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A model-based performance test for forest classifiers on remote-sensing imagery

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ABSTRACT

Ambiguity between forest types on remote-sensing imagery is a major cause of errors found in accuracy assessments of forest inventory maps. This paper presents a methodology, based on forest plot inventory, ground measurements and simulated imagery, for systematically quantifying these ambiguities in the sense of the minimum distance (MD), maximum likelihood (ML), and frequency-based (FB) classifiers. The method is tested with multi-spectral IKONOS images acquired on areas containing six major communities (oak, pine, fir, primary and secondary high tropical forests, and avocado plantation) of the National Forest Inventory (NFI) map in Mexico. A structural record of the canopy and optical measurements (leaf area index and soil reflectance) were performed on one plot of each class. Intra-class signal variation was modelled using the Discrete Anisotropic Radiative Transfer (DART) simulator of remote-sensing images. Atmospheric conditions were inferred from ground measurements on reference surfaces and leaf optical properties of each forest type were derived from the IKONOS forest signal. Next, all forest types were simulated, using a common environmental configuration, in order to quantify similarity among all forest types, according to MD, ML and FB classifiers. Classes were considered ambiguous when their dissimilarity was smaller than intra-class signal variation.

DART proved useful in approximating the pixel value distribution and the ambiguity pattern measured on real forest imagery. In the case study, the oak forest and the secondary tropical forest were both distinguishable from all other classes using an MD classifier in a 25 m window size, whereas pine and primary tropical forests were ambiguous with three other classes using MD. By contrast, only two pairs of classes were found ambiguous for the ML classifier and only one for the FB classifier in that same window size. The avocado plantation was confounded with the primary tropical forest for all classifiers, presumably because the reflectance of both types of forest is governed by a deep canopy and a similar shadow area. We confronted the results of this study with the confusion matrix from the accuracy assessment of the NFI map. An asset of this model-based method is its applicability to a variety of sensor types, eco-zones and class definitions.

1. Introduction

The classification of remote-sensing images for forest cartography is essential to regional biodiversity mapping. Yet, because of the heterogeneity of forest settings, the distinction between forest types remains a difficult challenge. The application of common automatic classifiers (e.g. ISODATA, *K*-means) and visual labelling of the resulting unsupervised clusters still seem, at least until recently, a widely used strategy in operational forest mapping programs at regional scale (i.e., Benjamin et al., 1996; Vogelmann et al., 2001; Wulder et al., 2003). Comprehensive or partial accuracy assessments of these maps were achieved (Laba et al., 2002; Wickham et al., 2004; Remmel et al., 2005). At high

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taxonomic resolution, confidence levels reported for many forest classes were lower than those reported in other studies on the same type of imagery with more sophisticated classifiers (e.g. Magnussen et al., 2004; Salovaara et al., 2005; Lu et al., 2003). However, the latter studies occurred in more confined, more homogeneous geographical areas and concerned a smaller number of classes. In some of these case studies, classifiers with ancillary information on forest stand structure yield better accuracy than the one obtained with classifiers that do not incorporate such information. For example, Spectral Mixture Analysis (SMA) uses spectral end-members (shadow or sunlit fractions) that contain sub-pixel structural information, and SMA yielded accuracy improvements for the classification of successional stages of the Amazonian tropical forest (Lu et al., 2003). Moreover, Lu (2005) found that a more detailed structural information (the measurement of tree height distribution on the ground) was highly correlated with a combination of Landsat TM bands; a linear regression of these quantities further improved the accuracy of the classification. A drawback of these approaches, however, is again their limited transferability to broader scales, other forest communities, or other remote-sensing configurations. Indeed, the relationships that linked forest stand structural information to the reflectance data were empirically derived and only valid for the environment close to the image at hand (Lu, 2005). From these observations, a set of questions may be posed by the forest map producer in a highly biodiverse region: Would any more sophisticated classifier perform better than the common automatic classifiers at regional or national scales, for a wider set of forest classes? Or: For which set of forest classes is it worthwhile to look for better, more sophisticated, algorithms instead of settling for the commonly used (or available) classifiers?

Considering the above-mentioned improvements in accuracy, one way to address these questions could be to refer to an expert system, based on the description of the structure of forest stands, capable of estimating *a priori* ambiguities among classes for a given classifier. Indeed, high ambiguity between two forest types for a few conventional classifiers would encourage the forest map producer to look for a more sophisticated classifier. Such result could even pose the question of whether it is suitable to classify these forest types via automatic classification or if it is preferable to use visual classification instead, a strategy employed for example in the case of the National Forest Inventory (NFI) in Mexico (Mas et al., 2002; Mas and Ramírez, 1996). Conversely, low ambiguity between two forest types for a given classification method would ensure the appropriateness of the classification method and stop the quest for a better classifier (e.g. Baban and Kamaruzaman, 2001, in a sub-tropical setting). It is recently argued indeed (Wilkinson, 2005) that more research efforts should be dedicated to improving other areas of the map production process (Fassnacht et al., 2006) rather than mainly focusing on better classification algorithms.

In this research, we propose a framework based on forest plot inventory, ground measurements and simulated imagery, in order to test a few classifiers' *a priori* performance on pairs of classes among a given set of forest types and for any given remote-sensing platform. This framework is applied to the case of 6 forest types pertaining to classes at community level (Palacio-Prieto et al., 2000) of the Mexican NFI map (see Mas et al., 2002), namely oak, pine, fir, primary and secondary high tropical forests, and avocado plantation.

2. Background

3D modeling of forest plots offers various advantages to foresters. For example, it allows tree mapping based on plot inventory, which enables the precise estimation of key structural indices of the forest such as canopy gap distribution (Silbernagel and Moeur, 2001). Additionally, radiative transfer coupled with 3D modeling has permitted the evaluation of radiation budgets of forest parcels and intercepted radiation by tree crowns (e.g. Gastellu-Etchegorry and Trichon, 1998; Courbaud et al., 2003). In terms of bi-directional reflectance, the comparison between simulated and real imagery of forests is a difficult task. At scales well above tree crown, the average signal is dominated by the macroscopic properties of illuminated and shadowed crown and ground components. In this case, the average reflectance of homogeneous stands is simulated with forward models of canopy scattering (e.g. Goel and Thompson, 2000; North, 1996; Pinty and Verstraete, 1991; Strahler, 1996). This approach has been successfully assessed against real imagery in mainly coniferous stands made of repeated individuals of one or two species (Gemmel and Varjo, 1999; Courbaud et al., 2003; Disney et al., 2006). No such exercise was achieved for scales approaching crown size and with a flexible scheme integrating a greater diversity of tree species and heterogeneous understory spectral signatures.

The 3D Discrete Anisotropic Radiative Transfer (DART[4]) ray-tracing model (Gastellu-Etchegorry et al., 2004) simulates remote-sensing images of heterogeneous natural and urban landscapes, using 3D generic representations of these landscapes. This simulator has been successfully tested against reflectance results of other radiative transfer models (Pinty et al., 2004). Gastellu-Etchegorry and Trichon (1998) stress the difficulty in accurately positioning a simulated plot on a 25 m resolution imagery. Simulating remote-sensing imagery and not only average reflectance allows to work at resolutions close to crown scales. At very high (1–5 m) resolution, more recently available, forest plots are more easily identifiable on the image, and the amount of ground measurements necessary for statistically meaningful comparisons between simulated and real pixel sets is at least $5^2 = 25$ times less extensive than for 25 m resolution imagery, in which a one hectare plot contains only 16 pixels. Multi-spectral IKONOS imagery (4 m resolution) has recently been used for the classification of taxonomically close forests (e.g. Wang et al., 2004; Thenkabail et al., 2004).

We used the DART model to simulate the inherent heterogeneity of forest stands and the associated IKONOS multi-spectral remote-sensing images. This paper describes an approach that is essentially generic, and examines the utility of a 3D structural model with general assumptions on the canopy, in order to test the correspondence of such general model with the structural information given by 4 m multi-spectral imagery of a large variety of forest types. Our goal was to study ambiguities among these forest types on remote-sensing imagery in a systematic manner. For this purpose, a set of parameters, measurable in the field and in the laboratory, was handled as variables, while environmental heterogeneity exterior to the forest setting (viewing and illumination configurations, sensor response and atmospheric scattering) was controlled and fixed.

Clusters from commonly available unsupervised classifiers such as ISODATA or *K*-means are organized around the minimum distance (MD) principle. Another conventional parametric method is the maximum likelihood (ML) classifier. MD and ML principles were selected for the ambiguity estimate concerning relatively common classifiers. Among more sophisticated methods, the frequency-based (FB) classifiers have been successfully used for contextual image classification of very high resolution imagery (Lira and Maletti, 2002; Xu et al., 2003). The first order FB classifier

[4] DART is a patented model that is freely available for scientific applications at www.cesbio.cnes.fr.