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On the use of binary partition trees for the tree crown segmentation of tropical rainforest hyperspectral images

G. Tochon [a,b,*], J.B. Féret [b,c], S. Valero [c], R.E. Martin [b], D.E. Knapp [b], P. Salembier [d], J. Chanussot [a,e], G.P. Asner [b]

[a] GIPSA-Lab, 11 rue des Mathématiques, 38400 Saint Martin d'Hères, France
[b] Department of Global Ecology, Carnegie Institution for Science, 260 Panama Street, Stanford, CA 94305, USA
[c] CESBIO, 18 avenue Edouard Belin, 31400 Toulouse, France
[d] Technical University of Catalonia (UPC), Jordi Girona 1-3, edifici D5, 08034 Barcelona, Spain
[e] Faculty of Electrical and Computer Engineering, University of Iceland, Reykjavík, Iceland

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ABSTRACT

The segmentation of remotely sensed images acquired over tropical forests is of great interest for numerous ecological applications, such as forest inventories or conservation and management of ecosystems, for which species classification techniques and estimation of the number of individuals are highly valuable inputs. In this paper, we propose a method for hyperspectral image segmentation, based on the binary partition tree (BPT) algorithm, and we apply it to two sites located in Hawaiian and Panamean tropical rainforests. Different strategies combining spatial and spectral dimensionality reduction are compared prior to the construction of the BPT. Various superpixel generation methods including watershed transformation and mean shift clustering are applied to decrease spatial dimensionality and provide an initial segmentation map. Principal component analysis is performed to reduce the spectral dimensionality and different combinations of principal components are compared. A non-parametric region model based on histograms, combined with the diffusion distance to merge regions, is used to build the BPT. An adapted pruning strategy based on the size discontinuity of the merging regions is proposed and compared with an already existing pruning strategy. Finally, a set of criteria to assess the quality of the tree segmentation is introduced. The proposed method correctly segmented up to 68% of the tree crowns and produced reasonable patterns of the segmented landscapes.

1. Introduction

There is a growing need for large-scale assessment of biodiversity and species richness in ecosystems, as a means to improve forest conservation and management decisions. Tropical rainforest ecosystems are of critical interest since they are hotspots of biodiversity, greatly contributing to the world's biotic variety while covering only a small percentage of the terrestrial surface. Moreover, they are particularly vulnerable to multiple factor pressures such as exploitation of natural resources and climate change (Asner, Rudel, Aide, Defries, & Emerson, 2009; Thomas et al., 2004; Whitmore, 1990). In this context, information about the forest structure, the number, spatial distribution and identification of individual trees, the species richness and its evolution, and the dynamics of invasive species across landscapes are highly sought after for efficient management decisions applied to forest conservation. Related field data collection is extremely expensive, time-consuming and requires very skilled field workers. Such constraints call for supporting technologies and methods for the accurate and regular monitoring of the evolution of biological diversity over large spatial scales. Remote sensing appears as a particularly efficient tool for such applications (Rasi et al., 2013; Reiche et al., 2013). However, monitoring tropical forest ecosystems using remote sensing remains extremely challenging due to the complexity of the canopy in terms of density, structure and species richness (Papes et al., 2013; Pouteau & Stoll, 2012; Somers & Asner, 2013).

Among the various information that can be derived from remotely sensed data, individual tree crown (ITC) delineation is a particularly important product assisting in fine-scale analysis of ecological processes linked to vegetation structure and gap dynamics (Phinn et al., 2008), as well as improved tree species identification (Clark, Roberts, & Clark, 2005). Indeed, region properties such as texture, size, shape or radiometric variability, can be derived from each ITC delineated on an image, resulting in the combination of spatial and radiometric information. Such object-oriented approaches usually outperform traditional pixel-based methods for classification and other image processing applications such as spectral unmixing and object detection, and dramatically enrich contextual information delivered by remote sensing products. In practice, high spatial resolution ITC delineation can be useful to help monitor species of interest, such as dominant trees, rare or

* Corresponding author at: GIPSA-Lab, 11 rue des Mathématiques, 38400 Saint Martin d'Hères, France.
E-mail addresses: guillaume.tochon@gipsa-lab.grenoble-inp.fr (G. Tochon), feretjb@cesbio.cnes.fr (J.B. Féret).

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invasive species that are key indicators for environmental processes (Asner, Jones, Martin, Knapp, & Hughes, 2008). It can also be used to detect illegal logging, as logging practices are nowadays very selective and assisted by moderate resolution satellite images to detect large scale deforestation (Asner et al., 2005).

Several segmentation methods have been developed for ITC delineation based on high spatial resolution imagery derived from various sensors, from satellite very high resolution imagery to airborne Light Detection and Ranging (LiDAR) data. However, the selection of a segmentation algorithm is critical as the performances of these methods are usually strongly ecosystem-dependent. ITCs that are typically encountered in temperate forests offer several appealing characteristics for the development of segmentation algorithms. In fact, those trees have a regular shape and elongated silhouette, and the canopy is rather sparse. Existing segmentation algorithms devoted to the segmentation of temperate forests are taking advantage of those properties. For instance, it is often assumed in forested area high resolution digital imagery that an ITC is represented by bright pixels (the top of the crown, well illuminated by the sun) surrounded by darker pixels (either shaded portions of the crown or the ground) (Wulder, Niemann, & Goodenough, 2000). Using a topographical analogy, an ITC can be viewed as a peak and the valleys circling around it are its physical boundaries. The valley following approach exploits this idea by encircling bright pixels with darker boundaries, and was used by Gougeon (1995), Leckie et al. (2003, 2005), and Leckie, Gougeon, Walsworth, and Paradine (2003) for the segmentation of coniferous plantations, and by Warner, Lee, and McGraw (1998) for deciduous forests. Also relying on the topographical representation, region growing approaches implement seeds in local maxima of the image, each seed being therefore potentially located at the top of an ITC. Regions are gradually expanded from the seeds until a stopping criterion, based on the presence of valleys, is reached. Region growing methods were validated on Australian eucalypt forests by Culvenor (2002) and Whiteside and Ahmadb (2008) and on coniferous forests by Erikson (2004) and Pouliot, King, Bell, and Pitt (2002). The marker-controlled watershed method is analogous to region growing when gray tones are inverted in the topographical representation, that is, when local maxima corresponding to ITCs become local minima. Instead of expanding regions from bright values to dark ones, the watershed floods up the topographical map and creates regions corresponding to catchment basins. Markers play the same role as seeds in the region growing approach, and temper the algorithm sensibility to noise in order to avoid over-segmentation. This approach was validated by Wang, Gong, and Biging (2004) for the segmentation of Canadian coniferous forests. A comparison between valley following, region growing and marker-controlled watershed methods for coniferous and deciduous tree stands is drawn by Ke and Quackenbush (2011). Template matching can also be applied when all ITCs have a regular and elongated shape. It consists of synthetically modeling the tree shapes by a collection of templates being generalized ellipses with various physically possible parameter values. Each template is cross-correlated against any potential tree position in the digital image, and the locations of the highest correlations are considered to be ITC positions, while the corresponding templates are assumed to be the tree shapes. Template matching was used by Olofsson (2002) and Pollock (1996, 1998) for coniferous and mixed forests, and a comparison between template matching and region growing approaches applied to the delineation of Swedish spruce stands can be found in Erikson and Olofsson (2005). Finally, stochastic point process methods model the image as a realization of a marked point process of ellipses. The process, being the digital image, contains an unknown number of objects (trees), each of them being in an unknown configuration (its elliptic shape and orientation). An energy term corresponding to the fit between the model and the real image is defined, and the model is iteratively adjusted in order to decrease the energy term at each iteration. Prior knowledge about the general distribution of shapes and sizes is needed to operate the method, and those parameters can be easily derived when all trees have similar structures. Point processes were investigated by Perrin, Descombes, and Zerubia (2005) for poplar plantations and by Andersen (2003) for coniferous forests.

Cited methods, based on strong hypotheses about crown size and shape (existence of one unique maximum for each individual and limited overlapping between individuals) show good results for high resolution digital images of temperate forests. However, they perform poorly when applied to tropical dense forest ecosystems, where tree size and shape are highly variable, and individuals usually overlap. Varekamp and Hoekman (2001) proposed a method based on Fourier parameterized deformable models for Interferometric Synthetic Aperture Radar (InSAR) data. Using the intensity, the interferometric height-coordinate and the coherence magnitude measures proper to the InSAR imaging system, they matched ITCs with deformable ellipses, and applied their method to a tropical forest located in Kalimantan, Indonesia. Note that Zhou et al. (2010) also applied marked point processes to high resolution imagery and LiDAR-derived canopy height in order to detect individuals in high biomass mangroves, including only one to two canopy species. Results were encouraging; however they may not be replicable when applied to dense tropical forests given the relatively low heterogeneity of mangroves.

Over the last decade, several studies explored the potential of spectroscopic imagery for the tree species identification in dense tropical forests (Clark et al., 2005; Feret & Asner, 2013), as well as tree crown delineation (Bunting & Lucas, 2006) in open mixed forests. The differentiation between species is based on their spectral signature, which is related to leaf chemistry and individual tree structure. Detailed spectral information may then be a valuable input to detect boundaries between neighboring trees in dense tropical forests. However, it comes with a major challenge related to the high dimensionality of the data and the need of adapted algorithms for automated tree crown segmentation. To the best of our knowledge, there is no reference study for the segmentation of tree crowns in hyperspectral images of tropical rainforests.

Image segmentation applied to dense tropical forests is an ill-posed task: a given image can often be segmented at several levels of details, due to the complex architecture of the top of the canopy. For this reason, it is better to have a consistent hierarchy of segmentations rather than a collection of minimally related segmentations. This allows the user to tune the exploration level within the hierarchy to the precise goal (Jung, Pasolli, Prasad, Tilton, & Crawford, 2014; Tarabalka, Tilton, Benediktsson, & Chanussot, 2012). Mathematical tree structures are well suited for a hierarchical region-based representation of an image. In such structure, each node of the tree represents a given region in the corresponding image, and links between nodes illustrate a particular relationship between regions, such as inclusion or adjacency. Among all tree representations, the binary partition tree (BPT) has received much attention lately. Initially proposed by Garrido (2002) and Salembier and Garrido (2000) for grayscale and RGB images, BPTs have then been further extended to hyperspectral imagery by Valero, Salembier, and Chanussot (2013a) and are now used for classical hyperspectral remote sensing tasks such as segmentation (Valero, Salembier, & Chanussot, 2011; Veganzones, Tochon, Dalla-Mura, Plaza, & Chanussot, 2014), classification (Alonso-Gonzalez, Valero, Chanussot, Lopez-Martinez, & Salembier, 2013), unmixing (Drumetz et al., 2014) and object detection (Valero, Salembier, & Chanussot, 2013b; Valero, Salembier, Chanussot, & Cuadras, 2011), notably. The efficiency of the BPT to achieve a given task is greatly impacted by both the pre-processing applied to the image prior to the construction of the BPT and the post-processing of the BPT representation itself, called pruning.

Consequently, we propose in the following study to adapt the BPT representation to the segmentation of hyperspectral images of tropical rainforests, through an adapted pre-processing of the data and pruning of the BPT. The pre-processing stage consists of spectrally and spatially reducing the data by extracting discriminant information using Principal Component Analysis (PCA) and spatial pre-

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