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An unsupervised two-stage clustering approach for forest structure classification based on X-band InSAR data — A case study in complex temperate forest stands

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ABSTRACT

Forest structure at stand level plays a key role for sustainable forest management, since the biodiversity, productivity, growth and stability of the forest can be positively influenced by managing its structural diversity. In contrast to field-based measurements, remote sensing techniques offer a cost-efficient opportunity to collect area-wide information about forest stand structure with high spatial and temporal resolution. Especially Interferometric Synthetic Aperture Radar (InSAR), which facilitates worldwide acquisition of 3d information independent from weather conditions and illumination, is convenient to capture forest stand structure. This study purposes an unsupervised two-stage clustering approach for forest structure classification based on height information derived from interferometric X-band SAR data which was performed in complex temperate forest stands of Traunstein forest (South Germany). In particular, a four dimensional input data set composed of first-order height statistics was non-linearly projected on a two-dimensional Self-Organizing Map, spatially ordered according to similarity (based on the Euclidean distance) in the first stage and classified using the k-means algorithm in the second stage. The study demonstrated that X-band InSAR data exhibits considerable capabilities for forest structure classification. Moreover, the unsupervised classification approach achieved meaningful and reasonable results by means of comparison to aerial imagery and LiDAR data.

1. Introduction

Forest structure can be treated at different spatial scales. However, patch or stand level is the most important spatial unit for most forest plants and animals. By their size and longevity, trees determinate the structure, stand-internal environmental conditions and flora and fauna habitats (Kuuluvainen et al., 1996). In general, stand density, size distribution and horizontal as well as vertical tree distribution patterns are used for the description of stand structure (del Río et al., 2015). Stand structure is a consequence of species selection, stand dynamics, human, biotic and abiotic disturbances (Pretzsch et al., 2015b; Pommerening, 2006; Kuuluvainen et al., 1996). Managed forest stands are often limited in structure due to homogeneous one-age-cohort forests and thus restricted in diversity and complexity (Perry, 1994). As opposed to this, unmanaged or "close-to-nature" forest stands often exhibit a heterogeneous and much more complex structure with uneven-aged trees and diverse species composition (Pretzsch et al., 2015a; Bauhus et al., 2013). On the basis of such a complexity, characterized by spatial heterogeneity due to different tree size dimensions and diverse species compositions, the productivity and resilience of the forest is often positively influenced (Pretzsch, 2005; Carey and Wilson, 2001). Consequently, measures of stand structure diversity serve as an indicator for the stability of the forest ecosystem as well as a predictor for growth and development (Pretzsch, 2009). Moreover, stand structure is a surrogate for stand biodiversity, since high biodiversity is related to stands comprising multiple tree species and sizes (Bergen et al., 2009; McElhinny et al., 2005; Staudhammer and LeMay, 2001). Accordingly, stand structure plays a key role for sustainable forest management, since the biodiversity, productivity, growth and stability of the forest can be positively influenced by managing its structural diversity (Pommerening, 2006; Önal, 1997).

Terrestrial measurements as part of forest inventories of structure attributes, such as stand density, basal area or height, can be

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conducted to assess conservation and sustainability as well as temporal and spatial changes in forest structure and thus provide a basis of decision-making at local, national and global level (Gao et al., 2014; Kuuluvainen et al., 1996). However, the major disadvantage of traditional forest inventories (like National Forest Inventory in Germany, Sweden or Great Britain with an usual repetition rate of ten years) in terms of forest stand structure is its sample-based survey design. The spatial patterns cannot be captured properly without area-wide information. Furthermore, these inventories are very expensive, labor-intensive and only available for the minority of the forest areas worldwide.

In contrast, remote sensing techniques offer a good and cost-efficient opportunity to overcome these problems, since they provide area-wide data collection with high spatial and temporal resolution. Numerous studies investigate the potential of remote sensing data for the estimation of forest structure. On the one hand, forest attributes, such as height, basal area, canopy cover, stand density or biomass, are derived to describe the forest stand structure (e.g. Pfeifer et al., 2016; Naidoo et al., 2015; Gómez et al., 2012). On the other hand, forests are categorized or classified into different structure types according to parameters, such as height, species, biomass, canopy cover as well as heterogeneity (e.g. Huesca et al., 2016; Varghese et al., 2016; Falkowski et al., 2009).

Studies in this field are based on different remote sensing techniques, i.e. multispectral, hyperspectral, LiDAR (Light Detection And Ranging) or RaDAR (Radio Detection And Ranging) sensors. In case of multi- and hyperspectral data, spectral information in terms of reflectance (e.g. Gómez et al., 2012; Castillo-Santiago et al., 2010; Liu et al., 2008), spectral indices (e.g. Pfeifer et al., 2016; Chen et al., 2015; Peña et al., 2012) and texture features (e.g. Beguet et al., 2013; Kayitakire et al., 2006; Coburn and Roberts, 2004) are commonly used to detect forest structure. LiDAR acquisitions based on airborne platforms are widely used to derive height information to capture forest structure (e.g. Hollaus et al., 2011; Falkowski et al., 2009; Hyyppä et al., 2008). In the case of RaDAR, either backscatter intensity (e.g. Varghese et al., 2016; Naidoo et al., 2015; Chand and Badarinath, 2007) or derived height information (e.g. Karila et al., 2015; Karjalainen et al., 2012; Solberg et al., 2010) are frequently employed to estimate forest stand structure.

Among these remote sensing systems, active RaDAR sensors are convenient compared to passive optical (i.e. multi- and hyperspectral) sensors since they are operating in the microwave instead of the visible and infrared range of the electromagnetic spectrum. The longer wavelengths enable observations of the Earth's surface independently from cloud cover and illumination. Especially over tropical forest areas, the all-weather capability of radar systems is its biggest advantage over optical systems. Synthetic Aperture Radar (SAR) systems offer worldwide observations with high spatial and temporal resolution. Interferometric SAR (InSAR) systems facilitate the acquisition of 3d information and thus are an appropriate basis for the detection and investigation of forest structure in a global context. Depending on the wavelength and thus the penetration ability of the signal, such systems are sensitive to 3d distribution of different scattering elements of the forest (i.e. leaves, branches and trunks) and provide additional information on different vertical forest layers (Varghese et al., 2016; Yang et al., 2014). Compared to LiDAR data, InSAR data is preferable due to its worldwide availability and more cost-efficient acquisition.

However, only few studies explore the potential of InSAR data for forest type and/or forest structure classification. For example, Hoekman and Quiñones (2002) distinguished several forest classes based on polarimetric coherence from AirSAR C-, L- and P-band data of topical forest in Central Colombia. Liesenberg and Gloaguen (2013) classified interferometric L-band ALOS PALSAR data into different forest types in the tropical forest of Eastern Amazon in Brazil and De Grandi et al. (2015) used interferometric TanDEM-X data to map forest spatial structure in tropical forest of the Republic of Congo.

In contrast to previous studies that aim for forest structure classification using predominantly longer wavelengths (i.e. P- and L-band), the current study investigates forest structure classification based on X-band InSAR data. Furthermore, compared to other studies concerning forest structure classification which were carried out in tropical forests this work was carried out in complex temperate forest stands. Hence, this study contributes to fill the research gap in the field of forest structure classification using short wavelengths (i.e. X-band) with regard to temperate forests. The heterogeneity in height of the main forest layer is captured by means of interferometric height information derived from TanDEM-X data to distinguish different forest structure classes. In order to ensure easy transferability to any given forest, an approach without any requirement of a-priori information about the present forest structure and its complexity or the number of classes and class definitions is developed. For this purpose, an unsupervised two-stage clustering approach is proposed. In particular, a four dimensional input data set composed of first-order height statistics was non-linearly projected on a two-dimensional Self-Organizing Map, spatially ordered according to similarity (based on the Euclidean distance) in the first stage and classified using the k-means algorithm in the second stage. As case study, the temperate forest of Traunstein in Southeast of Bavaria (Germany) was chosen due to its structural richness and heterogeneous forest stands. Therefore, the objectives of this work encompass i) extraction and ii) classification of forest structure by means of an unsupervised approach based on height information derived from X-band InSAR data.

2. Materials

2.1. Study area

The highly structured, mixed, temperate municipal forest close to the city of Traunstein, Germany (47°52′ N, 12°38′ E) serves as study area (Fig. 1). Traunstein forest is supervised and used for teaching and research purposes by the Chair for Forest Growth and Yield Science of the Technical University of Munich (TUM). The study area is limited by the coverage of the TanDEM-X acquisition to a forest area of 243 ha bounded by the districts Bürgerwald and Heiligengeistwald. The topography ranges from 630 to 720 m above sea level and includes small areas with steep slopes. The soils are composed of glacier sediments which belong to the pre-alpine moraine landscape. The climatic conditions are characterized by a mean annual temperature of 7.3 °C and precipitation up to 1600 mm per year. The forest is predominantly composed of Norway spruce (*Picea abies*), European silver fir (*Abies alba*), European beech (*Fagus sylvatica*) and Sycamore maple (*Acer pseudoplatanus*). Traunstein forest passes through an ongoing reconversion from a homogeneous one-age cohort forest to a structurally rich, heterogeneous forest. The forest stands are very complex concerning tree species richness and heterogeneous stand structures due to "close-to-nature" silviculture (Pretzsch, 1996), which is reflected in a broad distribution of tree species (Fig. 2a) and growth stages (Fig. 2b). Therefore, Traunstein forest is a perfect example for the whole spectrum of silviculture types in Central Europe. Furthermore, as a result of new concepts of silviculture due to climate change and policy guidelines, more and more forests will undergo a change from homogeneous one-age-cohort forests to structurally rich heterogeneous forests. Consequently, forest Traunstein is predestinated as case study for forest structure classification in temperate forests.