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Monitoring, classification, and characterization of interior Alaska forests using AIRSAR and ERS-1 SAR

C.L. Williams
Institute of Northern Forestry, Pacific Northwest Research Station, USDA Forest Service, Fairbanks, AK 99775, USA
K. McDonald and E. Rignot
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
L.A. Viereck
Institute of Northern Forestry, Pacific Northwest Research Station, USDA Forest Service, Fairbanks, AK 99775, USA
J.B. Way and R. Zimmermann
Jet Propulsion laboratory, California Institute of Technology, Pasadena, CA 91109, USA

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ABSTRACT. At the Bonanza Creek Experimental Forest (BCEF), past ecological research has been directed at forest successional processes on the floodplain of the Tanana River and adjacent uplands. Research at the Bonanza Creek site continues on the mosaic of forests, shrublands, and wetlands in a wide variety of successional stages on the Tanana floodplain. This paper reviews research since 1988 into the capabilities of Synthetic Aperture Radar (SAR) for monitoring, classification, and characterization of these forests using radar remote sensing and modelling techniques. Classifications of successional stages, obtained by use of different classifiers on multi-frequency and multi-polarimetric AIRSAR data, are contrasted; these classifications have been used to predict classification accuracies obtained with ERS-1 data, and to estimate the utility of an ERS-1 and RADARSAT combination for classification. Forest classifications, used in combination with ground-truth data for more than 50 forest stands, are used to summarize the distribution of biomass on the landscape. This will allow projections of future biomass. Monitoring of forest phenology, seasonality of flooding, and freeze–thaw transitions is ongoing. Also, direct monitoring of dominant tree species is demonstrating diurnal variation and interrelationships among environmental, physiological, and backscatter measurements.

contents

Introduction

Landscapes in interior Alaska arc representative of the circumboreal taiga; their forests, subject to widespread periodic disturbance, consist of complex mosaics of different stages in vegetational succession (Van Cleve and Viereck 1981). The usc of Synthetic Aperture Radar (SAR) for remote sensing of these forests shows particular potential for ecological research. In the sub-Arctic, variations in annual cycles of freezing and thawing have dramatic consequences for ecosystems; these cycles influence both the biotic and the abiotic processes shaping landscapes. Active microwave sensors, such as SAR, arc sensitive. to the physical states of water and arc also able to penetrate cloud cover and darkness.

Work in progress since 1988 has shown Alaskan forests to be important silts foresting the ecological capabilities of SAR, because of the availability of both upland sites and relatively level floodplain sites, the existing detailed knowledge of both upland and floodplain successional processes, the records of stand history, composition, and geometry for a wide variety of stands, and the existing net work of meteorologic monitoring stations. Interdisciplinary ecological research continues into the future at the Bonanza Creek Long Term Ecological Research (LTER) site,

This paper summarizes ongoing research utilizing SAR in forests in interior Alaska. It includes a description of the study site and the available SAR imagery, examples of insights into landscape interpretation and phenology obtained with SAR, AIfNAR-based classifications of forest types, and predictions for the accuracy of classifications based on satellite-borne SAR. Two methods, onc direct and onc indirect, for estimating forest biomass arc described; one of these allows predictions of future biomass. Finally, it briefly describes backscatter modelling and physiological monitoring that arc establishing relationships between radar backscatter, forest structure, environmental change, and tree-canopy physiology.

The study site

The LTER site is located witbin and adjacent to the Bonanza Creek Experimental Forest (BCEF), 20 km southwest of Fairbanks, Alaska. The LTER site includes both the Tanana River floodplain and the adjacent uplands. The Tanana f-liver is one of three major rivers draining interior Alaska; it is primarily glacic.r-fed, with high suspended sediment loads, and with consequent braiding and meandering along its length. The meandering of the river has created a floodplain landscape of exposed silt bars, islands, terraces, and meander scrolls, with an associated mosaic of

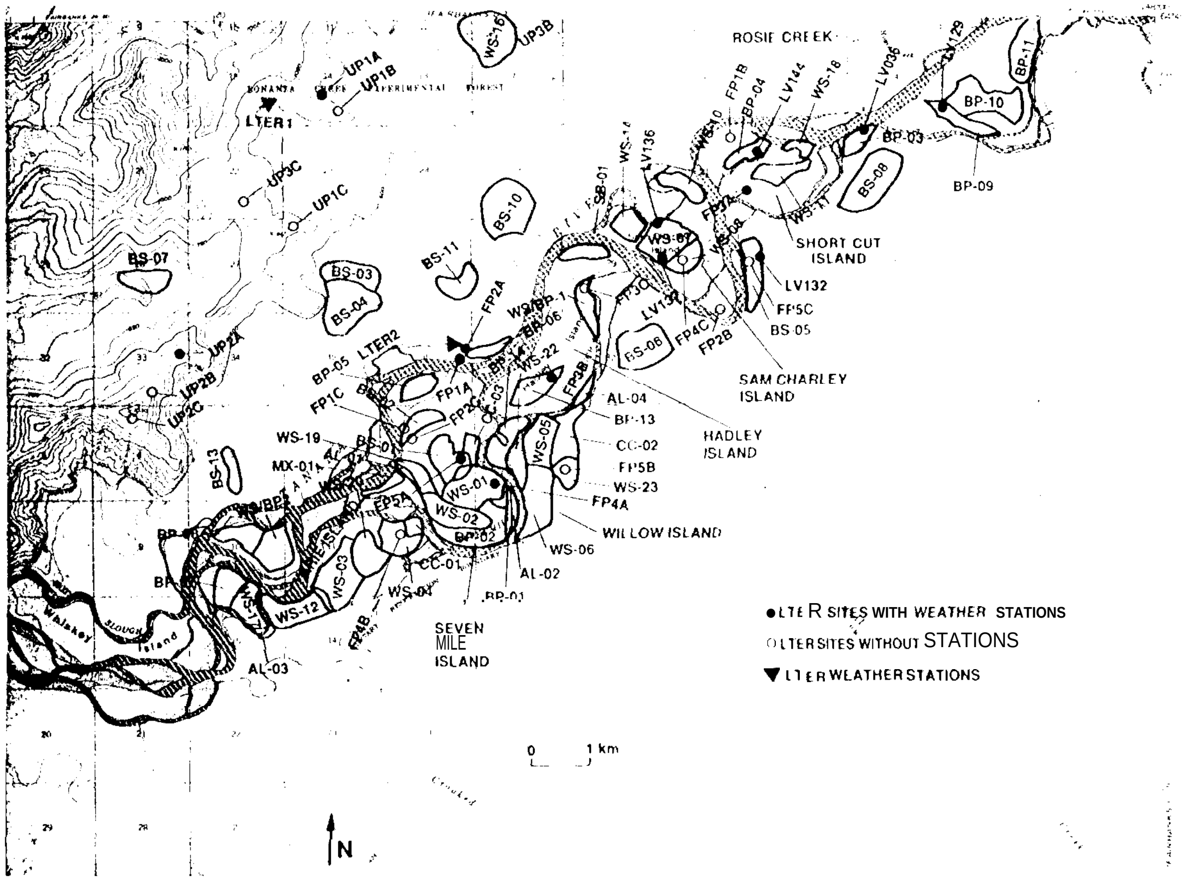

Fig. 1. Location of upland and floodplain forest stands and of weather stations at the Bonanza Creek LTER site. Stand types for floodplain LTER stands are FP1: willow; FP2: alder, FP3: balsam poplar; FP4: white spruce; and FP5: black spruce. The polygons represent stands where the geometry and composition are being measured specifically for use in remote sensing studies and represent areas from where radar backscatter has been extracted for classification analyses. Stand types for these stands are AL: alder; BP: balsam poplar; WS: white spruce; ES: black spruce; and CC: clearcut.

successional vegetation (Van Cleve and others 1993). Floodplain vegetation represents a primary successional sequence starting on newly formed silt bars near the river's edge. Upland vegetation is characterized by a secondary successional sequence initiated by wildfire. The vegetation and landforms of the Bonanza Creek LTER site reflect the major disturbance processes wild fires, insect infestations, and river geomorphic processes governing the development of boreal forests. Ecological research at BCEF during the last 30 years has resulted in development of detailed successional models and availability of long-term data for vegetation, soils, climate, and river morphology (Van Cleve and others 1991; Viereck and others 1993b; 1993c).

The LTER site includes 24 intensively studied upland and floodplain successional forest stands, with 10 weather stations distributed among the stands. These 24 stands represent eight distinct successional stages of the predominant upland and floodplain successional sequences. In 23 additional successional stands, detailed measurements of forest composition and forest geometry have been made for use in remote sensing studies (Fig. 1). Vegetational succession is generally similar to that found along all of the major rivers in interior Alaska and adjacent Canada. The general successional pattern begins on exposed silt bars, first colonized by willow species (*Salix* spp.), with subsequent generations dominated by alders (*Alnus tenuifolia*), balsam poplars (*Populus balsamifera*), and white spruce (*Picea glauca*). White spruce stands may persist for several generations before development of permafrost and replacement by black spruce (*Picea mariana*). Twelve stages of succession are recognized. Replacement of white spruce by black spruce and succession between black spruce and open bog are less well understood than earlier stages in succession (Viereck and others 1993b).

SAR coverage at Bonanza Creek

Image data from two currently available SAR sensors are being utilized in studies of interior Alaskan forests. Images from aircraft-borne SAR (AIRSAR) have been collected for three seasons, winter (March), spring (May), and summer (July), with March images taken at temperatures both well above and below 0°C and with variable amounts of river flooding in May. AIRSAR data include backscatter

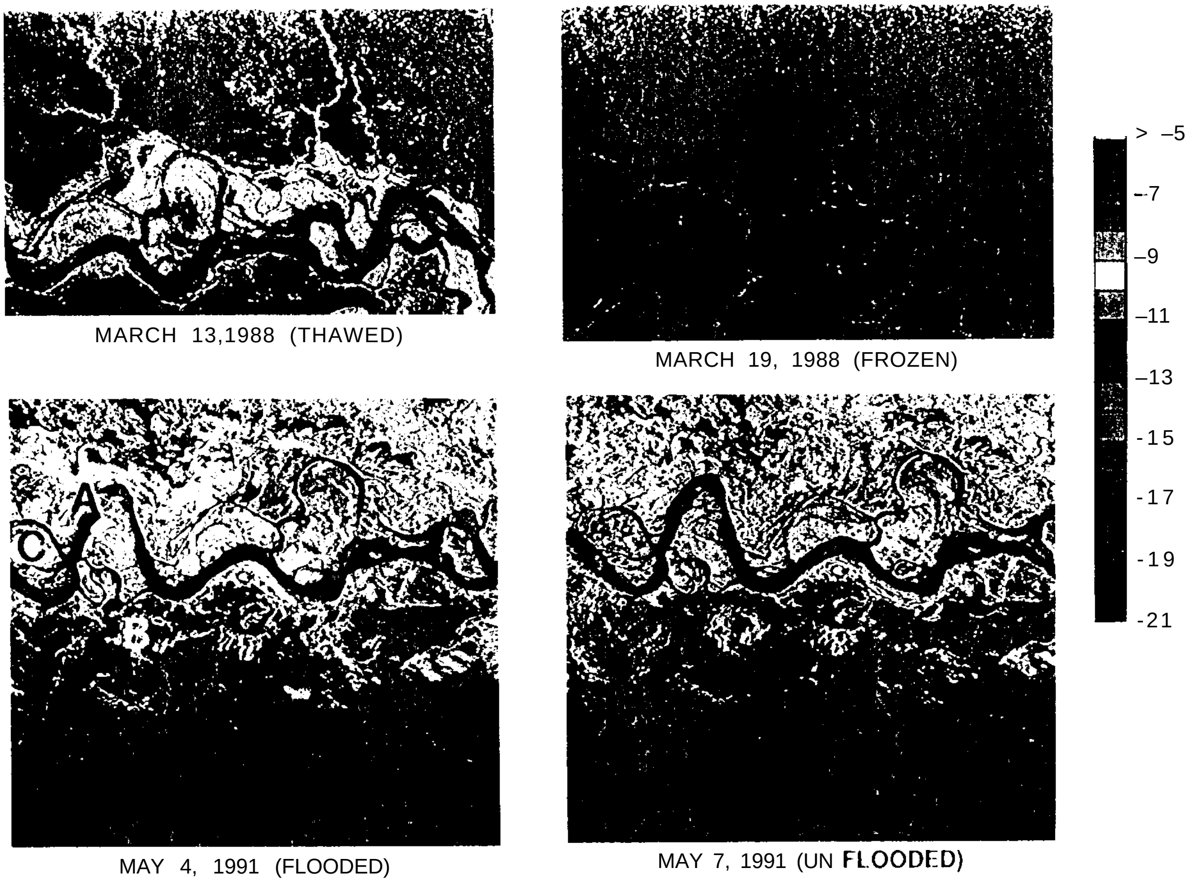

Fig. 2. Winter and Spring L-band AIRSAR images of Bonanza Creek Experimental Forest. Color bar shows total backscatter, expressed in decibels. The two March images show the dramatic decrease in backscatter as landscapes freeze. The two May images show the influence of ice jams (A) on flooding of the Tanana River floodplain during breakup. Flooding is seen both as increases in the surface area of open water wetlands (B) with low backscatter and as flooding of wooded areas (C), which exhibit high backscatter due to double-bounce backscattering mechanisms. Backscatter variation useful in forest classification and biomass mapping earl be seen by comparisons of these images with stand locations in Figure 1.

for three bands (C, L, and P), with four polarizations (HH, VV, HV, VH) for each band (Way and Smith 1991). The multi-frequency, multi-polarization nature of AIRSAR data allows differentiation of radar-scattering mechanisms under different canopy geometries (Van Zyl 1989), assists with backscatter modelling (McDonald 1991), and allows identification of optimal bands and polarizations for different ecological or engineering purposes (Williams and others 1992, 1993; Rignot and others 1994 b). Because of its multi-channel capabilities, AIRSAR may be used to simulate the specific band and polarization combinations of future spaceborne radar configurations (Williams and others 1992, 1993).

The ERS- 1 SAR, with its C-band, VV polarization configuration. provides only one observation channel with each sensor pass but provides frequent repeat coverage for examination of seasonal change (Way and Smith 1991).

Use of SAR for landscape interpretation

AIRSAR images from March 1988 (Fig. 2) at Bonanza Creek and ERS - 1 images from August- September 1991 further down the Tanana River (Rignot and Way 1994; Rignot and others 1994a) show the dramatic drop in backscatter that occurs as landscapes freeze.

Both ERS- 1 and AIRSAR images of the Tanana Valley display ecologically significant features of floodplain geomorphology, including oxbow lakes, meander scrolls, and abandoned channels. in addition, use of SAR to delineate patterns of flooding in May 1991 demonstrates differences between northern and southern portions of the floodplain (Fig. 2). Flooding on 4 May 1991 was caused during river breakup by the formation of ice jams across the main river channels; ice jams had dispersed, and flooding subsided by 7 May. Ice jams arc clearly evident as areas of increased backscatter in channels of open water with very low backscatter; this demonstrates the use of SAR for monitoring river freeze and breakup Flooding is seen botb as increases in surface area of lakes and wetlands containing open water (low backscatter) and as dramatic increases in backscatter caused by the presence of standing water in forests. Flooding upstream (to the left) of the ice

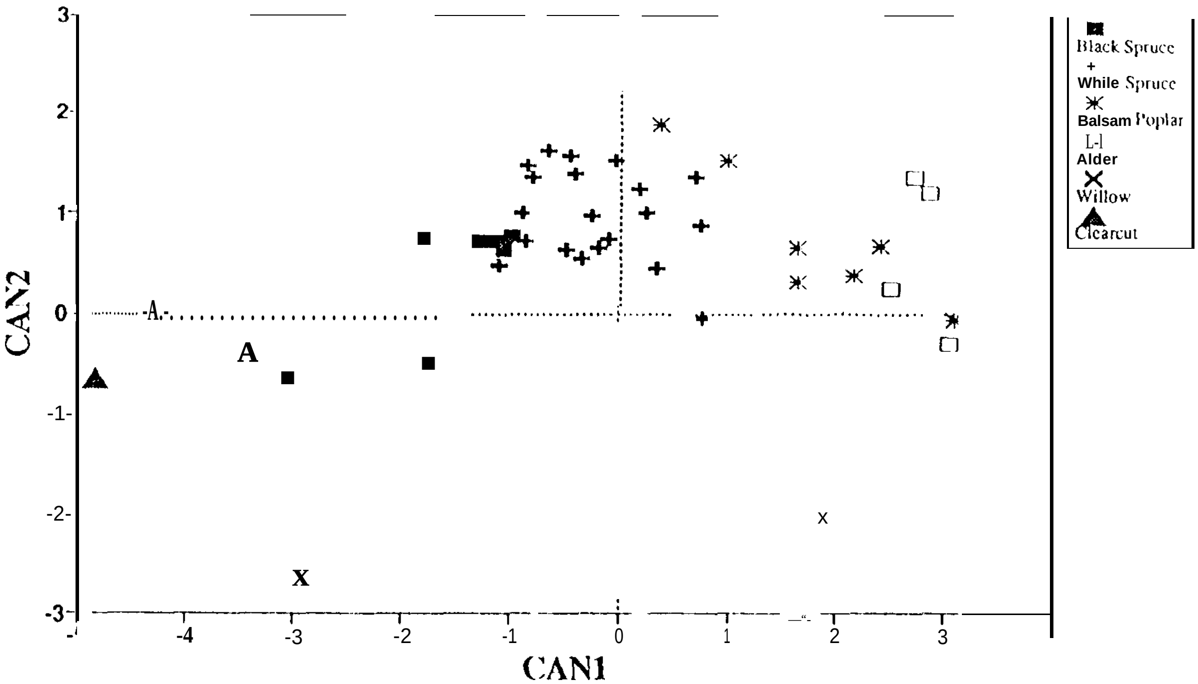

Fig. 3. Separation of six vegetation types of the Tanana River floodplain, Bonanza Creek LTER site. Discriminant analysis was applied to C-band AIRSAR backscatter, full polarization.

jams is most dramatic on the south side of the floodplain (top of figure); the north side of the floodplain is narrower and may show a steeper gradient as the river is being pushed north against adjacent uplands by the continued rise of the Alaska Range. Although in a year without ice jam formation, seasonal flooding typically affects treeless seasonal and permanent wetlands, most of the flooding caused here by ice jam formation is that of forested areas.

ERS-1 transects across Alaska provide examples of larger scale environmental monitoring with SAR (Rignot and Way 1994). Such transects show latitudinal differences across Alaska in freeze-thaw cycles, variation among years, and variation in abruptness of transitions between frozen and thawed slates. Spring snowmelt is identifiable, as distinctions among landscape components become blurred and images show reduced contrast. Likewise, wet snowfalls in early winter reduce image contrast.

Forest classification

Land cover of the world's boreal forests is composed of complex vegetation mosaics subject to periodic disturbance by wildfire, insect infestation, and riverine processes. Long-term monitoring of landscape change requires remote sensing of this mosaic of vegetation types and successional stages.

Discriminant analysis (Fig. 3) demonstrates the separability of successional stages in floodplain forests in interior Alaska using C-band full-polarimetric AIRSAR data Comparisons of single-channel classifications are possible with subsets of the AIRSAR data; C-band, HV-polarization consistently provides the best classifications (Table 1). Based on these classifications, none of the single-channel satellite-borne SARs was expected to classify forest types as accurately as *sensors* with cross. polarization. This prediction was tested for ERS-1 data. From AIRSAR data, classifications based on C-band, VV-polarization average 36% error; classifications based on ERS-1 data showed comparable accuracy: 46% on 25 April 1992 and 39% on 30 May 1992. Combining data from these two dates did not improve classification accuracy significantly.

A striking improvement in classification accuracy was obtained by combining AIRSAR C-band VV and HH polarization data with L-band HH polarization data. For this reason forest classifications based on images from ERS-1, JERS-1, and RADARSAT were expected to be 82% accurate, well within accuracy levels obtained with optical sensors (Williams and others 1993).

Similar classification accuracies have also been obtained on a pixel to pixel basis with a maximum *a posteriori* Bayesian classifier (Rignot and others 1994 b). With this classifier a combination of C-band HV and L-band HV yields the highest overall classification accuracy, with

Table 1. Error rates for single-channel classifications of vegetation types of the Tanana River floodplain. Discriminant analysis is applied to AIRSAR data both for classification and for accuracy assessment. Error rates are expressed as percentages of total numbers of stands.

Band/polarization	May 4	May 6	May 7	Mean
C/HV (consistently best)	18	11	13	14
C/VV (as in ERS-1)	26	50	33	36
C/HH (as in RADARSAT)	29	28	28	28
L/HH (as in JERS-1)	38	25	38	34

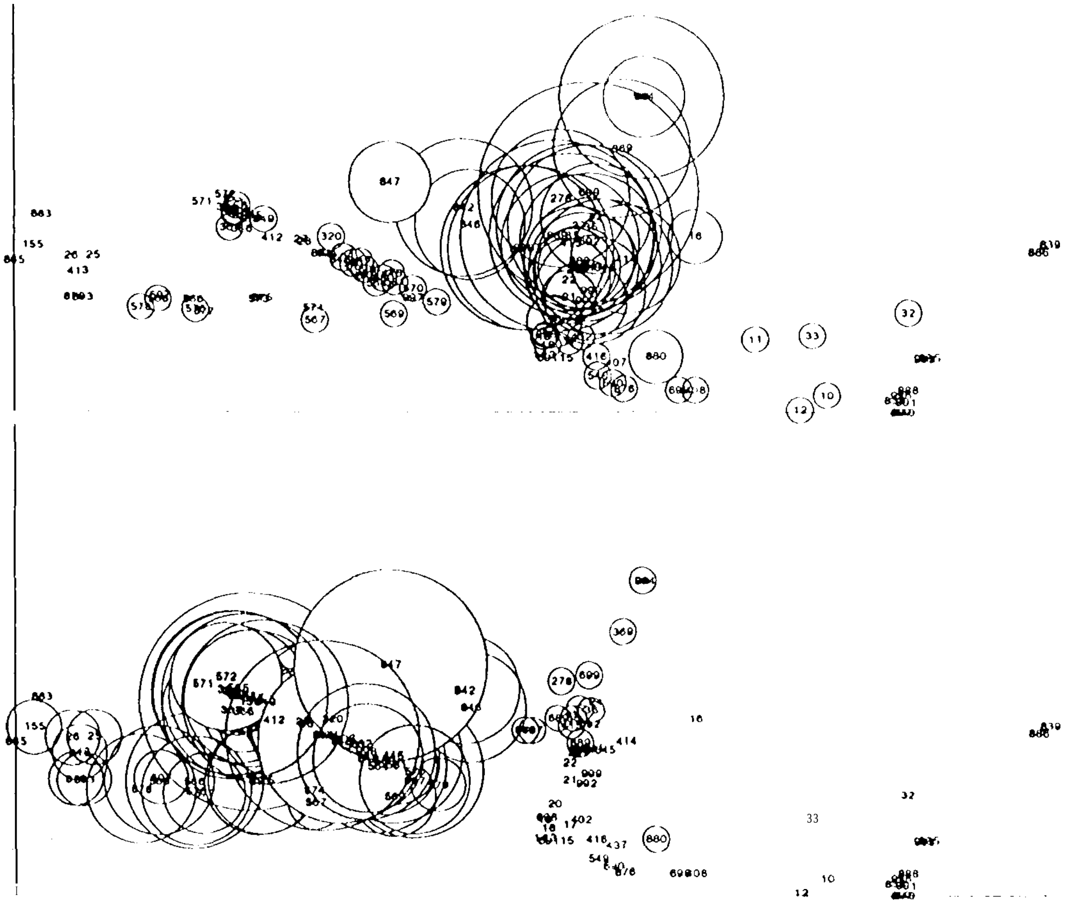

Fig. 4. DECORANA of tree and shrub vegetation for 120 Tanana River floodplain stands. Stands are represented by identification numbers. On each figure, distances between stands represent vegetational dissimilarity. Overlays for the top graph are *Populus balsamifera*; overlays for the bottom graph are *Picea glauca*. For each overlay, circle sizes represent percent cover in each stand for the chosen species.

10% error rates in the test stands (Table 2).

In addition, AIRSAR-based classifications showed potential as a means of identifying outlier or unusual forest stands, In Figure 4, detrended correspondence analysis (Hill 1979) of tree and shrub vegetation for 120 stands demonstrated that one stand (847), classified by discriminant analysis on different dates as either a balsam poplar or a white spruce stand, was in fact an intermediate stand with significant cover of both white spruce and balsam poplar.

Biomass estimation and prediction

Monitoring of biomass in boreal forests requires estimation of biomass levels exceeding 200 tonne ha^{-1}; biomass distributions are highly correlated with the distribution of successional stages on the landscape (Viereck and others 1993.1). AIRSAR imagery has been used to estimate and predict biomass in two ways, Direct estimation of biomass by inversion of regression curves relating backscatter to biomass for different available channels has proven especially useful at low biomass levels (Fig. 5; Rignot and others 1994c). Indirect estimation of biomass is underway using a model (Fig. 6) designed to incorporate existing long term data and ecological insight for the floodplain. This model combines classification of land cover with existing successional models, long-term photographic and field records, and known stand variations in biomass and productivity. Changes in the vegetation mosaic and in landscape-scale biomass can be projected into the past or the future (Fig. 7; Williams and others 1994).

Table 2. Confusion matrix resulting from vegetation classification with a maximum a *posteriori* Bayesian classifier (Rignot and others 1994 b). Percentages on the diagonal represent stands correctly classified into each vegetation) type. Column labelled 'From' designates identifications from ground-truth data. Overall error rate is 10%.

From\to:	CC	AL	BP	WS	BS	Water
Clearcut	78	0	0	0	2	0
Alder	0	68	3	1	1	0
Balsam poplar	0	31	89	6	0	0
White spruce	0	1	7	91	4	0
Black spruce	22	0	0	2	93	0
Water	0	0	0	0	0	100

Forest structure and function

Although landscape interpretation,

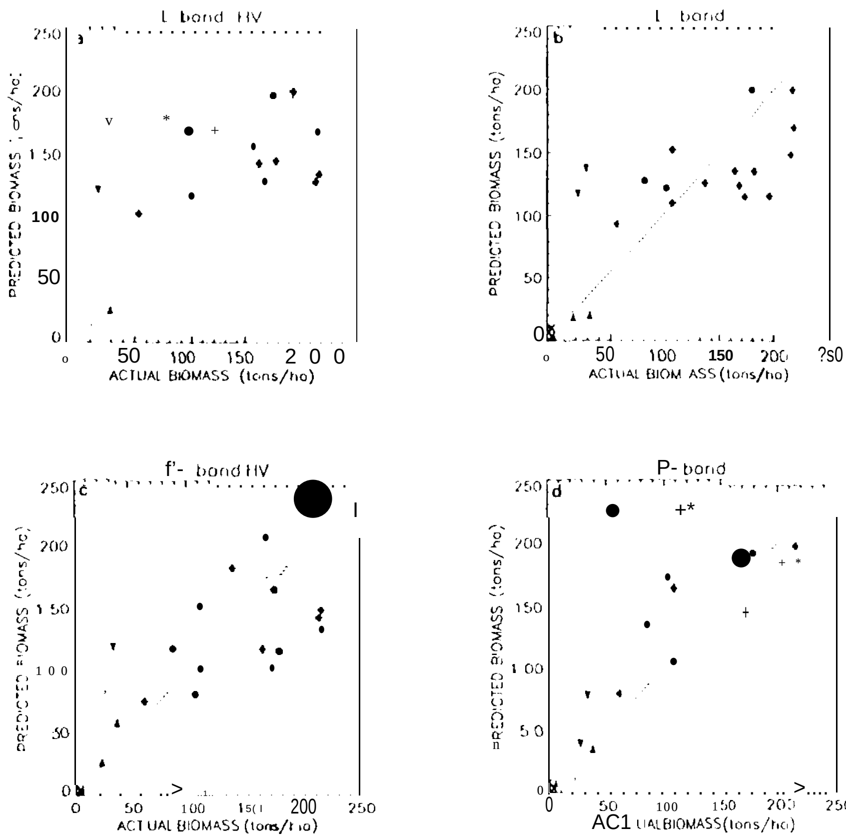

Fig. 5. Predicted biomass levels of forest stands from the Bonanza Creek Experimental Forest. Predictions were obtained from the following regressions relating logarithms of stand biomass to backscatter in decibels, where shv is backscatter of HV polarization, shh is backscatter of HH polarization, and svv is backscatter of VV polarization:

L-band HV: ln biomass = 9.204 + 0.200 shv -0.011 shv ^{2}

P-band HV: ln biomass = -3.372-1.408 shv -0,057 shv ^{2}

L band: ln biomass= 9.839-0.601 shv – 0.037 shv ^{2}-0.914 shh -- (),070. shh^2 + 2.396 SW + 0.150 SVV ^{2}

P band: ln biomass= 6.598-0.129 shv -0.007 shv ^{2}+ 0,370 shh + 0.011 shh ^{2} – 0.880 svv -0.050 Sw ^{2}

forest classification, and biomass estimation may be effective without understanding the exact relationships between backscatter and structure or function of biological systems, such understanding will ultimately become important for interpretation or predictions at larger spatial and temporal scales and under less controlled conditions. At Bonanza Creek, these relationships are being investigated with backscatter modelling and with physiological monitoring of dominant tree species. Backscatter modelling with the MIMICS model provides information about the kinds of structural and temporally changing biophysical properties that can be detected with spaceborne and airborne SAR (McDonald 1991). Physiological monitoring of three dominant tree species (*Picea glauca, Picea mariana, P opulus balsamifera*) has established linkages between water relations of [ret canopies. dielectric properties of vegetation, and radar backscatter (Zimmermann and others 1 994). The derived relationships between dielectric constant, xylem flux density, and water potential have potential utility for monitoring of forest health.

Summary and conclusions

This research has demonstrated applications for the usc of

Fig. 6. Model for mapping of biomass and productivity in boreal forests of interior Alaska (Williams and others 1994),

Successional model

Developed by Viereck and others 1960–present.

Provides transition probabilities as simple stochastic functions or as functions of stand age.

Long-term sites provide verification of transition probabilities.

Long-term aerial photographic records allow testing for projections of model back through time.

Classification of land cover

Maximum *a posterior* Bayesian classifiers and discriminant analysis on AIRSAR data classify land cover by forest type and successional stage

↓

Model projecting changes in vegetation mosaic through time

↓

Landscape scale biomass (and ultimately productivity) projections

Biomass and productivity measurements

large numbers of stands and stand types for which these have and will be measured provide mean values for successional stages and estimates of within-stage variation.

f or these stands, ages, species composition, and cover are also known.

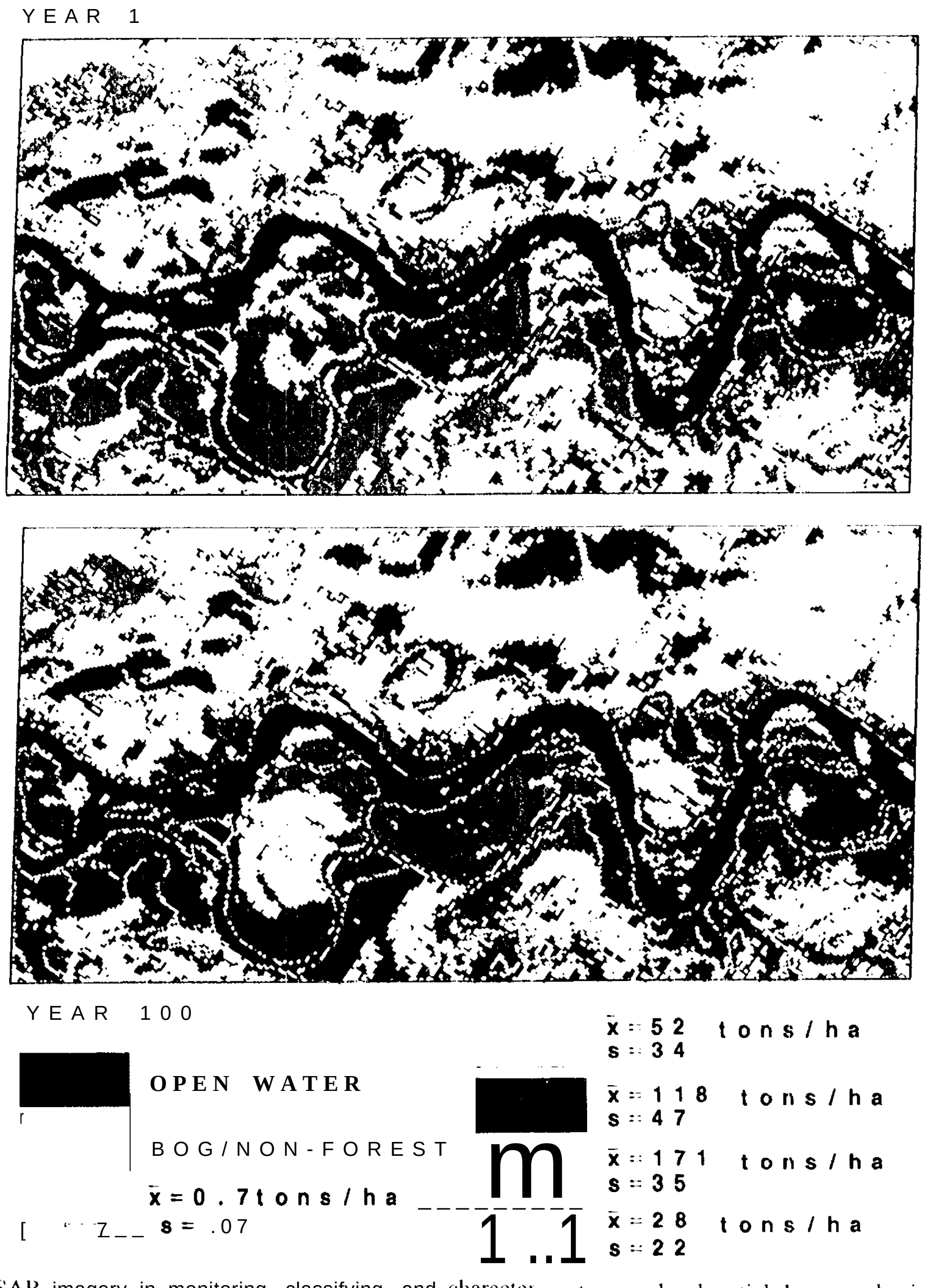

Fig. 7. Present and projected 100-year biomass distribution for the Tanana River floodplain, Bonanza Creek LTER site. This version of the model described in Figure 6 lacks algorithms for recruitment of early successional stages; photographic records will be used for this purpose, The land classification (Rignot and others 1994b) is from May 1991 AIRSAR imagery obtained during spring breakup; it shows an unusually high proportion of landscape as open water. After flooding subsides, most of the areas not in immediate proximity to the river are low biomass bog or black spruce forest. Biomass categories represent means and standard deviations of existing biomass measurements for the different successional stages.

SAR imagery in monitoring, classifying, and characterizing boreal forests of interim Alaska. Use of SAR imagery has obvious advantages in such regions, where there are long dark periods or frequent cloud cover, and where patterns of freezing and thawing of water have such dramatic ecological consequences. Both AIRSAR and ERS-1 images display geomorphological features and annual phonological cycles; flooding of forested and nonforested areas may also be distinguished, and patterns of snowmelt may reflect topography and vegetation pattern. Application of the MIMICS canopy-scattering model to forests at l{onan/aC'reck aids in interpretation of observed temporal and spatial changes; physiological monitoring is in place for the establishment of relationships between radar backscatter and canopy physiology.

Classification of at least five of the successional stages of floodplain forests is effective from AIRSAR imagery with both discriminant analysis and Bayesian classifiers; accuracy rates range between 80 and 90%. The availability of cross-polarization is important to these classifications; C-band HV and L-and C-band HV-polarization were the most useful combinations of sensors. As predicted from subsets of AIRSAR bands and polarizations, C-band VV-polarization data from ERS-1 was not su Tciently powerful for vegetation classifications, but the future combination of data from ERS-1, JERS-1, and RADARSAT may bc.

The successional stages distinguished by classification represent the full range of biomass and productivity in floodplain ecosystems. Landscape-scale mapping of biomass is underway, both directly by use of inversion equations and indirectly by using the strong correlations between successional stage and biomass. The relative precision and accuracy of these contrasting approaches arc currently under investigation. Use of successional stage classifications to map biomass is making possible projection of landscape-scale biomass patterns into the past or the future.

While continuing work has demonstrated the usefulness of SAR for a wide variety of ecological uses, SAR continues to be under-utilized in practical applications of these uses. An important next step is the development of funding mechanisms and data acquisition protocols making possible increased use of SAR imagery for ecological monitoring and for land management pur-poses.

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