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Assessment of forest recovery at Wu-Ling fire scars in Taiwan using multi-temporal Landsat imagery

Chuphan Chompuchan[a,b], Chao-Yuan Lin[a,*]

[a] Department of Soil and Water Conservation, National Chung Hsing University, 145 Xingda Rd., South Dist., Taichung 402, Taiwan
[b] Department of Irrigation Engineering, Kasetsart University (Kamphaeng Saen Campus), 1 Malaiman Rd., Kamphaeng Saen Dist., Nakhon Pathom 73140, Thailand

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ABSTRACT

Normalized Burn Ratio (NBR), a satellite-derived index widely used to map the burned area and to assess burn severity level, was reconceptualized to propose the indices of post-fire recovery condition and resilience. Time series Landsat imagery during 1994–2015 were used to observe the forest recovery of Wu-Ling fire scars in Taiwan. Burn Recovery Ratio (BRR) was newly developed as the indicator to better clarify the forest recovery status. Results show that BRR coupled with dNBR (bi-temporal NBR) could quantitatively describe the level of forest recovery through the heterogeneity of forest landscape which is confirmed by field investigation. Time of complete recovery (t_c), indicator of post-fire resilience, were predicted using curve-fitting of forest recovery trajectories to the exponential decay function. The spatial distribution of t_c could reveal the patterns of post-fire recovery across the fire scars. For wildfire prevention, the issue of fire recurrence should be concerned at the areas of fire-adapted species with low t_c value. For areas of deterioration sites with high t_c value, the rehabilitation project should be implemented to accelerate forest restoration.

1. Introduction

Wildfire is an important disturbance on the forest ecosystem and causes a lot of impact on both global and local scales. In recent years, there are several studies showing major concerns about wildfire impacts throughout short and long-term (Shakesby, 2011; Shakesby and Doerr, 2006; van Wagtendonk et al., 2004). For the post-fire forest recovery context, it is normally monitored for a longer period for understanding the ecosystem response to fire or the rehabilitated ecosystems developed through post-fire management (Ireland and Petropoulos, 2015), and it is also involved in the restoration of forest biomass or canopy structure, soil properties and variety of species etc. Remote sensing has been highly effective to explore large coverage of fire-disturbance in remote terrain and to monitor post-fire response (Spasojevic et al., 2016). From a remote sensing perspective on ecological application, post-fire forest recovery often relates to the changes of spectral values and their temporal dynamics which could then describe recovery conditions as well as ecology and successional patterns (Bartels et al., 2016; Chu et al., 2016; Cohen and Goward, 2004).

The Normalized Burn Ratio (NBR) is one of the most effective satellite-driven indices for post-fire environment studies. NBR consists of the near infrared (NIR) spectral region at 0.76–0.90 μm which is particularly sensitive to the changes in the chlorophyll content of live vegetation, and short wave infrared (SWIR) spectral region at 2.08–2.35 μm which is sensitive to water content in both vegetation and soils, and some soil conditions (Miller and Thode, 2007). The difference Normalized Burn Ratio (dNBR), bi-temporal NBR between pre- and post-fire, is broadly used to detect burned area and interpret burn severity level (Chafer, 2008; De Santis and Chuvieco, 2007; Epting et al., 2005; Escuin et al., 2008; Lee et al., 2008; Vlassova et al., 2014). Since NBR is mainly developed for assessing burn severity, several studies are concerned that NBR does not adequately convey information about ecosystem responses in an early succession (Keeley, 2009; Lentile et al., 2007; Murphy et al., 2008). Nonetheless, many studies confirmed a reasonably good performance of NBR for quantifying the long-term vegetation regeneration on fire scars (Chen et al., 2011; Epting and Verbyla, 2005; García and Caselles, 1991).

A time series of satellite-derived burn severity index acquiring over a relatively long period of time enables the generation of the disturbance-recovery trajectory as well as the characterization of ecosystem pattern and process (Gómez et al., 2011; Kennedy et al., 2014; Pasquarella et al., 2016; Walker et al., 2010). Conceptually, at any point during the post-burn, recovery should be the deduction of severity as shown in Fig. 1. It could be alternately defined that the long-term severity is the residual suffer level referencing with the pre-fire

* Corresponding author.
E-mail address: cylin@water.nchu.edu.tw (C.-Y. Lin).

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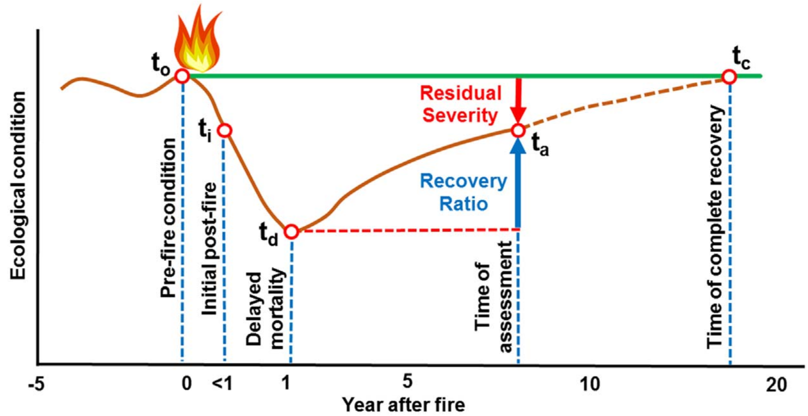

Fig. 1. Changes of residual severity and the correspondent recovery ratio (time axis is not scale, modified from Key, 2006).

condition, whereas the long-term recovery is the degree of regeneration from the greatest severity level. Therefore, forest recovery should be considered with 3 reference points in the consequent scale i.e. the time of pre-fire condition, the time of highest severity and the time of assessment. Generally, the highest severity level may not be reached few weeks/months after being burned due to the delayed mortality effect: the foliage that appears green and outwardly healthy soon after burning (Key, 2006), especially in a high dense canopy forest.

Two conceptual definitions of resilience have been widely used in the dynamics of ecological systems, generally referred to as ecological resilience and engineering resilience (Todman et al., 2016). Ecological resilience has been defined as the persistence of systems and their capacity to resist the amount of disturbance and still retain the main functions and processes (Holling, 1973). Engineering resilience has been defined as the time to return the disturbed ecosystems back to stable state (Pimm, 1984). Much of the current research shows that engineering resilience is potentially applicable to long-term ecosystem recovery following disturbance, through analysis of recovery trajectories (Díaz-Delgado et al., 2002; Newton and Cantarello, 2015; Nolan et al., 2015). From the trajectory of the forest recovery as shown in Fig. 1, time of complete recovery (t_c) could then be predicted. In this study, engineering resilience here is defined as t_c, and stable state is assumed as the level of pre-disturbed or undisturbed reference area.

This study aimed to develop the forest recovery index and predict the time of complete recovery considering the concept mentioned above, using multi-temporal Landsat imagery. Post-fire forest recovery was explored in Wu-Ling fire scars in central Taiwan. Aerial photos, the images extracted from Google Earth®, and field investigation were the supplementary data to clearly describe the variations in forest recovery.

2. Materials and methods

2.1. Study area

Wu-Ling farm is located at the south-east of Shei-Pa national park, Taiwan (Fig. 2). The main river is Qijiawan Creek which is the habitat of Formosan landlocked salmon (*Oncorhynchus masou formosanus*), a critical endangered species. During the 1960′s, a group of Taiwan's veterans resettled there as farmers and started the agricultural development of the mountain area. The area was named as "Wu-Ling farm" on 10th May 1963 (Veterans Affairs Commission R.O.C., 2011). In the late 1990s, the government's policy shifted towards environmental protection as well as sustainable development, and the agricultural activities therefore shifted to ecotourism eventually.

There are 2 fire scars, Huan-Shan and Sheng-Guang, located at the south-west and the east of Wu-Ling farm respectively. Historical records show that Huan-Shan site was burned on 3rd December 1995 and 11th February 2001; and Sheng-Guang site was burned on 11th May 2002. Both fire scars were approximately 350 ha with similar altitude range of 1600–2500 m a.s.l. and average slope of 28°. The main vegetation type was pine plantation forest. Due to the implementation of "Stand Conversion Project" from the Forestry Bureau during 1967–1975, Taiwan red pine was selected as the major plantation species with the purpose of improving poorly stocked natural forests through reforestation (Lin et al., 2005; Lo and Feng, 1987). The overstories were dominated by *Pinus taiwanensis* (Taiwan red pine), *Picea asperata* (dragon spruce), *Pinus armandii* (Chinese white pine), *Alnus formosana* (Formosan alder) and the understory was mainly covered with *Miscanthus sinensis* (Chinese silver grass). The whole Huan-Shan area and partial Sheng-Guang area are located in Shei-Pa national park which was established in 1992. The fires not only destroyed forests but also consequently affected the habitat of Formosan landlocked salmon. The rise in conservation awareness has focused attention on forest post-fire restoration work (Chen and Chen, 2015).

2.2. Data set

Cloud-free Landsat imagery (Path: 117, Row: 043), with spatial resolution 30 m, during years 1994–2015 were obtained for free from the United States Geological Survey (USGS) Earth Explorer website (URL http://earthexplorer.usgs.gov/) as listed in Table 1. Landsat 8 Operational Land Imager (OLI) surface reflectance scenes were preprocessed from Landsat 8 Surface Reflectance (L8SR) algorithm, however Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data need to correct the surface reflectance using Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) algorithm (U.S. Geological Survey, 2015a,b). Due to a slight difference between OLI and ETM+ reflectance, a simple empirical procedure developed by Flood (2014) was applied to remove between-sensor difference.

Multi-temporal datasets were acquired in the same period in order to minimize the between-scene misinterpretation caused by seasonal variation on crop phenology. Topographic effects due to low sun elevation angle in the winter image could degrade the surface reflectance value (Key, 2006; Picotte and Robertson, 2011; van Wagtendonk et al., 2004). In Taiwan, the precipitation is generally high during summer, resulting in less opportunity to retrieve cloud-free Landsat scenes. Therefore, in this study autumn series images (October–December scenes) were selected.

2.3. Methodology

2.3.1. Burn perimeter extraction and severity level

There were several studies in burned area delineation that use various spectral indices e.g. Normalized Difference Vegetation Index (NDVI) (Fernández et al., 1997), Global Environmental Index (GEMI)