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Editorial

An Overview of Remote Sensing for Mountain Vegetation and Snow Cover

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1. Introduction

Climate change has profoundly impacted elements of land surface at high latitudes and elevations, especially snow and vegetation. To date, the effects of rapid climate-change-induced snow changes on vegetation are poorly understood. Seasonal snow accumulation is the primary source of water input to terrestrial ecosystems at high latitudes and elevations, and it plays a vital role in vegetation growth. Remote sensing images with various spatial and temporal resolutions are widely used to monitor snow and vegetation cover at global and regional scales. However, the complicated topography and diverse local climates in mountainous areas make the distribution of or changes in vegetation and snow cover in these areas very elusive. The interactions between snow variation and vegetation growth, in particular, remain unknown. The time of snow accumulation and melting (snow phenology) is closely related to the vegetation growth condition. Variations in snow phenology will also have an indirect impact on regional vegetation dynamics. Aside from this point, one of the most critical features of snow cover in terms of ecosystems is its insulation capacity, which determines soil and vegetation temperatures during winter. Snow cover protects the vegetation from cold. Considering this context, we organized a Special Issue entitled "Remote Sensing for Mountain Vegetation and Snow Cover" for the journal *Remote Sensing*. This Special Issue aims to publish the latest research that can contribute to a better understanding of snow and vegetation variations, temporal and spatial patterns, and potential interaction mechanisms from a broad perspective.

We received a total of 22 submissions and published 18 research papers, all of which focused on remote sensing for mountain vegetation and snow cover. This editorial aims to offer an overview of the latest findings and contributions from the studies published in this Special Issue. We also provided a short outlook on the research topic of the remote sensing of mountain vegetation and snow cover.

2. Overview of Contribution and Future Perspectives

The eighteen papers in this issue cover a wide range of topics regarding remote sensing for mountain vegetation and snow cover, including the remote sensing algorithm development of snow cover, glacier and vegetation and cloud–snow confusion technology; the production of remote sensing basic data; spatiotemporal changes in snow cover and vegetation; the inter-relationship between vegetation and snow cover under climate change and intense human activities. We summarized this research progress via three dimensions.

First, 10 research papers in this Special Issue focused on developing the retrieval algorithms and products for snow cover, snow depth, glacier and vegetation. Using the commercial high-resolution imagery software PlanetScope, John et al. [1] mapped snow cover extent based on a machine learning (ML) approach using convolutional neural networks (CNNs). They found that the ML approach improved the capacity to detect snow in forests and identified snow better in canopy edges and open areas. High-resolution snow maps can support studies involving climate change research and evaluations of hydrological impacts in small snow-dominated river basins. Pan et al. [2] simulated the reflectance in the mid-infrared band with a radiative transfer model and then developed three fractional-snow-cover retrieval algorithms for NOAA AVHRR/2 imagery at 1 km and 5 km resolutions in the High Mountain Asia region. They found that the multiple endmember spectral mixture analysis algorithms had the highest accuracy in bare land, grassland and Himalayan areas. To resolve the issues of cloud obscuration and gaps in the MODIS NDSI (Normalized Difference Snow Index) product, Xing et al. [3] developed a cloud-gap filling method based on U-Net with partial convolutions and generated the MODIS NDSI products. These retrieval algorithms and accurate long-term snow-covered-area data are essential to climate change studies and water resource management. Two papers are devoted to the study of discriminating between snow and cloud via optical sensors. The study by Wang et al. [4] showed that a large amount of forest snow is misclassified as clouds, especially in boreal forest areas. These excessive cloud masks limit the application of snow products. They considered that the NDSI of cloud pixels varies greatly, but the NDSI of snow pixels is relatively stable over time, and a temporal-sequence cloud–snow-distinguishing algorithm using NDSI variance was proposed from the high-temporal-resolution Himawarri-8 geostationary meteorological satellite. This will greatly improve the accuracy of MODIS snow cover products. Wang et al. [5] developed a machine learning model combining DeepLab v3+ and conditional random field to identify cloud and snow in GF-1 WFV images. The method can provide a reference for high-resolution snow mapping and hydrology applications. Focusing on the remote sensing of snow depth, Amoruso et al. [6] further explored the capability of snow depth retrieval using the ratio between SAR cross- and co-polarization backscattering. Using Sentinel-1A images on the Central Pyrenees (Spain), they found that the spatial dispersion and non-negative matrix factorization of SAR backscattering are highly correlated to snow depth evolution. This provides a very effective tool which can be used to reproduce snow depth evolution. Due to the scale effect, the verification method based on points of ground observation is subject to great uncertainty, especially in mountainous areas. Hou et al. [7] compared three point-to-surface upscaling methods. They found the Bayes maximum entropy (BME) algorithm showed the highest accuracy. The method proposed in this study is expected to be more efficient in the evaluation of snow depth remote sensing data. Two papers are related to the remote sensing of vegetation. Syahali et al. [8] proposed a new numerical solution method called the relaxed hierarchical equivalent source algorithm (RHESA) to calculate volume scattering. This method provides the freedom to model any shape of scatterer compared with the analytical method. It has great prospects for future application, especially for complicated and dense media, such as vegetation in mountain regions. Wei et al. [9] produced the latest alpine vegetation classification map with a spatial resolution of 30 m in Sanjiangyuan National Park. They tested several classification methods and evaluated their accuracy in alpine vegetation classification. This study provides valuable information for alpine vegetation classification method selection and timely basic data for the sustainable management of Sanjiangyuan National Park. In addition, another paper concerns remote sensing in glaciers. Yan [10] generated a high-quality DEM from C-band Sentinel 1A/1B ascending and descending pass SLC images and evaluated the overall accuracy based on Shuttle Radar Topography Mission (SRTM) DEM and ICESat/GLAS. They utilized the new DEM to estimate the glacier elevation changes and glacier mass balance. This study demonstrates that ascending and descending orbit data of Sentinel-1A/1B satellites are promising for use in the detailed retrieval of surface elevation changes and mass balance in mountain glaciers. All these studies suggest that more attention should be paid to remote sensing elements for mountainous water resources and climate change, including glaciers, snow and vegetation. The combination of multiple remote sensing data and various new algorithms is a scientific frontier for the sustainable management of water resources.

Second, three papers address spatiotemporal changes in snow cover and vegetation [11–13]. Zhao et al. [11] used the daily MODIS cloud-free snow cover product to calculate various snow phenology variables, including snow cover area (SCA), snow cover onset (SCS), snow cover melt (SCM) and snow cover day (SCD). These variables revealed the snow's spatiotemporal characteristics (distribution and variability) in China from 2000 to 2020. They found that the snow cover in China has demonstrated a trend of decreasing SCA, decreasing SCD, advancing SCS, and advancing SCM, with SCM advancing faster than SCS in the past 20 years. The correlation of SCP with temperature or precipitation has significant spatial and seasonal differences and shows characteristic variation with altitude. These results can provide important data support for climate prediction, hydrological research, and disaster warnings. Focusing on the impact of climate warming and human activities on snowmelt, Wu et al. [12] evaluated the long-term impact of climate warming on snowmelt rates during the past 40 years (1981–2020) over China's three mainly stable snow cover regions using snow water equivalent (SWE) datasets. They found higher ablation rates in spring in locations with a deeper SWE. Due to SWE being reduced in these deep snowpack areas, moderate and high rates of snowmelt showed trends of decline. The slower snowmelt rate was closely related to vegetation improvement. These findings strengthen our understanding of the assessment of ecological and environmental changes towards the sustainable use of freshwater resources in spring and the earlier summer months in snow-rich alpine regions. Vegetation is a key to maintaining ecosystem function and services. Liang et al. [13] assessed the trend in FVC (Fractional Vegetation Cover) and its drivers across the Gannan Plateau, the southeastern edge of the Qinghai–Tibet Plateau (QTP), by integrating high-resolution satellite remote sensing images and meteorological data from 2000 to 2020. They found that aridity was the dominating factor in the spatial distribution of FVC, while the ecosystem type showed a secondary effect, with forests having the highest FVC in each aridity class. From 2000 to 2020, 10.32% of the study area exhibited a significant increase in FVC. The precipitation surpassed temperature as the main driver for the FVC trend in semi-arid and semi-humid areas. The study provided an observational basis for better understanding and pattern prediction of ecosystem functioning and services under future climate change.

Seasonal snow accumulation and ablation processes significantly affect alpine and mountain ecosystems. Thirdly, the studies included in this Special Issue explore the interrelationships between vegetation and snow cover in the context of climate change and intensive human activity. Yang et al. [14] investigated the impact of snowpack changes on land surface phenology and its driving factors in the Tianshan Mountains from 1983 to 2015. Snow and vegetation phenology metrics were derived from satellite products and regional climate model simulations. They demonstrated that the annual mean start of growing season (SOS) and length of growing season (LOS) experienced a significant decrease and increase with a rate of −2.45 days/decade and 2.98 days/decade, respectively. It was shown that a significant decline in snow cover fraction (SCF) could advance the SOS, and snowmelt amount and annual maximum snow water equivalent (SWE) have an almost equally substantial positive correlation with annual maximum vegetation greenness, especially grassland. Two more papers analyzed the impact of snow cover phenology on vegetation change over the Tibetan Plateau. Ma et al. [15] analyzed the spatiotemporal variation in seasonal snow cover and SOS in alpine grasslands and preliminarily explained the mechanism by which snow cover acts on SOS changes by altering soil temperature (ST) and soil moisture (SM) in spring. They found that the snow end date (SED) and snow cover days (SCDs) exhibited an advancing trend and a decreasing trend in high-elevation areas, respectively, and the opposite tendency was observed in low-elevation areas. Delayed SED and more SCDs can provide increasingly moist soil conditions, supplying SOS development in alpine grasslands. Xu et al. [16] further explored the impact of snow cover changes on alpine vegetation by green-up data (GUD), which is similar to SOS. They found that the

GUD was advanced by 0.07 and 0.03 days and was postponed by 0.32 days when the SOD and SED were delayed by one day. The GUD of alpine grassland was also more sensitive to snow cover phenology than other vegetation types. The GUD showed a stronger negative sensitivity to the SCD in warmer areas and a stronger positive sensitivity to the SMOD in wetter areas. Tan et al. [17] investigated the relationship between snow cover, vegetation and soil temperature and further analyzed the influence of local factors on soil temperature in the Three River Source Region (TRSR) using a random forest model. They found that the stronger the correlation with soil temperature in areas with a larger SCD, the more the snow has a cooling effect on the shallower soil temperatures due to the high albedo of the accumulated snow and the repeated melting and heat absorption of the snow. In the snow season, vegetation lowers the ground albedo and warms the soil. In July and August, vegetation is negatively correlated with soil temperature due to heavy vegetation intercepting summer radiant energy and having a cooling effect on the soil. Gersh et al. [18] evaluated the temporal variability of post-fire snow albedo recovery relative to burn severity from 2000 to 2019, using pre- and post-fire daily, seasonal and annual landscape MODIS snow albedo data (MOD10A1). They found the surface snow albedo (SSA) darkened immediately following a forest fire, while the landscape snow albedo (LSA) brightened as more snow-covered surfaces became visible under the charred canopy. Post-fire LSA measurements showed an increasing trend in high and moderate burn severity areas over ten years following fire. LSA recovery over 10 years following fire did not resemble the antecedent pre-fire unburned forest but more resembled open meadows. Research has also indirectly shown that the forest canopy structure recovers more slowly.

Redistributions in snow cover resulting from global warming inevitably affect alpine vegetation growth. This Special Issue contains many research highlights related to the remote sensing of mountain snow cover and vegetation and the relationship between vegetation and snow. In the future, we expect important progress will be made in these research topics. The application of new remote sensing sensors, such as various satellites and unmanned aerial vehicles (UAVs), and imaging technology has greatly advanced snow cover and vegetation cover area inversion. However, the retrieval of snow depth and snow water equivalent, which are much needed for hydrological and climate change studies, is still a problem. At present, the spatial resolution of snow depth retrieval based on passive microwave data is low, and there is a signal saturation problem in the Ka-band for deep snow. Although SAR improves the resolution, the influence of ground scattering is greater, making C-band snow volume scattering weaker and unable to achieve reliable retrieval in shallow snow or areas with more water in the subsurface. Therefore, high-frequency (X-band or Ku-band) backscattering observations or low-frequency (L-band or P-band) InSAR phase variation may be more appropriate for SAR snow depth retrieval in shallow snow conditions. In addition, combining active and passive microwaves and Lidar will be beneficial to retrieving snow depth in the future. Secondly, new emerging remote sensing technologies will greatly improve our ability to obtain vegetation and snow parameters at finer spatial and temporal resolutions. These parameters will be easier to validate and integrate with in situ measurements. This will be beneficial to our understanding of the interacting mechanism between snow and vegetation, for example, how snow shapes plant traits and how vegetation affects snow accumulation and melting. In addition, the impact of future snow cover on regional agriculture can be further studied, mainly in the following four directions: (1) The impact of snow melt water on regional agricultural water resources in the future. (2) The adverse impacts of snow cover on agriculture, such as the impact of snowstorms on agricultural disasters and capacity building for disaster reduction. (3) The improvement in the regional climate brought about by snow melt water, and its impact on the planting structure, crop types and diet structure of regional agriculture. (4) The telecorrelation relationship among snow cover changes, regional climate and crop growth.

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