Using aerial photography to estimate wood suitable for charcoal in managed oak forests

D Ramírez-Mejía1,3, A Gómez-Tagle2,4 and A Ghilardi3

1 Graduate Program in Biological Science, Universidad Nacional Autónoma de México (UNAM), Mexico
2 Earth Science Department, INIRENA-UMSNH, Av. San Juanito Ixticuaro SN, Col. Nueva Esperanza, Morelia, Michoacán, 58330, Mexico
3 Centro de Investigaciones en Geografía Ambiental (CIGA) & Laboratorio Nacional de Análisis y Síntesis Ecológica (LANASE), Escuela Nacional de Estudios Superiores, UNAM, Mexico
4 Author to whom any correspondence should be addressed.

E-mail: algomez@umich.mx

Keywords: crown cover, allometry, small format aerial photography, aboveground biomass, Quercus spp, Mexico, forest management

Abstract

Mexican oak forests (genus Quercus) are frequently used for traditional charcoal production. Appropriate management programs are needed to ensure their long-term use, while conserving the biodiversity and ecosystem services, and associated benefits. A key variable needed to design these programs is the spatial distribution of standing woody biomass. A state-of-the-art methodology using small format aerial photographs was developed to estimate the total aboveground biomass (AGB) and aboveground woody biomass suitable for charcoal making (WSC) in intensively managed oak forests. We used tree crown area ($CA_{ap}$) measurements from very high-resolution (30 cm) orthorectified small format digital aerial photographs as the predictive variable. The $CA_{ap}$ accuracy was validated using field measurements of the crown area ($CA_f$). Allometric relationships between: (a) $CA_{ap}$ versus AGB, and (b) $CA_{ap}$ versus WSC had a high significance level ($R^2 > 0.91$, $p < 0.0001$). This approach shows that it is possible to obtain sound biomass estimates as a function of the crown area derived from digital small format aerial photographs.

1. Introduction

Across the global south, charcoal is frequently produced from clear cutting or selective logging of woody plants that resprout (Chidumayo and Gumbo 2013). The sustainable management of resprouters for charcoal production requires data on their structure and growth capacity; which in turn are affected by the species’ sprouting ability (strong versus weak) (Bond and Midgley 2001), forest management practices (clear cutting versus thinning; short versus long rotations) (Aguilar et al 2012), and local biophysical conditions (Leonardsson and Gotmark 2015). In other words, good quality data on the resprouters’ structure and growth are site-specific and should be generated in situ if adequate sustainable forest management plans are to be designed and implemented.

In order to design sustainable charcoal production programs in data-poor landscapes, cost-effective methods are needed for measuring the aboveground woody biomass productivity of resprouters. One way of attaining this is to estimate the biomass stocks between multiple time intervals, so as to model regrowth rates. However, while past field measurements of biomass stocks are missing for most charcoal production areas of the world, historical aerial photographs could be available.

The most accurate methods for estimating aboveground woody biomass are those involving direct measurement of individual trees by destructive sampling (Brown et al 1989, Brown 1997, Pacala et al 1996, Návar 2009). Common field-measured predictive variables for the development of allometric models are diameter at breast height (DBH) and total tree height (Picard et al 2013). In other words, good quality data on the resprouters’ structure and growth are site-specific and should be generated in situ if adequate sustainable forest management plans are to be designed and implemented.

In order to design sustainable charcoal production programs in data-poor landscapes, cost-effective methods are needed for measuring the aboveground woody biomass productivity of resprouters. One way of attaining this is to estimate the biomass stocks between multiple time intervals, so as to model regrowth rates. However, while past field measurements of biomass stocks are missing for most charcoal production areas of the world, historical aerial photographs could be available.

The most accurate methods for estimating aboveground woody biomass are those involving direct measurement of individual trees by destructive sampling (Brown et al 1989, Brown 1997, Pacala et al 1996, Návar 2009). Common field-measured predictive variables for the development of allometric models are diameter at breast height (DBH) and total tree height (Picard et al 2013). In other words, labor-intensive methods alone do not provide information about the continuous spatial distribution of woody biomass (Lu 2007). This can be overcome by integrating field-based allometric equations with remote sensing and spatial analysis (Castillo-Santiago et al 2013, Dubayah and Drake 2000, Dong et al 2003, Lefsky et al 2005, Lu 2007, Zolkos et al 2013), a technique
that has proved useful even for regional and global stand-to-walk aboveground biomass (AGB) estimates (Saatchi et al 2011, Cartus et al 2014, Baccini et al 2012, Avitabile et al 2011).

Methods less dependent on field data rely on the availability of high spatial resolution products (< 1 m per pixel) such as high-resolution digital aerial photographs, multi- and hyperspectral sensor imagery as well as light detection and ranging (LiDAR) systems coupled with modern computation and data management capabilities. These allow us to infer tree descriptive parameters such as crown area, biomass volume, tree density, tree height and species composition (Drake et al 2003, Leckie et al 2003, Holmgren and Persson 2004, Koukoulas and Blackburn 2005, Næsset and Gobakken 2008, Gougeon and Leckie 2006, Massada et al 2006, Poppescu 2007, Breidenbach et al 2010). However, these tools are often not feasible to implement due to budget constraints. But most important, the newer the sensor, the less the availability of past images.

When dealing with high-resolution biomass estimations (such as those needed for local woodland management plans), allometric models have been calibrated by relating field-based DBH measurements with AGB determination in order to develop empiric equations to estimate biomass (Brown et al 1989, Brown 1997, Baccini et al 2004, 2008, Aguilar et al 2012, Segura and Kanninen 2005). The estimation of tree biomass from aerial imagery has been around for at least two decades. Earlier approaches (e.g. Brandtberg and Walter 1998, Korpela 2004) were based on either automated or manual analysis of digitized analog aerial photographs and photogrammetrical software. These techniques gave a good overall agreement between image-based, ground-based crown diameter and total stem volumes, but rather limited accuracy regarding individual tree height in dense forest (Korpela 2004, Næsset 2002). But the level of agreement depends on adequate single-tree crown delineation, which is affected by forest density, structure, species composition as well as tree position within the photograph. Korpela (2004) reports that the best delineation occurred in trees close to the photograph nadir. More recent approaches include digital aerial photographs, multispectral sensors and LiDAR sensors. None of these approaches deal specifically with young sprouts typically exploited for charcoal production, which have quite a different architecture to non-managed stands (Aguilar et al 2012, Chidumayo 2014). Sousa et al (2015), for example, report a canopy to the biomass model that could be useful for bioenergy purposes, but oaks in their study area were never cleared cut, but ‘...pruned with a periodicity of approximately 5 years in order to enhance fruit production and the stands are predominantly mature’. Furthermore, none of the previous studies dealt specifically with wood suitable for charcoal (WSC), as the portion of AGB actually useful for charcoal making. Oak forests and rangelands (Quercus spp.) in many developing countries across the tropics represent a major woodfuel source, and are intensively coppiced for charcoal on rotations of varying duration, usually by clear cutting in order to save time and effort carrying trunks and thick branches to the kilns (e.g. Aguilar et al 2012, Jomaa et al 2003, Aus-Der-Beek et al 2006, Herrera and Chave 2006, Nygren 2005, Wakeel et al 2005, Shrestha 2003, Barrow and Hicham 2000, Somanathan 1991). Oaklands traditionally managed for charcoal are no exception regarding the lack of legal permits for exploitation and commercialization (Masera et al 2015). It has been reported that many charcoal producing areas across developing countries have been traditionally managed without any kind of permits (Masera et al 2015, Sander et al 2013, Zulu and Richardson 2013). Barring a few exceptions (e.g. Chidumayo 2014, Castillo-Santiago et al 2013, Chidumayo 1991, 2013, Chidumayo 1988), charcoal producing areas have been neglected by foresters and ecologists due to their low economic potential as timber sources, and high level of anthropization, respectively.

Similar to other data-poor landscapes, there is a need for high-resolution estimates of WSC.

The present study was designed and performed to calibrate allometric models relating the crown area of young oak sprouts measured in aerial photographs with AGB and WSC at tree and stand level. The underlying objective was to show that high-resolution estimates of AGB and WSC, aimed as a source of information for sustainable charcoal production, can be produced in a simple and relatively cost-effective way with little previous information on the characteristics of the managed woodland. Therefore, this framework could be implemented where applicable in similar settings.

2. Methods

Photogrammetric measurements of the tree crown area were obtained from very high-resolution (30 cm) small format digital aerial photographs to derive indirect allometric equations and to estimate the basal area (BA), AGB and WSC. To account for the existing variation, the estimates of BA, AGB and WSC were obtained at two different levels of analysis: (1) individual trees, and (2) stand level (aggregation of individual trees). The stand level will be referred to as ‘grouped trees’ from now on.

2.1. Study area

The study area comprises the eastern portion of the Cuitzeo lake basin located in the Trans-Mexican Volcanic Belt in central Mexico (figure 1). It is located between 19°53′15″ and 20°04′30″ N and 100°50′20″ and 101°19′30″ W and at a mean altitude of 1830 m.a.s.l. (Morales-Manilla 2010). It covers an area of 4026 km² and harbors the second largest water body in Mexico, the Cuitzeo Lake, with an extension of 242 km² (López et al 2007, Mendoza et al 2011).
The climate is temperate subhumid with dry winters, and from north to south it exhibits a gradient of increasing precipitation and decreasing temperature. The long-term (1951–2010) reports of the Servicio Meteorologico Nacional (National Mexican Weather Service) indicate mean annual precipitation ranges from 695 mm in Cuitzeo (station 16027) in the north to 1116 mm in Acuitzio del Canje at the southmost portion of the basin (station 16001, SMN 2010a, 2010b). While mean annual temperature ranges from 18.2°C in Cuitzeo town (station 16027) to 16.9°C in Acuitzio del Canje (station 16001) (SMN 2010a, 2010b). This corresponds to a transitional zone between the dry and humid temperate climates (López et al. 2007). The Cuitzeo basin is a mosaic of land covers, where only 20% of its total extension is covered by mixed pine-oak forests. The dominant land uses are agriculture (rainfed and irrigated) and grasslands covering almost 50% of the total surface of the basin (Mendoza et al. 2011). Approximately one million people inhabit the study area (density = 254 pop km⁻²).

An important aspect of the population dynamics within the Cuitzeo basin is its emigration to Morelia, the nearest major urban settlement, which accounts for almost 79% of the urban population (López et al. 2007). One of the main economic activities of the rural communities is charcoal production using traditional techniques to supply the urban settlements (Castillo-Santiago et al. 2013, Serrano-Medrano et al. 2014). *Quercus castanea Née* and *Quercus laeta* are the most frequently used species for charcoal production, and both are endemic to Mexico (Aguilar et al. 2012). These oak species tend to resprout after cutting and therefore may form a tree-trunk structure called a stool in which several boles correspond to one individual. Interviews with land owners indicate that the oak forests in this region have been harvested intensively to produce charcoal for at least 60 years. Clear cutting is the main harvesting practice in the study area. This is because earth mound kilns are built by piling the wood at a location, and so selective logging will significantly increase the effort of carrying the wood into the kiln, which is always done ‘by hand’. Furthermore, land owners and cattle grazers are seldom charcoalers, meaning that there is no real interest from key stakeholders for sound oakland management. Typical rotation cycles vary between 5–7 years to 15 or even 20 years, depending on site quality and agreements among land owners and charcoalers within an informal and unregulated production system (Camou-Guerrero et al. 2014).

### 2.2. Field survey

No previous information concerning allometric relationships between the crown area and BA for managed oak trees was available for the study area. Therefore, ground inventories were necessary. Two field campaigns were conducted in extensively managed oak forest sites located throughout the eastern region of the Cuitzeo basin (figure 1). The first campaign was conducted during the spring of 2014 and the second during the spring of 2015. Only *Quercus* spp. individuals were sampled during the field campaigns, and the dominant species in terms of distribution and relative abundance was *Q. castanea*. Field measurements included: (1) the DBH, typically measured at a height of 1.30 m above the ground and a trunk circumference >10 cm, and (2) the crown diameter (tree crown spread) as the average length of two perpendicular lines across the crown area.

The field BA was obtained from the DBH measurements for each coppice shoot. For tree individuals with
### Table 1. Dasometric characteristics of individual trees and grouped trees.

|                          | min   | max   | mean | sd   |
|--------------------------|-------|-------|------|------|
| **Individual trees**     |       |       |      |      |
| N (number of individual  | 35    | 151   | 52   | 32   |
| trees per site)          |       |       |      |      |
| Field-measured BA (m²)   | 0.001 | 0.122 | 0.024| 0.008|
| Field-measured crown area (m²) | 7.69  | 149.56| 37.72| 26.06|
| Photo-measured crown area (m²) | 2.79  | 146.93| 27.88| 20.25|
| **Grouped trees**        |       |       |      |      |
| N (number of stands per  | 12    | 25    | 15   | 6    |
| site)                    |       |       |      |      |
| Field-measured BA (m²)   | 0.011 | 1.48  | 0.192| 0.24 |
| Field-measured crown area (m²) | 11.33 | 852.54| 105.26| 147.78|
| Photo-measured crown area (m²) | 9.32  | 771.97| 100.7| 135.59|

**Figure 2. Flight route for aerial photograph acquisition and field sample sites.**

Several coppice shoots, we sum up the BA of each shoot to obtain the total BA for each tree (equations 1 and 2).

\[
BA_1 = \left( \frac{DBH_1}{2} \right)^2 \cdot \pi 
\]  
(1)

\[
BA_{\text{total}} = \sum_{i=1}^{n} AB_i
\]  
(2)

Since treetops from sprouting oak trees usually exhibit asymmetric architecture, the projected field crown area (CA_f) was estimated approximating the crown shape to an ellipse (equation 3, table 1).

\[
CA_f = \frac{CD_{\text{INS}}}{2} \cdot \frac{CD_{\text{EW}}}{2} \cdot \pi
\]  
(3)

where CD_{INS} and CD_{EW} represent the field crown diameter in the north-south and east-west direction, respectively.

Twelve sites of 9–14 ha were sampled, each one hosting between 35 and 151 trees. Within the sites, the sampled trees were unevenly distributed in 12–25 natural stands of ca. 0.15 ha. Each individual tree was georeferenced using differential correction for improving the accuracy of GPS positioning.

### 2.3. Aerial photography acquisition and processing

High-resolution near vertical small format digital aerial photographs were acquired from an aerial platform (Cessna 182) during March 2014 and April 2015 using a Nikon AF Nikkor 24 mm objective and small format digital cameras Nikon D70 SLR and D300S (figure 2).

Both cameras were previously calibrated to assess lens distortion and swath distance to flight altitude relation. Central image position coordinates were registered with a WAASS-enabled GPS unit (GPSMAP 60CS, Garmin, Inc.), while roll, pitch and yaw angles were recorded during flight by means of an Arduino UNO board coupled to an Arduino compatible logger shield (Adafruit, Inc.) and a 9 degrees of freedom inertial measurement unit (9DOF Razor IMU, SparkFun Electronics, Inc.). Furthermore, aerial photographs...
were orthorectified using `i.ortho.photo` module implemented in GRASS GIS v6.4.3 (GRASS Development Team 2012, Rocchini et al. 2012). Ground control point coordinates for the orthorectification process were acquired at distinctive and easy to identify landmarks both in the field and aerial photographs during the field surveys. The spatial resolution of the orthorectified aerial photographs was 30 cm (WGS84/UTM Zone 14 N).

2.4. Crown area estimation using aerial photographs
Individual tree crowns were delineated using a mirror stereoscope and high-contrast color prints of the aerial photographs. The tree crown limits were on-screen digitized using GRASS GIS v6.4.3 (GRASS Development Team 2012). Individual tree measurements were aggregated to obtain grouped tree areas (figure 3). Field verification and delineation of interpreted features occurred within the first month after the acquisition of the image.

2.5. Biomass estimation using photo-derived crown measurements
To estimate the total AGB and WSC using the crown area measured in aerial photographs (CA\textsubscript{ap}) as the predictor variable instead of DBH, first we evaluated the existence of an allometric relationship between the field-measured DBH (expressed as BA) of the oaks' coppice-shoots and CA\textsubscript{ap}.

The data gathered during the two field surveys were divided into two sets as follows: (1) field measurements of the first field survey (2014) were used to evaluate the BA versus CA\textsubscript{ap}, and (2) field measurements for the second field campaign were used to estimate the biomass and generate the allometric equations between CA\textsubscript{ap}, versus AGB and CA\textsubscript{ap} versus WSC.

We calculated the BA from the DBH field measurements for *Q. castanea* and *Q. spp.* coppice shoots. Since typical sprouting oak trees or stools managed for charcoal making exhibit several coppice shoots, as opposed to unharvested oaks trees, it was necessary to sum up the BA of the coppice shoots belonging to the same tree (equation 2). In this way it was possible to establish a 1:1 relationship between the total individual tree BA and individual tree photo-measured crown area (CA\textsubscript{ap}). We followed the same approach to evaluate the allometric relationship between the BA for grouped trees (*Q. spp*) and the CA\textsubscript{ap} corresponding to those grouped trees, i.e. we sum up the total stand BA and total stand CA\textsubscript{ap}.

Regressions models were generated to evaluate the allometric relationship between BA versus CA\textsubscript{ap} and we identified a strong linear relationship between BA versus CA\textsubscript{ap} (figure 4).

Then, we proceeded to calculate the total AGB and WSC. We used as input values to estimate the biomass, the field measurements from the DBH for single coppice shoots (*n* = 1604 coppice shoots, 366 individual trees). The allometric equations that allow us to estimate both the total AGB and WSC from the field-measured DBH were generated in a previous study conducted by Aguilar et al. (2012) in the same study area (table 2).

The AGB and WSC were obtained for each coppice shoot. For tree individuals with several coppice shoots, we sum up the WSC and AGB of each shoot to obtain the total biomass component for each individual tree.

2.6. Statistical analysis
Once the biomass components were obtained, linear regression models were generated for the two levels of analysis (individual and grouped trees) and for both sample periods (2014 and 2015) to evaluate the allometric relationships between: (1) CA\textsubscript{f} versus CA\textsubscript{ap}, (2) CA\textsubscript{ap} versus BA, (3) CA\textsubscript{ap} versus AGB, and (4) CA\textsubscript{ap} versus WSC. Field- and photo-measured crown area were used as independent variables to generate the allometric models. All variables were log-transformed for the adjustment of linear regressions. The statistical analysis was conducted using the R v3.2.0 software (R Development Team 2015).
Table 2. Biomass equations for regrowth coppice-shoots of *Q. castanea* and *Q. spp* (Source: Aguilar et al 2012).

| Species   | Biomass component                                    | a    | b    | \(R^2\) |
|-----------|------------------------------------------------------|------|------|---------|
| *Q. castanea* | Woody biomass suitable for charcoal (WSC)           | 0.0324 | 2.7425 | 0.97    |
|           | Total aboveground biomass (AGB)                      | 0.0416 | 2.7154 | 0.97    |
| *Q. spp*   | Woody biomass suitable for charcoal (WSC)           | 0.0273 | 2.7813 | 0.96    |
|           | Total aboveground biomass (AGB)                      | 0.0342 | 2.759  | 0.95    |

Notes: Equations are in the form \(y = a(DBH)^b\), ‘\(y\)’ in kg per coppice-shoot and ‘DBH’ in centimeters per coppice shoot. Parameters \(a\) (scaling coefficient) and \(b\) (scaling exponent) were solved by the Gauss–Newton non-linear least squares algorithm. All scaling exponents differ significantly from 1 (\(p < 0.0001\)).

Figure 4. Linear models between field- (CA\(_{f}\)) and photo-measured (CA\(_{pa}\)) crown area versus tree BA for individual *Q. castanea* trees (top) and grouped *Q. spp* trees (middle) and linear models between field-measured crown area (CA\(_{f}\)) and photo-measured crown area (CA\(_{pa}\)) for individual *Q. castanea* trees (top) and grouped *Q. spp* trees (bottom).
3. Results

In both field campaigns, we found significant relationships between field-measured CA and photo-measured CA for both individual trees ($R^2 = 0.88$, $p < 0.001$) and grouped trees ($R^2 = 0.96$, $p < 0.001$) (figures 4 and 5). Thus, the estimation of the BA was expressed as a function of $CA_{ap}$ in the form $\ln(AB) = \ln (AC_{ap}) + b$. For individual trees sampled during the spring of 2014, the $R^2$ values were equal to 0.73 for individual Q. castanea trees and 0.90 for grouped trees (Q. spp). Allometric relationships were highly significant ($p < 0.001$) in all cases.

The adjusted $R^2$ values were higher when the crown areas of the individual trees were aggregated. As we increased the sample efforts during spring 2015, the relationship between $CA_{ap}$ and BA for the individual and grouped trees became more accurate than that observed during 2014 (figure 5).

The regression analysis for the AGB and WSC estimation using $CA_{ap}$ as the predictor variable was highly significant with $R^2$ values of 0.82 for Q. castanea trees and 0.91 for grouped trees (figure 6). These results indicate that it is possible to use $CA_{ap}$ as a proxy variable for the estimation of the total AGB and WSC (table 3). Similar to the results obtained for the relationship between $CA_{ap}$ and AB, biomass estimations for individual Q. castanea trees showed adjusted $R^2$ values lower than the grouped trees.

4. Discussion

Although the idea of estimating biomass from the crown area measured in aerial photographs is not novel (Ilvessalo 1950), this study explored the generation of a cost-effective framework for estimating biomass by using an intensively managed oak forest as a case study. No previous approaches of this kind have been applied before to these ecosystems and such information is urgently needed due to its implications for forest management and woodfuel security. The only accurate equations available to estimate the total AGB and WSC in our study area were developed by Aguilar et al (2012). However, they used DBH as the predictive variable. In this study, we present an approach to
generate sound biomass estimates using the tree crown area measured in high-resolution aerial photographs, instead of field-measured DBH, as the predictor variable. Although tree height is considered an important variable in forest inventories (Korpela and Anttila, 2004) as well as in AGB estimation as clearly stated by Chave et al. (2014), when aerial photographs at detailed scales (1:10 000–1:15 000) are digitized with very high-resolution scanners (~20 µm) yielding a submeter nominal pixel resolution and processed with photogrammetrical techniques, mean tree height can be estimated. Nevertheless, with this approach, in forests stands, height is normally underestimated (Næsset 2002, Korpela and Anttila 2004) with errors ranging from 2.47–5.42 m (Næsset 2002, Korpela and Anttila 2004). Correction of these errors implies field measurement of tree height at sampling points to better predict mean tree height at the stand scale using a regression between aerial image-derived mean stand height and field-measured mean stand height (Næsset 2002). With this approach, the predicted mean heights overestimated true heights with less precision in very young forest stands, and higher precision in young and mature stands (Næsset 2002). Due to the associated uncertainty when tree height is to be estimated using photogrammetrical methods coupled with small-frame digital images, we decided to focus on the CA_{ap} versus BA relation and employ the AGB and WSC models that did not need tree height as an input. Biomass estimates at a regional scale are useful for generating information across large areas (Jenkins et al. 2003, Baccini et al. 2004, Ralevic et al. 2010, Castillo-Santiago et al. 2013). However, at a local scale, field measurements still constitute the most accurate method to ensure that the allometric equations reflect the actual growing stock volume (Nogueira et al. 2008, Návar 2009, Picard et al. 2012). For instance, trees from intensively managed (i.e. coppiced) oak forests exhibit different architectural and growth patterns to those of primary oak forests, mainly due to the reduced growing space available to coppice shoots, which develop typical stool structure (Ducrey and Turrel 1992, Bellingham and Sparrow 2000, Logli and Joffre 2001, Espelta et al. 2003, Konstantinidis et al. 2005, Sands and Abrams 2009). In contrast, mature open-growth trees present very large crowns in proportion to their DBH and species (Johnson 2000). As a result, the use of standard allometric equations developed for primary oak forests, which exhibit different tree proportionality ratios, can alter biomass parameters leading to gross errors in biomass estimation (Picard et al. 2012).

The equations developed in this contribution are relatively simple. However, there are several aspects that need to be addressed before applying them in other regions. First, the equations were developed for coppice oak trees with DBH ≤ 30 cm, so attention should be paid if they are used to estimate the biomass of non-resprouting oak trees with larger DBH values. A second aspect is related to image acquisition date and time. In this regard, varying phenological and lighting conditions can affect the spectral responses of the Quercus species and the discernibility of trees, leading to biased crown area estimates (Gougeon and Leckie 2006, Barbier et al. 2010). For Quercus tree species, particularly Q. castanea, the spectral response of leaves varies seasonally, facilitating the identification of oak trees in aerial photographs acquired before spring (from mid-February until mid-March). Furthermore, it is important to consider that parameters of individual trees measured in aerial photographs are indirect, and the allometric equations are inherently uncertain and susceptible to systematic errors (Korpela 2004). Thus, very high-estimation accuracy at individual tree level cannot be expected (Gougeon and Leckie 2006, Vastaranta et al. 2011, Kaartinen et al. 2012).

As illustrated in this study, the allometric models developed to test the relationships between AC_{ap} versus AGB and AC_{ap} versus WSC showed in all cases a higher $R^2$ for grouped trees. Nonetheless, the analysis of this work at the individual tree and stand level (grouped trees) provides useful tools for obtaining accurate measurements of the crown area and precise biomass estimations. This makes the proposed framework less site-specific, allowing its replicability in other regions, subject to similar management practices.

Further research must evaluate the applicability of the methodology presented in this paper and the possibility to process historical aerial photographs in order to estimate the AGB and WSC at different dates. This would make it possible to analyze the AGB and WSC changes in time and evaluate the AGB productivity rates at different locations.

Finally, one aspect that should be considered to improve this framework applicability and make it fully operational is related to the degree of tree-crown identification and delineation automation. Multi-scale automated or semi-automated algorithms for identifying individual trees within forest...
stands still need to be systematically tested and validated. Although very promising software and approaches to perform automated tree-crown identification and delineation exist, e.g. eCognition by Trimble Inc. (www.ecognition.com/) or SPRING by Brazil’s National Institute for Space Research (www.springgis.org/languages/english/index.html), the research on this subject highlights the need for a sound baseline for calibrating and validating automatic tree-crown identification and delineation (Gao et al. 2006, Gao and Mas 2008). In this respect, the information generated by visual interpretation (i.e. manual tree-crown identification and delineation) is crucial for calibration and validation purposes, which provide feedback to further improve the results of the automated techniques.

5. Conclusions

The aim of this work was to develop a framework for the estimation of the AGB and WSC at the individual tree and stand level using information from high-resolution aerial photographs coupled with field measurements and species-specific allometric equations previously developed for the study site. We used as a case study an intensively managed oak forest used to produce charcoal. We identified strong and highly significant relationships between the photo-measured crown area and BA, AGB and WSC. The advantages of this framework are: (1) the reduction of field measurements and the associated costs, (2) it can be easily replicated, since it requires a minimum input of parameters (i.e. crown area measurements), (3) it is flexible, since it works at different levels of analysis (i.e. individual trees and grouped trees), (4) it allows us to predict values for the BA, total AGB and WSC in terms of kilograms of dry matter and volume and, (5) it allows us to combine different sources of information to support forest management programs focusing on sustainable energy development. Future research is needed on cost-benefit comparisons between aerial photographs and high-resolution satellite imagery for estimating WSC for the estimation of the AGB and WSC at the individual tree and stand level using information from high-resolution aerial photographs coupled with field measurements and species-specific allometric equations previously developed for the study site. We used as a case study an intensively managed oak forest used to produce charcoal. We identified strong and highly significant relationships between the photo-measured crown area and BA, AGB and WSC. The advantages of this framework are: (1) the reduction of field measurements and the associated costs, (2) it can be easily replicated, since it requires a minimum input of parameters (i.e. crown area measurements), (3) it is flexible, since it works at different levels of analysis (i.e. individual trees and grouped trees), (4) it allows us to predict values for the BA, total AGB and WSC in terms of kilograms of dry matter and volume and, (5) it allows us to combine different sources of information to support forest management programs focusing on sustainable energy development. Future research is needed on cost-benefit comparisons between aerial photographs and high-resolution satellite imagery for estimating WSC.

Acknowledgements

This work was supported by UNAM’s PAPIIT IA101513 and Universidad Michoacana de San Nicolás de Hidalgo CIC projects 522209-2014 and 107853-2015. The first author received a graduate studies stipend from CONACYT (No. 549946). We also express our thanks to Mr Hugo Zavala (CIGA, UNAM) for technical support as well to Cap. Rivera (Ave-Express) for sound comments on camera system deployment. Finally, we acknowledge the valuable comments and suggestions by anonymous referees, who helped improve the manuscript. The authors declare no conflicts of interest. Author contributions: A.G.-T. and A.G. developed the conceptual framework, A.G.-T., A.G. and D.R.-M. designed the research; D.R.-M. performed the research and analyzed the data; A.G.-T., D.R.-M., and A.G. wrote the paper.

ORCID iDs

A Gómez-Tagle https://orcid.org/0000-0001-7640-5205

References

Aguilar R, Ghilardi A, Vega E, Skutsch M and Oyama K 2012 Sprouting productivity and allometric relationships of two oak species managed for traditional charcoal making in central Mexico Biomass Bioenergy 36 192–207

Aus-Der-Beek R, Venegas G and Pedroni L 2006 Charcoal production in a Costa Rican montane oak forest Ecology and Conservation of Neotropical Montane Oak Forests ed M Kappelle (Berlin: Springer) pp 407–19

Avitabile V, Herold M, Henry M and Schmullius C 2011 Mapping biomass with remote sensing: a comparison of methods for the case study of Uganda Carbon Bal. Manage. 6 7

Baccini A, Friedl M A, Woodcock C E and Warbington R 2004 Forest biomass estimation over regional scales using multisource data Geophys. Res. Lett. 31 1–4

Baccini A, Laporte N, Goetz S J, Sun M and Dong H 2008 A first map of tropical Africa’s above-ground biomass derived from satellite imagery Environ. Res. Lett. 3 43011

Baccini A et al. 2012 Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps Nat. Clim. Change 2 182–5

Barbier N, Couteron P, Proisy C, Malhi Y and Gastellu-Etchegorry J P 2010 The variation of apparent crown size and canopy heterogeneity across lowland Amazonian forests Glob. Ecol. Biogeogr. 19 72–84

Barrow C J and Hicham H 2000 Two complementary and integrated land uses of the western High Atlas Mountains, Morocco: the potential for sustainable rural livelihoods Appl. Geogr. 20 369–94

Bellingham P J and Sparrow A D 2000 Resprouting as a life history strategy in woody plant communities Oikos 89 409–16

Bond W J and Midgley J J 2001 Ecology of sprouting in woody plants: the persistence niche Trends Ecol. Evol. 16 45–51

Bond W J and Midgley J J 2003 The evolutionary ecology of sprouting in woody plants Int. J. Plant Sci. 164 S103–14

Brandenburg T and Walter F 1988 Automated delineation of individual tree crowns in high spatial resolution aerial images by multiple-scale analysis Mach. Vis. Appl. 3 64–73

Breidenbach J, Nasseet E, Lien V, Gobakken T and Solberg S 2010 Prediction of species specific forest inventory attributes using a nonparametric semi-individual tree crown approach based on fused airborne laser scanning and multispectral data Remote Sens. Environ. 111 911–24

Brown S 1997 Estimating Biomass and Biomass Change of Tropical Forests: A Primer vol 134 (Rome: Food and Agriculture Organization)

Brown S, Gillespie A J R and Lugo A E 1989 Biomass estimation methods for tropical forests with applications to forest inventory data Forest Sci. 35 881–902

Camou-Guerrero A, Ghilardi A, Mwampamba T, Serrano M, Ortiz-Avila T, Vega E, Oyama k and Masera O 2014 Análisis de la producción de carbón vegetal en la Cuenca del Lago de Cuitzeo, Michoacán, México: implicaciones para una producción sustentable Invest. Amíti. 6 127–38
Cartus O, Kellndorfer J, Walker W, Franco C, Bishop J, Santos L and Fuentes J M M 2014 A national, detailed map of forest aboveground carbon stocks in Mexico Remote Sens. 6 3559–88
Castillo-Santiago M A, Ghilardi A, Oyama K, Hernandez-Stefanoni J L, Torres I, Flamenco-Sandoval A, Fernandez A and Mas I F 2013 Estimating the spatial distribution of woody biomass suitable for charcoal making from remote sensing and geostatistics in central Mexico Energy Sustain. Dev. 17 177–88
Chave J et al 2014 Improved allometric models to estimate the aboveground biomass of tropical trees Glob. Change Biol. 20 3177–3190
Chidumayo E N 1988 Estimating fuelwood production and yield in regrowth dry Miombo woodland in Zambia Forest Ecol. Manage. 24 59–66
Chidumayo E N 1991 Woody biomass structure and utilization for charcoal production in a Zambian Miombo woodland Biosour. Technol. 37 43–52
Chidumayo E N 2013 Forest degradation and recovery in a Miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots Forest Ecol. Manage. 291 154–61
Chidumayo E N 2014 Estimating tree biomass and changes in root biomass following clear-cutting of Brachystegia-Julbernardia (Miombo) woodland in central Zambia Environ. Conserv. 41 54–63
Chidumayo E N and Gumbo D J 2013 The environmental impacts of charcoal production in tropical ecosystems of the world: a synthesis Energy Sustain. Dev. 17 86–94
Dong J, Kautzmann R K, Myneni R B, Tucker C J, Kauppi P E, Liski J, Buermann W, Alexeys A and Hughes M K 2003 Remote sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources, and sinks Remote Sens. Environ. 84 393–410
Drake J B, Knox R G, Dubayah R O, Clark D B, Condit R, Blair J B and Hoffman M 2003 Above-ground biomass estimation in closed canopy neotropical forests using lidar remote sensing: factors affecting the generality of relationships Glob. Ecol. Biogeogr. 12 147–59
Dubayah R O and Drake J B 2000 Lidar remote sensing for forestry J. Forest Soc. Am. Forest 98 44–6
Ducruy M and Turrell M 1992 Influence of cutting methods and dates on stump sprouting in Holm oak (Quercus ilex L.) coppice Amn. Sci. Forest 49 449–64
Espelta J M, Retana J and Habrouk A 2003 Resprouting patterns after fire and response to stool cleaning of two coexisting Mediterranean oaks with contrasting leaf habits on two Mediterranean stands by digital photogrammetry Forest Ecol. Manage. 142 53–63
López E, Mendoza M E, Bocca G and Acosta A 2007 Crecimiento urbano y sus consecuencias a nivel regional en la cuenca del lago de Cuatizo, México Urbanización, cambios globales en el ambiente y desarrollo sustentable en América Latina ed R Sánchez and A Bonilla pp 113–33
Lu D 2007 The potential and challenge of remote sensing-based biomass estimation Int. J. Remote. Sens. 27 1297–328
Masera O, Drigo R, Bailis R, Ghilardi A and Ruiz-Mercado I 2015 Environmental burden of traditional bioenergy use Amn. Rev. Environ. Resour. 40 121–50
Massada A B, Carmel Y, Tzur G E, Grunzweig J M and Yakir D 2006 Assessment of temporal changes in aboveground forest tree biomass using aerial photographs and allometric equations Can. J. Forest Res. 36 2585–94
Mendoza M E, Granados E L, Geneletti D, Pérez-Salcirop D R and Salinas V 2011 Analysing land cover and land use change processes at watershed level: a multitemporal study in the Lake Cuatizo Watershed, Mexico 1975–2003 Appl. Geogr. 31 237–50
Morales-Manilla L M 2010 Características Físicas, Área de Estudio Atlas de la cuenca del lago de Cuatizo: Análisis de su geografía y entorno socioambiental ed S Crum, L Galicia and I Israde-Alcantara (Mexico, DF: UNAM-UMSNH) pp 20–23
Návar J 2009 Allometric equations for tree species and carbon stocks for forests of northwestern Mexico Forest Ecol. Manage. 257 427–34
Nogueira E M, Fearnside P M, Nelson B W, Barbosa R I and Keizer E W H 2008 Estimates of forest biomass in the Brazilian Amazon: new allometric equations and adjustments to biomass from wood-volume inventories Forest Ecol. Manage. 256 1853–67
Nygren A 2005 Community-based forest management within the context of institutional decentralization in Honduras World Dev. 33 639–55
Næset E 2002 Determination of mean tree height of forest stands by digital photogrammetry Scand. J. Forest Res. 17 464–59
Jenkins J C, Chojnacky D C, Heath L S and Birdsey R A 2003 National-scale biomass estimators for United States tree species Forest Sci. Soc. Am. Forest 49 12–35
Johnson E W 2000 Forest Sampling Desk Reference (New York: CRC)
Jomaa I, Auda Y, Saleh B A, Hamze M and Safi S 2003 Landscape spatial dynamics over 38 years under natural and anthropogenic pressures in Mount Lebanon Landscape Urban Plan 87 67–75
Kaatrinen H et al 2012 An international comparison of individual tree detection and extraction using airborne laser scanning Remote Sens. 4 950–74
Konstantinidis P, Tsioroula G and Galatsidas S 2005 Effects of wildfire season on the resprouting of kermes oak (Quercus cocciifera L.) Forest Ecol. Manage. 208 15–27
Korpela I and Anttila P 2004 Appraisal of the mean height of trees by means of image matching of digitised aerial photographs Photogramm. J. Finland 19 23–36
Korpela I 2004 Individual tree measurements by means of digital aerial photogrammetry Silva Fennica Monogr. 3 93
Leckie D, Gougeon F, Hill D, Quinn R, Armstrong L and Shreenan R 2003 Combined high-density lidar and multispectral imagery for individual tree crown analysis Can. J. Remote. Sens. 30 199–209
Lefsky M A, Turner D P, Guy M and Cohen W B 2005 Combining lidar estimates of aboveground biomass and Landsat estimates of stand age for spatially extensive validation of modeled forest productivity Remote Sens. Environ. 95 549–58
Leonardsson J and Gotmark F 2015 Differential survival and growth of stumps in 14 woody species after conservation thinning in mixed oak-rich temperate forests Eur. J. Forest Res. 134 199–209
Loglì F and Joffre R 2001 Individual variability as related to stand structure and soil condition in a Mediterranean oak coppice Forest Ecol. Manage. 142 53–63
Macedo M, Soares P, Coelho F, Sequeira R, Pires R, Almeida S and Cardoso L 2015 Biomass estimation in closed canopy neotropical forests using lidar remote sensing: factors affecting the generality of relationships Ann. Rev. Ecol. Evol. Syst. 46 427–54
Maggio N and Conti S 2014 Recent advances in remote sensing-based biomass estimation J. Remote Sens. 5 307–33
Næsset E and Gobakken T 2008 Estimation of above- and below-ground biomass across regions of the boreal forest zone using airborne laser Remote Sens. Environ. 112 3079–90

Pacala S W, Canham C D, Saponara J, Kobe J A Jr and Ribbens R K 1996 Forest models defined by field measurements: estimation, error analysis and dynamics Ecol. Monogr. 66 1–43

Picard N, Saint-André L and Henry M 2012 Manual for building tree volume and biomass allometric equations: from field measurement to prediction Las Naciones Unidas para la Alimentación y la Agricultura y el Centre de Coopération Internationale en Recherche Agronomique pour le Développement (Rome, Montpellier: FAO/CIRAD)

Popescu S C 2007 Estimating biomass of individual pine trees using airborne lidar Biomass Bioenergy 31 646–55

Popescu S C 2007 Estimating biomass of individual pine trees using airborne lidar Biomass Bioenergy 31 646–55

R Core Team 2015 R: A language and environment for statistical computing R Foundation for Statistical Computing Vienna, Austria (http://www.R-project.org/)

Ralevic P, Ryans M and Cormier D 2010 Assessing forest biomass for bioenergy: operational challenges and cost considerations Forest Chron. 86 43–50

Rocchini D, Metz M, Frigieri A, DeLucchi L, Marcantoni M and Neteler M 2012 Robust rectification of aerial photographs in an open source environment Comput. Geosci. 39 145–51

Saatchi S, Marlier M, Chazdon R L, Clark D B and Russell A E 2011 Impact of spatial variability of tropical forest structure on radar estimation of aboveground biomass Remote Sens. Environ. 115 2836–49

Sander K, Gros C and Peter C 2013 Enabling reforms: analyzing the political economy of the charcoal sector in Tanzania Environ. Res. Lett. 13 (2018) 025006

Segura M and Kanninen M 2005 Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica1 Biotropica 37 2–8

Serrano-Medrano M, Arias-Chalico T, Ghilardi A and Masera O 2014 Spatial and temporal projection of fuelwood and charcoal consumption in Mexico Energy Sustain. Dev. 19 39–46

Servicio Meteorológico Nacional 2010a Normales climatológicas, estación 16001 Acuitzio del Canje, periodo 1951–2010 (http://smn.cna.gob.mx/tools/RESOURCES/Normales5110/NORMAL16027.TXT)

Servicio Meteorológico Nacional 2010b Normales climatológicas, estación 16027 Cuitzeo, periodo 1951–2010 (http://smn.cna.gob.mx/tools/RESOURCES/Normales5110/NORMAL16027.TXT)

Shrestha B B 2003 Quercus semecarpifolia Sm in the Himalayan region: ecology, exploitation and threats Himalayan J. Sci. 1 126–8

Somanathan E 1991 Deforestation, property-rights and incentives in central Himalaya Econ. Polit. Weekly 26 Pe37

Sousa A M O, Goncalves A C, Mesquita P and da Silva J R M 2015 Biomass estimation with high resolution satellite images: a case study of Quercus rotundifolia Isprs J. Photogramm. 101 69–79

Team RC. R Language Definition 2015 CRAN sites

Team RC. R Language Definition 2015 CRAN sites

Vastaranta M et al 2011 Effects of individual tree detection error sources on forest management planning calculations Remote Sens. Mol. Divers. Pres. Int. 3 1614–26

Wakeel A, Rao K S, Maikhuri R K and Saxena K G 2005 Forest management and land use/cover changes in a typical micro watershed in the mid elevation zone of Central Himalaya, India Forest Ecol. Manage. 213 229–42

Zolkos S G, Goetz S J and Dubayah R 2013 A meta-analysis of terrestrial aboveground biomass estimation using lidar remote sensing Remote Sens. Environ. 128 289–98

Zulu L C and Richardson R B 2013 Charcoal, livelihoods, and poverty reduction: evidence from sub-saharan Africa Energy Sustain. Dev. 17 127–37