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Multiple attribute decision making for individual tree detection using high-resolution laser scanning

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ABSTRACT

A canopy height model (CHM) is a standard LiDAR-derived product for deriving relevant forest inventory information, including individual tree positions, crown boundaries and plant density. Several image-processing techniques for individual tree detection from LiDAR data have been extensively described in literature. Such methods show significant performance variability depending on the vegetation characteristics of the monitored forest. Moreover, over regions of high vegetation density, existing algorithms for individual tree detection do not perform well for overlapping crowns and multi-layered forests. This study presents a new time and cost-efficient procedure to automatically detect the best combination of the morphological analysis for reproducing the monitored forest by estimating tree positions, crown boundaries and plant density from LiDAR data. The method needs an initial calibration phase based on multi attribute decision making-simple additive weighting (MADM-SAW). The model is tested over three different vegetation patterns: two riparian ecosystems and a small watershed with sparse vegetation. The proposed approach allows exploring the dependences between CHM filtering and segmentation procedures and vegetation patterns. The MADM architecture is able to self calibrate, automatically finding the most accurate de-noising and segmentation processes over any forest type. The results show that the model performances are strongly related to the vegetation characteristics. Good results are achieved over areas with a ratio between the average plant spacing and the average crown diameter (TCI) greater than 0.59, and plant spacing larger than the remote sensing data spatial resolution. The proposed algorithm is thus shown a cost effective tool for forest monitoring using LiDAR data that is able to detect canopy parameters in complex broadleaves forests with high vegetation density and overlapping crowns and with consequent significant reduction of the field surveys, limiting them over only the calibration site.

1. Introduction

Single tree-level forest information plays a crucial role in hydrological, meteorological, and ecological applications sensitive to vegetation evolution at local and regional scales. Some of these applications consist of monitoring forest regeneration and damage evaluation (Chen et al., 2006), biomass and carbon stock estimation (Popescu and Wynne, 2004), wildfire simulation models (Finney, 1998), quantifying woodland structure and habitat quality for birds (Hinsley et al., 2002) flow resistance models for hydraulic roughness estimation (e.g., Petryk and Bosmajian, 1975; Thompson and Roberson, 1976; Kouwen and Fathi-Moghadam, 2000; Järvelä, 2004; Baptist et al., 2007) and for atmospheric turbulent flux modeling (Eagleson, 2002). Tree crown boundaries, individual tree positions and the spatial variability of plant density represent important forest parameters. Traditional methods of investigating such parameters include labor-intensive forest inventories and complex sampling designs (Shivers and Borders, 1996). Moreover, the existing methods are time-consuming, subjective and more applicable primarily to small areas (Avery and Burkhart, 1994).

New technologies, such as remote sensing and new computer vision algorithms, have enabled the introduction of semi-automated forest assessments based on delineation of single tree crowns and individual tree detection. Several large area inventories have been achieved with very high-resolution remote sensing using automated pattern recognition (e.g., Gougeon and Leckie, 2003). However, as the spectral and textural characteristics derived from remotely sensed images are not directly related to tree morphology, these methods can produce inaccurate estimates

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(Gong et al., 2002). In recent years, airborne LiDAR technology has been used to detect individual tree crowns and biophysical characteristics (Andersen et al., 2005; Hyyppa et al., 2001; Popescu and Wynne, 2004; Næsset and Økland, 2002). Compared with passive images, LiDAR has the advantage of directly measuring the three-dimensional coordinates of canopies, providing information for crown geometric shapes. Despite LiDAR-derived products can never reveal certain tree patterns measured in the field, such as suppressed trees, grouped trees in dense forests and understory (Popescu and Zhao, 2008; Zhao et al., 2009), they represent powerful tools for deriving relevant forest inventory information.

Several methods for tree detection developed for optical imagery have been extended to LiDAR data. An efficient method for automated segmentation is the morphological watershed algorithm (Vincent and Soille, 1991; Soille, 1999), and its recent variants (Osma-Ruiz et al., 2007; Rambabu and Chakrabarti, 2007). Watershed segmentation has also been used to detect tree crown boundaries and positions through several formulations: classical approach (Andersen et al., 2005), marker-controlled watershed segmentation (Chen et al., 2006) and watershed using the transformation distance (Kwak et al., 2007). Such methods show significant performance variability depending on the vegetation characteristics of the monitored forest. To avoid "over-segmentation" in the application of a watershed algorithm to LiDAR data, the canopy height model (CHM, a digital crown height model) is usually pre-processed using different filters such as Gaussian (Dralle and Rudemo, 1996; Persson et al., 2002) or convolution (Hyyppa et al., 2001), with a static or variable window (Popescu and Wynne, 2004). Despite the fact that filter and window size influence significantly the CHM smoothing process (Chen et al., 2006), the linkage between filtering parameters and segmentation performances is still poorly explored.

Although the use of LiDAR data for producing CHM estimates has produced encouraging results over coniferous forests, similar performances have not been assessed over broadleaved woodlands or multi-layered forest canopies, characterized by a complex plant morphology with overlapping crowns (Maltamo et al., 2004). As a result, new methodologies for detecting tree crown characteristics and positions need to be validated over a range of different forest conditions.

The overall goal of this study was to develop a new time and cost-efficient procedure to automatically detect the best combination of the image morphological analysis for reproducing the monitored forest by estimating tree positions, crown boundaries and plant density variability using airborne LiDAR data. The model needs an initial calibration phase based on multiple attribute decision making (MADM) simple additive weighting method (SAW) (Hwang and Yoon, 1981). The main novelty is that the MADM architecture can be easily applied on several forest patterns detecting automatically, in a ensemble of the most used segmentation algorithms and de-noising filters, the optimal image processing depending on the canopy characteristics of the investigated area. The model is tested over three different vegetation patterns: two riparian ecosystems along the Serchio and the Sieve River floodplains (Tuscany Region, Italy) and a small watershed with sparse vegetation located in the Sevilleta National Wildlife Refuge (New Mexico, USA).

2. Methods

2.1. Study areas

The study area location is important for the description of the different forest environments that are considered necessary to calibrate the model. The first study area is located along the Serchio River in the Township of Gallicano, 28 km north of the city of Lucca (Tuscany Region, Italy) (Fig. 1A). The site is made up of a small area ($\approx$0.0025 km^2) containing a fluvial island with a very high vegetation density downstream of the Campia bridge. This mature woodland results from the evolution of riparian ecosystems that have not been altered by flood events for some time. The most common species are Lombardy poplar (*Popolus nigra*), willow (*Salix alba*), black alder (*Alnus glutinosa*), and field maple (*Acer campestre*). The vertical distribution of tree crowns indicates a non-coetaneous biplanar riparian formation, originating from natural dissemination, formerly managed via cutting, and currently in the pole forest evolutionary stage.

The second study area is situated along the Sieve River, 20 km north-east of the city of Florence (Tuscany Region, Italy) (Fig. 1B). The site is composed of a small area ($\approx$0.001 km^2) set on the river bank and is characterized by high vegetation density with overlapping tree crowns. Common species are Lombardy poplar (*P. nigra*), black locust (*Robinia pseudoacacia L.*) while the undergrowth is comprised of field maple (*A. campestre* L.), elder (*Sambucus nigra* L.), cornel (*Cornus mas*) and bramble (*Rubus ulmifolius* S.). The vertical distribution of the crowns indicates a mixed riparian formation of the biplanar type, originating from natural dissemination and currently in a high forest evolutionary stage. In this phase, social differentiation is reduced, conditioning first the longitudinal and then the diametrical growth. Stalks are larger in diameter and are less flexible to winds, with the result that the crown is limited to the upper part of the tree.

The third test area is located in the northwest part of the Sevilleta National Wildlife Refuge (SNWR) site in central New Mexico, 90 km south of Albuquerque (Fig. 1C). The site comprises a small ($\approx$0.1 km^2) first-order catchment dissected by an east flowing ephemeral channel giving rise to opposing north and south-facing slopes and an east facing headslope (Gutiérrez-Jurado et al., 2007). In the study basin, opposing hillslopes are characterized by marked differences in ecosystem composition and soil profile properties, with the south-facing slope consisting of creosote bush (*Larrea tridentata*) and the north-facing hillslope dominated by one seed juniper (*Juniperus monosperma*) (Gutierrez-Jurado et al., 2006) with sparse or open canopies vegetation.

Fig. 2 shows some pictures of the canopy for each study area and highlights the significant variability of vegetation density between the three investigated areas, as afore-mentioned.

2.2. Datasets

Light detection and ranging (LiDAR) is a remote sensing technology that can provide highly accurate measurements of both the forest canopy and ground surface. Airborne laser scanning systems can provide terrain elevation data for open areas with a vertical accuracy of $\sim$15 cm and 23 cm under conifer forest canopies (Reutebuch et al., 2003). Laser scanning is based on distance measurements and precise orientation of these measurements between a sensor, whose position is known, and a reflecting object, whose position is unknown. The orientation and the position of the sensor at the time of each emitted pulse is known through the use of an integrated inertial navigation system and a differential global positioning system. By classifying the laser pulses iteratively into terrain and non-terrain returns, it was possible to produce a digital terrain model (DTM) and a digital surface model (DSM) (Brandtberg et al., 2003). The difference between the DSM and DTM models is called, in this study, canopy height model, and represents a 3D representation of the tree heights within the target forest area. We derive canopy height models with 1-m spatial resolution for each study area.

The area of the calibration sites mainly depends on the vegetation characteristics. To capture the variability of vegetation