PROJECT TITLE: Monitoring Boreal Land cover and Ecosystem Dynamics at Regional Scales Using Integrated Space Borne Radar Remote Sensing and Ecological modeling.

Project IDs: NAG5-9333, NAG5-9315

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MAJOR FINDINGS

This report covers science team activities for the final year (2003) of our NASA LCLUC investigation, which includes activities carried out under projects NAG5-9333 and NAG-9315, and extends work reported in our previous annual reports. The objective of this project was to develop an improved boreal forest monitoring framework, consistent with the objectives of the Global Observation of Forest Cover (GOFC) program, combining (1) a SAR-based land cover map that partitioned the landscape into ecologically distinct classes; (2) monitoring of seasonal freeze/thaw dynamics with spaceborne scatterometers to better quantify landscape phenology; and (3) an ecosystem simulation model to quantify carbon flux dynamics on regional scales. The scope of this investigation combined mapping and monitoring of boreal land cover with ecological modeling for assessment of regional and continental scale carbon flux dynamics. The domain for this study encompassed the BOREAS study region of central Canada, Alaska and the pan-Arctic basin.

We evaluated whether satellite radar remote sensing of landscape seasonal freeze-thaw cycles provides an effective measure of active growing season timing and duration for boreal ecosystems (Kimball et al., 2004b). Landscape daily radar backscatter measurements from the SeaWinds scatterometer on-board QuikSCAT were evaluated across a regional network of North American coniferous forest sites for 2000 and 2001. Our results show that the onset of the growing season, as indicated by ground-based sap flow and CO₂ flux measurements, is relatively abrupt and coincides with the influx of snow melt water into previously frozen soils in spring. Cessation of the growing season
in the fall, however, appears to coincide with decreases photoperiod and mean daily temperatures below approximately 1-3°C. Ku-band daily radar backscatter measurements from SeaWinds effectively bound the seasonal non-frozen period between initiation of snow melt in spring and snow pack arrival and seasonal freezing of vegetation and soil in fall. Radar remote sensing measurements of the initiation of the growing season corresponded closely with both site measurements and ecosystem process model (BIOME-BGC) simulations of these parameters because of the sensitivity of the Ku-band scatterometer to snow cover freeze-thaw dynamics and associated linkages between growing season initiation and the timing of seasonal snowmelt and thawing of surface soil layers. In contrast, remote sensing estimates of the timing of growing season termination were either weakly or not significantly associated with site measurements and model simulation results due to the relative importance of light availability and other environmental controls on stand phenology in the fall. Regional patterns of estimated annual net primary production (NPP) and component photosynthetic and autotrophic respiration rates for boreal evergreen forest sites also corresponded favorably with remote sensing estimates of the seasonal timing of spring thaw and associated growing season onset, indicating the importance of these parameters in determining spatial and temporal patterns of NPP and the potential utility of satellite radar remote sensing for regional monitoring of the terrestrial biosphere. The results of this study indicate that boreal forests sequester approximately 1% of annual NPP on a daily basis immediately following initiation of the growing season in spring. In contrast, boreal forests sequester less than 1% of annual NPP on a daily basis just prior to the end of the growing season in fall due to low temperatures and limited photo-period. Thus any errors in classifying freeze-thaw state dynamics have a 3-fold greater impact on estimated carbon cycle dynamics in the spring relative to the fall. These results demonstrated the utility of high-repeat (e.g., daily) satellite microwave remote sensing of landscape freeze-thaw processes for monitoring growing season and associated boreal carbon cycle dynamics.

We conducted a temporal classification of satellite remote sensing daily brightness temperatures from Special Sensor Microwave Imager (SSM/I) series observations for boreal regions of North America (McGuire et al., 2003) and the Pan-Arctic basin and Alaska (McDonald et al., 2004) to determine spatial patterns, annual variability and long-term trends in the timing of spring thaw events from 1988 to 2001. The results of this investigation indicate that the timing of seasonal thawing and subsequent initiation of the growing season in early spring has advanced by approximately 8 days from 1988 to 2001 for the pan-arctic basin and Alaska. These trends are highly variable across the region with North America experiencing a larger advance relative to Eurasia and the entire region. Interannual variability in the timing of spring thaw as detected from the remote sensing record corresponded directly to seasonal anomalies in mean atmospheric CO₂ concentrations for the region, including the timing of the seasonal draw down of atmospheric CO₂ from terrestrial NPP in spring, and seasonal maximum and minimum CO₂ concentrations. The timing of seasonal thaw for a given year was also found to be a significant (P < 0.01) predictor of the seasonal amplitude of atmospheric CO₂ for the following year. These results imply that the timing of seasonal thawing in spring has a major impact on terrestrial NPP, net carbon exchange and atmospheric CO₂ concentrations at high latitudes (>50°N). The initiation of the growing season has also
been occurring earlier, on average, since 1988 and may be a major mechanism driving observed atmospheric CO₂ seasonal cycle advances, vegetation greening and enhanced productivity for the northern high latitudes.

To clarify relationships between growing season onset as defined from the satellite microwave remote sensing record and NPP, we applied a satellite remote sensing based Production Efficiency Model (PEM) to calculate regional patterns and annual anomalies in terrestrial NPP using daily meteorological information from the NCEP Reanalysis and mean monthly LAI and FPAR information from the NOAA AVHRR Pathfinder product (Kimball et al., 2004c). Our results show a general decadal trend of increasing NPP for the region of approximately 2.7 %, with respective higher (3.4 %) and lower (2.2 %) rates for North America and Eurasia. NPP is both spatially and temporally dynamic for the region, driven largely by differences in productivity rates among major biomes, and temporal changes in photosynthetic canopy structure and spring and summer air temperatures. Mean annual NPP for boreal forests was approximately 3 times greater than for Arctic tundra on a unit area basis and accounted for approximately 55 % of total annual carbon sequestration for the region. Variability in maximum canopy leaf area and NPP also correspond closely to microwave remote sensing observations of the timing of the primary seasonal thaw event in spring. Relatively early spring thawing appears to enhance NPP, while delays in seasonal thawing and growing season onset reduce annual vegetation productivity. These results show that advances in seasonal thawing and spring and summer warming for the region associated with global change are promoting a general increase in NPP and annual carbon sequestration by vegetation at high latitudes, partially mitigating anthropogenic increases in atmospheric CO₂. These results also imply that regional sequestration and storage of atmospheric CO₂ is being altered, with potentially greater instability and acceleration of the carbon cycle at high latitudes.

We conducted an investigation of multi-sensor Radar backscatter sensitivity to spring thaw dynamics with respect to landscape complexity using Quikscat scatterometer (Ku-band, 25km spatial resolution), ERS (C-band, VV polarization, 200m spatial resolution) and JERS-1 (L-band, HH polarization, 100m spatial resolution) Synthetic Aperture Radar (SAR) data during spring thaw transitions in complex boreal landscapes of Alaska. ERS and JERS SAR temporal backscatter characteristics were evaluated under variable land cover and topographic slope, aspect and elevational characteristics. We performed a multi-scale analysis of SAR and scatterometer measurements to assess trade-offs in spatial and temporal resolution for detecting spring thaw transitions. The time series SAR and scatterometer based freeze-thaw and land cover classifications were verified from a network of surface temperature and biophysical monitoring sites. Our results show that while the relatively coarse resolution SeaWinds Ku-band backscatter data capture regional freeze-thaw state transitions there is substantial sub-grid scale spatial heterogeneity during the spring thaw transition period that is better resolved using higher spatial resolution SAR data. Both JERS and ERS time series backscatter data were sensitive to landscape spring thaw transitions, which varied according to land cover type, fire disturbance history and topography. South facing slopes and lower elevations tend to thaw earlier in spring than north facing slopes and upper elevations. Additionally, boreal broadleaved deciduous forests tend to occupy sites that thaw earlier in spring, while
boreal evergreen coniferous stands occupy colder sites that thaw later in the season. The SARs also distinguished differences in the timing of freeze/thaw transitions associated with varying fire disturbance regimes and vegetation successional states. Recent burn sites, for example, tended to thaw earlier than older, established forest stands. Seasonal time series of JERS backscatter data showed larger transitional dynamic ranges than ERS data and were more sensitive to freeze-thaw spatial heterogeneity. These findings demonstrate the need to consider landscape heterogeneity when applying remote sensing techniques for monitoring freeze-thaw and phenological processes in boreal ecosystems. They also identify freeze-thaw state as an indicator of biophysical constraints (e.g., low temperature, soil moisture and growing season length) to boreal vegetation community structure and distribution.

**IMPACT AND FUTURE WORK**

A major goal of this project has been to improve the characterization of seasonal carbon dynamics at high latitudes by utilizing the unique information provided by satellite microwave remote sensing. We have conducted studies integrating radar-based freeze-thaw information from a variety of sensors within an ecosystem model framework for regional and temporal assessment of the boreal carbon cycle. Our results show that satellite radar remote sensing provides relatively unique and spatially explicit information regarding land cover type, vegetation structure and energy state that can improve regional assessment and monitoring of boreal carbon cycle dynamics. We have found that the onset of the growing season as detected by spaceborne active/passive microwave remote sensing primarily determines the timing of seasonal snowmelt and the relaxation of thermal and moisture constraints to photosynthesis and vegetation productivity. Interannual variability in the timing of these events has a major impact on annual productivity and atmospheric CO₂ concentrations at high latitudes. Timing of the growing season also appears to be advancing with global warming and may be a major mechanism driving increased vegetation productivity, seasonal advances in atmospheric CO₂ cycles and terrestrial sink strength for atmospheric carbon.

The landscape freeze-thaw variable as detected from a variety of satellite microwave sensors is an effective surrogate for surface energy state and biophysical controls on canopy conductance, vegetation growth, productivity and surface-atmosphere CO₂ exchange. Daily monitoring capabilities provided by satellite scatterometers and radiometers capture regional patterns and temporal dynamics in freeze-thaw state and growing season variables and provide effective measures of annual variability in NPP and atmospheric CO₂ concentrations. Relatively high spatial resolution SAR’s are more effective at resolving sub-grid scale spatial complexity in land cover, topography and associated freeze-thaw state dynamics. However, the relatively coarse temporal fidelity of current generation SAR’s prohibit effective monitoring of freeze-thaw dynamics and associated carbon cycle linkages over large regions. This study has provided a valuable contribution to the justification and development of a next generation satellite active and passive microwave sensor (HYDROS; [http://hydros.gsfc.nasa.gov](http://hydros.gsfc.nasa.gov)) that is currently scheduled for launch in 2010. HYDROS is a new NASA Pathfinder mission dedicated to global assessment and monitoring of soil moisture and freeze-thaw state (Entekhabi et al.,
HYDROS will provide longer wavelength, L-band, surface backscatter information and 1-3 day repeat monitoring capabilities at spatial scales of 3km or less at high latitudes for superior detection and monitoring of boreal freeze-thaw state dynamics.

Future studies should consider relationships between disturbance (fire, insect) history and associated land cover change impacts to carbon, energy and hydrologic budgets, as well as linkages to recent changes in seasonal growing seasons and NPP. Observational records over the last 50 years indicate that fire activity increased substantially during the 1970s and 1980s for North American boreal forest in association with a warming climate (e.g., McGuire et al. 2003). The successional pattern following stand replacing fires in North America is generally one of herbaceous vegetation and deciduous shrubs followed by relatively productive mixed deciduous and coniferous forests dominated by aspen, birch and white spruce replacing lower productivity stands dominated by more fire prone black spruce and moss vegetation. We have found regional fire disturbance to have major impacts on both boreal carbon and hydrologic cycles (Kang et al., 2004). The most significant increases in recent NPP trends occur in regions of northwestern Canada and central Alaska that have also experienced both increased fire activity and growing season length. Spring and summer warming trends that appear to be enhancing growing seasons and regional NPP may also be enhancing regional fire activity. Satellite observations of increased NPP and advancing growing seasons also indicate a potential positive feedback to increased fire activity through additional vegetation biomass accumulation and associated fuel loading for fires. Increased fire activity may also be a mechanism driving enhanced NPP for the region, since fires increase soil nutrient availability to plants by promoting earlier seasonal thawing, warmer soils and deeper soil active layer depths, as well as replacing older and less productive stands with younger, more productive vegetation. Longer growing seasons and warmer temperatures may also be promoting increased fire activity by creating drier conditions through increased ET. Thus satellite evidence of increasing growing seasons and enhanced productivity may be both a causal mechanism and response to increasing fire activity. Further research is needed to clarify these relationships.

TEAM ACTIVITIES

Meetings attended:
October 14-18, 2002; IARC Circum-Pacific Carbon Meeting, Oahu HI.
October 27-28, 2002; NSF ATLAS Synthesis Workshop, Victoria CN.
June 18-21, 2003; IARC Carbon Synthesis Workshop, Skogar Iceland.
October, 2003; NSF SEARCH Open Science Meeting, Seattle WA.

Professional Publications:


**Papers and Posters Presented at Meetings:**


Figure 1: Mean annual NPP and primary thaw date as derived from the NOAA AVHRR Pathfinder and SSM/I for Alaska and northwest Canada. Both NPP and primary thaw timing correspond strongly to regional land cover, topography and latitude. Higher latitudes and upper elevations show generally lower NPP and delays in spring thaw timing relative to lower latitudes and elevations. Boreal forests also show both higher productivity and earlier seasonal thawing than arctic tundra. Masked areas are shown in gray and represent unvegetated surfaces including permanent ice and snow, open water and barren land.
Correspondence Between Satellite Remote Sensing Derived Annual NPP (AVHRR Pathfinder) and Spring Thaw Timing (SSM/I) for the 1988-2000 Period.

**Figure 2:** Correspondence between annual anomalies of AVHRR Pathfinder derived NPP and maximum annual LAI (LAI_{mx}), and SSM/I derived spring thaw timing for Alaska and northwest Canada. Years with earlier seasonal thawing are associated with increased vegetation growth, while relative delays in seasonal thawing promote reduced productivity.
Figure 3: Relationship between NOAA CMDL station network measurements of the spring 0-ppm crossing date of the seasonal atmospheric CO2 cycle and pan-Arctic average thaw date anomalies derived from SSM/I AM and PM node data. The timing of the spring 0-ppm crossing of the normalized monthly CO2 concentration curve for high latitude CMDL stations is used here as a surrogate for growing season initiation (McDonald et al., 2004). Timing of primary thawing in spring as derived from the SSM/I corresponds significantly to the timing of growing season initiation as inferred from the seasonal pattern of high latitude atmospheric CO2 concentrations. Earlier seasonal thawing corresponds with earlier onset of the growing season at high latitudes, while delayed seasonal thawing promotes the opposite response. The PM node results show a stronger correspondence to growing season dynamics than AM node results.

(McDonald et al., Earth Interactions, 2004)
Figure 4: Relationship between NOAA CMDL station network measurements of growing season length as defined by the period between spring and fall 0-ppm crossing dates of the normalized seasonal atmospheric CO2 cycle, and pan-Arctic average thaw date anomalies derived from temporal classification of SSM/I daily (PM node) data. The period between the spring/fall 0-ppm crossings of the normalized monthly CO2 concentration curve for high latitude CMDL stations is used here as a surrogate for growing season length (McDonald et al., 2004). Timing of primary thawing in spring as derived from the SSM/I corresponds significantly to the timing of growing season length as inferred from the seasonal pattern of high latitude atmospheric CO2 concentrations. Earlier seasonal thawing corresponds with longer growing seasons at high latitudes, while delayed seasonal thawing promotes the opposite response. An apparent anomaly is observed shortly after the 1991 Pinatubo volcanic eruption. A relative delay in growing season onset coincided with a substantially longer growing season. Pinatubo is known to have caused short-term global cooling, which may reduced respiration relative to photosynthesis resulting in a longer seasonal duration of net CO2 sink activity at high latitudes.
Figure 5: Spatial patterns of NPP and spring thaw trends for the pan-Arctic basin and Alaska as derived from NOAA AVHRR Pathfinder and SSM/I based satellite remote sensing. Masked areas are shown in gray and represent unvegetated surfaces including permanent ice and snow, open water and barren land.