ISPRS Journal of Photogrammetry and Remote Sensing 88 (2014) 174–192

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Detecting subcanopy invasive plant species in tropical rainforest by integrating optical and microwave (InSAR/PolInSAR) remote sensing data, and a decision tree algorithm

Abduwasit Ghulam [a,*], Ingrid Porton [b,c], Karen Freeman [c]

[a] Center for Sustainability, Saint Louis University, USA
[b] Saint Louis Zoo, 1 Government Drive, St. Louis, MO 63110, USA
[c] Madagascar Fauna and Flora Group, BP442, Toamasina 501, Madagascar

ARTICLE INFO

Article history:
Received 6 November 2012
Received in revised form 15 December 2013
Accepted 23 December 2013
Available online 21 January 2014

Keywords:
Betampona Nature Reserve
Guava
Madagascar cardamom
Molucca raspberry
Invasive plants
Remote sensing

ABSTRACT

In this paper, we propose a decision tree algorithm to characterize spatial extent and spectral features of invasive plant species (i.e., guava, Madagascar cardamom, and Molucca raspberry) in tropical rainforests by integrating datasets from passive and active remote sensing sensors. The decision tree algorithm is based on a number of input variables including matching score and infeasibility images from Mixture Tuned Matched Filtering (MTMF), land-cover maps, tree height information derived from high resolution stereo imagery, polarimetric feature images, Radar Forest Degradation Index (RFDI), polarimetric and InSAR coherence and phase difference images. Spatial distributions of the study organisms are mapped using pixel-based Winner-Takes-All (WTA) algorithm, object oriented feature extraction, spectral unmixing, and compared with the newly developed decision tree approach. Our results show that the InSAR phase difference and PolInSAR HH–VV coherence images of L-band PALSAR data are the most important variables following the MTMF outputs in mapping subcanopy invasive plant species in tropical rainforest. We also show that the three types of invasive plants alone occupy about 17.6% of the Betampona Nature Reserve (BNR) while mixed forest, shrubland and grassland areas are summed to 11.9% of the reserve. This work presents the first systematic attempt to evaluate forest degradation, habitat quality and invasive plant statistics in the BNR, and provides significant insights as to management strategies for the control of invasive plants and conversation in the reserve.

1. Introduction

As one of the world's most diverse hotspots for plant and animal species diversity (Ganzhorn et al., 2001; Myers et al., 2000), Madagascar's rainforests are an extreme example of a tropical forest ecosystem severely threatened by deforestation and habitat fragmentation caused by land-cover and land-use change (LCLUC) (Vagen, 2006). Multiple studies estimate that the deforestation rate in Madagascar is about 1100 km^2 per year, resulting in 90% of the original forest cover already being lost and/or degraded, especially in highly populated lowlands (Ganzhorn et al., 2001; Green and Sussman, 1990). These studies suggest that deforestation and environmental degradation in Madagascar are strongly linked to shifting cultivation and population growth and, therefore, human induced land use change. Climate change characterized by increased frequency and intensity of heat waves, drought and bushfires may have further exacerbated the destruction of the forest by land cover modifications, which also allow for the transfer and introduction of invasive plant species to those areas further impacting endemic species. The range and abundance of invasive plant species are important factors influencing forest health and biodiversity. In fragile ecosystems suffering environmental degradation and fragmentation, traits such as rapid growth rate and large reproductive output displayed by many invasive species often provide a competitive advantage for limited water and nutritional resources (Richardson and Rejmanek, 2011). The near absence of inhibitory predators and parasites often leads to prolific growth and rapid increase in the geographic range of exotic species, and can lead to marked reductions in local and regional biodiversity.

Réserve Naturelle Intégrale de Betampona (Betampona Nature Reserve abbreviated as BNR) represents one of the few remaining intact areas of lowland forest in eastern Madagascar, and has been recognized as potentially the most diverse location per surface area within the whole of Madagascar for both flora and fauna. Several

* Corresponding author. Tel.: +1 314 977 7062.
E-mail address: awulamu@slu.edu (A. Ghulam).

0924-2716/$ - see front matter © 2013 International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS) Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.isprsjprs.2013.12.007

elements of the flora and fauna are new to scientific study and are as yet undescribed; some species are known to exist only in the BNR and many of these species are endangered or critically endangered (Rosa et al., 2012). Establishment of the natural reserve itself in 1927 has not guaranteed a sufficient protection (Green and Sussman, 1990). Under the umbrella of the Madagascar Fauna and Flora Group (MFG), the reserve has been the target of significant conservation efforts from zoos, botanical gardens and related institutions from around the world since the early 1990s. However, it continues to be eroded through the gradual attrition of the impact of human settlements around the reserve, illegal logging, poaching and, slash and burn agriculture. One prominent result of the anthropogenic disturbances in the BNR is the steady encroachment of non-native plants, including *Psidium cattleianum* (guava) and *Rubus moluccanus* (Molucca raspberry), as well as some native plants, e.g., *Aframomum angustifolium* (Madagascar cardamom), many of which have become aggressive invaders in the disturbed habitat. Although forests are not immune to plant invasions, closed-canopy forests are relatively resistant to infestations as communities (Godoy et al., 2011). However, the degree to which a habitat might be altered depends on the invasibility of the alien plants and local biotic and abiotic characteristics (Larson et al., 2001; Pino et al., 2006; Rouget and Richardson, 2003). Some non-native species, particularly guava, can develop shade tolerance and grow into shrubs and trees under closed-canopies (Strahm, 1999), and eventually replace the endemic flora by forming dense thickets that prevent the regeneration of native trees. The increasing extent of invasive plants has become one of the greatest threats to the BNR ecosystem, highlighting the increasing urgency to develop spatially explicit, fine-scale records of plant invasions for the reserve's managers.

Understanding the potential impact of invasive plants on native ecosystems and preventing them from further spread is of particular interest for biodiversity studies and conservation management. Remote sensing may be used to map and monitor spatio-temporal distribution of invasive plants provided that highly invasive species are spectrally separable from native and/or introduced species that do not proliferate across the landscape (Asner et al., 2008). An integrated approach based on hyper-spectral and hyper-spatial remote sensing data that involves the use of object oriented feature extraction, spectral unmixing and landscape pattern analysis has shown great potential in characterizing the location, density and spatial structure of *Psidium gujava* (cultivated for fruit) in agricultural ecosystems (Walsh et al., 2008). There exist a growing number of studies on mapping invasive plant species based on spectral discrimination of the plants using spectral unmixing and sub-pixel classifications of optical remote sensing imagery (Cheng et al., 2007; Frazier and Wang, 2011; Hamada et al., 2007; Laba et al., 2008; Underwood et al., 2007; Walsh et al., 2008). Spectral signatures of plants are expressions of canopy biochemical and structural properties including leaf area index (LAI), leaf/canopy water content, chlorophyll concentration, leaf internal structure, leaf angle orientation and specific leaf area (leaf area per unit mass). Arguably, plants may show similar spectral profiles because they are composed of the same spectrally active materials, i.e., pigments, water, cellulose, etc. (Jacquemoud and Baret, 1990). Translating canopy spectra to individual species composition is often challenging particularly in tropical forests in the context of invasive species (e.g., guava), which can grow under the closed canopy.

Conservation planning and management efforts are mostly interested in detecting and removing invasive plants at the early invasion stage since effective control is best achieved when plants are young and patches are small and disconnected (Walsh et al., 2008). However, the early stages of invasive plant colonization may occur far below the forest canopy, rendering them virtually invisible using standard canopy census methods. Passive optical remote sensors have limited ability to penetrate beyond upper canopy layers (Weishampel et al., 2000). The environmental context in which a weed grows cannot be neglected in successful detection of infestation in complex habitat (Andrew and Ustin, 2008). The optimal strategy for remote sensing of invasive plant species in tropical rainforest would include combining information from multiple sensors or data fusion to fully exploit spectral, spatial, temporal and/or vertical structure profile of the forest, which might be used to infer understory species at the early stage of invasion. For example, the use of Synthetic Aperture Radar Interferometry (InSAR) and polarimetric InSAR (PolInSAR) may provide unique monitoring capabilities through its ability to penetrate clouds and forest canopies, and collect images at any time of day or night, without atmospheric limitations. There have been a few reports in the scientific literature on the use of Radarsat-2 polarimetric data to map invasive plant species, primarily in prairie landscapes (Coleman, 2010). However, applying the approach to tropical rainforest has not been explored in detail and remains a significant challenge.

Synthetic aperture radar (SAR) signals in longer wavelengths (e.g., L-band and P-band) can penetrate the forest canopy, and have been favored for estimating vertical forest structure by many studies (Cloude and Pottier, 1997; Freeman and Durden, 1998; Lee et al., 2004). The Wishart classification of P-band PolSAR data has had some success in discerning different tree ages within a homogeneous forest (Lee et al., 2001) using the assumption that volume scattering mechanisms are dominant in these frequencies. However, the presence of multiple reflections from leaves, branches and trunks, along with surface reflections from bare forest floor can introduce a significant signal from surface scattering mechanisms in more heterogeneous forests. In contrast, the shorter wavelengths in the C band (5.6 cm) have a limited ability to penetrate to the forest understory and floor, and therefore, may be more useful in mapping plant species in forest canopies or sub-canopies, where scattering mechanisms are dominated by surface scattering. A number of studies have suggested that C band PolSAR data can be used to infer canopy and subcanopy relationships (Freeman and Durden, 1998), on the basis of volume and basal area in a mixed mature forest (Cloude and Pottier, 1997). Coherence and interferometric phase differences derived from SAR images provide a direct measure of the distribution of the scatterers in a terrain. When generated with the inputs being the same polarization, e.g., HH (horizontal transmit and horizontal receive) or VV (vertical transmit and vertical receive) combination from two different acquisitions collected at different times (repeat-pass scenario), InSAR coherence provide meaningful information of how things have changed over time. For example, burn severity due to wild fires is strongly associated with coherence, i.e., coherence increases with the increase of burn severity (Tanase et al., 2010). Since random changes in land cover types like forest or water may cause drastic decrease of coherence while stable objects such as bare land surfaces, rocks or shrubland may show a larger coherence. Therefore, interferometric land use (ILU) composite based on coherence image, mean and difference of intensity images has shown a potential in land cover classification (Nizalapur et al., 2011; Santoro et al., 2006). On the other hand, coherence between two different polarization combinations (e.g., HH and VV) from the same acquisition may provide an image of polarimetric phase difference between the two different polarization combinations that might help to distinguish different materials in the scene. Recent studies have indicated that polarimetric phase differences between HH and VV, HH and HV (horizontal transmit and vertical receive) or HH and VH (vertical transmit and horizontal receive), polarimetric coherence and depolarization ratio and their color composites derived from PALSAR datasets are best to discriminate invasive plant species in tropical rainforests (Ghulam et al., 2011). However, we lack a systematic understanding of the advantages and