The ecological implication of such a climatic change is particularly important because experiments with NASA's DC-8 aircraft were acquired over the BCEF at 8.65 and 19.35 GHz, respectively. Quad polarized AIRSAR mounted on JPL's P-, L- and C-band (.450, 1.26 and 5.31 GHz, respectively) were used to generate the expected backscatter over a range of multi-temporal changes in radar backscatter using the JPL aircraft synthetic aperture radar (AIRSAR). This indicates it is possible to use spaceborne imaging radars such as the European Space Agency's (ESA's) Earth Remote Sensing (ERS-1) synthetic aperture radar (SAR) to monitor both phenologic and environmental change in forests, as well as map forest species by taking advantage of seasonal forest signatures. These results also demonstrate the importance of knowing the seasonal state of the forest when estimating canopy properties from SAR.

**TEST SITE AND AIRSAR DATA SET**

In order to determine the feasibility of using imaging radars to monitor the seasonal cycles of boreal forests and map forest types, experimental work is ongoing at the Bonanza Creek Experimental Forest (BCEF) just southeast of Fairbanks, Alaska. The site is a floodplain succession forest consisting primarily of balsam poplar, white spruce and black spruce. Approximately 30 stands in BCEF have been identified for this study. To date, canopy characteristics have been collected for 12 stands.

Airborne SAR data using the Jet Propulsion Laboratory's (JPL's) P-, L- and C-band (.450, 1.26 and 5.31 GHz, respectively) quad polarized AIRSAR mounted in NASA's DC-8 aircraft were acquired over the BCEF test site on March 13, March 17 and March 19, 1988. The data were calibrated radiometrically to +/-1.9 dB. The measured difference in L-band backscatter for the frozen and thawed days for the 12 stands and two clearcuts is large (2-6 dB) at all three polarizations with the greatest difference at vertical and cross polarizations. A large change in the bole dielectric constant between warm and frozen conditions can account for the large change in backscatter.

**PREDICTED SEASONAL MICROWAVE SIGNATURES**

A process-oriented ecophysiological model that summarizes our current understanding of productivity and decomposition in boreal forests has recently been developed (Bonan 1991a,b). This model requires stand level physiological measurements as well as characterization of the spatial (in terms of forest species) and temporal (in terms of phenologic and environmental state) patterns for validation. Recent results of radar signature modelling and measurement of multi-temporal changes in radar backscatter using the JPL aircraft synthetic aperture radar (AIRSAR) indicate it is possible to use spaceborne imaging radars such as the European Space Agency's (ESA's) Earth Remote Sensing (ERS-1) synthetic aperture radar (SAR) to monitor both phenologic and environmental change in forests, as well as map forest species by taking advantage of seasonal forest signatures. These results also demonstrate the importance of knowing the seasonal state of the forest when estimating canopy properties from SAR.

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IMPLICATIONS FOR FOREST SPECIES CLASSIFICATION

The above results indicate that it is possible to monitor both phenologic and environmental change in Alaskan forests and that, by using a variety of seasonal states, it is possible to map the major forest species along the floodplain. Using the AIRSAR scene of BCEF, the ability to monitor change and map species has been demonstrated using a semi-operational geophysical processor similar to the one developed by the ice community for determining ice type and motion with ERS-1 data over the polar regions (Kwok et al. 1990a; Kwok et al. 1990b).

Using only the L-band HH results, the following classification units could be identified for WS/BP as a single forest unit:

\[-9.8 \, \text{dB} < \sigma_0 < -7.5 \, \text{dB}\]  \quad \text{thawed WS/BP, (1)}

\[-13.5 \, \text{dB} < \sigma_0 < -9.8 \, \text{dB}\]  \quad \text{frozen WS/BP (2)}

and for BS as a single unit:

\[-13.7 \, \text{dB} < \sigma_0 < -10.7 \, \text{dB}\]  \quad \text{thawed BS (3)}

\[-15.1 \, \text{dB} < \sigma_0 < -13.7 \, \text{dB}\]  \quad \text{frozen BS. (4)}

Frozen and thawed WS/BP stands were identified using the original AIRSAR data as input and equations (1) and (2). On March 13, thawed WS/BP stands were correctly identified; thawed BS stands were mistaken for frozen WS/BP stands. On March 19, all WS/BP stands were correctly identified as frozen; most BS stands were outside the limits specified for frozen or thawed WS/BP. Frozen and thawed BS were identified using equations (3) and (4). On March 13, thawed BS stands were correctly identified. Thawed WS/BS stands were outside the limits set for frozen and thawed BS. On March 19, frozen BS stands were correctly identified, however, WS/BP stands were identified as thawed BS. These results illustrate the use of SAR to monitor freeze/thaw conditions at L-band HH.

The AIRSAR data was then segmented into classes/regions corresponding to different stands (Rignot 1990). An empirical look-up table of the backscatter characteristics of the different forest stands was then used to assign a forest type to each cluster. Finally, the entire image was classified using a minimum distance discriminant function. The results obtained using L-band HH data on March 13 produced four classes separated by more than 2.5 dB. Using the look-up table, the brightest class was identified as representing WS/BP, whereas the others represent BS, CC and RIVER, respectively. The separation of WS/BP and BS is clear and matches very well with the available ground map of WS/BP and BS.

IMPLICATIONS FOR MODELLING CARBON FLUX IN ALASKA

This ability to classify forest species and monitor environmental and phenologic stages ERS-1 data can be interfaced with Bonan's ecophysiological model in two ways using ERS-1 data. First, spatial and temporal estimates of forest physiology derived from ERS-1 data can provide critical data needed to better validate the ecophysiological model. For example, ERS-1 data can be used to distinguish when the ground and tree stem are frozen or thawed, both of which are simulated by the ecophysiological model. Additional physiological parameters such as foliage water potential may also be estimated from ERS-1 data. Second, the forest landscape near Fairbanks is a mosaic of vegetation types that reflects fire history, successional differences in litter quality, nutrient availability, soil temperature, the forest floor and stand structure and life-history characteristics of tree species. Remotely-sensed areal estimates of particular forest types (e.g., black spruce, deciduous, etc.) can be combined with the model to scale stand-level CO2 fluxes to landscape-average fluxes.

The percent areal extent of WS/BP, BS, CC and RIVER was estimated using the classified AIRSAR scene from March 13; the scene contains 30.6% WS/BP, 32.0% BS, 24.7% CC and 12.7% RIVER (Table 1). The annual CO2 flux for each of these landscape types was then simulated using Bonan's ecophysiological model (1991b). Table 1 shows the tree, moss, microbe and total ecosystem CO2 fluxes where a negative flux indicates CO2 uptake. The net annual landscape flux of the BCEF floodplain forest is estimated at -7100 g m\(^{-2}\) yr\(^{-1}\).

SUMMARY

With the launch of ERS-1 in the spring of 1991 followed by JERS-1, RADARSAT and eventually the EOS SAR, the opportunity to begin long-term monitoring of seasonal phenologic and environmental change for use in ecophysiological and CO2 flux models should allow important advances in our understanding of the role of the boreal forests in the global carbon cycle.

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| Stand    | Area   | Tree  | Moss  | Microbe | Ecosystem |
|----------|--------|-------|-------|---------|-----------|
| WS/BP    | 30.6%  | -2204 | -108  | 418     | -1894     |
| BS       | 32.0%  | -354  | -200  | 171     | -383      |
| CC       | 24.7%  | 0     | -200  | 171     | -29       |
| RIVER    | 12.7%  | 0     | 0     | 0       | 0         |
| Landscape| 100.0% | -788  | -146  | 225     | -710      |

Note: Negative fluxes indicate CO₂ uptake, positive fluxes indicate CO₂ release.