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Complementarity of Radar and Visible–Infrared Sensors in Assessing Rangeland Condition

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Ground investigations of rangeland use and condition are restricted by resource and travel limitations. Management of these vast, multiuser resources could be enhanced by information from remote sensing. Microwave radar imagery is becoming readily available and its all weather capability provides greater reliability than visible–infrared (VIR) sensors. The objective of this study was to evaluate a combination of radar and visible–infrared sensors as tools in rangeland monitoring. Data from Landsat Thematic Mapper (TM) and SPOT VIR sensors were compared with data from airborne and ERS-1 synthetic aperture radar (SAR) sensors to determine similarities and contrasts with a view to exploiting any synergism. The study site was the Agriculture and Agri-Food Canada Onefour Research Substation in southeastern Alberta. The TM and SPOT VIR sensor bands were highly correlated. The radar sensors were correlated with each other to a lesser degree. Correlations between VIR and radar were not high. Vegetation type influenced VIR reflectance and radar backscatter. Russian wildrye pastures had high radar backscatter as well as high VIR reflectance. Native range had low VIR reflectance and low radar backscatter. Crested wheatgrass pastures had low VIR reflectance and high radar backscatter. Other features, such as exposed sedimentary Cretaceous softrock, had high values for both sensor groups, while intermittent water bodies or shallow depressions characterized by high clay content and strong microtopography had high radar backscatter but low VIR reflectance. More information can be obtained from the combination of both types of sensor than from either alone.

INTRODUCTION

Rangeland is a vast multiuser resource. In the Northern Great Plains of Canada alone there are 24 M ha of mixed prairie (Willms and Jefferson, 1993). Monitoring this important resource by conventional methods is both time-consuming and labor-intensive. Remote sensing offers new opportunities for monitoring the condition and productivity of rangeland.

Ground-based and satellite studies show that visible–infrared (VIR) data can be used to monitor biomass production of fescue (Brown et al., 1983) and shortgrass prairie (Anderson et al., 1993; Major et al., 1988). However, the small amount of above-ground vegetation on shortgrass prairie makes it difficult to differentiate between plant species or range condition (Brown et al., 1981). Additionally, cloud cover limits the use of VIR satellite data. Landsat 5 Thematic Mapper (TM) and SPOT (Système Probatoire d'Observation de la Terre) High Resolution Visible (HRV) satellites have cycles of 16 and 26 days, respectively, but can only acquire data on cloud-free areas. Over western Canada the chance of obtaining a Landsat image with less than 20% cloud cover is only 29% (Brown et al., 1984).

In 1991 the European Earth Resources Satellite (ERS-1) and the Japanese Earth Resources Satellite (JERS-1) were launched, and the impending launch of the Canadian Radarsat in 1995 will make radar data, with its all-weather capabilities, more readily available.

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The cloud-penetrating properties of radar make it an attractive alternative for monitoring rangeland using remote sensing. On the tallgrass prairie in Kansas, Martin et al. (1989) found that C-band (4.75 GHz, 63 mm wavelength) radar backscatter was related to green live vegetation but not senescent vegetation. This is consistent with moisture being a driving factor in radar backscatter (Major et al., 1991). In the shortgrass prairie of southern Alberta, airborne C-band radar differentiated species; however, roughness of the soil surface rather than vegetation *per se* may be the distinguishing feature (Smith et al., 1994). Management practices rather than species composition were implicated in radar backscatter variation from mixed seminatural and improved grasslands in Ireland (Critchley et al., 1987).

Complementary data from Landsat or SPOT and SIR-B (Shuttle Imaging Radar B) radar imagery have been used in mapping forest resources (Lozano-Garcia and Hoffer, 1993) and tropical vegetation (Nezery et al., 1993). Complementarity may be achieved by the use of two sensors, which provide more information than could be obtained from either alone, or, radar imagery may replace unavailable VIR data.

Ground-based VIR and scatterometer studies in southern Alberta mixed shortgrass prairie indicate potential complementarity of radar and VIR spectral reflectance in monitoring rangeland (Major et al., 1994). In this study we investigated the complementarity of VIR reflectance from SPOT and Landsat TM and radar backscatter from airborne synthetic aperture radar (SAR) and ERS-1 in relation to range vegetation on the Agriculture Canada Research Substation at Onefour, Alberta.

MATERIALS AND METHODS

Site Description

The study site was the mixed shortgrass prairie at the Agriculture and Agri-Food Canada Research Substation at Onefour, Alberta (Lat. 49°, 0–11'N, long. 110°, 20–33'W, approximate elevation 920 m). The climate of the region is characterized by low precipitation (280 mm), a high rate of evaporation (800 mm), extremes of temperature (−40–+40°C), frequent high winds, and abundant sunshine. Moisture is the principal climatic factor limiting plant growth.

The area is representative of the *Stipa–Bouteloua* community in the mixed prairie ecosystem described by Coupland (1961). The dominant plant species are blue grama (*Bouteloua gracilis*) and needle-and-thread (*Stipa comata*) with other grasses and forbs present (Smith et al., 1994). In general, the vegetation is highly nutritious and palatable but is of low productivity. The average annual dry matter production of the *Stipa–Bouteloua* community, over a 50-year-period, has been estimated at 388 kg / ha (Smoliak, 1986). Since the inception of the Substation in 1928, some pastures have been cultivated and reseeded to crested wheatgrass (*Agropyron cristatum*) or Russian wildrye (*Elymus junceus*) (Fig. 1a).

Drainage is largely into temporary sloughs, although the local drainage basin is a part of the Milk River system, which flows into the Missouri River in Montana. The dominant regional surface form, and associated parent material, is undulating to flat morainal (till) interspersed by northwest to southeast ridged glaciofluvial ridges (Shetsen, 1987). These ridges are mainly in the southern region of the study area which includes fields 31, 44, 45, 56, 70, 71, 72, 80, and most of 68 and 69 (Fig. 1a). Local relief within this area is usually less than 3 m on undulating terrain (Barendregt, 1977) and less than 10 m in ridged areas (Table 1). The surface textures of the area are mainly fine sandy loam and light loam (Wyatt et al., 1941). The profile is associated with the residual rock formations, which, in this case, are principally Bearpaw shales.

Image Acquisition and Processing

Aircraft SAR, ERS-1, SPOT, and Landsat TM images of the test site were acquired in August 1991. The characteristics of the aircraft SAR image which was obtained using the Canada Centre for Remote Sensing (CCRS) Convair 580 (Livingstone et al., 1987), together with those for the satellite images, are presented in Table 2.

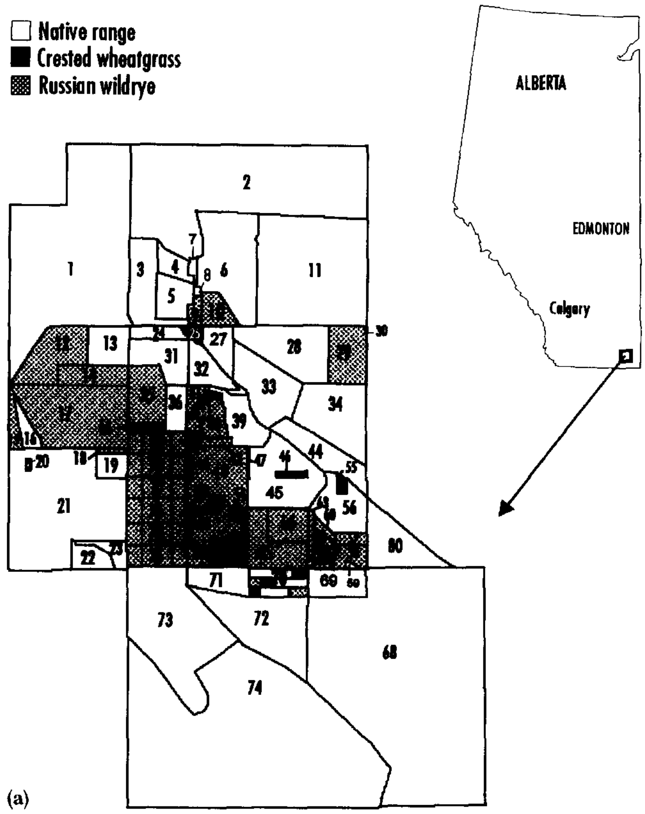
All data were obtained on computer compatible tape and copied to a VAX VMS system and preprocessed using the CCRS Landsat Digital Imagery Analysis System (LDIAS) (Goodenough and Menard, 1988). A 5 × 5 pixel median filter was performed on the radar images prior to copying them into the Unix-based GRASS (Geographical Resource Analysis Support System) GIS system. The imagery for each sensor was registered to a map indicating roads and fences (Fig. 1a). The pixel size specified for the GRASS raster map containing the image was set to 6 m.

Image Analysis

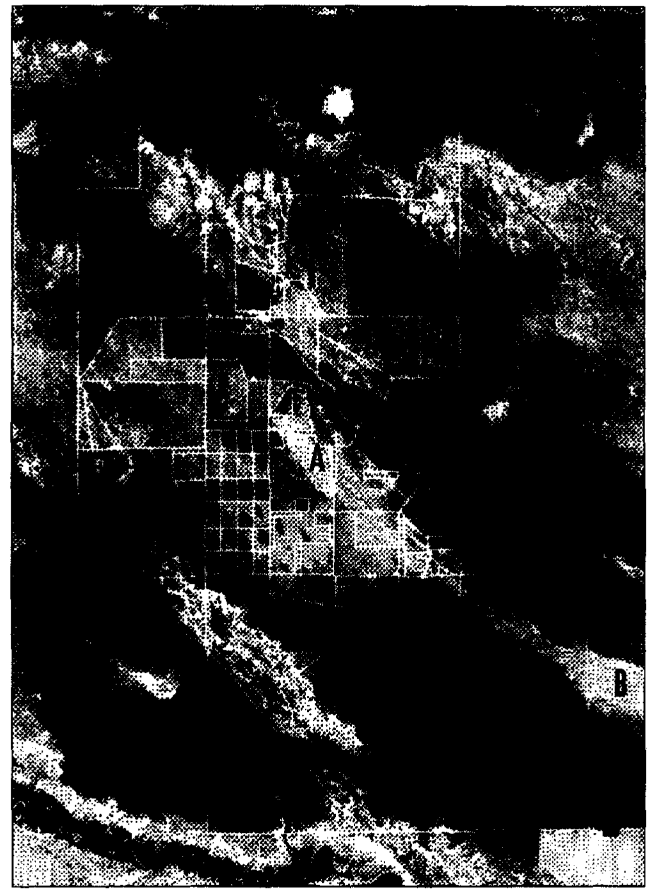
The image data were not calibrated for each sensor; thus the absolute digital numbers (DN) and tones of the imagery cannot be compared. Relative comparisons are, however, valid. The complementarity of the data was assessed using qualitative and quantitative procedures. The SAR image did not cover all of fields 1–11, 68, and 71–74 shown in Figure 1a, and thus, where appropriate, they were excluded from the analysis. In the qualitative analyses, similarities and differences in rangeland characteristics measured by the two sensor types were determined by visual examination of the grey scale images for the various sensors and composite images made from the radar and VIR data. In the quantitative analysis, DN from 2500 randomly selected pixels were extracted, and

Table 1. Soil Characteristics of the Agriculture and Agri-Food Canada Substation at Onefour, Alberta

Land Type	*Field No.*	*Surface Form*	*Parent Material*	*Surface Texture*	*Soil Classification*		*Comments*
					Dominant	*Significant*	
Uplands (with exposed Cretaceous softrock)	1, 2, 3, 4, 6, 29	Undulating to rolling ice- thrust ridges with inclined to steep residual	Residual Oldman member	Loamy (sandy)	Orthic Regosol	Brown Solonetzic and Brown Chernozemic	Apron deposits occur in valleys between upland benches and ridges
Plains	21, 34, 44, 72, 80 and most of 68	Undulating to ridged	Morainal (with glaciofluvial and glacio-lacustrine veneer to blanket)	Loamy	Brown Chernozemic	Brown Solonetzic	Most extensive land type of study area; eroded pits vary from 0–50% on this land type
Basins	59, 61, 64 and 68 (highly reflective)	Level to depressional	Lacustrine (and fluvial)	Clayey	Brown Solonetzic	Orthic Regosol	Transported material derived from softrock exposures in uplands land type
Incised valleys	22 and occurs in 73 and 74	Steeply sloping and dissected	Morainal veneer to blanket over softrock (and exposed softrock)	Undifferentiated	Orthic Regosol	Brown Chernozemic	Includes Lost River valley and tributaries



(a)



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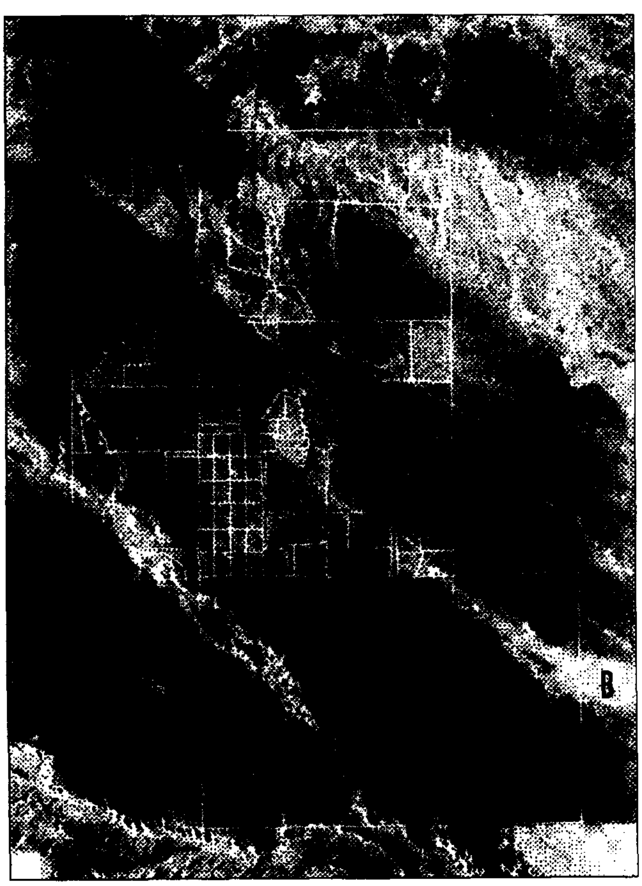

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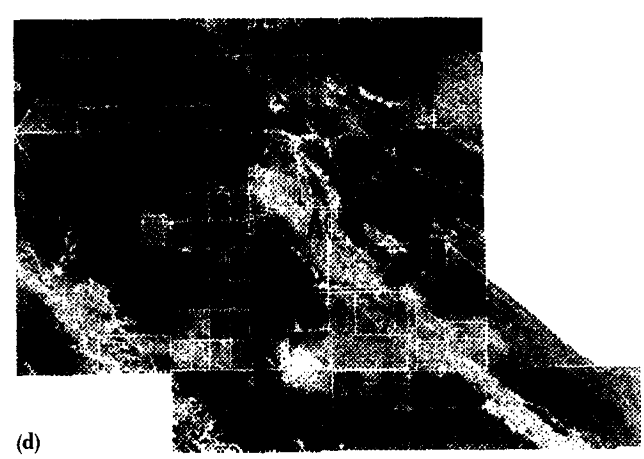


(d)

Figure 1. a) Plan of native range and reseeded pastures; b) a SPOT panchromatic image; c) an ERS-1 image, and d) a nadir swath mode airborne SAR image of the Agriculture and Agri-Food Canada Research Substation, Onefour, Alberta.

Table 2. Characteristics of Imagery

Imagery	*Date*	*Characteristics*
Airborne SAR	01 August 1991	C-band (5.3 GHz, 5.66 cm) HH-polarization 0–74° (nadir mode) 6 m resolution
ERS-1	10 August 1991	C-band (5.3 GHz, 5.7 cm) VV-polarization 23° incidence angle 30 m resolution
Landsat TM	14 August 1991	Six visible-infrared bands (0.45–2.35 μm) 30 m resolution
SPOT	17 August 1991	Panchromatic (0.51–0.73 μm) 10 m resolution

Table 4. Rangeland Species Differentiation Using Different VIR and Radar Sensors[a]

Sensor	*Native Range (DN)*	*Crested Wheatgrass (DN)*	*Russian Wildrye (DN)*
Airborne SAR	70.0 b	77.1 a	81.2 a
ERS-1	56.2 b	75.1 a	76.8 a
SPOT	64.8 b	69.3 b	94.0 a
TM Band 1	117.8 b	113.1 b	133.2 a
TM Band 2	109.5 b	108.2 b	126.5 a
TM Band 3	102.3 b	105.3 b	122.2 a
TM Band 4	120.0 b	118.9 b	129.8 a
TM Band 5	184.4 b	184.9 b	194.7 a
TM Band 7	146.6 c	154.9 b	167.1 a

[a] In each row, numbers followed by the same letter did not differ significantly at $P < 0.05$.

relationships within and between sensor types were determined using correlation analysis. Mean DN for each of 50 fields of known species composition were extracted and summarized according to species. Univariate (ANOVA) and multivariate (MANOVA) analyses of variance were used to determine the ability to distinguish vegetation type using single or multiple sensors. The results of the MANOVA were used in a discriminant function analysis (DFA) to graphically illustrate complementarity among sensor types.

RESULTS AND DISCUSSION

At Onefour, from 1928 to 1975 some pastures were cultivated and reseeded to crested wheatgrass or Russian wildrye while others were left in native species. Crested wheatgrass and Russian wildrye were seeded in rows varying between 0.3 m and 1 m, depending on the area. The Substation, thus, provides an opportunity to assess the potential of SPOT, TM, airborne SAR, and ERS-1 to differentiate most of the common vegetation types and soil characteristics found in southeastern Alberta. Figures 1b–d show the grey scale SPOT, ERS-1, and airborne SAR images.

Correlation analysis showed airborne SAR and ERS-1 to be only weakly correlated with SPOT or TM data (Table 3). The SPOT, TM Bands 1, 2, and 3 and, to a lesser extent, TM Band 4 were well correlated. The data from airborne SAR and ERS-1 were only weakly correlated. The steeper angle of incidence of ERS-1 than that of airborne SAR and the different polarization of ERS-1 (VV) and airborne SAR (HH) could account for the weakness of the relationship. There was 7.6 mm precipitation at Onefour on 6 August 1991, but the mean daily temperature of 23-27° on the 7–10 August likely eliminated rainfall and moisture as a factor responsible for the weak relationship between airborne and ERS-1 data.

The reflectance and backscatter characteristics varied significantly among sensors and species of vegetation (Table 4). Reflectance of TM Bands 1–5 and SPOT panchromatic were significantly higher for Russian wildrye compared to crested wheatgrass and native range. No significant differences in reflectance were observed between crested wheatgrass and native range. The reflectance of TM Band 7 varied significantly among the three vegetation types. Russian wildrye showed highest, crested wheatgrass intermediate and native range lowest reflectance. Radar backscatter in the airborne SAR and ERS-1 was higher for the two seeded species than for native range.

Table 3. Correlation Coefficients between Digital Number (DN) of Rangeland Vegetation as Measured Using Different VIR and Radar Sensors ($P < 0.05$)

	SPOT	*TM Band 1*	*TM Band 2*	*TM Band 3*	*TM Band 4*	*TM Band 5*	*TM Band 7*	*Airborne SAR*	*ERS-1*
SPOT	1.00	0.75	0.78	0.77	0.61	0.35	0.53	0.22	0.42
TM Band 1	0.75	1.00	0.97	0.96	0.62	0.60	0.78	0.24	0.32
TM Band 2	0.78	0.97	1.00	0.98	0.73	0.54	0.73	0.26	0.34
TM Band 3	0.77	0.96	0.98	1.00	0.70	0.62	0.80	0.28	0.36
TM Band 4	0.61	0.62	0.73	0.70	1.00	0.35	0.34	0.12	0.35
TM Band 5	0.35	0.60	0.54	0.62	0.35	1.00	0.87	−0.09	−0.09
TM Band 7	0.53	0.78	0.73	0.80	0.34	0.87	1.00	0.14	0.11
Airborne SAR	0.22	0.24	0.26	0.28	0.12	−0.09	0.14	1.00	0.33
ERS-1	0.42	0.32	0.34	0.36	0.35	−0.09	0.11	0.33	1.00

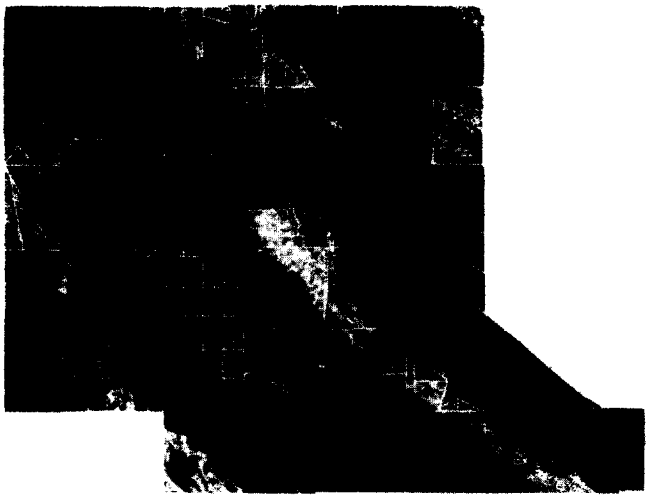


Figure 2. Color composite of SPOT (red), ERS-1 (green), and SAR nadir swath (blue).

In August, live vegetation is rare at Onefour. The normalized difference vegetation indices (NDVI) calculated for the three species were 0.01 for Russian wildrye and crested wheatgrass and 0.04 for native range, indicating that VIR reflectance was measuring bare soil and senesced vegetation. Senesced vegetation was abundant in crested wheatgrass pastures, where ground cover was about 85%. Ground cover in Russian wildrye pastures, where soil erosion and row effects were evident 20–40 years after reseeding, was 40%. Native range had sparse, short vegetation and 55% ground cover. The significantly higher reflectance of TM Band 7 from the two seeded species compared to that from native range, probably indicated greater levels of senesced vegetation and bare soil (Thomson et al., 1985).

Radar responds to moisture and roughness. In southeastern Alberta range vegetation moisture is minor compared to soil moisture, so that radar measures either soil moisture or roughness or both (Major et al., 1994). Field 29 was reseeded to Russian wildrye in 1970 but due to poor germination is now primarily native range. However, the field has rough microtopography, which may explain the high backscatter evident in the radar images, particularly the airborne SAR (Figs. 1b–d).

The results of the correlation analysis and the univariate analyses of variance suggested that the two types of sensor, VIR and radar, provide different information and have potential for complementarity (Tables 3 and 4). In contrast to VIR, crested wheatgrass could be distinguished from native range using radar, but, unlike VIR, crested wheatgrass could not be distinguished from Russian wildrye using the radar.

Color composite images using the various sensors assisted in identifying complementarity or similarity in the information provided by each sensor. A composite image of SPOT (red), ERS-1 (green), and SAR narrow mode (blue) showed high VIR reflectance and low radar backscatter for native range (Fig. 2), high VIR reflectance and radar backscatter for Russian wildrye, and high radar backscatter and low VIR reflectance for crested wheatgrass. Field 70 showed differences in VIR reflectance and radar backscatter with vegetation types. A study was established in 1954 to compared three methods of grazing on native range, Russian wildrye, and crested wheatgrass (Smoliak, 1968). Fences separating the plots were removed in 1977, but the experiment and its associated treatments were still evident in airborne SAR and VIR images.

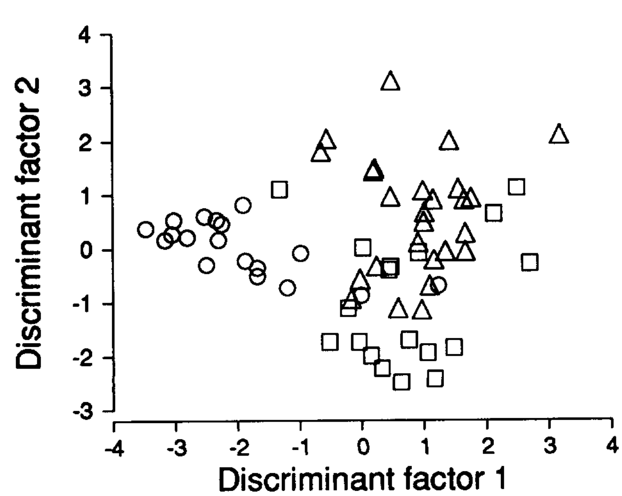
Table 5. Canonical Coefficients Defining Discriminant Functions DF 1 and 2[a]

Sensor	*DF1*	*DF2*
SPOT	−0.056	0.890
ERS-1	−0.918	−0.549
Airborne SAR	0.316	0.723

[a] Absolute values of coefficients, in descending order, rank the relative importance of the sensor in the DF.

Discriminant function analysis was used to quantify the results of the composite image with respect to vegetation types. As in the composite image, the data from SPOT, ERS-1, and airborne SAR were used. The results using TM data as the VIR component were similar and are not presented. The first discriminant function accounted for 79% of the difference and was primarily due to ERS-1. The second discriminant function described 57% of the remaining variation and was primarily due to differences in SPOT and airborne SAR (Table 5). Both discriminant functions described significant differences among vegetation type (DF1, chi-square stat = 79.645, df_6, $p < 0.001$: DF2 chi-square stat = 22.82, df_2, $p < 0.001$) (Fig. 3). The results of the MANOVA showed significant

Figure 3. Discriminant function analysis showing the separation of native range (○), crested wheatgrass (□), and Russian wildrye (△) using a combination of VIR and radar sensors.



differences in the three vegetation types using a combination of VIR and radar (Wilkes' lamda $P < 0.001$), and *post-hoc* contrast analysis showed that the three vegetation types differed significantly from each other.

In addition to vegetation type, the ERS-1 and airborne SAR data in the composite images highlighted regions of subsurface water in intermittent water bodies and rivers. In the SPOT image the intermittent basins appeared dark, possibly due to higher vegetative growth, while in the airborne SAR these areas were bright, probably indicating higher soil moisture content and greater vegetative growth. The intermittent basins were not highlighted to the same degree in the ERS-1 image, possibly due to the different incident angle and polarization of the SAR sensors.

On both the VIR and radar images an ephemeral channel running from the northwest to the southeast was prominent (Figs. 1b–d, A). Water flows intermittently southward through this channel carrying silt and clay to the drainage basin (fields 1, 2, 3 and 6 in Fig. 1a) from the region of exposed Cretaceous softrock in the south of the study site. The silt and clay together with adsorbed salts have been deposited as the water flows through the drainage channel. The highest concentration of sodium salt occurs in the drainage basin, the brightest region on the radar and VIR images (Figs. 1b–d, B). The radar backscatter in this region was high due to the high water content and the salt-induced increase in the dielectric constant of the soil. This region also appeared bright in the VIR imagery probably due to reflection from bare soil rather than from vegetation. The ephemeral channel originated in an area of contorted glacial bedrock where the ridges were highlighted more by radar than by VIR.

CONCLUSIONS

A combination of VIR reflectance and radar backscatter more accurately identified vegetation types than either technique alone. Native range has a relatively smooth surface and, hence, a lower radar backscatter than either crested wheatgrass or Russian wildrye. Crested wheatgrass fields showed little evidence of row effects compared to Russian wildrye; however, crested wheatgrass is a bunch grass, and its surface was rougher than native range. This, combined with low VIR reflectance, resulted in radar highlighting the crested wheatgrass fields in combined images. For Russian wildrye, the rough soil surface due to erosion between the rows and the clumpiness of the vegetation resulted in high backscatter. The larger amount of bare soil in the Russian wildrye pastures resulted in high reflectance with VIR sensors.

This study indicated that radar and VIR measured different aspects of rangeland. The VIR responded mainly to vegetation and radar to geology and surface topography. However, radar maybe more sensitive than VIR to range vegetation where the vegetation forms a significant component of the region.

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