A digital mapping method for linking high-resolution remote sensing images to individual tree crowns

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ABSTRACT

1. Remote sensing data provides unique information about the Earth’s surface that can be used to address ecological questions. Linking high-resolution remote sensing data to field-based ecological data requires methods to identify objects of interest directly on georeferenced remote sensing digital images while in the field.

2. Mapping individual trees with a GPS often has location error and is focused on the position of the tree stem rather than the crown, often creating a mismatch between field data and the pixel information.

3. We describe a mapping process that uses a consumer-grade GPS and tablet computer to spatially match individual trees measured in the field directly to a digital image of their crowns taken from above the canopy. This paper outlines the reasons for using digital field mapping and a summary of the equipment and process, with supplemental material providing a detailed field protocol.

4. As more remote sensing data with a resolution capable of resolving individual trees become available, the opportunities to leverage these data for ecological studies grow. We provide guidelines for those wanting to apply imagery to expand the spatial scale and extent of ecological studies.

INTRODUCTION

Increasing availability of high-resolution remote sensing (RS) data, where the pixel size is smaller than the features of interest, allows ecologists and RS scientists to directly connect objects in images with features on the ground at a scale relevant to ecological studies. For example, high-resolution RS images have generated ecological data that contributes to quantifying growth and death rates (D. B. Clark et al., 2004), assessing landscape species composition and diversity (Colgan & Asner, 2014; Graves et al., 2016), mapping foliar traits across ecological gradients (Chadwick & Asner, 2016; Singh, Serbin, McNeil, ...
Kingdon, & Townsend, 2015), and measuring landscape carbon storage (Colgan, Asner, & Swemmer, 2013; Jucker et al., 2016).

Linking field data from individual trees to RS data requires accurate identification of individual tree crowns in RS images. This is often challenging because of position errors of both Global Positioning System (GPS) receivers and georeferenced images. Furthermore, field data is usually associated with the location of a tree’s stem whereas RS data shows the tree’s crown. Crowns can be offset from their stems due to light competition, avoidance of neighboring crowns, and mechanical damage (Schröter, Härdtle, & von Oheimb, 2012). Despite the potential for inaccurate matching of a stem’s GPS-based location to image pixels, collecting location data in the field with direct reference to image data is not common practice in ecological research.

This paper describes a workflow to spatially match individual trees measured in the field to a digital image of their crowns taken from above the canopy. Individual tree crowns have been mapped in various applications (Clark, Roberts, & Clark, 2005; Colgan et al., 2013; Dalponte, Ørka, Ene, Gobakken, & Næsset, 2014; Graves et al., 2016), which has laid the groundwork for the workflow described here. However, details of the field process, hardware, and software have had little documentation. As more data of the scale and type usable for individual tree mapping becomes available, we hope this paper serves as a guideline for those wanting to use imagery for ecological applications.

Why use digital field mapping

The practice of mapping using a field-based computer and a GPS to identify and document the location of features of interest, called digital mapping, has been used widely in geology (Clegg et al., 2006; Pavlis, Langford, Hurtado, & Serpa, 2010) but less so in ecology. It is common practice in ecology studies using RS to collect GPS location data of individuals independent of the RS image and try to link the two datasets together after field data collection. While appropriate for applications where the features of interest are large and obvious, the imprecision of associating an independently collected GPS point with an image may be problematic because the incorrect pixels will be associated with the measured tree.
Some advantages associated with digital mapping in geosciences that are relevant to ecological studies are: the location data is carefully collected, assessed and validated in the field; little post-processing of location data and uncertainties is required; and the process builds skilled mappers that use image interpretation, reasoning, field skills, and knowledge about the system to create reliable data. We present additional advantages that focus on digital field mapping for features in a forested landscape.

**Overcoming a poor GPS signal in forested landscapes**

A primary reason for digital field mapping is to avoid inaccurate and uncertain data by using a GPS signal alone to mark the location of individual trees. Many consumer/recreation-grade GPS receivers ($200-500) continuously collect location information, regardless of the signal strength and position accuracy (Wing, 2008). This is especially problematic in forests. Even a moderately closed canopy, such as pine forests of the southeastern US (Figure 1), can reduce the accuracy of point locations from consumer-grade GPS receivers (Wing, 2008). In contrast, mapping and survey-grade GPS receivers ($500-thousands) can provide high measurement accuracies (sub-meter) and limit point collection to when there is a strong signal (which can be very limited in forests with dense canopies). However, field ecologists may be limited to using consumer-grade GPS receivers due to their low cost and relative ease of use. Therefore, as an alternative, higher accuracy methods using consumer-grade equipment is needed.

The method we describe for mapping tree crowns uses a consumer grade GPS but does not rely on the GPS signal alone to mark the location of the object of interest. Rather, the person marking the location is interacting with the image in real-time in the field and with the aid of the GPS signal. Location data is paired directly with the mappable features (i.e. tree crowns) while in the field to ensure proper spatial alignment of field and image data.

**Identifying objects in the field**

A second reason to use digital field mapping is to support working at the scale of individual tree crown *objects* rather than individual points or pixels. Object-based image analysis, in which pixels are
grouped into meaningful polygons on which subsequent analysis is performed (Blaschke et al., 2014), has grown in popularity because of greater availability of high-resolution data and segmentation techniques that automate object identification. Also, object-based analysis has greater accuracy than pixel-based analysis in a variety of applications (Kaszta et al., 2016; Meneguzzo, Liknes, & Nelson, 2013).

For object-based analysis it is important to ensure the objects created in the images accurately represent reality on the ground (Ke & Quackenbush, 2011; Zhen, Quackenbush, & Zhang, 2016). For example, automated segmentation techniques can incorrectly group multiple crowns together, or split a single crown into multiple parts. This inaccuracy may affect the output of the analysis when the number and size of objects is a critical part of the analysis. Therefore, field data of individual tree crown objects can aid in training and evaluating segmentation models.

Use in ecological studies

High resolution RS allows for the identification of individual trees and measurement of their size and analysis of properties from image information such as spectral reflectance. Remote sensing data analyzed at the scale of individual trees can produce unique ecological datasets that are; 1) at an individual organism scale, 2) have continuous spatial coverage, 3) and cover large geographic extent. For example, RS-derived information on the size and height of individual trees can be used to make individual-based estimates of above ground carbon (Colgan et al., 2013; Coomes et al., 2017), and evaluate individual based models of vegetation dynamics (Shugart et al., 2015) and can be used to study species distributions and environmental change (Franklin, Serra-Diaz, Syphard, & Regan, 2017).

MATERIALS & METHODS

In this workflow, we use a RS image uploaded on tablet computer running a Geographic Information System (GIS) with an integrated GPS. The workflow (Figure 2) has three steps; 1) acquiring and preparing the imagery, 2) field data collection, and 3) lab digitization and data extraction. The data needed for this process are georeferenced RS images. The data products are spatial polygons of individual
tree crowns (ITCs) georeferenced to the RS data. Methods described here are specific to data from the Airborne Observation Platform (AOP) of the National Ecological Observatory Network (NEON) but can also be used with other georeferenced digital images, such as the growing amount of available high-resolution imagery from satellites or drones.

Hardware and software

The workflow relies on a portable tablet computer equipped with GIS software and GPS capabilities. We focus on the use of tablet computers or rugged field computers because they can use an external GPS, have a large screen, and allow for easy import and export of custom data. There are numerous options for tablets, programs, and GPS receivers, but a few key features are necessary (Figure 3, Table 1).

First, the tablet should have either internal GPS capabilities or the ability to connect to an external GPS receiver. While the internal location systems can use assisted-GPS (A-GPS), the WiFi network, or cellular towers to determine the location (Zandbergen, 2009), the ability to connect to an external consumer-grade GPS receiver that uses multiple satellite systems is valuable when working in remote areas. Second, the GIS software should allow for importing of custom raster files, and for creating, editing, and exporting of vector data. The ability to upload custom raster data is necessary because field digitization occurs directly on the image from which the data will be extracted. To our knowledge, very few GIS tablet applications have this feature (Table 1).

Image preparation (Step 1)

Since RS data is commonly delivered and stored as raster data, it is often very large in size, with high-resolution hyperspectral data being particularly large. Field mapping does not use all this information simultaneously; rather the mapper displays spectral and spatial subsets that are most useful for the task. Creating image subsets and manipulation is often not possible with tablet-GIS systems, or is inefficient because the software is not optimized for use in the field (Pavlis et al., 2010). To minimize the amount of
image manipulation, and maximize data collection in the field, image preparation to create spatial subsets and displays of the image to be used for field mapping is best done before going to the field.

The most important image manipulation step is to create an image that is optimal in color, contrast, and extent for identifying the objects of interest. Multi or hyperspectral RS data requires the selection of individual bands to create a 3-band composite image. While visible color representation (red/green/blue or RGB) of the canopy is useful because it is how the human eye views the world (Figure 4), differences among tree canopies can be hard to identify with RGB combinations. Using bands in the near and short-wave infrared region of the spectrum highlight differences among individual crowns driven by species, canopy structure, or foliar characteristics not visible to the human eye. Another component of optimizing visualization is image stretching, a common practice in computer-based raster visualization that allows the image color to be spread across the full range of pixel values (Gillespie, Kahle, & Walker, 1986). In addition to reducing the spectral size of the image, it is important to create spatial subsets that reduce the size of the image used in the field as many tablets have limited processing power and memory to open a large file. In addition to hyperspectral data, RS products, such as a canopy height model (CHM) from LiDAR data, and high-resolution true-color photos can also be used for field mapping if accurately aligned with the hyperspectral data (Figure 6).

Mapping is done on directly on geo-referenced images to be used for analysis, which presents a temporal mismatch between when the image data is collected and when the mapping is done. We found minimal change in an individual tree’s canopy from one to three years after image collection. Discrepancies between the image and the field, such as a fallen tree that exists in the image but is not in the canopy, can be easily identified during the process. We have also found that ITCs are accurate over multiple years of imagery.

Field mapping (Step 2)

The product of field work is rough outlines of ITCs made with direct reference to the RS data to be used for analysis. In digital field mapping, the GPS signal is used as reference to locate identifiable features
in the image; survey techniques are used to locate the approximate location and size of a tree crown; and
image interpretation is used to identify the exact location and crown edges. A detailed field protocol is
provided in the Appendix, and an overview of the process is described here.

First, the GPS signal will help establish a reference point where the mapper’s physical location is
identified in the image. Because the GPS signal will have interference under a canopy, it is best to establish
this reference point in a relatively open area with distinct features, such as a dead or unusual tree on the
edge of a forest patch, or a large canopy gap. Second, once the mapper is oriented in the image, the location
and size of nearby tree crowns can be identified using surveying techniques. Measuring devices, such as a
meter tape, laser range finder, and compass (Figure 3, Table 1), are used to 1) measure the distance and
orientation of target trees from the reference location, and 2) measure the size and orientation of the crown.
Third, image interpretation skills are used to roughly digitize the crown (Figure 5). In this step, the mapper
must understand the shape, size, and position of the tree to be able to identify which pixels belong to the
target crown. Field digitization is often not straightforward, and a skilled mapper will be able to make the
best call as to which pixels should be considered as part of the tree crown. The digital mapping approach
ensures that most digitization decisions are made in the field, rather than in an office or lab, which helps to
prevent inaccuracies from being passed through data processing and analysis.

Data digitization & extraction (Step 3)

After trees have been roughly mapped in the field, the polygons must be refined in the lab (Figure
6). Lab digitization allows the mapper to use GIS software with full features, which unlike the tablet GIS
application, allows for greater image manipulation, refined polygon creation, and access to reference
images with higher resolution and/or more spectral bands. Additionally, uncertain data can be flagged for
revisit in the field if possible.

The practice of digital mapping requires strong image interpretation skills and familiarity with high-
resolution images to identify the individual crowns and understand what crowns can or cannot be mapped.
Therefore, the process is designed to be iterative between the image preparation, field mapping, and lab
digitization. Taking the images into the field gives the mapper an intimate understanding of how the surface is represented in the image.

**CONCLUSIONS**

We believe that digital field mapping of individual tree crowns will be an increasingly used method for defining the location, size, and characteristics of individual trees. We echo the lessons for digital field mapping highlighted by Pavlis et al. (2010): the technology is rapidly advancing; there are software issues to be improved; and we have described just one of many systems for field mapping of trees. In geology, digital field mapping has largely been accepted because barriers to initial adoption (use and cost of new technology, time to learn a new method, and perceived complexity) were outweighed by the advantages associated with a streamlined workflow where location data is directly matched to data used for analysis. We hope this documentation of the process will lead to improved workflows and solutions from those wanting to use imagery for ecological applications.
ACKNOWLEDGEMENTS

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REFERENCES


Table 1. Equipment and tools for digital field mapping.

<table>
<thead>
<tr>
<th>Equipment (image reference)</th>
<th>Description of use</th>
<th>Used in this study</th>
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<tbody>
<tr>
<td>Tablet (A)</td>
<td>For running GIS application (displaying location and image data, creating vector data)</td>
<td>iPad ($1,000)</td>
</tr>
<tr>
<td>GPS (B)</td>
<td>External GPS to link with iPad or to record paths. Built in GPS system is also an option if working in area that has cellular reception.</td>
<td>Bad Elf GPS Pro/Pro+ ($200-300)</td>
</tr>
<tr>
<td>Range finder (C) &amp; Meter tape (D)</td>
<td>For measuring distances between trees and known locations, measuring crown diameter</td>
<td>Nikon Forestry Pro ($400)</td>
</tr>
<tr>
<td>Compass (E)</td>
<td>For measuring the angle between tree and known location. Transparent compass useful for overlaying on tablet</td>
<td>Suunto compass ($30-60)</td>
</tr>
<tr>
<td>Field notebook (F)</td>
<td>Documentation of all additional data collection. Match these data to unique tree id number that is recorded for each polygon in the GIS software.</td>
<td>Rite in the Rain field notebook</td>
</tr>
<tr>
<td>GIS software</td>
<td>To load raster data, create and edit vector data. Free versions are usually available, but desirable features often require payment</td>
<td>GIS Pro by Garafa ($300)</td>
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<td></td>
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<td>Other options:</td>
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<td>QGIS</td>
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<td>Mapit (Standard or Pro versions)</td>
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<td>ArcGIS Collector</td>
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Figure 1. False-color aerial remote sensing image for an open pine forest at Ordway-Swisher Biological Station (Melrose, FL). GPS points of the tree stem (solid circles) were collected with a consumer-grade unit and field mapped crowns (open polygons) were created using the methods described in this paper.
Figure 2. Workflow, tools, and data products for field mapping on remote sensing data.
Figure 3. Typical equipment used for field mapping. Letters A-F match the equipment descriptions in Table 2.
Figure 4. Examples of band combinations to visualize tree canopies in NEON-AOP data. Image examples generated with linear 2% stretch. Arrows highlight individual tree crowns.
Figure 5. Mapping individual tree crowns with tablet computer in a field setting. Left; An iPad tablet with a false-color composite image with yellow tree crown polygons. Right; The author digitizing the tree crown on the iPad tablet.
Figure 6. Example of mapped individual tree crowns after lab digitization in three types of NEON-AOP remote sensing data products.