EXPLORING THE POTENTIAL FOR A FUSED LANDSAT-MODIS SNOW COVERED AREA PRODUCT

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ABSTRACT

Results from nine 3 x 3 km study areas in the Rocky Mountains of Colorado, USA demonstrate there is potential for using sporadically acquired Landsat images in combination with daily coarse resolution fractional snow covered area (SCA) images to produce daily high resolution binary SCA images. The results also highlight several challenges to implementing this type of approach. The approach described here consistently yields accurate results in locations with persistent winter and spring snow cover where ten or more partially snow covered images are available to populate the image database, but is less successful in areas with shallower or more ephemeral snow covers or when fewer images are available to populate the image database. This work represents a first step towards developing an algorithm to combine Landsat and MODIS data to produce daily 30 m resolution binary SCA images. Further research should focus on testing the accuracy of this approach across a range of landscape types and snow cover regimes, developing methods to improve prediction accuracy when snow cover is nearly complete or nearly absent, and developing methods to compensate for the effects of canopy cover on SCA retrievals. (KEYWORDS: Landsat, MODIS, snow covered area, remote sensing)

INTRODUCTION

Daily binary and fractional snow covered area (SCA) products are currently available from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) at 500 m spatial resolution, while daily snow water equivalent is available from the AMSR-E instrument at 25 km spatial resolution. In many areas, however, there is often substantial variability in SCA at much finer spatial scales. This is particularly true in regions with complex topography, consistently high winds, or heterogeneous vegetation and land cover. Understanding these finer scale SCA patterns is important because changes in land cover and vegetation structure likely to impact snow cover distribution (e.g. shrub encroachment into tundra, forest establishment at treeline, fires) often occur at scales much finer than 500 m. In addition, when combined with additional in situ measurements, the intra-annual temporal evolution of fine scale SCA patterns may serve as a proxy for variables such as snow depth and snow water equivalent, which are far more difficult to measure via remote sensing. Finally, in areas where significant wind redistribution of snow occurs over the course of a winter, a large portion of spring runoff may originate from accumulation areas that occupy only a tiny fraction of the landscape. These areas can easily be overlooked by coarse resolution SCA estimates.

The Landsat TM and ETM+ sensors provide nearly thirty years of imagery that can be used to map finer scale SCA patterns. Thirty meter data available from the Landsat sensors can provide insight into SCA pattern stability over time, and, in areas where stable SCA patterns exist, have great potential for enhancing the spatial resolution of daily SCA estimates derived from coarser resolution sensors such as MODIS. This study examines the feasibility of using sporadically acquired Landsat imagery to enhance the spatial resolution of coarse resolution fractional SCA estimates. The primary research objective is to develop a method for predicting the spatial distribution of SCA within a given area for which the total fraction of SCA is known and for which distribution patterns from other dates covering a range of snow cover fractions are also known. This work represents the first step towards using 30 m resolution Landsat imagery in combination with 500 m resolution MODIS (or similar) fractional SCA data to produce a daily 30 m resolution binary SCA product.

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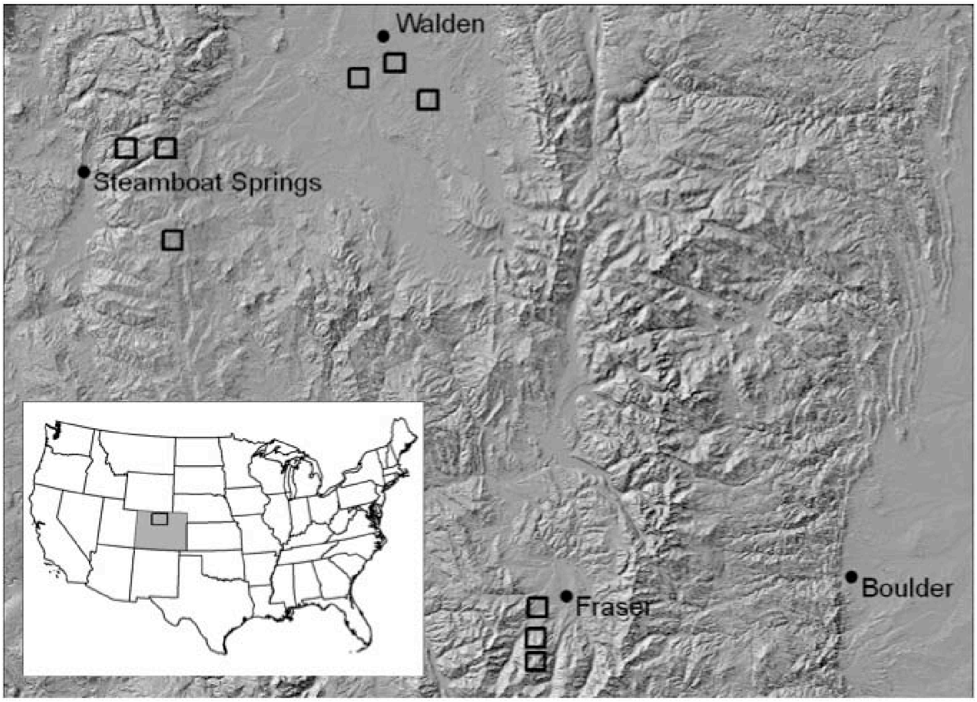

Figure 1. Study area locations. Colorado is shown in grey in the inset, with the extent of the detailed map shown by the black outline. 3 x 3 km study areas (blocks) are identified by squares with dark outlines.

STUDY AREA AND METHODS

The study areas consist of nine individual 3 x 3 km blocks located in the Rocky Mountains of Colorado, USA (Figure 1). Each 3 x 3 km block is centered on an intensive observation area used in the Cold Land Processes Experiment (Cline et al., 2003). Mean elevations for the blocks range from 2474 m to 3514 m, and the blocks include a variety of land cover types characteristic of the Rocky Mountains of Colorado, including alpine tundra, subalpine forest, subalpine meadow, and montane grassland/rangeland (Table 1).

Study Area	Elev.	Land Cov	Kappa	Kappa (5-95% SCA)
Spring Creek	2736	F/M	0.783	0.864
Buffalo Pass	3141	F/M	0.776	0.777
Walton	2952	F/M	0.528	0.628
Illinois Creek	2474	R	0.395	0.405
Potter Creek	2481	R	0.335	0.420
Michigan River	2542	R	0.482	0.602
St. Louis Creek	2741	F/M	0.288	0.461
Fool Creek	3135	F/M	0.693	0.693
Alpine	3514	F/A	0.589	0.703

Table 1. Descriptive statistics and mean kappa scores for each study area. Kappa (5-95% SCA) is the mean kappa score for SCA images with snow cover from 5-95%. For land cover, F = forest, M = meadow, R = rangeland, and A = alpine.

An image database consisting of all cloud-free, partially snow covered Landsat TM and ETM+ (with functioning scan line corrector) images acquired during the months of March, April, May, June, and July between 1999 and 2008 was assembled for each 3 x 3 km block. Images in which snow cover appeared to cover the entire block or appeared to be absent from the entire block were not included in the database. The SNOWMAP algorithm (Hall et al. 1995, Klein et al. 1998), was then applied to each image in the database to classify each pixel as snow covered or snow free. SNOWMAP uses the Normalized Differenced Snow Index (NDSI) (Dozier, 1989) to classify pixels as snow-covered or snow-free, as well as an additional test using NDSI in combination with the Normalized Differenced Vegetation Index (NDVI) to identify snow-covered pixels under forest canopy that might otherwise be classified as snow-free. Application of the SNOWMAP algorithm resulted in 100 x 100 pixel multi-band images with each band representing a SCA image corresponding to a single date. The fraction of total snow covered pixels (hereafter referred to as $fSCA_{3km}$) for the 3 x 3 km block for each band was retained.

As stated earlier, the ultimate aim of the approach presented here is to use 30 m Landsat imagery to enhance the spatial resolution of existing coarse resolution fractional SCA images. In order to conduct a preliminary evaluation of the approach without the potentially confounding error associated with coarse resolution fractional SCA estimates, spatially aggregated 30 m Landsat SCA estimates were used to calculate the fractional SCA estimates that would otherwise be provided by MODIS or another coarse resolution sensor providing daily data. Each Landsat-derived 30 m SCA image was withheld from the image stack as a validation image and also used to calculate the fraction of the 3 x 3 km block that was snow covered (herafter referred to as $fSCA_{3km}$) for that image date. The remaining images in the stack were used to develop a predicted 30 m SCA image covering the extent of the 3 x 3 km block. The inputs to the SCA prediction algorithm were therefore the $fSCA_{3km}$ value and the remaining SCA images in the stack. In order to produce each predicted 3 x 3 km SCA image, a snow cover frequency image was calculated by tabulating the number of times each pixel was classified as snow covered across all dates (excluding the withheld validation image) in the image stack. A randomized number between 0 and 0.9999 was added to the snow frequency image so that no two pixels within the image would have identical values. Values from this image were then converted to rank values from 1 to 10,000 (the total number of 30 m pixels located within the 3 x 3 km block), with number 1 corresponding to the pixel with the highest snow frequency plus random offset value and number 10,000 corresponding to the pixel with the lowest snow frequency plus random offset value. The $fSCA_{3km}$ value for the target date was then multiplied by 10,000 to determine a ranking threshold value above which all pixels would be classified as snow free, with pixels falling below the threshold value to be classified as snow covered. The resulting predicted SCA image was then compared to the withheld SCA image and the kappa statistic (Congalton et al. 1983) of agreement between the predicted and withheld SCA images was calculated and retained.

RESULTS

Agreement between Landsat-derived 30 m SCA and predicted 30 m SCA varied considerably between dates within a single study area as well as between study areas (table 1). Prediction accuracy was consistently poor when a study area was nearly completely snow covered or nearly completely snow free; kappa scores for this range of snow cover were lower than for all others (figure 4) and excluding SCA target images with < 5% or > 95% SCA resulted in higher mean kappa scores for nearly all study areas (table 1) . The mean kappa score for all SCA distribution predictions was 0.561, but rose to 0.659 when only predictions for target dates with > 5% and < 95% SCA were considered.

The low accuracy for the St. Louis Creek study area reflects the small size of the image database for this study area (5 images compared to between 10 and 24 images used for other study areas). Prediction accuracy was consistently poor for the three low elevation rangeland sites (Illinois Creek, Potter Creek, and Michigan River), where snow cover is shallow and sometimes ephemeral. On the other hand, prediction accuracy at the Spring Creek and Buffalo Pass study areas, where a deep snow cover typically evolves over the course of the winter, was consistently high.

Figure 2 depicts the series of binary SCA images used to calculate the snow persistence image shown in the lower right hand corner for the Buffalo Pass study area. Figure 3 provides a comparison between Landsat-derived and predicted SCA for several dates covering a range of kappa scores from 0.82 to 0.35.

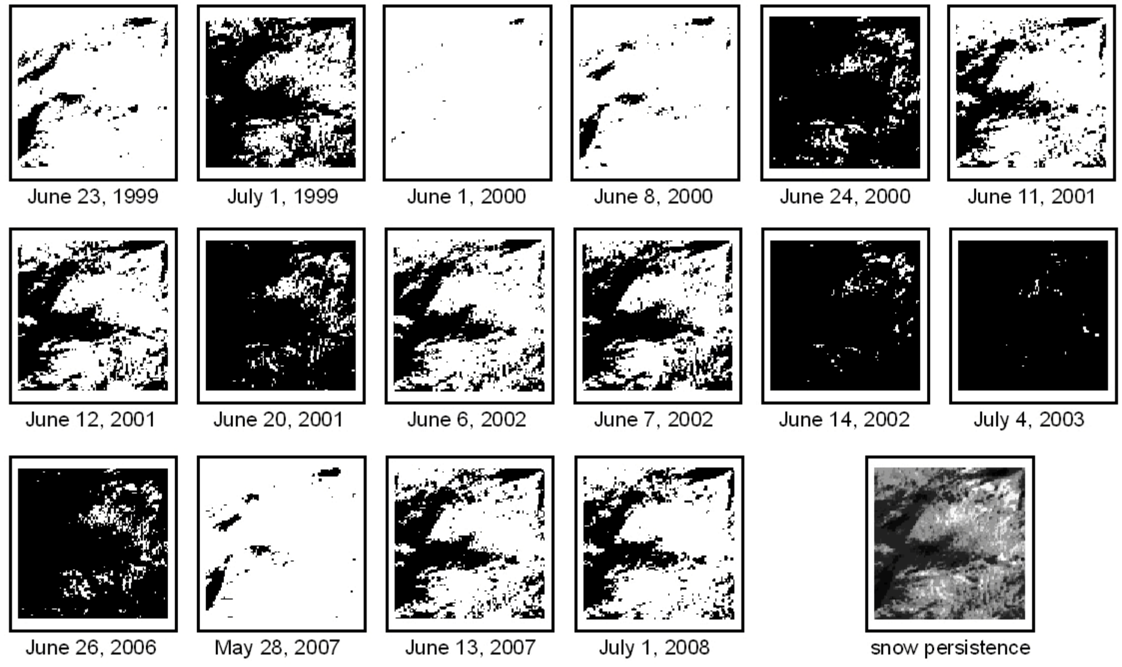

Figure 2. SCA images from all dates and the resulting snow persistence image from the Buffalo Pass study area.

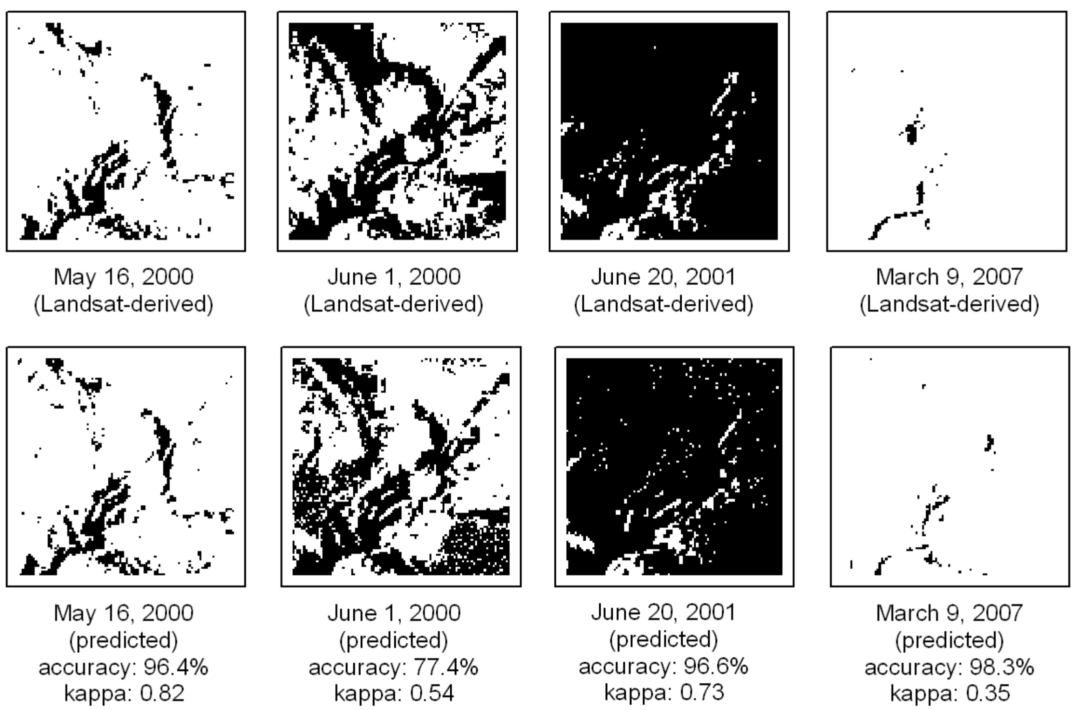

Figure 3. Comparison of selected Landsat-derived and predicted SCA images. Images were selected to represent a wide range of accuracies and SCA percentages.

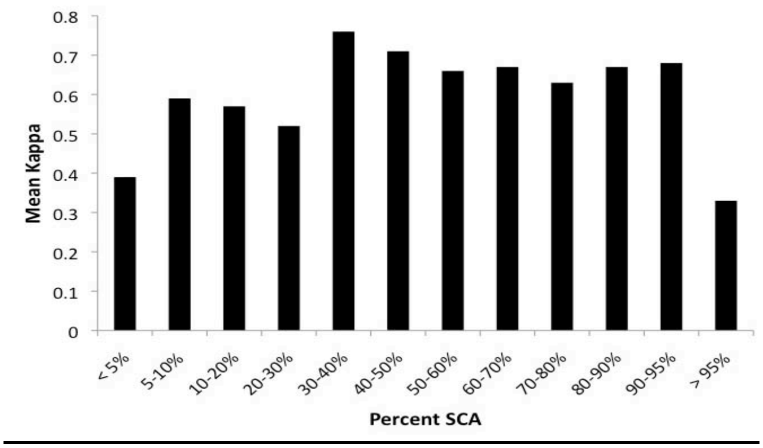

Figure 4. Mean kappa score for SCA percent classes.

DISCUSSION

These results demonstrate strong potential for using sporadically acquired high resolution images in combination with daily coarse resolution fractional SCA estimates to produce high resolution daily SCA estimates. The results also highlight some of the challenges to effectively implementing this approach. In particular, these results suggest that predictions with nearly full snow cover or minimal snow cover are particularly difficult, that a substantial image database (10 or more scenes from a range of SCA conditions) is necessary for accurate predictions, and that predicting SCA for areas with shallow and ephemeral snowpacks is particularly difficult.

A number of additional questions must be addressed before an effective algorithm for predicting high resolution SCA can be developed and implemented. One of the most crucial questions to address is how to compensate for the reduced fraction of SCA mapped under forest canopies. Although this is a much more severe concern for fractional (subpixel) SCA retrievals, it may still be a significant factor for binary SCA retrievals under specific conditions (e.g. melting snow cover contaminated with leaf litter and other debris under dense forest canopies). An effective algorithm will likely need to include an estimate of canopy density, derived either directly from the image used for snow cover mapping or provided as an ancillary dataset. An additional question that will need to be addressed is how to deal with so-called “edge effects” where artifacts from the boundaries of coarse resolution pixels are visible in the resulting high resolution product.

It is important to note that before the approach described here can be implemented at regional scales or larger, it will be necessary to test the approach across the full spectrum of landscapes and snow cover regimes. The results presented here demonstrate that even within a single small region, the accuracy of this algorithm varies considerably by location within the region. Additional analysis will need to be conducted in order to determine if the accuracy of this approach can be determined a priori on the basis of land cover, topography, climate regime, or some combination of these factors. This analysis may also suggest a slightly different approach to daily high resolution SCA mapping may be required in some areas. In particular, incorporating land cover and topographic data in areas where it is available may provide substantial improvements in accuracy in some areas.

Finally, it is noteworthy that hydrologists, landscape ecologists, and other scientists may find the 30 m resolution snow frequency maps generated by the process described here useful for understanding snow patterns even in the absence of a daily 30 m resolution SCA product. These maps have the potential to identify the location of late lying snow patches that are ecologically significant because they serve as havens for certain plant communities and hydrologically significant because they continue to produce runoff long after the majority of the area has become snow free.

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