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Structural diversity indices based on airborne LiDAR as ecological indicators for managing highly dynamic landscapes

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ABSTRACT

An objective, quantifiable index of structural biodiversity that could be rapidly obtained with reduced or no field effort is essential for the use of structure as universal ecological indicator for ecosystem management. Active remote sensing provides a rapid assessment tool to potentially guide land managers in highly dynamic and spatially complex landscapes. These landscapes are often dependent on frequent disturbance regimes and characterized by high endemism.

We propose a modified Shannon–Wiener Index and modified Evenness Index as stand structural complexity indices for surrogates of ecosystem health. These structural indices are validated at Tall Timbers Research Station the site of one of the longest running fire ecology studies in southeastern U.S. This site is dominated by highly dynamic pine-grassland woodlands maintained with frequent fire. Once the dominant ecosystem in the Southeast, this woodland complex has been cleared for agriculture or converted to other cover types, and depends on a frequent (1- to 3-year fire return interval) low- to moderate-intensity fire regime to prevent succession to mixed hardwood forests and maintain understory species diversity. Structural evaluation of the impact of multiple disturbance regimes included height profiles and derived metrics for five different fire interval treatments; 1-year, 2-year, 3-year, mixed fire frequency (a combination of 2- and 4-year fire returns), and fire exclusion. The 3-dimensional spatial arrangement of structural elements was used to assess hardwood encroachment and changes in structural complexity. In agreement with other research, 3-year fire return interval was considered to be the best fire interval treatment for maintaining the pine-grassland woodlands, because canopy cover and vertical diversity indices were shown to be statistically higher in fire excluded and less frequently burned plots than in 1- and 2-year fire interval treatments. We developed a LiDAR-derived structural diversity index, LHDI, and propose that an ecosystem-specific threshold target for management intervention can be developed, based on significant shifts in structure and composition using this new index.

Structural diversity indices can be valuable surrogates of ecosystem biodiversity, and ecosystem-specific target values can be developed as objective quantifiable goals for conservation and ecosystem integrity, particularly in remote areas.

1. Introduction

Stand structural changes in forested or woodland systems often reflect biodiversity changes (Smith et al., 2008) and provide insight into ecosystem function (Spies, 1998). Conventionally compositional biodiversity measures have been the “go-to” approach in developing a proxy for ecosystem functionality sustainability (e.g. SAFE model, Andriantiatsaholiniaina et al., 2004) and ecosystem service models (e.g.: INVEST, Tallis et al., 2011). Compositional biodiversity indices are powerful indicators of ecosystem health, but cost and time-prohibitive, particularly at coarse spatial scales and in remote and poorly studied areas. However, structural biodiversity indicators might well provide more comprehensive and repeatable surrogate measures given time and budget constraints. Field-derived structural measures target stand stage

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classification with canopy cover as the most widely used indicator (Smith et al., 2008) due to its cost-effectiveness and determinant effect on other structural measures. However, field-derived measures quickly increase in cost and decrease in effectiveness given the need for landscape-wide management strategies (i.e. prioritization for conservation or active silvicultural management).

A surrogate measure of biodiversity in a forested setting using structural components needs to include an easy to implement unbiased indicator of structural complexity or spatial arrangement. Indices of structural complexity have been proposed (McElhinny et al., 2006) that combined 13 core attributes, some requiring extensive field sampling (e.g. number of hollow-bearing trees, life-form richness, litter dry weight). Other diversity indices, such as the Shannon Diversity Index (SHDI) (Shannon et al., 1949) often used in community ecology as a measure of species composition biodiversity, have been applied to landscape ecology. Initially, SHDI was adapted to provide a measure of patch type diversity (McGarigal and Marks, 1995; Hietala-Koivu et al., 2004; Zhang et al., 2008), synthesizing complex spatiotemporal patterns of landscape diversity. In more recent years, a modified SHDI has integrated vertical structure, thus providing a three dimensional index of basal area-weighted tree heights (Staudhammer and LeMay, 2001; Frazer et al., 2005). Limitations of the development and validation of structural diversity indices include the enormous effort required in acquisition of foliage height density data (cover at fine height intervals), the difficulty in converting the data to spatial scales relevant to ecological modeling, and the often long delay in providing feedback to silvicultural managers of highly dynamic landscapes (i.e. where intervention is required every 2–3 years).

Airborne LiDAR has rapidly become a powerful technology in forestry and natural resource management, particularly with the ability to measure 3-D structure at broad spatial scales (Lefsky et al., 2002a; Newton et al., 2009). This active remote sensing technique has demonstrated the ability to characterize forest stands and approximate forest inventory data with canopy height (Lovell et al., 2003; Clark et al., 2004; Coops et al., 2007), basal area, above-ground biomass (Drake et al., 2002a, 2002b; Lefsky et al., 2002b), and leaf area (Roberts et al., 2003; Lefsky et al., 2005). In addition, one of the most promising ecological applications of small footprint LiDAR is the direct acquisition of vertical foliage distribution, which provides detailed information of the forest subcanopy elements. Canopy height profiles derived from high resolution LiDAR have a variety of ecological applications which include characterizing successional stages of forest stands (Harding et al., 2001), predicting species richness (Goetz et al., 2007; Hinsley et al., 2009; Müller et al., 2009) and assessing habitat features for both wildlife assemblages and species (Goetz et al., 2010; Seavy et al., 2009).

LiDAR (Light Detection And Ranging) datasets provide a means to evaluate three-dimensional forest structure (Zimble et al., 2003) with a much reduced effort and cost than ground based measurements. Field constraints such as accessibility, lack of objective and efficient measurement techniques, and high personnel and equipment costs have quickly made use of LiDAR remote sensing more attractive to land managers and conservation ecologists. As a result of such popularity, reduced acquisition costs, and greater density of data returns, this technology should be key in the development of a structural diversity indicator for biodiversity modeling and ecosystem health.

The importance of developing a remotely derived structural indicator of biodiversity and ecosystem health lies in the necessity of quickly assessing, monitoring, and adapting management strategies for sustainability. This is most critical in ecosystems that are highly dynamic and depend on frequent disturbance and thus require continual management. Often, these are systems that have the highest biodiversity and are at most risk from modifications of natural disturbance regimes [e.g., cerrado, longleaf pine (*Pinus palustris*), ponderosa pine (*P. ponderosa)*, tallgrass prairie]. We propose an approach that uses key structural measures and the structural diversity index, LiDAR-derived Height Diversity Index (LHDI), as a surrogate for ecosystem integrity and as a benchmark trigger for on-the-ground management. It is so designated for distinctiveness from compositional or landscape metrics. Once established, these ecosystem-specific triggers or targets may be universally applied and function as early detection indicators of deteriorating conditions and the need for rapid intervention. Furthermore, a structural diversity index can be a relevant input to enhance several ecosystems services models, especially those developed on a spatial platform, such as the INVEST (Tallis et al., 2011) biodiversity, carbon storage & sequestration, and managed timber production models.

This work validates the application of practical, repeatable, and objective structural metrics, including a LiDAR derived structural complexity index on a highly dynamic, disturbance driven landscape. The study site selected, Tall Timbers Research Station, is representative of the highly dynamic pine woodland and savanna ecosystems in the southeastern U.S., an open pine-dominated system with high understory biodiversity. The role of fire in shaping the composition and understory species richness of these communities is well established in the literature (Walker and Peet, 1983; Mehlman, 1992; Waldrop et al., 1992; Glitzenstein et al., 2003, 2008). Our study further benefits from a long-term study design (>50 yrs), consistent implementation, and detailed compositional studies of species richness as indicator of biodiversity (Hermann, 1995; Beckage and Stout, 2000; Glitzenstein et al., 2012). Because fire exclusion has clear consequences in ecosystem shifts – from open pine woodlands or savanna to dense hardwood dominated forests with reduced species richness (Masters et al., 1995; Glitzenstein et al., 2008) – the need to establish an early indicator of ecosystem health and biodiversity shifts is critical. We propose that remotely derived structural indices allow a universal method to be applied in developing ecosystem-specific targets for management or intervention.

The objective of this study was to evaluate the use of airborne LiDAR in the development of practical, repeatable, and objective structural metrics, as surrogates for structural complexity and biodiversity in a landscape with frequent disturbances. This study also proposes an ecosystem-specific structural diversity index as an early indicator of the need for intervention that is validated herein for pine-savannas. We hypothesize that LiDAR derived indices will provide an equivalent threshold for management intervention as more time consuming and thus costly traditional field measurements.

2. Materials and methods

2.1. Study area

This study took place at Tall Timbers Research Station (TTRS), located just north of Tallahassee, Florida, and covering 1600 hectares within the Red Hills region of north Florida (Fig. 1) (~long. 30°39′ N, lat 84°13′ W). The upland pine ecosystems at TTRS are old-field derived from a agriculture dominated landscape, and currently dominated by a mixed canopy of loblolly pine (*P. taeda*), shortleaf (*P. echinata*) and longleaf (Hermann, 1995; Masters et al., 2005). The groundcover at the study site is dominated by many legumes and sunflower family members and interspersed with grasses (broomsedge bluestem, *Andropogon virginianus*, primarily), but lacking the wiregrass (*Aristida beyrichiana*) typical of native longleaf pine savanna ecosystems (Hermann, 1995).

The TTRS actively manages its secondary upland pine forest using low intensity transition season (February–April) prescription