Investigating Relationships Between Land-Cover, Forest Structure, and In-Situ and Airborne Passive Microwave Snow Water Equivalent in a Boreal Forest Environment

PETER TOOSE,[1] CHRIS DERKSEN,[2] ANNE WALKER,[2] AND ELLSWORTH LEDREW[1]

ABSTRACT

The Meteorological Service of Canada (MSC) has developed a suite of land-cover sensitive algorithms to extract snow water equivalent (SWE) estimates from satellite passive microwave brightness temperatures. In the boreal forest, however, accurate passive microwave SWE retrievals using the MSC coniferous forest algorithm are hampered by consistent under-estimation. In February 2003, a collection of in situ and passive microwave airborne SWE datasets were acquired in a boreal forest environment in central Saskatchewan, Canada. In addition to the SWE datasets, information on land-cover from satellite imagery, and vegetative parameters from a forest inventory were also assembled. The analysis of the airborne passive microwave SWE estimates compared to in situ SWE measurements highlighted a distinct underestimation of airborne SWE estimates in all forested land-covers and an overestimation of SWE in open clear-cut areas. The magnitude of SWE underestimation in forested land-covers rises with an increase in the amount of forest vegetation-cover present. More specifically, the underestimation appears to be a function of increased canopy closure, rather than an increasing number of tree stems per hectare, as there is a strong negative correlation between airborne SWE estimates and increased canopy closure while a weak positive correlation exists between airborne SWE estimates and increasing number of tree stems per hectare. Better understanding of the relationships between land-cover, forest stand properties and snow cover variables can improve passive microwave SWE estimation in a boreal forest environment.

Keywords: passive microwave, snow water equivalent, boreal forest, land-cover

INTRODUCTION

Better understanding and improved monitoring capabilities of Canadian and global snow water equivalent (SWE) distribution and magnitude will lead to improvements in water resource management for agricultural production, forestry management, and hydroelectricity production, and act as valuable inputs for Global Climate Model (GCM) validation. Conventional methods of in situ snow course measurements used for monitoring SWE in North America are time consuming, inefficient and sparsely distributed (Brown *et al.,* 2000). To better monitor SWE, the Meteorological Service of Canada (MSC) has developed a suite of land-cover sensitive algorithms to extract SWE estimates from Special Sensor Microwave/Imager (SSM/I) spaceborne passive microwave brightness temperatures. For details on algorithm development refer to Goodison and Walker (1994), and Goita *et al.,* (2003). The MSC SWE forest algorithms are based on the

---

[1] University of Waterloo, Geography Department, 200 University Ave W, Waterloo, ON, N2L 3G1
[2] Meteorological Service of Canada, 4905 Dufferin St. Toronto, ON, M3H 5T4

brightness temperature difference of the vertically polarized naturally emitted passive microwave radiation from the earth's surface (37V–19V GHz). The 37V GHz radiation is sensitive to snow pack scattering while the 19V GHz frequency remains largely unaffected by the snow pack, acting as a baseline to which the 37V GHz can be compared. In densely forested regions, however, accurate passive microwave SWE retrievals are uncertain because of consistent underestimation (Derksen *et al.,* 2003). There are a number of complex scattering and emission processes that occur in a forested environment in comparison to the relatively simple open prairie environment where the MSC originally developed the capability to retrieve SWE. These complex processes include the attenuation of the ground surface microwave emissions by the forest canopy, and the vegetation radiating its own microwave energy in addition to the ground emissions (Kurvonen and Hallikainen, 1997). Snow suspended in the forest canopy can further increase the complexity of the attenuation and radiation of passive microwave energy available for detection by satellite radiometers.

Better understanding of the relationships between land-cover, forest stand properties and snow cover variables have the potential to improve passive microwave SWE estimates for boreal forest environments. However, little investigation has been done using high resolution airborne datasets to better define these relationships (Derksen *et al.,* 2005).

METHODS

In February 2003, a series of datasets were acquired in a boreal forest environment in central Saskatchewan, Canada as summarized in Table 1. The SWE datasets acquired for this analysis include both passive microwave airborne estimates and in situ measurements. The passive microwave airborne brightness temperature dataset was collected over a ~625km^2 flight line grid using 19.35 and 37 GHz radiometers mounted on the National Research Council, Twin Otter aircraft. The MSC open prairie and coniferous forest SWE algorithms were applied to the airborne brightness temperatures to produce SWE estimates with footprint dimensions of approximately 100 m. (For complete details on the airborne dataset, see Derksen et al., 2005). Coincident in situ snow surveys were conducted within and around the boundaries of the ~625km^2 flight grid at 68 sites representative of the prevailing land-cover. Measurements at each site focused on SWE, snow depth, density, and snow structure/stratigraphy. In order to increase the sample size, both measured and estimated SWE values were used in this analysis. Estimated SWE was calculated from measured snow depths and average site snow densities measured with an ESC-30 snow sampler.

Table 1. Datasets used in this analysis

Year of Origin	Description
2003	12,555 passive microwave airborne SWE estimates (~100m foot-print)
2003	3045 in situ SWE values (419 measured SWE - 2626 estimated SWE)
2001	Landsat 5 TM land-cover supervised classification
2003	Forest vegetation and land-use inventory

An August 2001 Landsat 5 TM image of central Saskatchewan was acquired for the study area. A supervised minimum distance classification was applied to the image and six dominant categories of land-cover were identified: coniferous, deciduous, clear-cut, regrowth/disturbed, open environment, and water. The open environment differs from the clear-cut land-cover and is typified by sparsely populated tree-coverage and shrubs often in a wetland. The 2003 forest vegetation and land-use inventory was provided by the local forest industry. This digital spatial dataset contains vegetation parameters for forest stands which include: canopy closure, dominant species type, number of tree stems per hectare, as well as land-cover and land use information.

Table 2. Classes of in situ and passive microwave SWE estimates

Land-Cover Classes	Canopy Closure Classes	Stems/Hectare Classes
Regrowth/Disturbed Coniferous Water Deciduous Open Environment Clear-Cut	Degree of Canopy Closure 0-100% (class interval of 10%)	Number of Stems/Hectare 0/ha -12,000+/ha (class interval of 250/ha to 500/ha)

The datasets were integrated using geographic information systems and once combined, the airborne and in situ SWE data were separated into land-cover, canopy closure, and number of tree stems per hectare classes as outlined in Table 2. Pearson's r correlation was then calculated for the following variables: average airborne and in situ SWE estimates and canopy closure class, and average airborne and in situ SWE estimates and number of tree stems per hectare class. Relative frequency histograms of airborne and in situ SWE estimates were also created for the six dominant land-cover classes.

RESULTS

The relative frequency histograms shown in Figure 1 illustrate the difference in airborne and in situ SWE estimates in the different land-cover classes. In the coniferous and deciduous land-cover classes, the airborne SWE distinctly underestimates compared to the in situ measurements. In the clear-cut land-cover, this pattern is reversed - the relative frequency histogram illustrates an overestimation of airborne SWE compared to the in situ SWE measurements.

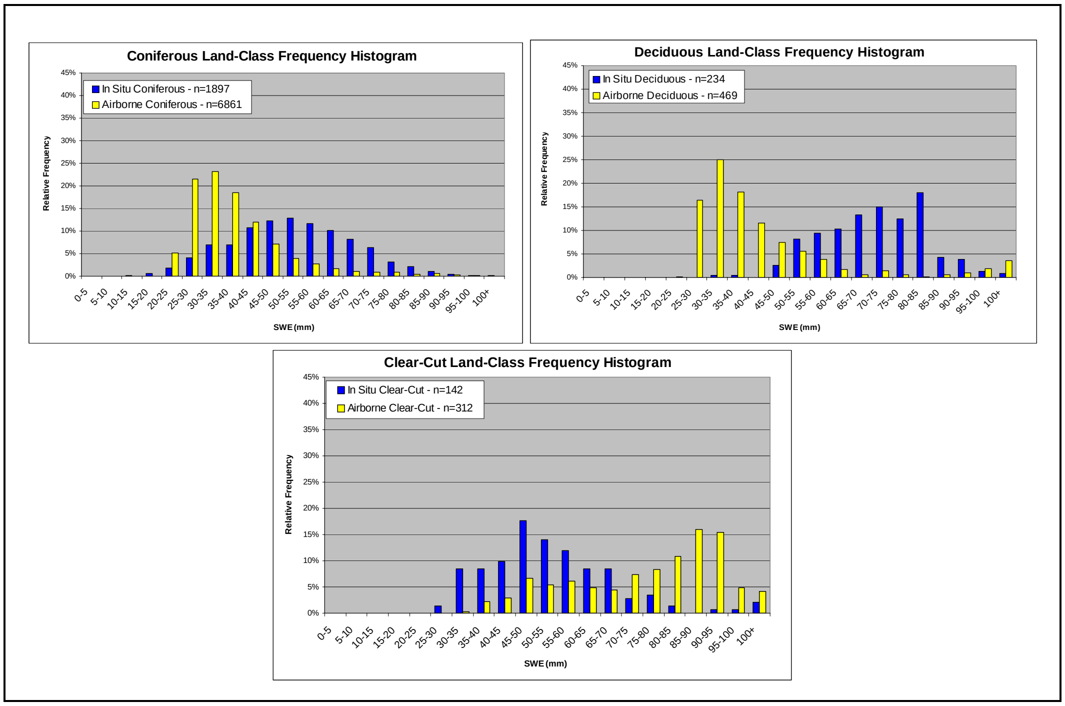

Figure 1. Relative frequency histograms of in situ and airborne passive microwave SWE estimates in different land-cover classes.

Figure 2a shows a strong negative correlation between airborne SWE retrievals and the degree of canopy closure. A pearson's r correlation of -0.89 was calculated between these two variables.

The SWE standard also illustrates a reduction in the magnitude of SWE variability as canopy closure increases, presumably as the relatively consistent vegetative signal dominants scattering from the snowpack. Figure 2b shows only a moderate negative correlation between in situ SWE measurements and canopy closure (r=-0.52). The in situ SWE standard deviations show no changes in the magnitude of variability with canopy closure. Increasing canopy closure results in lower snow accumulation at the surface due to increased interception and sublimation loss. The results in Figure 2 show that the canopy influence on microwave brightness temperature exceeds the influence on surface snow catchment.

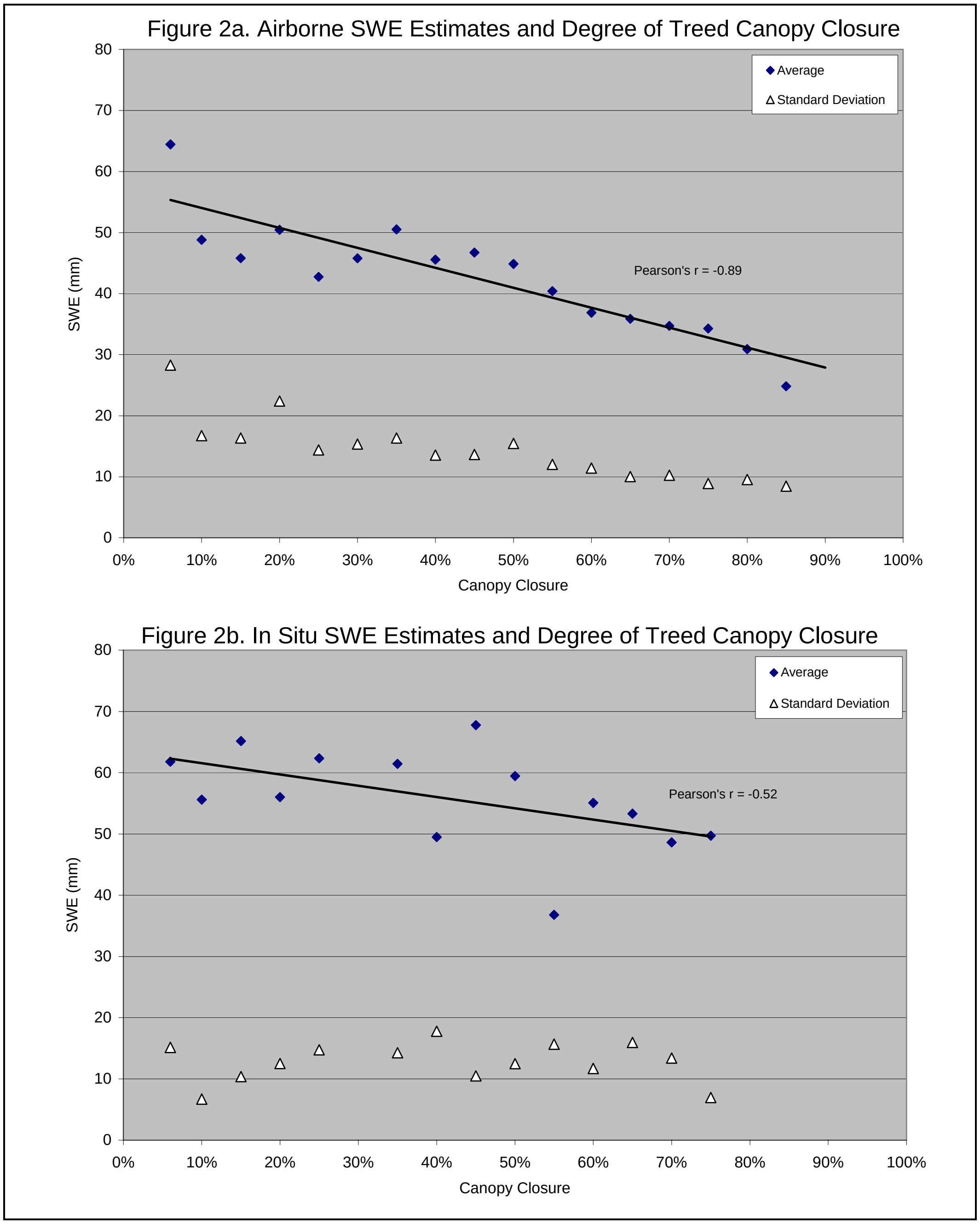

Figure 2. Comparison between canopy closure and airborne SWE estimates (2a) and in situ SWE measurements (2b)

Figure 3 shows the relationship between SWE estimates and the number tree stems per hectare in a forest stand. There is a very weak positive correlation between both airborne and in situ SWE estimates and the number of tree stems per hectare. The calculated pearson's r correlation for the airborne and in situ SWE to the number of stems per hectare was 0.30 and 0.32 respectively. Both the in situ and passive microwave SWE estimates show similar correlations, however the magnitude of the passive microwave SWE estimates is lower than the in situ SWE values in almost every tree stems per hectare class. The plotted SWE standard deviations show no trends of decreasing or increasing magnitude as the number of stems per hectare increases.

Figure 3a. Airborne SWE Estimates and the Average Number of Tree Stems Per Hectare

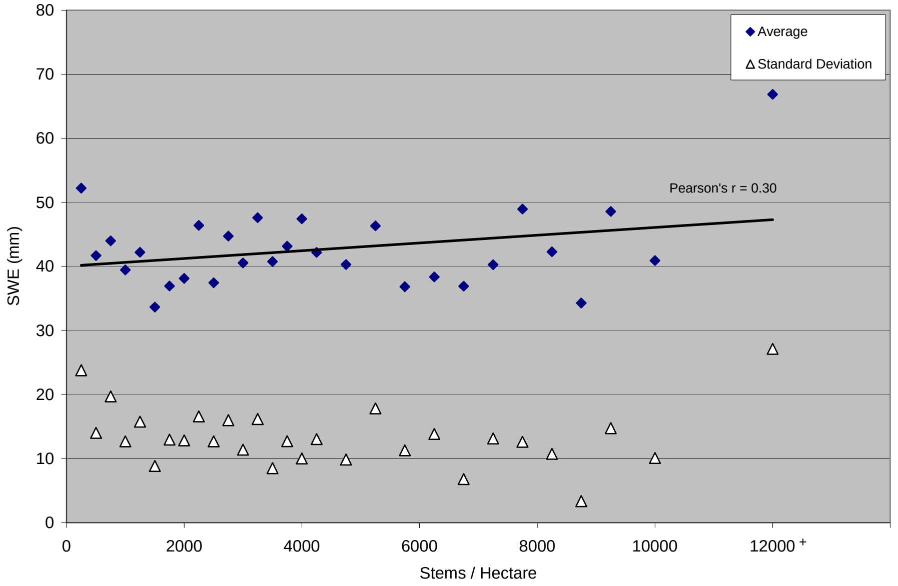

Figure 3b. In Situ SWE Estimates and the Average Number of Tree Stems Per Hectare

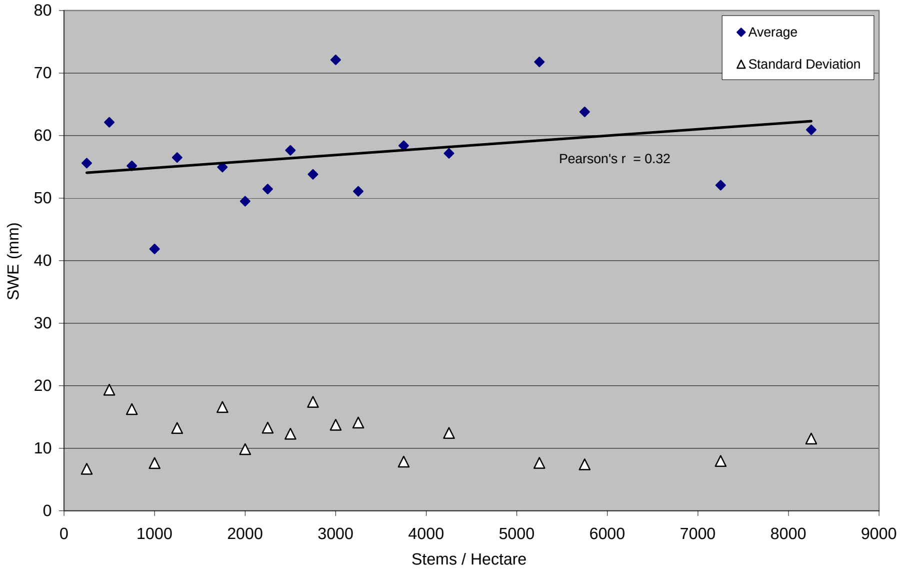

Figure 3. Comparison between number of tree stems per hectare and airborne SWE estimates (3a) and in situ SWE measurements (3b)

DISCUSSION AND CONCLUSIONS

The extensive in situ SWE dataset (both measured and estimated) acquired across a focussed study domain provides an excellent source of ground truthing for the high resolution airborne SWE dataset. An examination of the relative frequency histograms illustrates that different land-covers will influence passive microwave SWE retrievals in a boreal forest environment. The current coniferous forest algorithm consistently underestimates airborne SWE retrievals in most forested land-covers. This underestimation is most likely due to the influence of vegetation on the passive microwave signal. The open prairie algorithm also did not perform well in the clear-cut land-cover of the boreal forest environment. The consistent overestimation of airborne SWE retrievals using this algorithm suggests that the open land-cover of the prairies and the clear-cut land-cover of the boreal forest are too dissimilar to use the same SWE algorithm for both environments. Evaluations at the satellite scale, however, have shown good performance of the MSC algorithm suite in mixed forest environments (Derksen et al., 2003) so the integration of these distinct land cover types into a large satellite footprint clearly has an impact on algorithm performance.

The correlation analysis illustrated a reduction in the magnitude of airborne passive microwave SWE estimates and SWE variability as canopy closure increases in a boreal forest environment. The in situ ground measurements do not show the same degree of correlation with canopy closure, however they do show some reduction in SWE magnitude, which could be attributed to increased canopy interception and subsequent sublimation. It is apparent, however, that the passive microwave SWE estimates in a boreal forest environment are more strongly correlated to the degree of canopy closure rather than on-the-ground SWE conditions. The findings of Hallikainen *et al.*, (2000) agree with these results, suggesting that much of the passive microwave energy received at the radiometer in densely forested regions is largely made up of energy emitted from the forest vegetation rather than ground emissions.

The same relationship is not evident when the in situ and passive microwave SWE estimates are compared with the number of tree stems per hectare. The correlation analysis identified a very weak positive relationship, with the passive microwave SWE estimates too low in almost all stems per hectare classes. This correlation is virtually the same for both in situ and passive microwave SWE estimates. The strength of this correlation is such that the possibility of any relationship at all is questionable, or it may be an actual manifestation of a minor increase in snow deposition in areas of high density tree stems per hectare. Recently reforested lands in the study area are typified by high density tree stems per hectare which prevents wind re-distribution of snow, these recently planted trees also have immature canopy development, therefore reducing snow interception and sublimation, all potentially contributing to an increase in snow deposition.

It is important to note that specific vegetation parameters can vary substantially within the same land-cover class, thus highlighting the shortcomings of estimating SWE based strictly on land-cover information. Not all measurements of vegetation density are useful for determining vegetation influence on passive microwave brightness temperatures. Analysis in this study showed that the density of the number of tree stems per hectare is not as important as the density of the canopy closure in attenuating and emitting passive microwave energy received at the radiometer. The implications of these results suggest that it is ideal to have information on canopy density in addition to land-cover information to most accurately account for vegetation influence on the passive microwave signals used for estimating SWE in the boreal forest.

ACKNOWLEDGEMENTS

Thanks to A. Silis for experiment and sampling design and the many MSC Climate Research Branch personnel who assisted with the in situ snow surveying. Thanks to W. Strapp, I. Macpherson, M. Couture, S. Basic, and J. Beer for their assistance in all aspects involved with the planning, executing, calibrating and post-processing of the passive microwave airborne dataset. Thanks to S. Hubber, R. Granger, and N. Bussieres for their assistance with the Landsat TM land-cover classification.

REFERENCES

Brown R, Walker A, and Goodison B. 2000. Seasonal snow cover monitoring in Canada - an assessment of Canadian contributions for global climate monitoring. *Proceedings, 57th Eastern Snow Conference, Syracuse, New York*, 131-141.

Derksen C, Walker A, and Goodison B, and Strapp JW. 2005. Integrating in situ and multi-scale passive microwave data for estimation of sub-grid scale snow water equivalent distribution and variability. *IEEE Transactions on Geoscience and Remote Sensing.* **43** (5): pp 960-972

Derksen C, Walker A, and Goodison B. 2003. A comparison of 18 winter seasons of in situ and passive microwave derived snow water equivalent estimates in Western Canada. *Remote Sensing of Environment.* **88** (3): pp. 271-282

Goita K, Walker A, Goodison B. 2003. Algorithm development for the estimation of snow water equivalent in the boreal forest using passive microwave data. *International Journal of Remote Sensing.* **24** (5): pp. 1097-1102

Goodison B, Walker A. 1994: Canadian development and use of snow cover information from passive microwave satellite data. *ESA/NASA International Workshop,* pp 245-262.

Hallikainen M, Jaaskelainen VS, Pulliainen J, Koskinen J. 2000. Transmissivity of boreal forest canopies for microwave radiometry of snow. *Geoscience and Remote Sensing Symposium, 2000. Proceedings. IGARSS 2000. IEEE 2000 International.* **4**: pp. 1564 - 1566

Kurvonen L, Hallikainen M. 1997. Influence of land-cover category on brightness temperature of snow. *IEEE Transactions on Geoscience and Remote Sensing.* **35** (2): pp. 367–77