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Fractional snow cover estimation in complex alpine-forested environments using an artificial neural network

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ABSTRACT

There is an undisputed need to increase accuracy of Fractional Snow Cover (FSC) estimation in regions of complex terrain, especially in areas dependent on winter snow accumulation for a substantial portion of their water supply, such as the western United States. The main aim of this research is to develop FSC estimation in complex alpine-forested environments using an Artificial Neural Network (ANN) methodology as a fusion framework between multi-sensor remotely sensed data at medium temporal/spatial resolution (e.g.16-day revisit time; 30 m; Landsat), and high spatial resolutions (e.g.1 m; IKONOS). This research is the first known attempt to develop a multi-scale estimator of FSC from surface equivalent reference data derived from IKONOS multispectral data. It is also the first endeavor to estimate FSC values by combining terrain and snow/non-snow reflectance data. The plasticity of the developed ANN Landsat-FSC model accommodates alpine-forest heterogeneity, and renders unbiased, comprehensive, and precise FSC estimates. The accuracy of the ANN Landsat based FSC is characterized by: **(1)** very low error values (mean error ~ 0.0002; RMSE ~ 0.10; MAE ~ 0.08 FSC), **(2)** high correlation with the ground equivalent reference datasets derived from 1 m resolution IKONOS images (r^2 ~ 0.9), and **(3)** robust FSC estimation that is independent of terrain/vegetation alpine heterogeneity. The latter is supported by a spatially uniform distribution of errors, and lack of correlation between terrain (slope, aspect, terrain shadow distribution), Normalized Difference Vegetation Index, and the error ($r^2 = 0$).

1. Introduction

Enhanced understanding of present and future climate, water cycle, and ecological changes requires accurate assessment of seasonal snow cover (Bates, Kundzewicz, Wu, & Palutikof, 2008; Campbell, Mitchell, Groffman, Christenson, & Hardy, 2005; Foster et al., 1996; Frei, Brown, Miller, & Robinson, 2005; Lemke et al., 2007; Rango, 1996; Roesch, Gilgen, Wild, & Ohmura, 1999). The climatological, hydrological, and ecological importance of snow cover is linked to its energy storage, high reflectance, good insulating properties, significant heat capacity, substantial water storage, and eventual release of this storage during the melting season (ACIA, 2005; DeWalle & Rango, 2008; Gray & Male, 1981; Lemke et al., 2007).

Since the middle of the 20th century, the snow covered area (SCA) in the Northern Hemisphere decreased about 10%, mainly due to a decrease in snow precipitation, an increased precipitation ratio of rainfall to snow, and an earlier melt in spring and summer (ACIA, 2005; Brown, 2000; Knowles, Dettinger, & Cayan, 2006; Lemke et al., 2007; Mote, Hamlet, Clark, & Lettenmaier, 2005; Robinson, Dewey, & Heim, 1993; Robinson & Frei, 2000; UNEP, 2007). Alpine regions, such as the Rocky Mountains, Tibetan Plateau, the Himalayas, the Andes, and mountains of the Middle East showed the greatest decrease in SCA, resulting in a large scarcity in water availability to neighboring dry lowlands. They rely on river water discharge from mountains. These regions are occupied by one-sixth of the world's population, and have suffered pronounced water shortages, widespread poverty, and famine (Arnell, 1999; Barnett, Adam, & Lettenmaier, 2005; Barnett et al., 2004; UNEP, 2007; UNESCO, 2006; UNESCO/IHP/HWRP, 2009; Wiltshire et al., 2013). With the current high rate of population growth (Asia, South America), decline in ground water due to extensive over-pumping, and biological/chemical pollution, water shortages are likely to be the main limitations of future economic and social development, and human health in these regions (Arnell, 2004; UNESCO, 2006; UNESCO/IHP/HWRP, 2009; Wiltshire et al., 2013).

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For most of the 19th and 20th centuries, monitoring of SCA and Snow Water Equivalent (SWE) was based on sparse ground and field measurements (Brown & Goodison, 1996; Hughes & Robinson, 1996). During the last decades of the 20th century, active and passive satellite imagery enhanced and broadened monitoring of SCA and SWE on global and continental scales (Cline, Bales, & Dozier, 1998; Frei et al., 2012; Hall, Riggs, & Salomonson, 1995; Hall, Salomonson, & Riggs, 2001; Hall et al., 2004). At present, remotely sensed SCA estimation is based on several approaches: supervised or unsupervised classification (Baumgartner & Apfl, 1994), spectral mixture analysis (Painter, Dozier, Roberts, Davis, & Green, 2003; Painter, Roberts, Green, & Dozier, 1998; Painter et al., 2009), Landsat and MODIS Normalized Difference Snow Index (Landsat NDSI, MODIS NDSI) (Crane & Anderson, 1984; Dozier, 1989; Hall, Riggs, Salomonson, DiGirolamo, & Bayr, 2002; Hall et al., 1995), and linear models of snow cover reflectance (Metsamaki, Vepsalainen, Pulliainen, & Sucksdorff, 2002; Metsamaki et al., 2012; Solberg & Andersen, 1994).

Currently available binary snow/non-snow maps provide accurate SCA data in uniform and non-forested regions, at hemispheric and global scales. In forested and topographically uniform terrains, improved accuracy of snow cover estimation has been achieved through merging MODIS NDSI and MODIS NDVI (Klein, Hall, & Riggs, 1998). The relative accuracy of MODIS NDSI-based snow maps may approach 99% in non-forested and topographically uniform terrains, and at 85 - 90% in forested, flat terrains with fully developed snow cover (Hall, Foster, & Salomonson, 2001).

Using empirical relations between Landsat fractional snow cover, based on a binary classification (snow/non-snow), and MODIS Aqua/Terra images at 500 m spatial resolution, NASA MODIS fractional snow cover products introduced significant improvements at regional and global scales in SCA monitoring. Nevertheless, their applications in open alpine and/or forested terrains are still restricted (Nolin, 2010; Raleigh et al., 2013; Salomonson & Appel, 2004, 2006). Recently, Painter et al. (2003, 2009) applied spectral mixing analysis, and delivered the MODIS Snow Cover Area and Grain Size (MODSCAG) model, pursuing further enhancement of SCA monitoring in alpine-forested regions. However, this approach did not account for fine scale topographic effects due to interactions between forest, snow, and elevation, slope steepness, exposition, shadow effects, solar illumination, slope to slope scattering, varying look geometry, snow depth and patchy snow cover. To fully resolve the complexity of SCA distribution in alpine-forested environments, these factors must be considered. A broader overview of all available snow products and their accuracy can be found in Konig, Winther, and Isaksson (2001), Hall, Riggs, and Salomonson (2001), Hall and Riggs (2007) Nolin (2010), Frei et al. (2012), Dietz, Kuenzer, Gessner, and Dech (2012), and Rittger, Painter, and Dozier (2013).

Despite the importance of alpine regions to the hydrologic cycle and regional water supplies, a broad variety of remotely sensed datasets, and advanced snow cover monitoring methods, the present understanding of the spatial and temporal distribution of snow cover in alpine and forested-alpine regions is insufficient (Bales et al., 2006; Viviroli, Durr, Messerli, Meybeck, & Weingartner, 2007; Viviroli, Weingartner, & Messerli, 2003). Thus one of the most crucial needs in alpine snow cover monitoring is to recognize, explain, and deconvolve fine scale interactions between snow and vegetation that are spatially and temporally interconnected with the complex alpine terrain. The spatial interrelation between a single tree and surrounding snow is the primary spatial scale, at which alpine snow cover needs to be examined. This is much finer than the Ground Instantaneous Field of View (GIFOV) of many remote sensing instruments (Czyzowska-Wisniewski, Van Leeuwen, Hirschboeck, Marsh, & Wisniewski, 2014).

Traditionally, estimation of snow cover has been based on linear models, however, to fully resolve the complexity of relations between environmental factors in alpine regions, it is necessary to switch to models such as non-linear estimators that can capture patterns and processes that may not behave linearly (Dozier & Painter, 2004; Ray & Murray, 1996; Roberts, Smith, & Adams, 1993).

The most pertinent current needs in SCA monitoring are:

(1) to develop and deliver robust detailed fractional snow cover (FSC) products that improve SCA monitoring in temporally and spatially heterogeneous watersheds and forested-alpine terrains, that can be used in SWE estimation for regional water management;
(2) to provide detailed distributions of FSC in mountainous regions for temporal/spatial distribution of water availability and sensitivity to recent climate change;
(3) to use FSC products as input for climate models at multiple scales; and
(4) to estimate SCA and SWE for use in ecological studies such as vegetation cover, water stress, primary production, fire, insect outbreaks, and pulses in tree demography (Swetnam, Allen, & Betancourt, 1999; Swetnam & Betancourt, 1980, 1998; Swetnam & Lynch, 1993).

This research focuses on issue 1 and has a two-fold aim:

(1) to provide accurate FSC estimation in both topographically uniform and complex alpine-forested environments, and
(2) to investigate the application of Artificial Neural Network (ANN) methodology in data mining and multi-scale remotely sensed data fusion between high spatial resolution data (IKONOS, 1 m panchromatic band, 4 m multispectral bands) and medium spatial/temporal resolution Landsat data (30 m multispectral bands).

2. Data

2.1. Research areas

Study areas with diverse topography, vegetation, and snow cover were chosen to test the ANN methodology for assessing fractional snow cover and are represented by three locations: two alpine-forested sites, located in the San Juan Mountains, SW Colorado, USA and one hilly-forested site, located on the Missouri Plateau of the Great Plains, Wyoming, USA (Fig. 1).

The first alpine site, Creede, area ~143 km^2, is located in the Weminuche Wilderness, at the continental divide between the Little Colorado River and the Upper Rio Grande River Watersheds, with an elevation range of 2445 – 4000 m asl (mean elevation 3370 m asl).

The second alpine site, Telluride, area ~ 72 km^2, is located at the Upper Colorado River near Telluride city, with elevation ranging from 2632 to 4195 m asl (mean elevation 3367 m asl). Vegetation cover for both alpine sites is mainly represented by mixed-conifer forest (2270 – 2880 m asl), spruce-fir forest (2880 - 3500 m asl), and high alpine meadows (above ~ 3600 m asl). The mixed-conifer forest shows an abundance of ponderosa pine (*Pinus ponderosa*), southwestern white pine (*Pinus stribiformis*), Douglas-fir (*Pseudosuga menziesii*), white fir (*Abies concolor*), blue spruce (*Piceapungens*) and cork bark fir (*Abies Lasiocarpa Nutt.*). The spruce-fir forest is dominated by Engelmann spruce (*Picea engelmannii*) and cork bark fir (*Abies Lasiocarpa Nutt.*) (Blair & Bracksieck, 2011; DeVelice, Ludwig, Moir, & Ronco, 1986).

The third research site, Dakota, area ~ 145 km^2, is located in the Missouri Watershed, in the Black Hills of South Dakota, WY, with an elevation range of 1369 – 2028 m asl (mean elevation 1780 m asl). The lower elevations are occupied predominately by ponderosa pine (*Pinus ponderosa*) and burr oak *(Quercus macrocarpia)*. Higher elevations are occupied by ponderosa pine *(Pinus ponderosa),* white spruce *(Picea glauca),* lodgepole pine *(Pinus contorta),* aspen *(Populus tremuloides)* and birch *(Betula papyrifera)*. On the northern slopes, near the top of the hills, Black Hills spruce *(Picea glauca var. densata)* appears (Burns, 1983; Hoffman, 1986; Hoffman & Alexander, 1976, 1987; Thilenius, 1970).