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Discrimination of vegetation strata in a multi-layered Mediterranean forest ecosystem using height and intensity information derived from airborne laser scanning

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ABSTRACT

Height and intensity information derived from Airborne Laser Scanning (ALS) was used to obtain a quantitative vertical stratification of vegetation in a multi-layered Mediterranean ecosystem. A new methodology for the separation of different vegetation strata was implemented using supervised classification of a two-dimensional feature space spanned by ALS return height (terrain corrected) and intensity. The classification was carried out using Gaussian mixture models tuned on a control plot. The approach was validated using extensive field measurements from treated plots, ranging from single vegetation strata to a more complex multi-layered ecosystem. Plot-level canopy profiles derived from ALS and from a geometric reconstruction based on field measurements were in very good agreement, with correlation coefficients ranging from 0.73 (for complex, 3-layered) to 0.96 (simple, single-layered). In addition, it was possible to derive plot-level information on layer height, vertical extent and coverage with absolute accuracies of some decimetres (simple plots) to a meter (complex plots) for both height and vertical extent and about 10 to 15% for layer coverage. The approach was then used to derive maps of the layer height, vertical extent and percentage of ground cover for a larger area, and classification accuracy was evaluated on a per-pixel basis. The method performed best for single-layered plots or dominant layers on multi-layered plots, obtaining an overall accuracy of 80 to 90%. For subdominant layers in the more complex plots, accuracies obtained were as low as 48%.
Our results demonstrate the possibility of deriving qualitative (presence and absence of specific vegetation layers) and quantitative, physical data (height, vertical extent and ground cover) describing the vertical structure of complex multi-layered forest ecosystems using ALS-based height and intensity information.

1. Introduction

Vegetation stands can be described in many ways using properties related to composition, function and structure, where the descriptors to be used are determined by management objectives. Knowledge on vegetation structure is central to forest stand descriptive work and provides essential information on the vertical and horizontal organisation of plants. Certain structural properties such as basal area, canopy height, leaf area index, and vertical stratification (itself being a function of canopy geometry and foliar arrangement) are related to important ecosystem processes, and are fundamental to the understanding of forest dynamics. The risk of fire, and damages due to wind and pest depend to a certain degree on canopy structure (Bergeron et al., 2009; MacLean, 1996; Sandberg et al., 2001), where the presence/absence of different vertical stratification layers and the continuity/discontinuity between them can determine stand vulnerability. Methods evaluating vertical forest stand properties are thus important tools in risk assessment schemes. Furthermore, the vertical structure of forests is a vital attribute that determines habitat quality for many forest-dwelling organisms (Camprodon & Brotons, 2006a; Humphrey et al., 1999), and the species composition of the ground flora (Ferris et al., 2000). Consequently, vertical structure has been used for habitat assessments (Graf et al., 2009b), and could be used as a quantitative indicator of biodiversity for the assessment of sustainable forest management (Ferris & Humphrey, 1999). Vegetation structure is affected by complex interactions of many ecosystem parameters. Some of these are inherent to the system (e.g. competition for light), others are external as effects of topography or disturbances. Our interest is in mapping structural properties that

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are relevant in the context of managing a forested ecosystem, e.g. by monitoring fuel build-up of the understory, which is of high societal relevance in many fire prone countries. Unfortunately, the vertical structure is a forest stand property that cannot be directly mapped using passive remote sensing techniques.

Wildland fires are a threat to socio-economic values in many countries and are controlled by spatially and temporally varying boundary conditions, e.g. such as weather, fuel, and topography (Countryman, 1972; Pyne et al., 1996). Fuel has a strong influence on fire behaviour, so that its characterisation and mapping are key issues for fire behaviour assessment through modelling but also for management planning and fuel hazard mapping (Andersen et al., 2005; Riano et al., 2003). Several fuel characteristics are required to assess fire behaviour, including moisture content, fuel load, size of the fine particles but also its horizontal and vertical spatial distributions. Such data can be used in spatially explicit fire models to assess fire behaviour. These models (Farsite (Finney, 1998), Behave (Andrews, 1986) and FIRETEC (Linn et al., 2005)) provide estimates of fire intensity and rate of spread to be expected with the given fuel load and distribution and prescribed atmospheric conditions. Fuel vertical stratification is an important component in determining potential wildland fire behaviour, especially the transition from surface to crown fires (e.g. by the presence of a shrub layer in between), which represents a significant change in terms of fire behaviour and fire fighting opportunities (Pimont et al., 2006; Van Wagner, 1977).

As pointed out earlier, fuel maps are essential for planning the managing (e.g. manual shrub removal) and fuel hazard mapping (very different from basic fuel maps) in the context of fire prevention. In France, the elaboration of fire prevention plans has been required by law or local regulation in many communities since 1985. In addition, because fuel is almost the only fire factor (opposed to weather and topography) that can be managed, a significant part of fire prevention is based on fuel treatments. Fuel management techniques include mechanical treatments, controlled grazing and prescribed burning (Xanthopoulos et al., 2006). Subsequent fuel treatments may consist of maintaining low shrub fuel loads at fuel breaks as well as in security buffer zones around road networks, or by shrub clearance around houses situated in the wildland–urban interface (WUI). In France, the State Forest Service (Office National des Forêts, ONF) and local communities are the principle actors responsible for maintaining fuel breaks, for example by shrub clearance based on phytovolume threshold values (Etienne et al., 1994). Additionally, France has introduced a legislation for human settlements in the WUI that oblige owners of properties located in high fire risk regions to clear the shrub layer within a minimum distance of 50 m around buildings and other installations (French Forestry Act 2001, art. L-321-5.3). The possibility of efficiently monitoring extensive areas and mapping the status of the shrub layer could significantly improve the elaboration of prevention plans, as well as the fuel management planning and the identification of strategic areas to be fuel treated in the WUI or on fuel breaks. It would be especially true if an extensive mapping of shrub layer properties was possible.

LiDAR (Light Detection And Ranging) remote sensing is unique among optical earth observation technologies in that it provides a direct methodology for assessing the elevations on the earth's surface. Using a time-of-flight measurement of a laser pulse in combination with known orientation and position of a measurement platform, the three-dimensional locations of scattering objects can be estimated. Application of this data was mainly for surveying purposes, however other applications such as forest inventory have been tested as well (Ginzler et al., 2007; Næsset, 2002, 2004; Popescu & Wynne, 2004). ALS (Lefsky et al., 2002; Næsset, 2002; Popescu & Wynne, 2004; Wehr & Lohr, 1999) have proven efficient at the landscape level to provide three-dimensional information and stand properties of various forest ecosystems (Hyde et al., 2005). Large footprint (>10 m) LiDAR systems are suitable for estimating common forest parameters (e.g. forest height, forest biomass and vertical structure of forest canopies) at the stand level with high accuracies (Dubayah & Drake, 2000), while small-footprint (<1 m) LiDAR systems can be used to estimate forest properties down to the level of single trees (Hyyppä et al., 2001; Morsdorf et al., 2004, 2006). Up to now, ALS data has been less successful in providing accurate information about vertical components of grasslands and shrublands where vegetation height is commonly underestimated due to difficulties discriminating between the ground and low shrubs (Jason & Bork, 2007; Rango et al., 2000). Shrubland communities and forest ecosystems with important shrub layers are dominant wildland fuel types in the Mediterranean region, for which data about height and cover density are valuable information in predicting potential fire behaviour. A first attempt in the Mediterranean region at exploiting the structural information of ALS in combination with imaging spectrometry has been carried out by Koetz et al. (2008). Multiband images of ALS-based height and density metrics were generated and combined in that study with airborne imaging spectrometry data to form a multi-dimensional dataset containing distinct features of a number of land-cover types, including build-up areas. This unique approach increased the accuracy of a support vector machine (SVM) based classification of fuel related land-cover types opposed to using imaging spectrometry data alone.

In the present study airborne laser scanning data was used to explore the possibilities to detect and characterise the vertical stratification of vegetation types in the French Mediterranean region, including lower vegetation layers such as the shrub layer. It focuses on the structural information comprised in the ALS data, based on assessing its explanatory value in comparison with detailed field measurements in a controlled environment. The main objectives of this study are to use small-footprint airborne laser scanning data (i) to test algorithms for automatically describing the vertical stratification of plant communities, and (ii) to develop a robust methodology for mapping forest fuel layer properties, including fuel treatments. Special considerations are given to the possibility of using ALS intensity measurements for improved classification of fuel layers. The methods will be tested and validated on treated field plots, where the different vertical strata were either isolated or combined.

2. Study area

2.1. Description

Our surveyed area consists of a forested area situated in the calcareous Provence in the French Mediterranean region: the Lamanon study area (Bouches-du-Rhône). The study area comprises of similar vegetation types ranging from open shrublands to dense multi-layered forest ecosystems. The area has been selected because it contains gradients from simple single-layered ecosystems with distinct vertical stratification layers to complex multi-layered ecosystems with a continuous vertical stratification, thus making them suitable for testing LiDAR under difficult conditions and identifying possible limitations due to the density or complexity of the plant cover. The Lamanon study area is an experimental study site in a mixed Mediterranean pine–evergreen oak woodland with Aleppo pine (*Pinus halepensis*) in the upper and holm oak (*Quercus ilex*) in the lower tree canopy layer, and the shrub layer dominated by box (*Buxus sempervirens*). All three species are evergreen with foliar abscission occurring all-year-round although distinct seasonal peaks do occur. At the study site, shoot and leaf development mainly occurs during early spring (March–May) for all three species, while foliar abscission peaks shortly after shoot development for *Q. ilex* (June–July), and during the dry season (July–August) for *B. sempervirens* and *P. halepensis.* Foliar biomass had not recovered to their maximum values in October at the time of ALS data collection, but the fluctuations (all vegetation strata taken together) observed at a similar study site within the same region show small variations with a minimum in June–December (R. Huc and