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Remote sensing approach to detect post-fire vegetation regrowth in Siberian boreal larch forest

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ABSTRACT

Remote sensing with time series data offers considerable potential in the trajectory of post forest fire dynamics beyond the current monitoring of structural attributes that are displayed in the post-fire area. Many studies have addressed this topic by using time series remote sensing indices; however, this approach has sometimes been demonstrated as an unrealistic and biased representation of the post-fire forest patterns due to the saturation issues of vegetation indices. These saturation issues then lead to an underestimation of the forest successional stages and an overestimation of the forest recovery rate. This paper aims to develop a framework for trajectory of the post-fire forest patterns in the Siberian boreal larch forest (*Larix sibirica*) with the synergistic use of different remote sensing based vegetation-cover indicators derived from the Landsat time series and the WorldView-2 images. A time-series of the forest recovery index (FRI) and fractional vegetation cover (FVC) has been analyzed to estimate the rates of forest regeneration and vegetation recovery across different burn severity levels in the Siberian larch forest. The results showed that the FRI method can be used to observe the regrowth of the larch forest from the tenth year after the fire overlapping with the period of significant increase in the sapling stem volume. The post-fire larch forest canopy can fully recover to the pre-fire condition with respect to the magnitude of the FRI values after 30–47 years where the highest regeneration rate was observed in the moderate burn severity areas followed by the low and high burn severity. On the other hand, the FVC method was positively correlated with burn severity and more sensitive for evaluating the early stages of the forest succession in which the FVC dramatically increases after 5–6 years after the fire. The significant growth of FVC was accentuated by the maximum emergence of the sapling density as well as the rapid growth of herbaceous plants, grasses, shrubs, and shade-intolerant trees immediately after the fire, which could not be evaluated using the FRI. Both time series of the FRI and the FVC are valuable tools for determining the dominant stages of the post-fire larch forest succession in order to understand the relationships between fire disturbance and natural cycles of the boreal larch forest.

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1. Introduction

Fire is an important factor in boreal forests regulating the diversity of forest species, forest types and stand ages which in turn influence natural cycles such as carbon and hydrological cycles (Kasischke and Stocks, 2000). When characterizing patterns of post-fire tree regeneration it is thus especially important to determine how an ecosystem responds to fire disturbances as well as to understand the changes of natural cycles influenced by forest cover change, including effects on hydrological and carbon cycles. Boreal forests are unique in that the return interval of stand-replacing fire is often shorter than the time required for the climax community to dominate (Johnstone et al., 2004).

Even though the patterns of post-fire boreal forest recovery have been very well demonstrated from field surveys (e.g. Cai et al., 2013; Dorisuren, 2008; Johnstone et al., 2004; Johnstone et al., 2011; Zyryanova et al., 2010), observations of post-fire forest succession using remote sensing remain challenging. Remote sensing with time series data offers considerable potential in the trajectory of post-fire forest dynamics as well as the classification of successional stages. Many studies have demonstrated the capability of a remote sensing tool for studying vegetation dynamics in which indices such as the normalized difference vegetation index (NDVI), the soil adjusted vegetation index (SAVI), the normalized difference shortwave infrared index (NDSWIR), the enhanced vegetation

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index (EVI), the albedo, the NDVI-based net primary productivity (NPP), and the fraction of absorbed photosynthetically active radiation (fAPAR) were the most common indicators representing the recovery of vegetation after fire disturbance (e.g. Cuevas Gonzalez et al., 2009; Cuevas-González et al., 2008; Epting and Verbyla, 2005; Hicke et al., 2003; Jin et al., 2012; Tanase et al., 2011; Jones et al., 2013; Yi et al., 2013).

Monitoring the patterns of post-fire vegetation using these indices is site specific and varies substantially depending on the indices. Additionally, an assumption that an index such as the NDVI of vegetation recovery equates to forest stand recovery (e.g. larch and black spruce forests) may not be ideal as a realistic and unbiased representation of the true post-fire forest recovery particularly in early stages of the forest successions (Frolking et al., 2009). Therefore, the selection of remote sensing indices used to study the return of the forest to its pre-fire condition is critical. The indices must be relevant and have a clear relationship with the ground measurements in order to accurately evaluate how a forest ecosystem responds to a fire disturbance as well as the influences of fire disturbance on carbon storage and other natural cycles within the ecosystem.

Some authors have invested efforts in deriving quantitative measurements of the forest regeneration from remote sensing data. The most common approach to do so is to scale pixels between the bare soil and the dense vegetation index values to determine the fractional vegetation cover (FVC), which is defined as the vertical projection areal proportion of the landscape occupied by green vegetation (Gitelson et al., 2002). The vegetation indices (e.g. NDVI) and the spectral mixture analysis (SMA) are the most frequently used techniques in remote sensing to estimate the FVC (Veraverbeke et al., 2012; Yang et al., 2013). Roder et al. (2007) derived trajectories in post-fire vegetation change by exponential functions using the SMA based green vegetation cover from time series Landsat imagery (covering 25 year). The trends of vegetation changes at different times after the fire were used to visually interpret three early stages of the post-fire forest recovery in the Ayora region of Spain, including an initial establishment of grasses and herbaceous species, a gradual development of shrub layer, and subsequent colonization of tree individuals. Solans Vila and Barbosa (2010) investigated different methods to derive post-fire vegetation cover regrowth in Mediterranean environments and found that the vegetation cover fractions extracted from the NDVI based quantitative index to be the superior method, even surpassing SMA, due to its high levels of accuracy. Vegetation regrowth detection based on fraction-NDVI methodology allows for observations to be made regarding vegetation regrowth regardless of the rate of regeneration (Solans Vila and Barbosa, 2010). Studies where the FVC technique was used to monitor post-fire environments have shown promising results. The accuracy of FVC estimates mainly depends on selection of the end members; endmember variables include bare soil and dense vegetation pixels, the saturation effect of vegetation indices such as NDVI at high leaf area index (LAI) levels as well as effects on satellite imagery due to changes in season and variations in topography and atmosphere (Enßle et al., 2014; Solans Vila and Barbosa, 2010). The integrated forest *z*-score (IFZ) proposed by Huang et al. (2008) has recently been used to automatically reconstruct forest disturbance using the dense Landsat time series stacks in the vegetation change tracker (VCT) algorithm (Huang et al., 2009, 2010). Since the IFZ indicates the probability of the non-forest pixel becoming a forest pixel, its temporal changes can be an indicator for the evaluation of the post-fire forest recovery (Huang et al., 2009). Very few studies have used the IFZ to determine the extent of the post-fire disturbance regrowth within a given forest stand (e.g. boreal forest); if regrowth did occur, when it started and how long it took to return to the pre-fire condition would need to be determined. This can be used to accurately estimate the stand age of the forest after the fire. In addition to the FVC estimate, the IFZ measurement is expected to account for and separate different characteristics of the post-fire forest patterns in which both forest (e.g. *Larix sibirica*) and non-forest species (e.g. grasses, shrubs) recover together.

The aim of this paper is to propose a synergistic approach of remote sensing based on vegetation cover indicators to determine different stages of the post-fire forest successions in the Siberian boreal larch (*L. sibirica*) forest. The fractional vegetation cover (FVC) and the forest recovery index (FRI) derived from the Landsat time-series and the WorldView-2 images were used to evaluate the temporal and spatial patterns of the post-fire forest regrowth under different burn severity effects. Since the integrated forest *z*-score (IFZ) has been originally designed for reconstructing the forest disturbance history by indicating how the forest pixels turn to non-forest pixels (Huang et al., 2009), this study proposed forest recovery index (FRI) defined as the reciprocal of the IFZ values in order to track the recovery rate of the burned area to return to its pre-fire condition. We hypothesized that the FVC method can be used to monitor the early stages of post-fire forest succession while the FRI method can account for delaying the regeneration of forests species after the fire, and it can be used to monitor late recovery stages of the post-fire larch forest to pre-fire conditions. We evaluated the effectiveness and discussed any problems and challenges of these remote sensing indices in comparison with our field measurements and other studies in the boreal regions.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located in the mountainous area of Hovsgol province (49°38′ N, 100°10′ E) in northern Mongolia. The Hovsgol topography is characterized by the large Darhad valley at 1550–1600 m above sea level (masl), the Hovsgol Lake, and the high mountain ranges up to 3100 masl. The Hovsgol province is the most densely forested area in Mongolia with 31 781 km^2 of closed forest accounting for 30% of Mongolia's total closed forest area (James, 2011). The Hovsgol forests are located on the widespread mountain permafrost between the Siberian taiga and the Central Asian steppe zones and are composed of more than 90% Siberian Larch (*L. sibirica*) (IFFN, 2007). The area has been heavily affected by both anthropogenic and natural fires (Farukh et al., 2009; IFFN, 2007). This study mainly focused on a large wildfire that occurred in the area in June 1996 (Takeda et al., 2013) and affected about 280 km^2 of predominantly Siberian larch (*L. sibirica*) forest (Fig. 1). Based on similar characteristics and composition of vegetation, a small burn area from 1991 (Field 2, Fig. 1) was used in conjunction with the 1996 burn area (Field 1, Fig. 1) in order to collect field data of the forest patterns after the fires.

2.2. Overall processing flow

The processing flow (Fig. 2) of this study contains steps of image selection, preprocessing, calculation and analysis of the fractional vegetation cover (FVC) and the forest recovery index (FRI) derived from the integrated forest *z*-score (IFZ), and the trajectory based approach of FVC and FRI representing the temporal and spatial patterns of the post-fire forest recovery. We used the Landsat imagery (http://glovis.usgs.gov/) as a primary product for the trajectory of post-fire forest patterns in the 1996 burned area.

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