International Journal of Applied Earth Observation and Geoinformation 40 (2015) 1–10

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Discriminating lava flows of different age within Nyamuragira's volcanic field using spectral mixture analysis

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ARTICLE INFO

Article history:
Received 5 December 2014
Accepted 26 March 2015

Keywords:
Vegetation fraction
Lava flow
Spectral mixture analysis
Nyamuragira
ALI
Pleiades

ABSTRACT

In this study, linear spectral mixture analysis (LSMA) is used to characterize the spectral heterogeneity of lava flows from Nyamuragira volcano, Democratic Republic of Congo, where vegetation and lava are the two main land covers. In order to estimate fractions of vegetation and lava through satellite remote sensing, we made use of 30 m resolution Landsat Enhanced Thematic Mapper Plus (ETM+) and Advanced Land Imager (ALI) imagery. 2 m Pleiades data was used for validation. From the results, we conclude that (1) LSMA is capable of characterizing volcanic fields and discriminating between different types of lava surfaces; (2) three lava endmembers can be identified as lava of old, intermediate and young age, corresponding to different stages in lichen growth and chemical weathering; (3) a strong relationship is observed between vegetation fraction and lava age, where vegetation at Nyamuragira starts to significantly colonize lava flows ~15 years after eruption and occupies over 50% of the lava surfaces ~40 years after eruption. Our study demonstrates the capability of spectral unmixing to characterize lava surfaces and vegetation colonization over time, which is particularly useful for poorly known volcanoes or those not accessible for physical or political reasons.

1. Introduction

Volcanic activity poses a persistent hazard to human activities and to the environment. At dominantly effusive volcanoes, frequently occurring lava flows destroy vegetation, cover fertile soils and pose a threat to human lives and properties. Freshly emplaced lava is inhospitable to plant growth (Deligne et al., 2013) and animal activities and the time of post-eruption vegetation recovery ranges from several years to decades to centuries, controlling when affected residents may return to their previous lands (De Rose et al., 2011). Characterizing the time frame for soil formation and vegetation colonization of lava flows is hence vital for the estimation of long-term impacts of volcanic resurfacing on agriculture and natural ecosystems. It also provides a framework for volcanic hazard assessment through the evaluation of return periods of volcanic activity.

Although the vegetation cover of an area can be studied in the field (Sohn and McCoy, 1997), the synoptic view provided by remote sensing offers great potential for documenting and quantifying the overall dynamic process of vegetation recovery. Remote sensing is also increasingly contributing to monitoring volcanic activities and mapping volcanic terrains, notably for inaccessible volcanoes (e.g. Ernst et al., 2008). Most commonly used satellite images, however, have a relatively coarse spatial resolution, ranging from low (MODIS, 250 m to 1 km) to moderate (Landsat TM/ETM+, 30 m). Pixels at these resolutions are frequently mixed and thus pixel-based classification methods fail to accurately discriminate lava and vegetation. This is especially problematic for lava surfaces, which are characterized by variable roughness at centimetre to hundred metres scales (e.g. pahoehoe vs aa textures or lava channels and levees). This roughness creates high spatial variability in illumination, temperature, wind and humidity, as well as sediment trapping, which control the mechanical and chemical weathering of lava flows and the initiation of biological processes.

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http://dx.doi.org/10.1016/j.jag.2015.03.015
0303-2434/

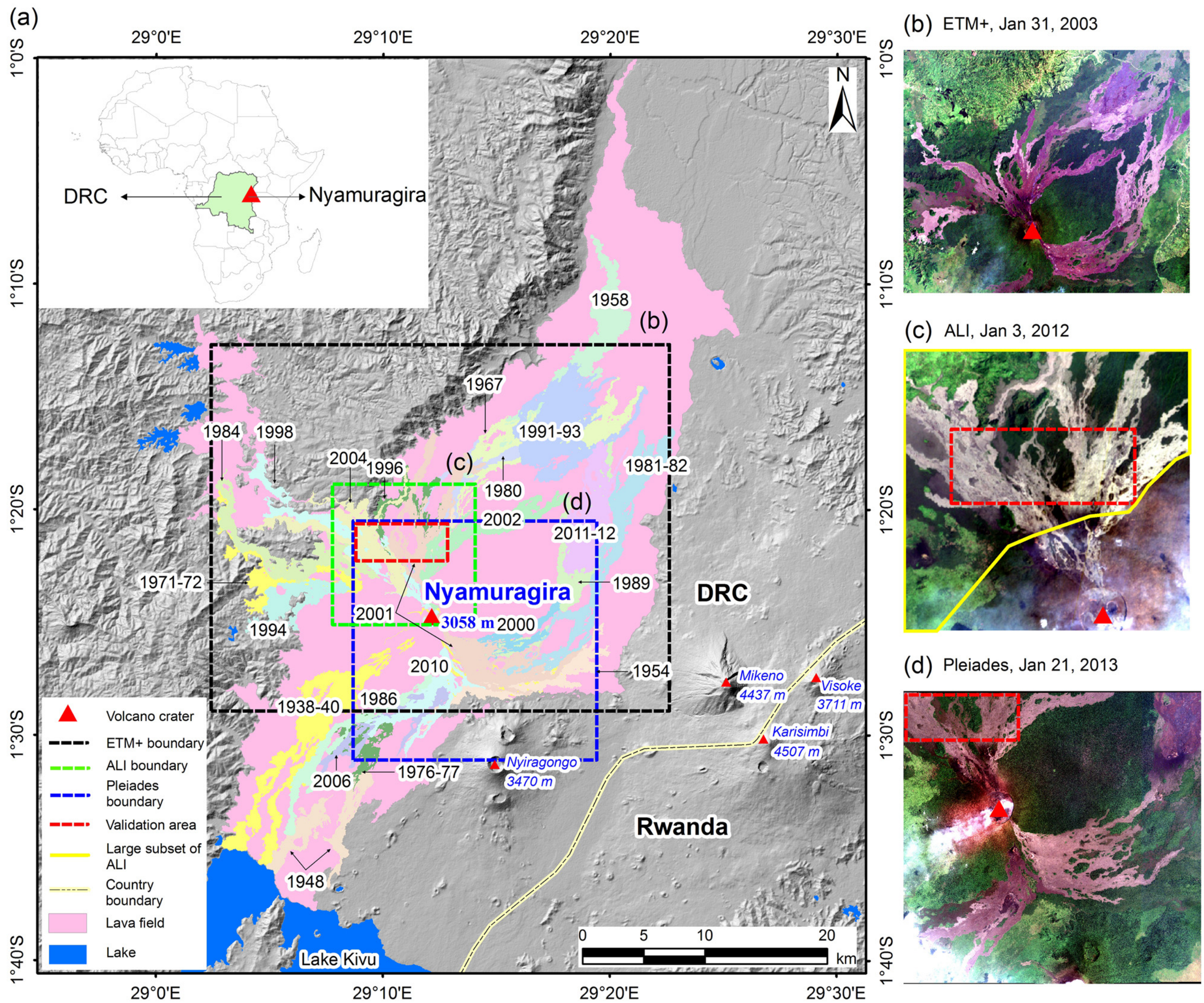

Fig. 1. Location map of Nyamuragira volcano showing lava flows erupted between 1938 and 2011 (adapted from Smets et al., (2010)). The three used satellite scenes are displayed in true colours on the right side with their acquisition date. Yellow lines in (c) indicate the extent of the large-scale ALI subset used for spectral unmixing. Red lines in (c) and (d) show the overlap between the ALI and Pleiades images, used for validation of the spectral unmixing results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Discriminating spectrally contrasting lava surfaces at sub-pixel resolution and quantifying the spatially heterogeneous vegetation recovery is therefore of great interest and cannot be addressed by traditional classification techniques.

Spectral mixture analysis (SMA) refers to a group of techniques used for extracting the fraction of spectrally pure materials present within mixed pixels. Many SMA related studies focus on mapping vegetation and impervious surfaces in urban areas (Deng and Wu, 2013; Van de Voorde et al., 2009 and references therein). The technique has also been applied to non-urban areas (e.g. Sohn and McCoy, 1997; Sonnentag et al., 2007; Zhang et al., 2005), but volcanic regions have received scant attention. Ramsey and Fink (1999) unmixed pumice deposits with endmembers of obsidian and blackbody using thermal infrared data on Medicine Lake volcano, California. Fully constrained linear spectral mixture analysis (LSMA) was tested to identify five endmembers of the Lunar Crater Volcanic Field, Nevada, using hyperspectral data (Heinz and Chang, 2001). Up to now though, LSMA has not yet been utilized to investigate the spectral evolution and vegetation colonization on lava surfaces with time. However, the large spectral contrast between the dark lava surfaces and the scattered vegetation growing on them, and potentially between fresh and highly weathered volcanic surfaces make them an ideal target for applying LSMA.

Therefore, in this study we test the potential of LSMA for lava surface discrimination within Nyamuragira's volcanic field. Specific objectives are: (1) to investigate the applicability of LSMA for characterizing lava flows; (2) to identify and interpret contrasted spectral endmembers; and (3) to document the spectral evolution and vegetation recovery patterns on lava flows through time.

2. Study area

Nyamuragira (Nyamulagira) is an active shield volcano located in the Virunga Volcanic Province of the Democratic Republic of Congo (DRC) (Fig. 1). It has a maximum elevation of 3058 m a.s.l. and a large lava field that covers over 1100 km^2 (Smets et al., 2010). It is the most active African volcano, erupting every 2–4 years, with 27 dated and mapped lava flows since 1938 (Smets et al., 2014, 2010).

The composition of Nyamuragira's lavas is very homogeneous over time and typical of lavas from the East Africa Rift System (Smets et al., 2014). Due to its equatorial climate, vegetation grows rapidly on Nyamuragira's lavas (Fig. 2). These characteristics and