it is observed that canopy area as measured from the QuickBird imagery is highly correlated with that measured in the field at the Geary location ($r^2 = 0.98$, n = 49). Total canopy area within plots varied from a minimum of 57 m^2 at the Geary location to about 630 m^2 at Woodward (Table 4)—an 11-fold difference. The Geary location exhibited both the lowest mean canopy area and highest variability compared to the other two locations.

Mean percent redcedar coverage ranged from about 12% at Geary to about 62% at Woodward. The highest redcedar coverage was at Woodward's plot 1 (70%), whereas the lowest coverage was 6% at Geary's plot 2.

Allometric Equation

Results of the PROC GLM analysis of the canopy area and field-measured dry AGM data presented in Table 4 showed that regression was homogeneous ($P > 0.10$) across location and that site was not a significant effect. Consequently, the final model was a simple linear regression of dry AGM on canopy area (Fig. 4a), yielding

$$Y = 6.41 \cdot X + 439.12. \quad [1]$$

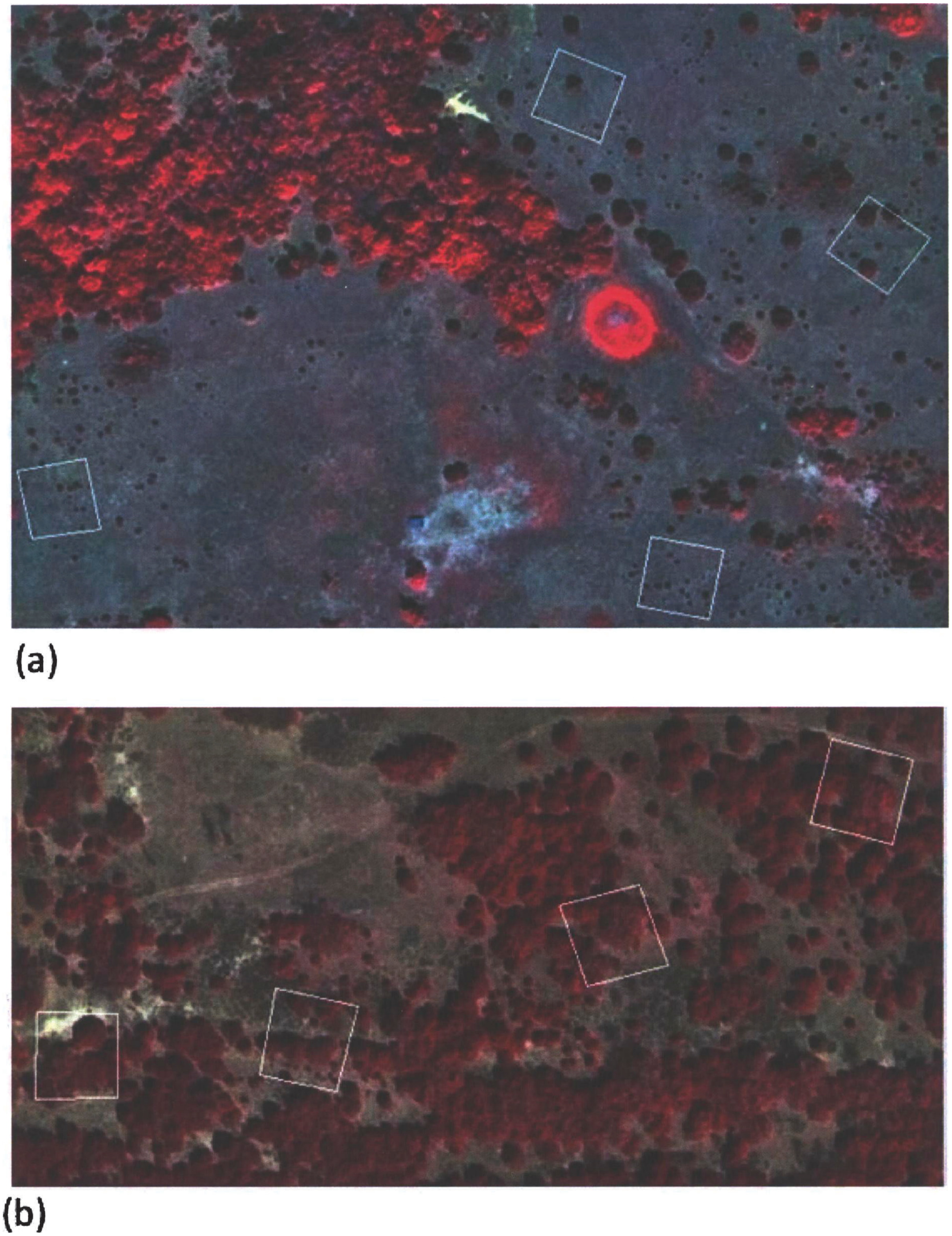


Figure 2. False color composite of the Geary, **a**, and Woodward, **b**, research sites generated from QuickBird wave bands 2, 3, and 4, which show the range of canopy coverage experienced in the study.

The regression indicated that total tree canopy area within a plot is a good predictor of total dry AGM in that plot ($r^2 = 0.85$, $n = 12$). The NRCS maps, however, provide red-cedar land area estimates for selected percent canopy coverage categories. Linear regression of percent canopy cover (Table 4) vs. dry AGM expressed on a unit hectare basis yielded

$$Y = 639.1 \cdot X + 4962.2 \quad [2]$$

($r^2 = 0.85$, $n = 12$; Fig. 4b).

Table 3. Number of red cedar trees per hectare, average weight per tree, and average dry biomass yield per hectare for four randomly selected plots at Cherokee, Geary, and Woodward, Oklahoma.

Location	Plot	Tree density	Tree weight	Mass yield
		trees ha^{-1}	kg	$T \cdot ha^{-1}$
Cherokee	1	1 743	14	24
	2	2 920	11	32
	3	877	48	42
	4	833	56	46
	Mean[1]	1 593 a	23 c	36 a
Geary	1	244	32	8
	2	222	24	5
	3	167	191	32
	4	78	131	10
	Mean	178 b	78 a	14 b
Woodward	1	888	58	52
	2	977	54	49
	3	410	76	30
	4	1 188	31	37
	Mean	866 ab	50 b	42 a

[1]Means within a column followed by the same letter are not different at $P < 0.05$.

Allometric Equation Validation

The range of total redcedar dry AGM of the validation area was determined to be 36–43 metric tons $\cdot$ ha^{-1} (55.1 $\pm$ 4.96% of 71.9 metric tons $\cdot$ ha^{-1} fresh weight). Redcedar coverage for the validation site as measured from the QuickBird satellite data was 51.9%, yielding 38.1 metric tons $\cdot$ ha^{-1} of dry AGM from Equation [2]—within the 36–43 metric ton $\cdot$ ha^{-1} range (field measured) noted above.

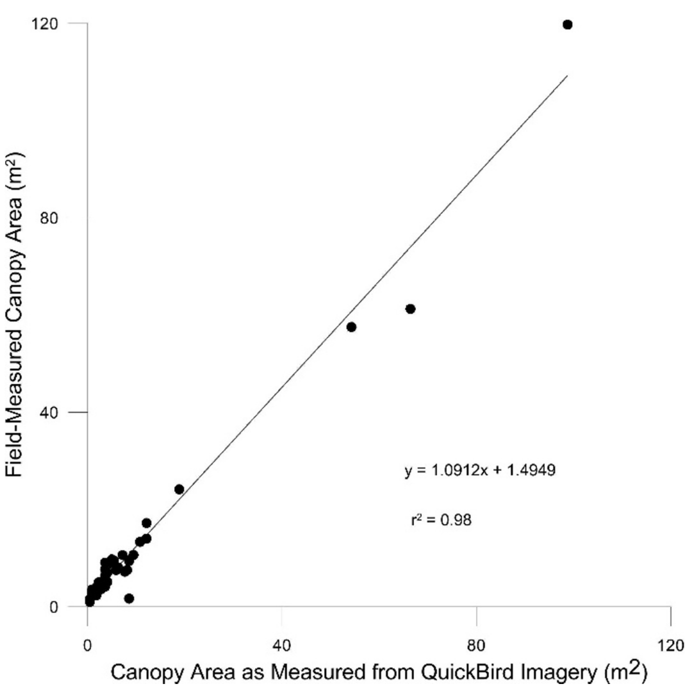


Figure 3. Scatterplot of canopy area as measured from QuickBird imagery versus field-measured canopy area at the Geary site ($n = 49$).

Table 4. Field-measured total dry aboveground dry mass and total canopy area and canopy coverage as measured from QuickBird satellite images for each plot at each location.

		Field measured	Measured from satellite imagery	
Site	Plot	Total dry above-ground dry mass	Total canopy area	Canopy coverage
		kg	m^2	%
Cherokee	1	2 170.5	370.8	41.2
	2	2 913.6	380.2	42.2
	3	3 807.7	418.8	46.5
	4	4 177.8	497.8	55.3
	Mean (SD)	3 267.4 (903.5)	416.9 (57.8)	46.3 (6.4)
Geary	1	708.8	77.2	8.6
	2	478.6	57.0	6.3
	3	2 863.5	217.3	24.1
	4	913.5	73.6	8.2
	Mean (SD)	1 241.1 (1 096.1)	106.4 (74.5)	11.8 (8.3)
Woodward	1	4 645.5	629.8	70.8
	2	4 387.0	609.6	67.7
	3	2 724.2	483.0	53.7
	4	3 304.6	521.2	57.9
	Mean (SD)	3 765.3 (905.1)	560.9 (70.2)	62.3 (7.8)

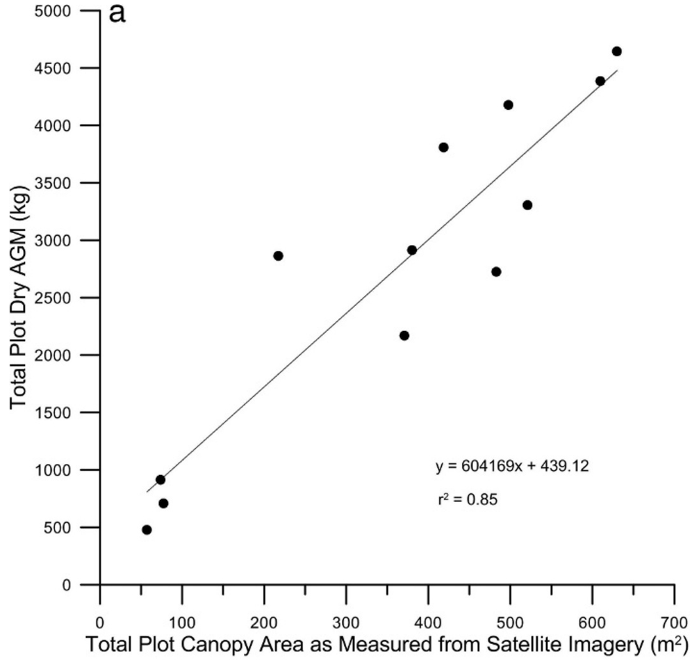
County-Level Mass Estimates

The NRCS canopy coverage estimates were used in Equation [2] to estimate, high, low, and median redcedar dry AGM for each of the 17 counties (Table 5). From Table 5 it is observed that redcedar dry AGM is highly variable across the 17 counties. Dewey County has about 2.0 million metric tons of dry redcedar AGM (median value), which is about twice that found in Blaine County, and an order of magnitude more than that found in Okfuskee County. Total dry redcedar AGM in these 17 counties ranges from a low of 8.3 to a high of 14.7 million metric tons, with a median value of about 11.5 million metric tons.

DISCUSSION

Detection of Eastern redcedar in western Oklahoma grasslands via multispectral remote sensing was a straightforward procedure, due to the spectral contrasts between the dormant warm-season grasses and the evergreen redcedar in the QuickBird images. Even in riparian or other areas where redcedar may be mixed with other woody species, winter time (or leaf-off) images can be used to detect the presence of redcedar, because it is generally the predominant evergreen species in central and western Oklahoma.

Field measurements indicated that redcedar canopy area was highly correlated with its dry aboveground mass (AGM), indicating that satellite imagery with sufficient spatial resolution may be used to measured dry AGM of redcedar. Hyperspatial imagery provided the necessary resolution to establish the relationship between individual tree canopy area and dry AGM, and finally to establish the relationship between canopy coverage (expressed as a percentage of canopy area per unit ground area) and dry AGM. Establishment of these



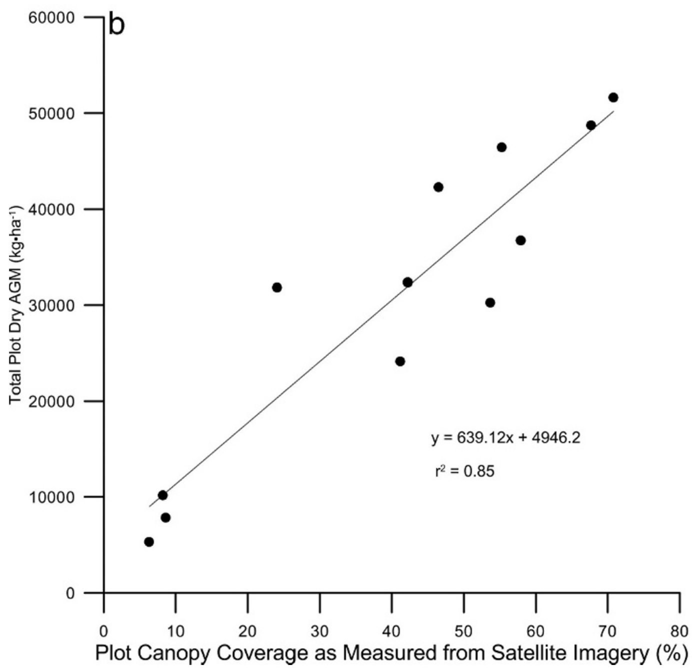


Figure 4. Scatterplot of **a**, total plot canopy area as measured from QuickBird imagery versus field-measured total aboveground dry mass in the respective plot, and **b**, percent redcedar coverage in each plot as measured from QuickBird imagery versus field-measured total aboveground dry mass in each plot expressed on a per-hectare basis. $n = 12$ in both cases.

relationships over the range of tree canopy area and canopy coverage experienced in this study is not possible with coarse spatial scale imagery.

Our relationship between redcedar canopy area measured with the use of QuickBird imagery and that measured in the field ($r^2 = 0.97$) is stronger than that of Song et al. (2010). These researchers related field-measured tree (deciduous) canopy area to that measured from both QuickBird and IKONOS hyperspatial data. They found that the QuickBird data only explained about 52% of the variation in the field-measured data, whereas the IKONOS data yielded a stronger relationship ($r^2 = 0.75$). In regards to conifers, they found that IKONOS hyperspatial data were also a good predictor of canopy area ($r^2 = 0.73$).

Table 5. High, low, and median values of redcedar dry aboveground dry mass (AGM) for 17 Oklahoma counties as determined from the Natural Resources Conservation Service (NRCS) redcedar coverage categories and Equation [2].

County	Low	High	Median
	---------- metric tons ----------		
Blaine	875 667	1 434 271	1 154 969
Canadian	511 550	872 693	692 122
Dewey	1 478 173	2 642 928	2 060 551
Eliss	280 872	525 222	403 047
Garfield	237 985	420 806	329 396
Kingfisher	312 615	501 404	407 009
Lincoln	445 342	862 444	653 893
Logan	355 580	688 701	522 140
Major	438 851	789 240	614 046
Murray	483 698	796 548	640 123
Noble	203 616	347 688	275 652
Okfuskee	117 275	241 712	179 493
Oklahoma	322 075	509 764	415 919
Pawnee	763 224	1 395 217	1 079 221
Payne	643 436	1 224 562	933 999
Pottawatomie	210 730	403 953	307 342
Woodward	615 070	1 088 737	851 904
Total	8 295 760	14 745 891	11 520 825

Our relationship between canopy coverage measured from QuickBird imagery and field-measured dry AGM ($r^2 = 0.85$) is comparable to that of Lucas et al. (2006), who noted a strong relationship between field-measured AGM and that measured from LiDAR data ($r^2 = 0.92$). Our relationship was stronger than that of Madugundu et al. (2008) who related field-measured AGM to that measured from the LISS-IV sensor on board the Indian Resource Satellite ($r^2 = 0.62$).

Although the NRCS redcedar coverage classes are broad, the mass estimates calculated herein are considered conservative because 1) the redcedar maps reflect conditions from 4 yr to 7 yr prior to when the present study was conducted, 2) the redcedar/oak mix category present in some of the NRCS redcedar coverage maps was not included in the county-level AGM estimates, and 3) understory redcedar is not detected by remote sensing.

It should be noted that the allometric equation developed herein is only applicable to the range of conditions noted in this study. However, it is our belief that the range of conditions studied represents most of the conditions in central and western Oklahoma.

IMPLICATIONS

Encroachment of woody species/shrubs into grasslands and associated problems are well recognized (Van Auken 2000; Briggs et al. 2002; Coppedge et al. 2007; Sankey and Germino 2008). This encroaching woody species may provide an opportunistic source of phytomass in the production of energy for small rural communities. Currently millions of dollars are spent annually on practices (e.g., fire, cutting) to remove woody shrub species from grasslands. Often, those that are cut are left lying on the ground occupying potentially valuable wildlife habitat or grazing land, and provide a seed bank for future generations of undesirable woody species. Exploitation of redcedar as a biofuel resource could help limit or reverse current rates of encroachment in native grasslands of Oklahoma and much of the southern Great Plains region, and reduce expenditures of public monies for grassland restoration. The procedures for quickly measuring redcedar mass developed herein can be readily implemented by interested parties. It should be a valuable aid for determining the feasibility of redcedar biofuel facilities, such as gasification plants, and the optimization of plant location by identifying areas with adequate redcedar AGM to support the industry.

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