Remote Sensing of Environment 113 (2009) 1868–1873

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Effects of soil moisture and water depth on ERS SAR backscatter measurements from an Alaskan wetland complex

Eric S. Kasischke [a,*], Laura L. Bourgeau-Chavez [b], Allison R. Rober [c], Kevin H. Wyatt [c], James M. Waddington [d], Merritt R. Turetsky [e,1]

[a] Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, Maryland, United States
[b] Michigan Tech Research Institute, Ann Arbor, Michigan, United States
[c] Department of Zoology, Michigan State University, East Lansing, Michigan, United States
[d] School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario, Canada
[e] Department of Plant Biology, Michigan State University, East Lansing, Michigan, United States

ARTICLE INFO

Article history:
Received 6 November 2008
Received in revised form 15 April 2009
Accepted 17 April 2009

Keywords:
Wetlands
Boreal region
Synthetic aperture radar
Water level
Soil moisture
Hydrology

ABSTRACT

We conducted a preliminary investigation of the response of ERS C-band SAR backscatter to variations in soil moisture and surface inundation in wetlands of interior Alaska. Data were collected from 5 wetlands over a three-week period in 2007. Results showed a positive correlation between backscatter and soil moisture in sites dominated by herbaceous vegetation cover ($r = 0.74$, $p < 0.04$). ERS SAR backscatter was negatively correlated to water depth in all open (non-forested) wetlands when water table levels were more than 6 cm above the wetland surface ($r = -0.82$, $p < 0.001$). There was no relationship between backscatter and soil moisture in the forested (black spruce-dominated) wetland site. Our preliminary results show that ERS SAR data can be used to monitor variations in hydrologic conditions in high northern latitude wetlands (including peatlands), particularly sites with sparse tree cover.

1. Introduction

The North American boreal region contains extensive areas of peatlands and other wetland types. Globally, northern peatlands are estimated to cover between 3.3 and 3.5×10^6 km^2, or nearly a quarter, of the boreal forest region (Vitt, 2006; Wieder et al., 2006). Peatlands have served as long-term sinks for atmospheric carbon dioxide (CO_2) and today serve as an important global carbon reservoir, containing an estimated 270–370 Pg of carbon or approximately one-third of the world's soil carbon (Gorham, 1991; Vasander & Kettunen, 2006).

Peat accumulates where net primary production exceeds carbon losses due to decomposition, dissolved export, and/or disturbance. Slow decomposition rates under cool temperatures and saturated conditions are thought to serve as one of the most important controls on rates of peat accumulation. Generally, spatial and temporal fluctuations in water table position control a number of important processes in northern wetlands, including plant community composition, the exchange of both CO_2 and methane (CH_4), runoff, and nutrient cycling and export. Water table position also creates feedbacks with the formation and degradation of permafrost that affect ecosystem structure and function (Vitt, 2006; Yi et al., 2007; Turetsky et al., 2007).

Over the past several decades, high latitude regions have experienced rapid climate change that has resulted in changing precipitation, soil warming, permafrost degradation, snow pack thickness, and growing season length (Hinzman et al., 2005). In general, warmer temperatures and increased evapotranspiration with climate change is expected to cause surface drying and lowering of water table positions in most northern wetlands. There has already been a recent decline in the surface area of open water bodies in wetland complexes throughout much of interior Alaska (Riordan et al., 2006). This wetland contraction is likely associated with increased summer water deficits with increased evapotranspiration, or drainage associated with permafrost thaw (Oechel et al., 2000, Hinzman et al., 2005).

In temperate regions, researchers have demonstrated that spaceborne, C-band (~6 cm wavelength) SAR data can be used to monitor variations in hydrologic conditions in both forested (Townsend, 2001; Bourgeau-Chavez et al., 2001; Lang & Kasischke, 2008; Lang et al., 2008) and non-forested wetlands (Kasischke & Bourgeau-Chavez 1997; Kasischke et al., 2003; Bourgeau-Chavez et al., 2005). In contrast, only a few studies have assessed the potential for remotely-sensed hydrologic monitoring in

* Corresponding author. Tel.: +1 301 405 2179; fax: +1 301 314 9299.
E-mail address: ekasisch@umd.edu (E.S. Kasischke).
[1] Currently with Department of Integrative Biology, University of Guelph, Guelph, Ontario, Canada.

0034-4257/$ – see front matter
doi:10.1016/j.rse.2009.04.006

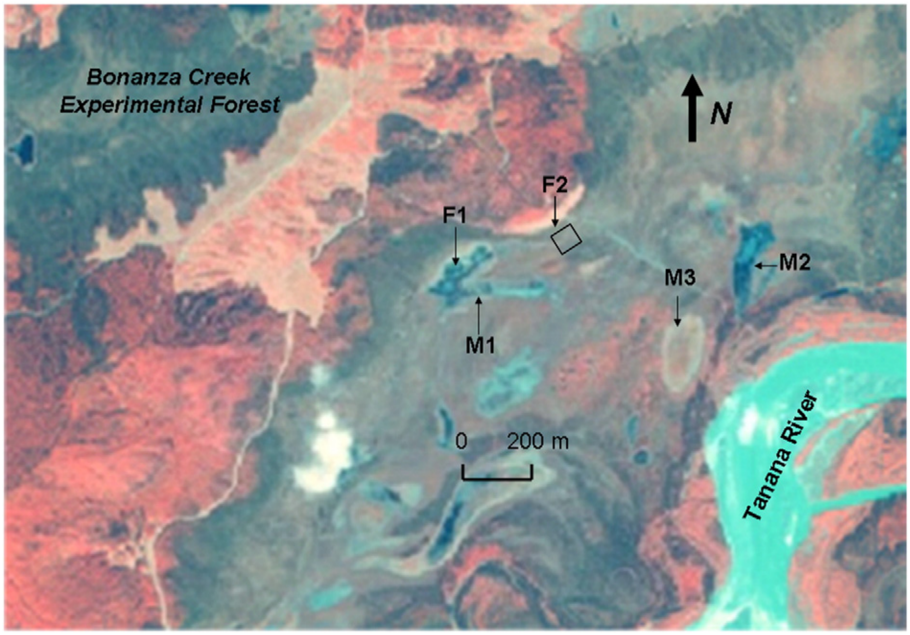

Fig. 1. Aerial photograph outlining the location of the five wetland study sites.

northern high latitude ecosystems. Morrissey et al. (1994, 1996) showed that ERS SAR data could be used to monitor variations in surface inundation in regions dominated by wet tundra. Several studies have focused on using time-series ERS and Radarsat C-band SAR data to improve mapping of different categories of boreal wetlands and peatlands (Li et al., 2007; Bartsch et al., 2007; Touzi et al., 2007; Racine et al., 2005) and Sass and Creed (2008) showed that the microwave backscatter from the ERS SAR was correlated with variations in surface moisture and inundation in a peatland complex in central Alberta.

Here, we present the results of a preliminary study of variations in ERS C-band SAR backscatter in several wetlands located in central Alaska. Our goal was to assess relationships between ERS backscatter and fluctuations in water table position and surface soil moisture over a 3 week period in the growing season of 2007.

2. Methods

2.1. Study sites

Our research was carried out in 5 wetland sites located just outside of the boundary of the Bonanza Creek Experimental Forest (35 km southeast of Fairbanks, Alaska) on the Tanana River floodplain (Figs. 1 and 2). Our study sites were located in two fens (minerotrophic peatlands with > 40 cm of peat), and three marshes (non-treed wetlands

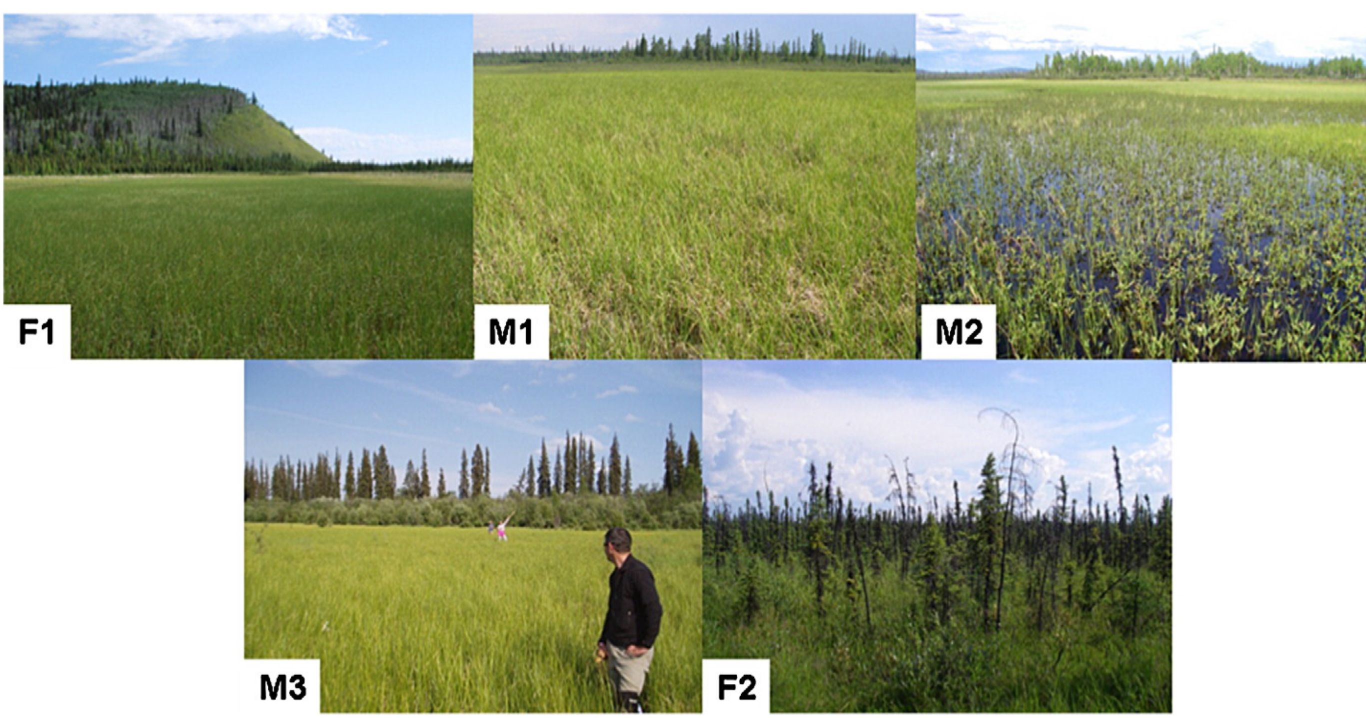

Fig. 2. Suface photographs of the five sites used in the study.

with<40 cm of peat). The first site (F1) is a moderately rich fen with surface water pH ranging from 4.61–5.48. This site is dominated by emergent marsh vegetation including *Equisetum*, *Carex*, and *Potentilla* species while the moss community is dominated by brown moss species. Peat thickness exceeds 1 m at this site. This site is currently being used for the Alaska Peatland Experiment and is described in more detail in Turetsky et al. (2008). The second site (M1) is located approximately 50 m from F1, and has surface water pH ranging from 5.73–6.22. This site did not have 40 cm or more of peat, and is thus classified here as a marsh system. The dominant vegetation is shorter tussock grasses, where inter-tussock spaces tended to be saturated. The third site (M2) is also classified as a marsh system, and is dominated by emergent vegetation including *Carex* and *Equisetum* species as well as *Menyanthes trifoliate* (Buck Bean). This site has a very thin layer of organic soil on top of the mineral soil layer, and is characterized by extreme annual hydrologic changes likely linked to river flow conditions. Surface water pH in this site ranged from 5.19–6.60. The fourth site (M3) is a tall tussock marsh system with surface water pH ranging from 6.03–6.44. As in M1, inter-tussock spaces tend to be saturated. This site has very little organic soil on top of a thick mineral soil A layer. The fifth site (F2) is a forested fen, with vascular species dominated by *Picea mariana* (black spruce), *Ledum groenlandicum* (Common Labrador Tea), and *Oxycoccus microcarpus* (Small Bog Cranberry). The moss layer is patchy and dominated by a variety of *Sphagnum* species. There is approximately 30 cm of peat at this site directly on top of the permafrost table (total peat depth is unknown due to the frozen conditions). While surface organic soils can be very wet at this site, there is typically no visible standing water on top of the moss surface.

2.2. Field data collection

At each of the 5 sites, we established two ~200 m, parallel transects separated by 50 m. Sampling points were located on each transect every 50 m. At site F1, we also established sample points every 25 m along a boardwalk that transected this site. On the days of the ERS SAR overpasses (June 24, June 27, July 10, and July 14), we collected soil volumetric moisture content (VMC), water level position (WL), and vegetation height measurements at each sampling point along the duplicate transects. At all sites, we collected two soil moisture measurements at ground level at each sample point. Data were collected from points located 0.5 m from the sampling location, at a 45° angle from each other. In addition, to characterize spatial and temporal variations in tussock moisture, soil moisture content was measured at the top of the nearest tussock at each sampling point in the tussock marshes. This sampling design provided between 18 and 26 soil moisture samples per site, which in previous research has been shown to be adequate to provide correlations between soil moisture and ERS SAR backscatter (Bourgeau-Chavez et al., 2007).

Moisture content was measured using the time-delay reflectometry (TDR) approach with a Delta-T Devices ThetaProbe Soil Moisture Sensor (ML2×). The ThetaProbe was inserted 3 cm into the organic soil or tussock for soil moisture readings. We calibrated the ThetaProbe for organic soils common to our study region by collecting four soil cores (5 cm diameter, 15 cm deep) at the F1 site in August 2007, frozen and returned to the lab. These soil samples were defrosted at air temperature, wrapped in Saran™ wrap and saturated. ThetaProbe soil moisture readings were calibrated using mass loss and ThetaProbe voltage readings over the range of soil moistures reported in the field over a three-week drying experiment. During this calibration, care was taken to avoid holes that resulted in subsequent re-insertions. A quadratic relationship was developed using these data, and the resulting equation applied to the voltage readings collected during the field studies. We applied this equation to all data except those from the black spruce fen (F2). Because this site had organic soils with lower bulk densities found at the other sites, we used the manufacturer calibration to estimate organic layer moisture. The use of the same equation at all wetland sites may contribute to the uncertainties in estimating soil moisture; however, we believe that larger uncertainties would have occurred if the standard calibration curves were used.

Because the water level at the F2 site was well below the surface, we only collected soil moisture data at this site. At the other sites, we measured water table position at each sampling point along both transects. We also noted whether the water table was above or below the organic soil surface. If standing water was present, we measured the distance from water surface down to the top of the organic soil surface.

At the four non-forested sites, we recorded vegetation height above the organic soil surface from 12 to 13 locations per site. In the tall tussock marsh site, we also measured the distance between top of tussock and soil surface in inter-tussock spaces.

2.3. ERS SAR data collection and processing

ERS-2 C-band SAR data were collected over the study area on four dates during 2007: June 24, June 27, July 10, and July 14. The ERS-2 data were processed and calibrated using the Alaska Satellite Facility's processing tool MAPREADY. The data were then georeferenced in Erdas Imagine software, using bilinear interpolation. All imagery was georeferenced to within a pixel. The field measured GPS locations were then overlaid onto the georeferenced SAR imagery, and a polygon was drawn that included all the GPS points for each study site. Air photos of the sites were also used to determine the exact location of the field defined test areas. Care was taken to avoid edges of the test areas. Within and between scenes radiometric corrections were applied to the data following Bourgeau-Chavez et al. (2007). Next all pixels within the polygons for each study area were used to calculate the mean of the backscatter from that study area for each image date. Mean backscatter was then converted to decibel (dB) units (σ_0) for analysis with the in situ data, using the formula

$$\sigma_0 = 10\ log_{10}(\text{mean backscatter intensity})$$

This data processing approach resulted in a data set that had a within scene uncertainty of ±0.5 dB and a between scene uncertainty of ±1.0 dB (Meadows et al., 1999).

3. Results

In the 3 weeks prior to the initial ERS SAR data collection on 24 June 34 mm of rain fell at the Bonanza Creek Experimental Forest

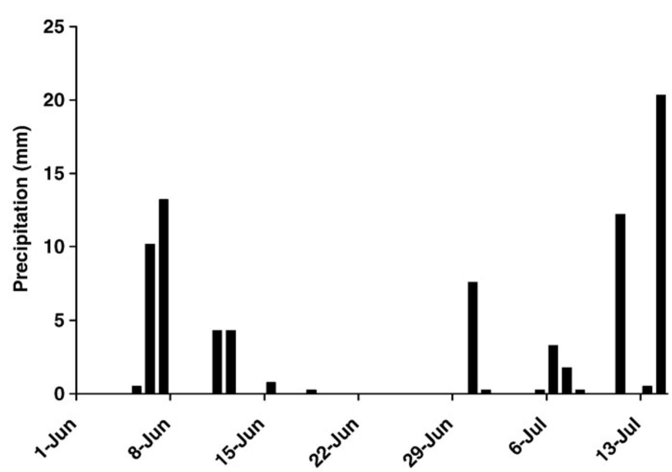

Fig. 3. Daily precipitation from a weather station located within the Bonanza Creek Experimental Forest, located approximately 1 km north of the study sites. While some precipitation occurred in the 24 h period prior to the ERS SAR data collection, the vegetation was dry at the time of field measurements.

weather station (located ~1 km north of the study sites), with 13 mm during the period of 24 June and 9 July, and 13 mm during the period of 11 and 13 July (Fig. 3). Two sites (F1 and M2) experienced slight decreases in WL over the study period, while two sites (M2 and M3) experienced slight increases (Fig. 4a). Over the entire 3 week sampling period, water table position averaged 1.6 cm ± 0.4 cm (average ± standard error), 7.4 cm ± 0.7 cm, 8.8 cm ± 0.7 cm, and 13.8 cm ± 0.7 cm in the F1, M1, M2, and M3 sites, respectively. The temporal trends in surface organic soil moisture content were variable, with slight decreases occurring in 2 sites (F1 and M1) and slight increases in two sites (M3 and F2). Over the entire 3 week sampling period, surface soil moisture content averaged 52.1% ± 2.7%, 62.0% ± 1.6%, 63.3 ± 1.7%, and 34.5 ± 2.5% in the F1, M1, M3, and F2 sites, respectively.

Across all sites, vegetation averaged 59.2 ± 1.5 cm in height. The tallest vegetation existed within the marsh site with tall tussocks (M3), where the vegetation had an average height of 70.2 cm ± 1.1 cm on top of tussocks that had an average height of 12.4 cm ± 2.0 cm). The shortest vegetation (avg. = 47.8 cm ± 1.6 cm) was found in the M2, with the other sites having average vegetation heights of 53.0 ± 1.5 cm (M1) and 66.0 cm ± 1.8 cm (F1).

Over the 3 week study period, the range in ERS backscatter values was 1.2 dB, 1.6 dB, 1.6 dB, 1.7 dB, and 3.1 dB in the F2, M3, M2, M1, and F1 sites, respectively. Across all sites, we found no correlations between ERS SAR backscatter and soil moisture. This lack of correlation was most likely due to the fact that there was variable vegetation cover and structure between the different sites that also contributed to variations in radar backscatter. In previous studies, Bourgeau-Chavez et al. (2007) found that while there was a positive correlation between ERS SAR backscatter and soil moisture in burned sites, there was no correlation in mature (unburned) black spruce forests. Other studies in Alaskan forests have shown that while variations in soil moisture do influence ERS SAR backscatter, sensitivity to soil moisture is reduced when biomass reaches levels of 1.0 kg m^{-2} and higher (Wang et al., 2000).

Positive correlations between ERS SAR backscatter and soil moisture were found for site F1 ($r = 0.99$, $p < 0.02$). Positive correlations also were found when data from the adjacent F1 and M2 sites were combined, neither of which contained taller tussocks ($r = 0.74$, $p < 0.04$; Fig. 5). There was a negative correlation between water table position and ERS SAR backscatter when the water table was located >6 cm above the soil surface (i.e. during complete inundation) ($r = -0.82$, $p < 0.001$; Fig. 6). During drier periods when water table position was <6 cm above the soil surface, there was no correlation between water table position and ERS SAR backscatter.

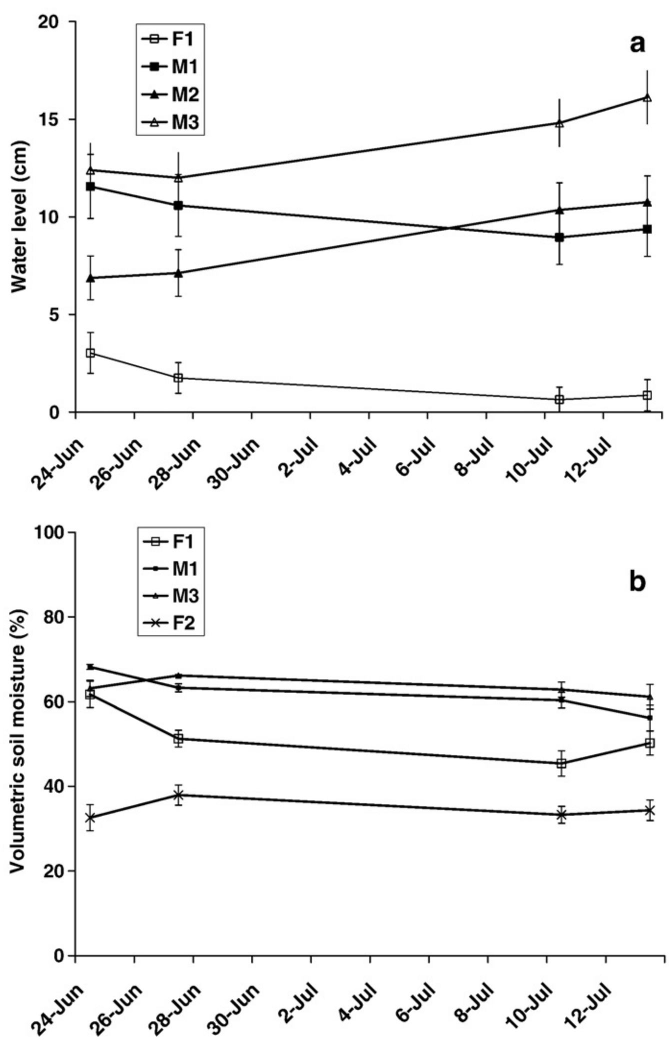

Fig. 4. a) Variations in water table position above the ground surface in four of the study sites over the dates when ERS SAR data were collected. b) Variations in soil moisture in four of the study sites over the dates when ERS SAR data were collected. Data are means ± 1 standard error.

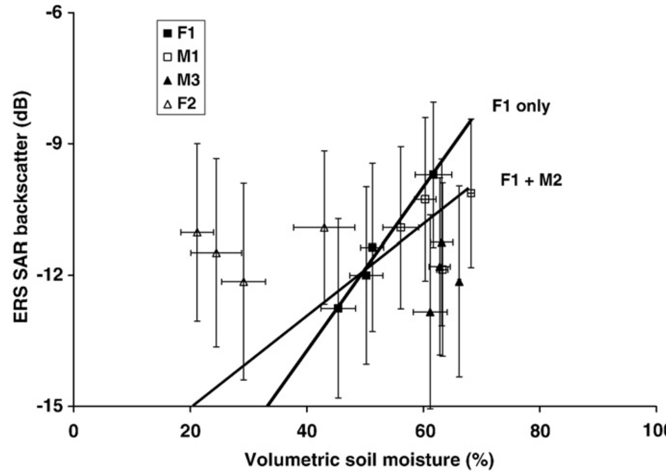

Fig. 5. Relationship between ERS SAR backscatter and volumetric soil moisture. Data are means ± 1 standard error.

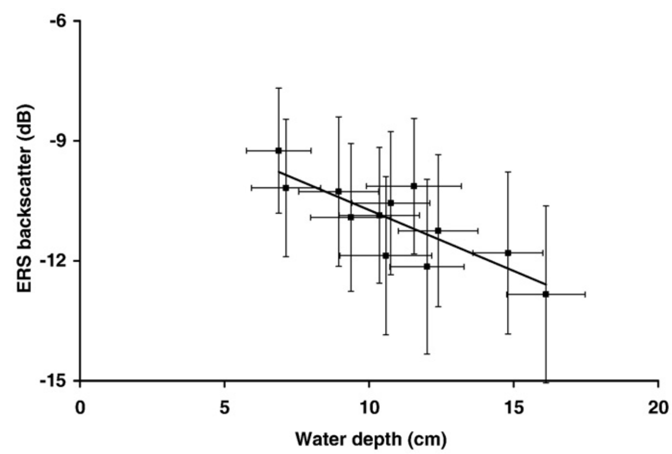

Fig. 6. Relationship between ERS SAR backscatter and water table position above the ground surface across all non-forested sites. Data are means ± 1 standard error.

4. Discussion

Our results from the limited dataset collected within several Alaskan wetlands and peatlands are consistent with findings in other regions. Similar to studies in wetlands located in southern Florida (Kasischke et al., 2003), we found a positive correlation between variations in ERS SAR backscatter and soil moisture. However, compared to the marl prairie ecosystems in Florida, our Alaskan sites had greater vegetation density and height, and more surface organic soils. Together, results from these two studies and other published work (Morrissey et al., 1996; Bourgeau-Chavez et al., 2007, Lang & Kasischke 2008; Sass & Creed 2008) demonstrate that C-band microwave backscatter is sensitive to variations to soil moisture across a range of soil and vegetation conditions.

The observed variation in ERS SAR backscatter as a function of water table position likely was caused by several factors. During dry periods, with average water table levels <6 cm above the soil surface, the sites experienced large spatial variation in surface moisture conditions, with part of the site covered by standing water and other parts with exposed surface soils. Increasing average water level corresponded to an increase in soil moisture and surface soil inundation across the sites, which corresponded to increasing ERS SAR backscatter (Fig. 5). ERS SAR backscatter is expected to change with increasing water table position (wetter conditions) because (i) ERS SAR backscatter is extremely low from water surfaces because of specular reflection; therefore, increasing inundation of the ground surface eliminates the backscatter return from moist soil, (ii) because the height of the vegetation above the water surface affects scattering between the water surface and the vegetation, increasing water table positions and inundation cause ERS SAR backscatter to decrease.

Because we obtained data from several sites over a short time period (3 weeks), we were unable to document how within-site variations in soil moisture and water depth influenced SAR backscatter. Instead, here we focus on between-site variations in hydrology and vegetation structure to examine the correlations between soil moisture, water table position, and ERS SAR backscatter (Figs. 5 and 6). However, given that the ERS SAR was sensitive to soil moisture across several open wetland systems in interior Alaska and the success of this system in other ecosystems, we feel it is likely that the ERS SAR (as well as spaceborne SARs deployed on other satellite systems) will be able to monitor seasonal and inter-annual variations in soil moisture and water levels in individual sites.

5. Conclusions

Future warming is expected to enhance evapotranspiration (ET) from northern wetlands (Roulet et al., 1992) despite expected increases in precipitation (Symon et al., 2005). Drier wetland conditions will result in vegetation stress and changes in vegetation composition, greater incidences of wildfire (Flannigan et al., 2005), and increasing permafrost degradation (Yi et al., 2007; Turetsky et al., 2007). As a result, future changes in the hydrology of northern wetlands are likely to be complex at regional and landscape scales, emphasizing the need for continued development and evaluation of spaceborne remote sensing techniques for monitoring wetland hydrology. Our limited study shows that C-band SAR data (with vertical transmit/receive polarization) has the potential to monitor variations in soil moisture and surface inundation in northern wetlands dominated by herbaceous vegetation. Because there was little variation in soil moisture in the forested wetland site over the course of our study, further research is needed to determine if C-band SAR data can be used to detect hydrologic variations in wetland ecosystems dominated by forests where flooding does not occur. Future studies should include sites with a wide range of vegetation cover and microtopography in boreal wetlands, and should evaluate the backscatter response of spaceborne SAR systems using different wavelengths and polarizations. Particular attention should be paid to collection and analysis of multi-polarization data from the PALSAR L-band SAR system, which has the same wavelength and polarizations as those proposed for NASA's Soil Moisture Active Passive (SMAP) mission. While SMAP will provide data with a coarse ground resolution (1–3 km), it will have the capability to collect data at high latitudes every two days. The high temporal repeat frequency will provide a unique capability for closely monitoring seasonal variations in the hydrologic conditions of northern wetlands, as well as variations in soil moisture in the burned upland ecosystems that are common to this region (Bourgeau-Chavez et al., 1997).

Acknowledgements

The research in the paper was supported by NASA through Grant NNG04GD25G and the Bonanza Creek Long-Term Ecological Research program (USFS Grant Number PNW01-JV11261952-231 and NSF Grant Number DEB-0080609).

References

Bartsch, A., Kidd, R. A., Pathe, C., Scipal, K., & Wagner, W. (2007). Satellite radar imagery for monitoring inland wetlands in boreal and sub-arctic environments. *Aquatic Conservation - Marine and Freshwater*, *17*, 305−317.
Bourgeau-Chavez, L. L., Harrell, P. A., Kasischke, E. S., & French, N. H. F. (1997). The detection and mapping of Alaskan wildfires using a spaceborne imaging radar system. *International Journal of Remote Sensing*, *18*, 355−373.
Bourgeau-Chavez, L. L., Kasischke, E. S., Brunzell, S. M., Mudd, J. P., Smith, K. B., & Frick, A. L. (2001). Analysis of spaceborne SAR data for wetland mapping and flood monitoring in Virginia riparian ecosystems. *International Journal of Remote Sensing*, *22*, 3665−3687.
Bourgeau-Chavez, L. L., Kasischke, E. S., Riordan, K., Brunzell, S. M., Nolan, M., Hyer, E. J., et al. (2007). Remote monitoring of spatial and temporal surface soil moisture in fire disturbed boreal forest ecosystems with ERS SAR imagery. *International Journal of Remote Sensing*, *28*, 2133−2162.
Bourgeau-Chavez, L. L., Smith, K. B., Brunzell, S. M., Richardson, C. J., Romanowicz, E. A., & Kasischke, E. S. (2005). Remote monitoring of regional scale inundation patterns and hydroperiod in the Greater Everglades using synthetic aperture radar. *Wetlands*, *25*, 176−191.
Flannigan, M. D., Logan, K. A., Amiro, B. D., Skinner, W. R., & Stocks, B. J. (2005). Future area burned in Canada. *Climatic Change*, *72*, 1−16.
Gorham, E. (1991). Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, *1*, 182−195.
Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., et al. (2005). Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change*, *72*, 251−298.
Kasischke, E. S., & Bourgeau-Chavez, L. L. (1997). Monitoring south Florida wetlands using ERS-1 SAR imagery. *Photogrammetric Engineering and Remote Sensing*, *33*, 281−291.
Kasischke, E. S., Smith, K. B., Bourgeau-Chavez, L. L., Romanowicz, E. A., Brunzell, S. M., & Richardson, C. J. (2003). Effects of seasonal hydrologic patterns in south Florida wetlands on radar backscatter measured from ERS-2 SAR imagery. *Remote Sensing of Environment*, *88*, 423−441.
Lang, M. W., & Kasischke, E. S. (2008). Using C-band synthetic aperture radar data to monitor forested wetland hydrology in Maryland's Coastal Plain. *IEEE Transactions on Geoscience and Remote Sensing*, *4*, 535−546.
Lang, M. W., Kasischke, E. S., Prince, S. D., & Pittman, K. W. (2008). Assessment of C-band synthetic aperture radar data for mapping coastal plain forested wetlands in the mid-Atlantic region, U.S.A.. *Remote Sensing of Environment*, *112*, 4120−4130.
Li, J. H., Chen, W. J., & Touzi, R. (2007). Optimum RADARSAT-1 configurations for wetlands discrimination: A case study of the Mer Bleue peat bog. *Canadian Journal of Remote Sensing*, *33*, S46−S55.
Meadows, P. J., Lauer, H., & Shattler, B. (1999). The calibration of ERS SAR imagery for land applications. *Earth Observation Quarterly*, *62*, 5−9.
Morrissey, L. A., Durden, S. L., Livingston, G. P., Stearn, J. A., & Guild, L. S. (1996). Differentiating methane source areas in arctic environments with multitemporal ERS-1 SAR data. *IEEE Transactions on Geoscience and Remote Sensing*, *34*, 667−673.
Morrissey, L. A., Livingston, G. P., & Durden, S. L. (1994). Use of SAR in regional methane exchange studies. *International Journal of Remote Sensing*, *15*, 1337−1342.
Oechel, W. C., Vourlitis, G. L., Hastings, S. J., Zuluetal, R. C., Hinzman, L., & Kane, D. (2000). Acclimation of ecosystem CO2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature*, *406*, 978−981.
Racine, M. J., Bernier, M., & Ouarda, T. (2005). Evaluation of RADARSAT-1 images acquired in fine mode for the study of boreal peatlands: A case study in James Bay, Canada. *Canadian Journal of Remote Sensing*, *31*, 450−467.
Riordan, B., Verbyla, D., & McGuire, A. D. (2006). Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images.*Journal of Geophysical Research*, *111* (article no. G04002).
Roulet, N., Moore, T., Bubier, J., & LaFleur, P. (1992). Northern fens - methane flux and climatic-change. *Tellus. Series B, Chemical and Physical Meteorology*, *44*, 100−105.
Sass, G. Z., & Creed, I. F. (2008). Characterizing hydrodynamics on boreal landscapes using archived synthetic aperture radar imagery. *Hydrological Processes*, *22*, 1687−1699.
Symon, C., Arris, L., & Heal, B. (Eds.). (2005). *Arctic climate impact assessment.* New York: Cambridge University Press.
Touzi, R., Deschamps, A., & Rother, G. (2007). Wetland characterization using polarimetric RADARSAT-2 capability. *Canadian Journal of Remote Sensing*, *33*, S56−S67.

Townsend, P. A. (2001). Relationships between forest structure and the detection of flood inundation in forested wetlands using C-band SAR. *International Journal of Remote Sensing*, *23*, 443−460.

Turetsky, M. R., Treat, C. C., Waldrup, M. P., Waddington, J. M., Harden, J. W., & McGuire, A. D. (2008). Short-term response of methane fluxes and methanogen activity to water table and soil warming manipulations in an Alaskan peatland. *Journal of Geophysical Research*, *113*, G00A10. doi:10.1029/2007JG000496

Turetsky, M. R., Wieder, R. K., Vitt, D. H., Evans, R. J., & Scott, K. D. (2007). The disappearance of relict permafrost in boreal north America: Effects on peatland carbon storage and fluxes. *Global Change Biology*, *13*, 1922−1934.

Vasander, H., & Kettunen, A. (2006). Carbon in boreal peatlands. In R. K. Wieder & D. H. Vitt (Eds.), *Boreal peatland ecosystemsEcological studies*, *Vol. 188* (pp. 165–194). Heidelberg, Germany: Springer-Verlag.

Vitt, D. H. (2006). Functional characteristics and indicators of boreal peatlands. In R. K. Wieder & D. H. Vitt (Eds.), *Boreal peatland ecosystems, Ecological studies*, *Vol. 188* (pp. 9–24). Heidelberg, Germany: Springer-Verlag.

Wang, Y., Kasischke, E. S., Bourgeau-Chavez, L. L., O'Neill, K. P., & French, N. H. F. (2000). Assessing the influence of vegetation cover on soil-moisture signatures in fire-disturbed boreal forests in interior Alaska: modeled results. *International Journal of Remote Sensing*, *21*, 689−708.

Wieder, R. K., Vitt, D. H., & Benscoter, B. W. (2006). Peatlands and the boreal forest. In R. K. Wieder & D. H. Vitt (Eds.), *Boreal peatland ecosystems, Ecological studies*, *Vol. 188* (pp. 1–8). Heidelberg, Germany: Springer-Verlag.

Yi, S. H., Woo, M. K., & Arain, M. A. (2007). Impacts of peat and vegetation on permafrost degradation under climate warming.*Geophysical Research Letters*, *34* (Article No. L16504).