Quantifying forest carbon stocks by integrating satellite images and forest inventory data

Quantifizierung der Kohlenstoffvorräte in Wäldern durch die Integration von Satellitenbildern und Waldinventurdaten

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Keywords: Aboveground Biomass, Remote Sensing, Sentinel-2A data, Vegetation indices

Schlüsselbegriffe: oberirdische Biomasse, Fernerkundung, Sentinel-2A-Daten, Vegetations-Indizes

Abstract

Reliable biomass and carbon stock estimation are central to obtain reference levels for quantifying carbon emissions. Forest inventory data combined with remote sensing data provides opportunities to map and monitor forest areas at various spatio-temporal scales. The current research is a pilot study focussed on the biomass and carbon estimation and mapping of subtropical scrub forests of Khanpur range, Harihur Forest Division, Pakistan considering 20 inventory plots using Sentinel-2A and Landsat-8 data. Six forest areas (Garamthun, Chhoi, Moharagutta, Sanaba, Dobandi and Saradana) were considered covering a total area of 697.3 ha. Average biomass of
the assessed plots was 104.6 t/ha and mean carbon stock was 49.7 t/ha. Garamthun forest had the highest values for both biomass (187.30 t/ha) and carbon (87.98 t/ha) followed by Choi with 148.22 t/ha of biomass and 69.6 t/ha carbon respectively. The total estimated carbon stock for these six forest types was 43570.9 t. The biomass was then correlated with spectral indices computed from Sentinel 2 image (NDVI, SAVI, DVI, PVI and MSAVI). NDVI performed significantly well among five other indices with the values of R2 of 0.81 followed by 0.7 and 0.58 for SAVI and DVI respectively. PVI and MSAVI responded poorly to biomass as compared to the other indices with the value of R2 of 0.20 and 0.11 respectively. Spatial distribution of biomass was mapped using NDVI, which was selected as the best model based on the values of R2. Further, Landsat-8 was also used and the similar five indices were derived for Landsat-8 imagery. Finally, both the indices derived from Sentinel-2A and Landsat-8 were compared. Scrub forests of Khanpur showed the largest potential for carbon sequestration and storage. It is suggested that this method is not only used for the Haripur district in Khyber Pakhtunkhwa, whose forest division extends merely over the area of 42491 ha; rather it should be applied to the entire forest area of Pakistan for national forest inventory. The research concluded that Sentinel 2 has the best combination of spectral capabilities and broad spectrum of applicability.

Zusammenfassung

Zuverlässige Schätzungen von Biomasse und Kohlenstoff sind sehr wichtig für die Quantifizierung der Treibhausgasemissionen. Waldinventurdaten in Kombination mit Fernerkundungsdaten ermöglichen das großflächige Monitoring von Waldgebieten auf unterschiedlichen räumlicher und zeitlicher Auflösung. Diese Pilotstudie konzentrierte sich auf die Biomasse- und Kohlenstoffschätzung und deren Kartierung für die subtropischen Buschwälder in der Khanpur Region in Pakistan (Forstabteilung Haripur) mittels 20 Probeflächen und Sentinel-2A und Landsat-8 Daten. Mit sechs Waldgebieten (Garamthun, Chhoi, Moharagutta, Sanaba, Dobandi und Saradana) wurde insgesamt eine Fläche von 697.3 ha untersucht. Durchschnittliche Biomasse der untersuchten Probeflächen war 104.6 t/ha und der Kohlenstoffvorrat war 49.7 t/ha. Garamthun weist die höchsten Werte auf, sowohl für Biomasse (187.30 t/ha) als auch für Kohlenstoff (87.98 t/ha), gefolgt von Choi mit 148.22 t/ha Biomasse und 69.6 t/ha Kohlenstoff. Der Kohlenstoffvorrat für alle 6 untersuchten Wälder wurde auf 43570.9 t geschätzt. Die Biomasse wurde dann korreliert mit spektralen Vegetationsindizes errechnet aus Sentinel-2A Daten (NDVI, SAVI, DVI, PVI und MSAVI). NDVI liefert die besten Ergebnisse mit einem Bestimmtheitsmaß (R2) von 0.81, gefolgt von R2 0.7 und 0.58 für SAVI und DVI. PVI und MSAVI haben am schlechtesten abgeschnitten im Vergleich zu den anderen Indizes mit R2 von 0.20 und 0.11. Die räumliche Verteilung von Biomasse und Kohlenstoff wurde mittels NDVI abgebildet. Außerdem, wurden aus Landsat-8 ebenfalls die 5 Vegetationsindizes berechnet und mit den Ergebnissen von Sentinel-2A verglichen. Die Buschwälder von Khanpur weisen großes Potenzi-
1. Introduction

Deforestation and forest degradation contributes to increasing carbon dioxide concentration in the atmosphere. CO₂ acts as a major greenhouse gas. Globally, forest area has decreased from 31.6% in 1990 to 30.6% in 2015 (FAO, 2015) particularly due to anthropogenic activities thereby contributing to global climate change. Alternatively, afforestation and forest restoration activities reduce GHG emissions from forest ecosystem. It is estimated that with decline in deforestation rate between 2001 and 2015, the carbon emissions from forests have also been decreased by more than 25% globally (FAO, 2015). Reducing Emissions from Deforestation and Forest Degradation (REDD+) is an initiative to reduce the deforestation, forest degradation and carbon emissions from forest ecosystems in developing countries. REDD+ implementation requires appropriate estimates of forest biomass and quantifying carbon stocks.

Field measurements provide to most reliable estimates of forest carbon (Tompson et al., 2010). On the other hand, its applicability to larger areas is restricted by large expenses, time and labor constraints. Remote sensing is considered to be a consistent and dependable solution to these challenges, as it provides large area coverage in both spatial and temporal domains (Shi, 2010; Du et al., 2014). These methods not only accelerate data collection process but also exactly monitor and map various forest characteristics at local and regional scale. (Lu, 2006; Rabindranath et al., 2008). By linking remote sensing with forest inventory data, reliable large scale maps of forest characteristics can be produced (Moreno et al., 2017). Although, remote sensing provides sound biomass estimates; but few errors like geometric, radiometric and atmospheric distortions may lead to overestimation or underestimation of forest features while dealing with different resolutions (Kindermann et al., 2008; Zheng et al., 2008). However, careful validation is needed to prove the reliability and accuracy. Options involve cross validation, validation with an independent dataset (not used for model development) or evaluation with other datasets (Mayaux et al., 2006; Friedl et al., 2010; Simard et al., 2011; DiMiceli et al., 2011; Galidaki et al., 2017). United Nations Framework Convention on Climate Change (UNFCCC) has recommended the methodological guidance for REDD+ activities to use remote sensing and ground-based carbon measurements for carbon biomass estimation, GHG emissions and forest area changes due to deforestation and forest degradation (Decision 4/CP.15, UNFCCC 2014).
Remote sensing data such as Landsat are widely for forest mapping, monitoring and biomass assessment (Hansen et al., 2013; Gasparri et al., 2010), its free data availability, spatial coverage and temporal capabilities make Landsat one of the most extensive and boundless used data for vegetation analysis (Gizachew et al., 2013). The biomass estimation through Landsat is commonly through establishing relationships between above ground biomass and different vegetation indices (Lu, 2005; Nelson et al., 2000; Foody et al., 2003). Sentinel 2 is the state of the art sensor providing products with wide spatial coverage, high spatial and temporal resolution (Fletcher, 2012; Drusch et al., 2012) for many of its applications in forestry sector; such as forest classification (Immitzer et al., 2016), biomass estimation and mapping (Chang and Hoshany, 2016), biophysical variables (Frampton et al., 2013; Sakowska et al., 2016; Korhonen et al., 2017), forest burn area management (Verhegghen et al., 2016) and species mapping (Ng et al., 2017). The Sentinel 2 product provides high resolution with four bands at 10 meters resolution; Blue-Band 2, Green-Band 3, Red-Band 4 and NIR-Band 8) and 20 meters resolution; NIR-Band 8A (Fletcher, 2012; Drusch et al., 2012; Adnan, 2017). Band resolutions, band widths and central wavelength information of Sentinel-2A are summarized in Table 1. These bands cover major portion of vegetation absorption and reflectance behavior. Other bands such as Band 5,6 and 7 provide information like Red-edge properties to analyze vegetation dynamics (Chen et al., 2007; Cao et al., 2016) and Band 12 and 13 provide information about canopy water content (Ceccato et al., 2001; Hunt and Qu, 2012). Moreover, these bands are also useful to develop strong relationship with forest attributes. Vegetation and forest attributes can be smoothly assessed by computing relationship between spectral indices and ground based measurements (Barati et al., 2011). Several studies applied Sentinel 2 spectral indices on vegetation and obtained significant results with acceptable accuracy (Delegido et al., 2011; Atzberger et al., 2012; Frampton et al., 2013; Vuolo et al., 2016; Majasalmi & Rautiainen., 2016). Presently, compared to other sensors such as LANDSAT, ASTER, SPOT and MODIS which have been used extensively for biomass estimation, Sentinel 2 sensor is very much less explored for its forestry applications specifically for biomass estimation.

This study will discover Sentinel 2 sensor product and evaluate its potential to estimate biomass by deriving various indices and spectral properties. The objectives of the study include; (1) estimate biomass and carbon storage in six selected forest areas (2) evaluation of several indices and to extrapolate the most suitable index for study area (3) compare various Sentinel-2A indices with Landsat-8 derived indices.
2. Materials and Methods

2.1 The study area

The Khanpur forest range falls under the jurisdiction of Haripur forest division of district Haripur as shown in Fig.1. Haripur is an administrative unit and located in the southern part of Khyber Puktunkhwa province of Pakistan. Geographically, Haripur is situated at latitude 33° 44’ to 34° 22’ and longitude 72° 35’ to 73° 15’. The total area of district Haripur is 1725 km² with 466 inhabitants per km². Agriculture is the main livelihood of rural population. The district has 77370 acres arable area. The total forest area of district Haripur is 42491 hectares which forms 23.1% of the total area (Working Plan, 2008).

For better management, Haripur forest division is further subdivided in five forest ranges namely; Haripur mian, Makhnial, Ghazi, Satora and Khanpur range. Generally the tract is mountainous. The elevation varies from 625 m to 2031 m. The parallel mountainous ridges running from north east to south west with intervening nullahs constitute Satura, Makhnial and Khanpur ranges. Haripur range is mostly plain. Ghazi Range is partly is plain and partly mountainous. Due to mountainous nature of the tract, climate varies from place to place depending upon the altitude. Due to low elevation Khanpur, Haripur and Ghazi have hot summers and very cold winters. Makhnial and Satura ranges have pleasant summers and less severe winters. Snowfall and winter rains are received from December to March. Major portion of the annual precipitation is received in monsoon season that is the seasonal shift in the direction of wind followed by heavy precipitation. In Pakistan, normal duration of monsoon rainfall is from June to October. The district Haripur has two major forest types i.e. Sub-tropical Chir Pine and Sub-tropical scrub forests. This research study focused on six reserved forest areas of only Khanpur scrub range which include Chhoi, Garamthun, Mohara-gutta, Sanaba, Dobandi and Saradana. The total area of Khnapur range is 1588.36 ha, out of which 158.24 ha is blank and the total area of above-mentioned six sampled forest areas is 697.3 ha (Working of Haripur reserved forests, 2008).
Figure 1: Overview and location of study area

Abbildung 1: Übersicht und Lage des Untersuchungsgebietes
2.2 Forest Inventory

A total of 20 circular sample plots of 0.1 ha area were randomly laid out in the forest and all the trees inside the circle were enumerated as shown in Figure 2. Locations of all plots were recorded using Global Positioning System (GPS) receiver. Sampling and measurements were conducted with great care as accuracy of biomass depends upon these variables (Chave et al., 2004; Samalca, 2007; Molto et al., 2013). Diameter at breast height (DBH) and height of all trees in a sample plot were measured for above ground biomass estimation. Six species encountered during inventory which include Acacia nilotica, Acacia modesta, Olea ferrugineae, Zizyphus jujuba and Ficus palmata, whereas Dodonaea viscosa is the main shrub species in the area. All the necessary materials that were used for data collection and further processing are given in Table 1.

![Sentinel-2A imagery and inventory plots](image)

*Figure 2: Sentinel-2A imagery and inventory plots*

*Abbildung 2: Sentinel 2A-Bild und Inventurplots*

<table>
<thead>
<tr>
<th>Table 1: Sentinel 2 Bands Description (ESA, 2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabelle 1: Beschreibung der Sentinel 2-Spektralbänder (ESA, 2010)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spectral band</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>B6</th>
<th>B7</th>
<th>B8</th>
<th>B8a</th>
<th>B9</th>
<th>B10</th>
<th>B11</th>
<th>B12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution (m)</td>
<td>60</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>20</td>
<td>60</td>
<td>60</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Central wavelength (nm)</td>
<td>443</td>
<td>490</td>
<td>560</td>
<td>665</td>
<td>705</td>
<td>740</td>
<td>783</td>
<td>842</td>
<td>865</td>
<td>945</td>
<td>1375</td>
<td>1610</td>
<td>2190</td>
</tr>
<tr>
<td>Bandwidth (nm)</td>
<td>20</td>
<td>65</td>
<td>35</td>
<td>30</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>115</td>
<td>20</td>
<td>20</td>
<td>30</td>
<td>90</td>
<td>180</td>
</tr>
</tbody>
</table>
For the carbon inventory all the trees with a DBH of ≥ 5 cm were measured except that of Dodonaea viscosa whose basal diameter was found to be less than < 5 cm so all plants of that species were measured at the base. Biomass of Dodonaea viscosa was determined using the following allometric equation (Litton, 2008):

\[ AGB = 0.13 D^{2.55} \]  \hspace{1cm} (1)

where
AGB is the aboveground biomass in g and D is the diameter at base in mm.

The heights of trees were measured with Haga Altimeter, diameter at breast height (1.37 m) with Diameter tape, radius of the circular plot with measuring tape and angles (degrees) with Suunto compass. Odd shaped trees i.e. buttressed or forked trees were also measured keeping in mind all the necessary points. Species volume was calculated using the local volume tables prepared by Pakistan Forest Institute, Pesha- war. The volume was calculated from diameter, height classes and form factor mentioned in volume table by using the formula (Equation 2). Volume for all species was estimated by assuming conical shape stem.

\[ Vol = BA \times Ht \times FF \]  \hspace{1cm} (2)

where
Vol is the volume in m³, BA is the basal area in m² and FF is form factor.

As there were six species under this research study, separate volume table for each one was used except Dodonaea viscosa whose biomass was directly calculated owing to the fact that diameter at base was too small therefore biomass was calculated directly using the equation (Litton, 2008). Volume of all other species was calculated by comparing diameter classes against their volumes mentioned in available literature i.e. “local metric volume tables prepared for Farmlands of Charsadda.” The volume of each plot was calculated by adding the volume of entire individual trees in that sample plot. The average volume per plot for every specie was also determined by adding up volume of all trees in that sample plot and dividing it with the total number of sample trees in that plot. Thus the volume of each sample plot was converted into volume/ha by multiplying the volume of each plot with 10, because area of each plot was 0.1 ha. Furthermore, in order to obtain the total volume of the Khanpur forests; volume/ha was multiplied with total number of ha in that forest. The above ground biomass was calculated by multiplying volume with basic wood density and biomass expansion factor (Schoene, 2002), to expand estimates to other non-merchantable parts of the tree (Milne et al., 1998; Fukuda et al., 2003; Penman et al., 2003). The formula is given below:
Biomass = V × BWD × BEF  \hspace{1cm} (3)

where

V is the timber volume in m³ and

BWD is the basic wood density in kg/m³;

BEF is the biomass expansion factor which is equal to 1.4.

For this research study, separate basic wood density values for each species were applied which are given in Table 3. It is generally considered that about half of the dry biomass consists of carbon (Roy et al., 2001, Malhi et al., 2004). Thus the dry biomass can be converted to carbon stock by multiplying it with 0.47 (Paustian et al., 2006). Below ground biomass (BGB) was estimated by multiplying the above ground biomass with 0.26 as per IPCC guidelines (Ravindranath and Otwald, 2008). IPCC is an acronym for Intergovernmental Panel on Climate Change. It provides the methods for the estimation of changes in carbon stocks and greenhouse gas emissions along with the changes in biomass content on forest lands. The dry biomass (above ground and below ground) can be converted to carbon stock by multiplying it with 0.47 (Paustian et al., 2006) to get Above Ground Carbon stocks (AGC) and Below Ground Carbon stocks (BGC) as it is generally considered that about half of the dry biomass consists of carbon (Roy et al., 2001, Malhi et al., 2004). The carbon stock was then converted into CO₂ equivalent by multiplying it with 3.66 (Pearson et al., 2007) which is the ratio of carbon atom in the molecular weight of CO₂. Thus, the total amount of CO₂ sequestered was determined. The quantity of carbon stocks facilitates the determination of total number of carbon credits as each carbon credit is equal to one metric ton of carbon dioxide. These carbon credits calculations are important part in national Greenhouse gases (GHGs) mitigation. Moreover, after assuming the price of a carbon credit, one can also estimate the revenue to be generated from these carbon credits. In this study, the price of carbon has been assumed to be 30 US$ per ton of carbon (Nordhaus, 2008).

2.2.1 Sentinel-2 and Landsat 8 Images Processing

The present study used Sentinel-2 imagery for biomass estimation because Sentinel-2 data product has overcome limitation of resolution (Gascon and Berger, 2007) that was previously provided by other open source sensors. The imagery was downloaded from Copernicus Sentinel Scientific Data Hub (https://scihub.copernicus.eu/) for Khanpur range (Dated October 28, 2016). The Sentinel product was named as S2_MSI_Level-1C with processing Level-1C. Product bands ranged from 443 to 2190 nm with Band 2, 3, 4 and 8 in 10 m, Band 5, 6, 7, 8A, 11 and 12 in 20 m and Band 1,
9 and 10 in 60 m. The product area was approximately 100 km² which covered not only the entire Haripur but also extended to other neighbor districts such as Rawalpindi, Abbottabad, Mansehra and Swabi. The primary step was image pre-processing before its use for biomass estimation purpose (Roy et al., 2016). The purpose was to avoid effects of atmospheric scattering or cloud cover shadows, to aid visual interpretation and to extract plenty of information from remotely sensed imagery. Pre-processing includes radiometric, geometric and terrain correction respectively. Sentinel-2 images were preprocessed in SNAP Tool Box (Egbers, 2016; Martins et al., 2017). Sen2Cor-2.3.1 is a plugin in SNAP tool box for atmospheric correction of the Sentinel-2 images. Level 1C product can be converted into atmospherically corrected Level 2A product (Wilm, 2016). The processing of Level 1C product includes cloud detection, scene classification, Aerosol optical thickness and water vapor content, all these were done by Sen2Cor 2.3.1 processor to obtain bottom of atmosphere conversion (BoA) (Knorn et al., 2015; Louis et al., 2016; Martins et al., 2017). Sub-setting of image was done for the area of interest where forest inventory was conducted. Furthermore, resampling of 20 m bands was done and inventory plots were overlaid (Figure 2). According to Chrysafis et al. 2017, different vegetation indices from Sentinel-2A product were computed using SNAP Tool box to assess biomass. Various indices, their formulae and Sentinel-2 bands were shown in Table 2. AGB (Above ground biomass) shape file created via ArcGIS 10.3 was overlaid on corresponding vegetation indices of both the acquired images. The values of masked pixels by inventory plots were extracted for all the indices. Similarly, The Landsat-8 Product was downloaded from USGS Earth Explorer (https://earthexplorer.usgs.gov/) for Khanpur range. The preprocessing was the first step; the ENVI 5.3 was used for preprocessing of the Landsat-8 imagery, including Radiometric Calibration, Reflectance Correction and Dark Subtraction. Further, the rectified image was used to compute various indices such NDVI, SAVI, MSAVI, PVI and DVI, as previously computed for Sentinel-2A imagery. The AGB point data was imported on these indices and the values of masked pixels was extracted.
Table 2: Vegetation Indices for Sentinel-2A and Landsat-8 Product

Tabelle 2: Vegetationsindizes für Sentinel-2A und Landsat-8 Daten

<table>
<thead>
<tr>
<th>Indices</th>
<th>Formula</th>
<th>Sentinel-2A</th>
<th>Landsat-8</th>
<th>Original Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Vegetation Index (NDVI)</td>
<td>(NIR - Red) ÷ (NIR + Red)</td>
<td></td>
<td></td>
<td>Rouse et al. 1973</td>
</tr>
<tr>
<td>Soil Adjusted Vegetation Index (SAVI)</td>
<td>((NIR - R) ÷ (NIR + R + L)) ÷ (1 + L)</td>
<td></td>
<td></td>
<td>Qi et al. 1994</td>
</tr>
<tr>
<td>Difference Vegetation Index (DVI)</td>
<td>NIR - R</td>
<td>(B8A - B4)</td>
<td>(B5 - B4)</td>
<td>Jordan 1969</td>
</tr>
<tr>
<td>Modified Soil Adjusted Vegetation Index (MSAVI)</td>
<td>1/2 [2(NIR+1)-sqrt((2(NIR+1)-8(NIR-R)))]</td>
<td>(B8A-B4)</td>
<td></td>
<td>Qi et al. 1994</td>
</tr>
<tr>
<td>Perpendicular Vegetation Index (PVI)</td>
<td>(a × NIR - R + b) ÷ sqrt(a^2 + 1)</td>
<td>(a × B8A - B4 + b) ÷ sqrt(a^2 + 1)</td>
<td>(a × B5 - B4 + b) ÷ sqrt(a^2 +1)</td>
<td>Perry &amp; Lutenschlager (1984)</td>
</tr>
</tbody>
</table>

Table 3: Basic Wood Density of important species in the study region (Sheikh, 1993)

Tabelle 3: Holzdichte wichtiger Baumarten des Untersuchungsgebietes (Sheikh, 1993)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Name of the Species</th>
<th>Wood Density (t/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td><em>Acacia nilotica</em> (Babul/Kikar)</td>
<td>0.75</td>
</tr>
<tr>
<td>02</td>
<td><em>Acacia modesta</em> (Phulai)</td>
<td>0.96</td>
</tr>
<tr>
<td>03</td>
<td><em>Olea ferruginea</em> (Kahu)</td>
<td>1.12</td>
</tr>
<tr>
<td>04</td>
<td><em>Zizyphus jujuba</em> (Ber)</td>
<td>0.93</td>
</tr>
<tr>
<td>05</td>
<td><em>Ficus Palmata</em> (Fig)</td>
<td>0.40</td>
</tr>
</tbody>
</table>
2.3. Statistical Analysis

Scatter plots were generated to analyze the relationship between biomass and individual indices. Correlation and regression analysis were performed between biomass and spectral indices. Different models were established (linear, polynomial, power, logarithmic and exponential). Coefficient of determination \((R^2)\) was calculated for each model. As a result, model fulfilling the condition of highest value of \(R^2\), was selected for effective biomass estimation and generation of biomass map as well.

3. Results and Discussion

3.1 Stem Number

The stocking of the six scrub forests have been summarized in Table 6. The total forest area in these six villages is 697.3 ha consisting of total 759783 trees. The respective forest areas of the sampling areas were obtained from Working Plan of Haripur (2008). Data shows that density was highest in Garamthun with 1350 trees per ha followed by Dobandi with 880 trees per ha (Table 6). The Mohara Gutta with 650 trees per ha was found to be least stocked forest area.

3.2 Volume (m³) (Plot level and Forest-wise)

The total trees per ha in the study area indicating that the forests were well stocked. As per Table 4, Acacia modesta is the species with the highest volume of 33.19 m³ per ha followed by Olea ferruginea whose volume equals to 22.37 m³ per ha. The volume of Acacia nilotica, Zizyphus jujuba and Ficus palmata were calculated as 0.99, 0.73 and 0.38 m³ per ha respectively. The total volume in the study area was estimated as 51045 m³ for five species except Dodonaea viscosa because local volume table was not available. The volume for each forest is summarized in Table 6. It was found that forest of Garamthun contains highest volume of 102.5 m³/ha followed by Chhoi, Mohara-gutta, Sanaba and Dobandi forests with 80.2 m³/ha, 31.2 m³/ha, 30.5 m³/ha and 29.1 m³/ha respectively. Whereas, Saradana forest had lowest volume with more than 20.7 m³/ha. (Nizami, 2012) studied different species of subtropical broadleaved evergreen forests (scrub) had major species Acacia modesta and Olea ferruginea and reported volume per hectare (m³/ha) at two different study sites (Kherimurat and Sohawa) with total volume (m³/ha) of 12.86 and 11.40 respectively. Regarding composition of tree species in study area, Acacia modesta is ranked highest with 57 % followed by Olea ferruginea with 39 % whereas Acacia nilotica, Zizyphus jujuba and Ficus palmata were last in the ranking.
Table 4: Species-wise volume for all species except Dodonea viscosa but its base diameter was directly converted to biomass by using allometric equation

Tabelle 4: Baumvolumen aller Baumarten (außer für Dodonea viscosa deren Durchmesser direkt mittels allometrische Gleichung in Biomasse umgerechnet wurde)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Name of Species</th>
<th>DBH Range (cm)</th>
<th>Height Range (m)</th>
<th>No of Sample Plots</th>
<th>Average Volume (m³) per ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td><em>Acacia modesta</em></td>
<td>6 to 28</td>
<td>4 to 11</td>
<td>20</td>
<td>33.19</td>
</tr>
<tr>
<td>02</td>
<td><em>Olea ferruginea</em></td>
<td>8 to 26</td>
<td>3 to 13</td>
<td>20</td>
<td>22.37</td>
</tr>
<tr>
<td>03</td>
<td><em>Acacia nilotica</em></td>
<td>4 to 12</td>
<td>3 to 8</td>
<td>20</td>
<td>0.99</td>
</tr>
<tr>
<td>04</td>
<td><em>Zizyphus jujuba</em></td>
<td>6 to 14</td>
<td>4 to 9</td>
<td>20</td>
<td>0.73</td>
</tr>
<tr>
<td>05</td>
<td><em>Ficus palmata</em></td>
<td>8 to 12</td>
<td>5 to 7</td>
<td>20</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>57.66</strong></td>
</tr>
</tbody>
</table>

3.3 Biomass and Carbon Stocks (Plot & Forest level)

The highest AGB and BGB was found to be 148.65 and 38.65 t/ha respectively whereas mean biomass (including both AGB and BGB) was found to be 104.6 t/ha as shown in Table 5. The highest estimated carbon stocks were 69.84 and 18.14 t/ha for AGC and ABC respectively whereas highest carbon stock (including both AGC and ABC) was determined as 87.98 t/ha. Carbon stock of Garamthun forest were the highest 32931.9 t carbon followed by Choi with 4987.6 t of carbon (Table 6). Whereas, the values of biomass and carbon were lowest for Saradana forest with 2567 t of biomass and 1206.4 t of total carbon stocks respectively. The total carbon stocks for these six forests types were 43570.9 t. Nizami, (2012) reported mean AGB (t/ha) for two dominant species (*Acacia modesta* and *Olea ferruginea*) in two study sites (Kherimurat and Sohawa) as 50.93 and 40.43 t/ha respectively. In the past study reported by Nizami (2012) mean carbon stocks were estimated as 25.54 and 20.23 t/ha at two sites (Kherimurat and Sohawa) respectively.
Table 5: Biomass and carbon stocks of the sample plots

Tabelle 5: Biomasse und Kohlenstoffvorrat der Probeflächen

<table>
<thead>
<tr>
<th>Plot No</th>
<th>AGB (t/ha)</th>
<th>AGC (t/ha)</th>
<th>BGB (t/ha)</th>
<th>BGC (t/ha)</th>
<th>Total Biomass (t/ha)</th>
<th>Total C (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>165.2</td>
<td>77.64</td>
<td>42.9</td>
<td>20.16</td>
<td>208.1</td>
<td>97.81</td>
</tr>
<tr>
<td>2</td>
<td>201</td>
<td>94.47</td>
<td>52.3</td>
<td>24.58</td>
<td>253.3</td>
<td>119.05</td>
</tr>
<tr>
<td>3</td>
<td>141.6</td>
<td>66.55</td>
<td>36.8</td>
<td>17.30</td>
<td>178.4</td>
<td>83.85</td>
</tr>
<tr>
<td>4</td>
<td>133.6</td>
<td>62.79</td>
<td>34.7</td>
<td>16.31</td>
<td>168.3</td>
<td>79.10</td>
</tr>
<tr>
<td>5</td>
<td>118.1</td>
<td>55.51</td>
<td>30.7</td>
<td>14.43</td>
<td>148.8</td>
<td>69.94</td>
</tr>
<tr>
<td>6</td>
<td>132.5</td>
<td>62.28</td>
<td>34.5</td>
<td>16.22</td>
<td>167</td>
<td>78.49</td>
</tr>
<tr>
<td>7</td>
<td>93</td>
<td>43.71</td>
<td>24.2</td>
<td>11.37</td>
<td>117.1</td>
<td>55.04</td>
</tr>
<tr>
<td>8</td>
<td>246.8</td>
<td>116.00</td>
<td>64.2</td>
<td>30.17</td>
<td>311</td>
<td>146.17</td>
</tr>
<tr>
<td>9</td>
<td>13.1</td>
<td>6.16</td>
<td>3.4</td>
<td>1.60</td>
<td>16.5</td>
<td>7.76</td>
</tr>
<tr>
<td>10</td>
<td>45.2</td>
<td>21.24</td>
<td>11.7</td>
<td>5.50</td>
<td>56.9</td>
<td>26.74</td>
</tr>
<tr>
<td>11</td>
<td>42.1</td>
<td>19.79</td>
<td>10.9</td>
<td>5.12</td>
<td>53</td>
<td>24.91</td>
</tr>
<tr>
<td>12</td>
<td>62.3</td>
<td>29.28</td>
<td>16.2</td>
<td>7.61</td>
<td>78.6</td>
<td>36.94</td>
</tr>
<tr>
<td>13</td>
<td>23.1</td>
<td>10.86</td>
<td>6</td>
<td>2.82</td>
<td>29.2</td>
<td>13.72</td>
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<td>41.1</td>
<td>19.32</td>
<td>10.7</td>
<td>5.03</td>
<td>51.7</td>
<td>24.30</td>
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<tr>
<td>15</td>
<td>31.9</td>
<td>14.99</td>
<td>8.3</td>
<td>3.90</td>
<td>40.2</td>
<td>18.89</td>
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<tr>
<td>16</td>
<td>50.3</td>
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<tr>
<td>17</td>
<td>33.4</td>
<td>15.70</td>
<td>8.7</td>
<td>4.09</td>
<td>42.1</td>
<td>19.79</td>
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<tr>
<td>18</td>
<td>26</td>
<td>12.22</td>
<td>6.8</td>
<td>3.20</td>
<td>32.7</td>
<td>15.37</td>
</tr>
<tr>
<td>19</td>
<td>32.2</td>
<td>15.13</td>
<td>8.4</td>
<td>3.95</td>
<td>40.6</td>
<td>19.08</td>
</tr>
<tr>
<td>20</td>
<td>28.1</td>
<td>13.21</td>
<td>7.3</td>
<td>3.43</td>
<td>35.5</td>
<td>16.69</td>
</tr>
<tr>
<td>Mean</td>
<td>83</td>
<td>39.02</td>
<td>21.6</td>
<td>10.15</td>
<td>104.6</td>
<td>49.17</td>
</tr>
</tbody>
</table>

Table 6: Total stem number, volume, biomass and carbon stocks of the examined forests

Tabelle 6: Gesamtanzahl der Bäume, Volumen, Biomasse und Kohlenstoffvorräte der untersuchten Wälder

<table>
<thead>
<tr>
<th>Name of Forest</th>
<th>Area (ha)</th>
<th>Stem number ha⁻¹</th>
<th>Total Stem number</th>
<th>Volume (m³/ha)</th>
<th>Total Volume (m³)</th>
<th>AGB (t/ha)</th>
<th>BGB (t/ha)</th>
<th>Biomass (t/ha)</th>
<th>Total Biomass (t)</th>
<th>Total C (t/ha)</th>
<th>C stock (t/ha)</th>
<th>Total C Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamrneh</td>
<td>374.1</td>
<td>1350</td>
<td>50305</td>
<td>102.5</td>
<td>38345.25</td>
<td>148.65</td>
<td>38.65</td>
<td>187.30</td>
<td>70683</td>
<td>69.84</td>
<td>18.142</td>
<td>32931.9</td>
</tr>
<tr>
<td>Chah</td>
<td>71.6</td>
<td>870</td>
<td>6245</td>
<td>80.2</td>
<td>5742.32</td>
<td>117.63</td>
<td>30.58</td>
<td>148.22</td>
<td>10612</td>
<td>55.27</td>
<td>14.335</td>
<td>4987.6</td>
</tr>
<tr>
<td>Mohana-Gatta</td>
<td>52.6</td>
<td>659</td>
<td>34190</td>
<td>31.2</td>
<td>1641.12</td>
<td>43.62</td>
<td>11.34</td>
<td>54.97</td>
<td>2891</td>
<td>20.49</td>
<td>5.311</td>
<td>25802</td>
</tr>
<tr>
<td>Sanaba</td>
<td>53.4</td>
<td>750</td>
<td>40050</td>
<td>30.5</td>
<td>1628.77</td>
<td>42.74</td>
<td>11.11</td>
<td>53.85</td>
<td>2875.5</td>
<td>2.016</td>
<td>5.217</td>
<td>25286</td>
</tr>
<tr>
<td>Dobondi</td>
<td>74.8</td>
<td>580</td>
<td>65552</td>
<td>29.1</td>
<td>2176.68</td>
<td>39.16</td>
<td>10.18</td>
<td>49.34</td>
<td>3690.6</td>
<td>18.37</td>
<td>4.747</td>
<td>22124</td>
</tr>
<tr>
<td>Sarandana</td>
<td>70.8</td>
<td>740</td>
<td>52392</td>
<td>20.7</td>
<td>1465.56</td>
<td>28.78</td>
<td>7.48</td>
<td>36.27</td>
<td>2567.1</td>
<td>13.48</td>
<td>3.478</td>
<td>1206.4</td>
</tr>
<tr>
<td>Total</td>
<td>697.3</td>
<td>759783</td>
<td>50996.6</td>
<td>20.7</td>
<td>1465.56</td>
<td>28.78</td>
<td>7.48</td>
<td>36.27</td>
<td>2567.1</td>
<td>13.48</td>
<td>3.478</td>
<td>1206.4</td>
</tr>
</tbody>
</table>
3.4 Carbon Sequestration Potential

The CO₂ equivalent sequestered by these forests was determined by multiplying carbon stock with 3.66. Thus the total amount of CO₂ sequestered by these forests was 159374 t. This is the resulting number of carbon credits as one carbon credit is equal to 1 t CO₂. Consequently, if the price of one carbon credit is assumed to be 30 US$ (Nordhaus, 2008), then the total worth of these forests in terms of carbon sequestration is 4781220 US$.

3.5 Testing Spectral Indices

Different vegetation indices were assessed for their correlation with above ground biomass values. There are several bands combinations for Sentinel-2A data (Table 2). Results obtained for different regression models for each index are shown in Table 7. Among these indices NDVI has the highest value of R² of 0.81, followed by SAVI and DVI with 0.70 and 0.58 respectively. Similarly, applying various regression models (linear, polynomial, power, logarithmic and exponential) the values of R² change as per data behavior and model assumptions. Landsat-8 imagery indices are summarized in Table 7. Three Landsat-8 indices; NDVI, SAVI and DVI gave low values of R² as compared to Sentinel-2A indices. However, two Landsat-8 indices (MSAVI and PVI) obtained much higher values of R² in comparison to Sentinel-2A. Values of R² of all Landsat-8 indices are tabulated (Table 7). Vafaei et al., (2018) reported that integration of Sentinel-2A with ALOS-2 PALSAR-2 can enhance biomass estimation with greater accuracy. Among these two biomass estimation of Sentinel-2A was more accurate. Adnan, (2017) reported that indices computed from Sentinel-2A have potential to estimate biomass in contrast to vegetation indices of other sensors. Coefficient of determination of NDVI depicted highest changes from 0.62 to 0.81 when the model was switched from linear to polynomial, followed by SAVI and DVI. Other indices MSAVI and PVI have revealed fewer changes while using different models. Scatterplots of all indices and their best models are shown in Figure 4. Whereas, scatterplots of all five indices are in Figure 5. The summary of the linear model for all indices is presented (Table 8). It explains that NDVI obtained the highest value of R² (0.71) followed by the SAVI and DVI. Comparative visualization of all indices with Sentinel-2A product is shown in Figure 3. NDVI map was relatively most appropriate to map biomass among other indices.
Table 7: Coefficient of Determination ($R^2$) of different models for Sentinel-2A and Landsat 8 Products

Tabelle 7: Bestimmtheitsmaß ($R^2$) von verschiedener Modellen und Vegetationsindices für Sentinel-2A und Landsat-8 Daten

<table>
<thead>
<tr>
<th>Model</th>
<th>Spectral Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S2A L8 S2A L8 S2A L8 S2A L8 S2A L8</td>
</tr>
<tr>
<td>Linear</td>
<td>0.62 0.56 0.67 0.55 0.58 0.52 0.04 0.53 0.05 0.52</td>
</tr>
<tr>
<td>Power</td>
<td>0.72 0.46 0.70 0.46 0.52 0.46 0.06 0.45 0.09 0.46</td>
</tr>
<tr>
<td>Polynomial</td>
<td>0.81 0.64 0.69 0.62 0.58 0.56 0.11 0.60 0.18 0.56</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>0.53 0.30 0.64 0.31 0.56 0.34 0.06 0.30 0.08 0.32</td>
</tr>
<tr>
<td>Exponential</td>
<td>0.79 0.67 0.68 0.66 0.51 0.59 0.05 0.65 0.06 0.59</td>
</tr>
</tbody>
</table>

Note: S2A = Sentinel-2A, L8 = Landsat-8

Table 8: Summary Statistics of Linear Model for Sentinel-2A

Tabelle 8: Statische Kennzahlen des linearen Modells für Sentinel-2A

<table>
<thead>
<tr>
<th>Indices</th>
<th>Equation</th>
<th>$R^2$</th>
<th>SE</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI</td>
<td>$Y = 450.18x - 153.09$</td>
<td>0.62</td>
<td>0.071</td>
<td>26.65</td>
</tr>
<tr>
<td>SAVI</td>
<td>$Y = 811.35x - 140.98$</td>
<td>0.67</td>
<td>0.038</td>
<td>33.75</td>
</tr>
<tr>
<td>DVI</td>
<td>$Y = 1243.8x - 92.87$</td>
<td>0.58</td>
<td>0.026</td>
<td>22.19</td>
</tr>
<tr>
<td>MSAVI</td>
<td>$Y = -236.57x + 156.99$</td>
<td>0.04</td>
<td>65.22</td>
<td>0.82</td>
</tr>
<tr>
<td>PVI</td>
<td>$Y = -558.38x + 159.05$</td>
<td>0.05</td>
<td>64.89</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Figure 3: Comparison of Sentinel-2A spectral indices with Sentinel-2A RGB image

Abbildung 3: Vergleich von Sentinel-2A Vegetationsindizes mit Sentinel-2A RGB-Bild
Figure 4: Scatterplots of Sentinel-2A spectral indices and biomass

Abbildung 4: Streudiagramm der Sentinel-2A Vegetationsindizes und Biomasse
Figure 5: Scatterplots of Landsat-8 spectral indices and biomass

Abbildung 5: Streudiagramm der Landsat-8 Vegetationsindizes und Biomasse

3.6 Mapping of Biomass

Among the various indices, NDVI performed as best predictor to estimate and map biomass of study sites. Therefore, biomass map was produced using raster calculator
in ArcGIS 10.3. Linear Model of both Sentinel-2A and Landsat-8 was used to develop biomass and carbon stock maps. Comparison of both maps for Sentinel-2A and Landsat 8 is shown in Figure 6. Moreover, high correlation was shown between predicted and observed biomass with the value of R2 (0.85) and Root Mean Square (RMSE) was 26 t/ha based on NDVI regression equation (linear model) for Sentinel-2A.

Figure 6: Biomass and Carbon Stocks Map for Sentinel-2A and Landsat-8

Abbildung 6: Biomasse- und Kohlenstoffvorräte für Sentinel-2A und Landsat-8
4. Conclusion

The study suggested that Sentinel-2A product has considerable potential to estimate biomass and map forest areas. The Sentinel-2A product has comparatively large spatial coverage and high resolution to perform efficiently for estimation of biomass than other open source sensors data products. In this study, three indices (NDVI, DVI, SAVI) of Sentinel-2A performed better as compared to indices derived by LANDSAT-8. However, two indices (PVI and MSAVI) had a poor performance. Further researches should be conducted to utilize Sentinel-2A data for deriving various forests attributes to evaluate its role in controlling climate change and to get effective results after its combination with forest inventory data. Such studies have potential applications in integration of remote sensing and forestry inventory for REDD+ readiness and implementation in study area (Chakraborty, 2010). The global data availability of Sentinel-2 and Landsat-8 data products shows great potential for regional and global scales biomass and carbon mapping and monitoring and can be used for European forests as well (Neumann et al., 2016).

The study concluded that scrub forest show great potential for carbon sequestration and storage. Thus, it can be considered vital in climate change mitigation in Pakistan. Khanpur sub-tropical scrub forest is of paramount significance as it stores suitable amount of carbon, and seemed to be unobstructed from any sort of anthropogenic influence. Thus study measured the worth of these forests in terms of carbon sequestration, showing that there is a great potential of CO2 sequestration and evaluated their environmental role in combating climate change. Hence, it is concluded that by raising and protecting these forests, a large amount of carbon can be sequestered in future. Therefore, supplementary carbon credits can be earned through carbon trading under REDD+ forest management (Reducing Emissions from Deforestation and forest Degradation).

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Improving in-season estimation of rice yield potential and responsiveness to top-dressing nitrogen application with Crop Circle active crop canopy sensor. Precis Agric 17(2):136-54.


1032.


Temporal Dynamics and size effects of Mistletoe
(Loranthus europaeus Jacq.) Infection in an Oak Forest

Jan Kubíček 1*, Zuzana Špinlerová 1, Radek Michalko 2, Tomáš Vrška 3, Radim Matula 1

Keywords: Growth decline; Host-Hemiparasite interaction; Loranthus europaeus Jacq., Quercus petraea (Matt) Liebl.

Abstract

Establishing a better understanding of changes in mistletoe abundance over time could prove useful in the development of future conservation and management strategies for mistletoe-host complexes. The purpose of this study was to describe and examine how time influenced host trees sessile oak (Quercus petraea (Matt) Liebl.) and the abundance dynamics of their hemiparasites yellow mistletoe (Loranthus europaeus Jacq.). The research was conducted in Podyjí National Park, Czech Republic, from 2011–2015. Each oak stem (1599) was visually checked for the presence of he-
miparasites during the bud growth period. We investigated the temporal dynamics of *L. europaeus* abundance (number of *L. europaeus* shrubs per *Q. petraea* stem) and volume (total volume of *L. europaeus* shrubs per stem) on individual host stems using linear mixed effects models. The abundance of *L. europaeus* increased with larger host diameter at breast height (DBH), time and their interaction. The abundance of *L. europaeus* slightly increased over time on hosts with smaller DBH, but this phenomenon slowed down as host DBH increased. Mistletoe abundance started decreasing over time on hosts with large DBH. The study showed that time plays an important role in determining the distribution of mistletoes in the stand. Thanks to the inclusion of the time component, it was possible to create a model that showed the most vulnerable groups of host trees to which forest management should focus on.

### Zusammenfassung:


### 1. Introduction

Mistletoes are a taxonomically diverse group of angiosperms that rely partially or completely on host plants (Watson 2011). Mistletoes can be found in a wide range of ecosystems around the world, from boreal forests to tropical rain forests to arid
woodlands (Norton and Carpenter 1998). The occurrence of individual species is limited by specific climatic conditions (Černý 1976, Sangüesa-Barreda 2018). Mistletoes establish xylem connections with their hosts to obtain water and other xylem-borne nutrients (Ehleringer et al. 1985). Most stem mistletoes produce their own metabolites whenever they have access to light and carbon dioxide (Watson 2001). They increase drought stress and compromise the carbon balance of the host tree (Glatzel and Geils 2008), which negatively affect the condition of the host plant (Kołodziejek et al. 2013). Trees with mistletoe have significantly higher crown transparency (Dobbertin and Rigling 2006) which may lead to serious damage or death of infected trees (McDowell et al. 2011). However, mistletoes also play important roles as nutritional resources within canopies (Watson 2001).

The presence and abundance of mistletoe plants in a given area are usually spatially non-random and are regulated by various abiotic and biotic factors (Gairola et al. 2013). The majority of mistletoe seeds are dispersed by birds (e.g., Turdidae family and Loranthus europaeus Jacq.); many birds are highly specialized to consume mistletoe berries and are entirely dependent on mistletoe fruit at certain times of the year (Janssen and Wulf 1999).

At the habitat-scale, mistletoes are influenced by the distribution of suitable host species (Rödl and Ward 2002) and dispersers and pollinators (Ladley et al. 1997, Norton and Reid 1997), the behaviour of avian dispersers (Aukema and Martínez del Río 2002), habitat fragmentation (Lavorel et al. 1999), and topographical features such as elevation, slope and aspect (Hawksworth 1961, Smith 1972, Ganguly and Kumar 1976, Merrill et al. 1987, Aukema 2004).

On the individual-tree scale, mistletoe infection is correlated with tree height (Downey et al. 1997) and diameter (Siegel 1980, Bannister and Strong 2001, Aukema and Martínez del Río 2002, Carlo and Aukema 2005, Idžojić et al. 2008, Gougherty 2013, Kołodziejak et al. 2013, Teodoro et al. 2013). Trees closer to the edge of a stand are more susceptible to hosting mistletoe (Lopez de Buen et al. 2002). Competition among trees has a negative effect on mistletoe occurrence (Matula et al. 2015). The establishment of mistletoes species is also influenced by previous infestations of a tree or a site (Aukema and Martínez del Río 2002).

The presence and abundance of mistletoe plants are well described, mainly as a result of short-term studies (Idžojić et al 2005, Idžojić et al. 2008, Lushaj and Lushaj 2009, Sayad 2017). Mistletoe population dynamics, i.e., the rate at which mistletoe populations build up or subside within trees, has only rarely been the subject of research. Mistletoe recruitment depends on a number of life cycle steps associated with pollination, including seed set, successful dispersal, and establishment on a suitable host (Reid et al. 1995). The life cycles of mistletoes are short compared to the life cycles of host trees. The average mistletoe population can double in 16 years (Scharpf and Parmeter 1982). This is because mistletoes produce fruit at a young age. L. europaeus
can produce fruits at an age of 3 years (Kubiček and Martinková 2010). Therefore, mistletoes in different stages of their life cycle can be found in the same habitat.

The purpose of this study was to describe and examine how time influenced host trees (*Quercus petraea* (Matt) Liebl.) and the abundance dynamics of their hemiparasites (*Loranthus europaeus* Jacq.). We think that a better understanding of changes in mistletoe abundance over time could prove useful in the development of future conservation and management strategies for mistletoes, which contribute to high biological diversity.

As far as we know, only a few studies have focused on the dependencies of host-hemiparasite abundance dynamics. Teodoro et al. (2013) demonstrated that suitable habitats for mistletoes occurred in discrete patches; additionally, local populations went extinct during the study and the colonization rate of previously non-occupied patches increased. Noetzli, Müller and Sieber (2003) found that a high degree of mistletoe attack had a negative effect on the growth of the host trees because the growth increments of the infested trees decreased compared to those of the uninfected trees.

In this study, we monitored the changes in infestation during 2011-2015 and compared the effects of host growth parameters on the intensity of infection and the differences in hemiparasite dimensions (volume).

We sought to answer the following questions:

- I: Do time dynamics influence the number of infected trees and shrub volume?
- II: Are there differences in hemiparasite dynamics between large and small DBH trees?

**Hypothesis I:** Larger trees have a higher occurrence of hemiparasites (Siegel 1980), which can inflict greater damage on their hosts (Kołodziejek et al. 2013). Mistletoe has a higher transpiration rate than the host plant (Glatzel and Geils 2008), so it extracts water and minerals from the host, even during drought, and reduces the number of resources available to the host (Garkoti et al. 2002). Over time, this can lower the abundance of hemiparasites as the attacked branches and crown of the tree die (Scharpf and Parmeter 1982). Therefore, we expect that time would have a negative effect on the number of infected trees. The volume of mistletoe shrubs on a single stem will increase or decrease with changes in the abundance of individual mistletoes per stem.

**Hypothesis II:** The die-off of infected branches shortens the average lifespan and slows the rate of population growth (Scharpf and Parmeter 1982). Therefore, we expect that mistletoe abundance would decrease with the age of the tree, i.e., there would be less mistletoe on old trees. Successful mistletoe establishment requires
host trees have branches 3–20 mm in diameter (Sargent 1995). Therefore, old trees will have a lower probability of new infection, because they lack branches that are suitable in size for mistletoe establishment.

Low DBH trees, which are younger and faster-growing trees, can potentially withstand the infection because of their better regeneration capability. On the other hand, these trees have faster-growing tissues with bigger and thinner cells and thinner bark; thus, when stressed, these trees might be more easily penetrated by mistletoe haustoria - root like attachments that obtain nutrients from its host (Thoday 1961). We expected that smaller trees would have a lower rate of infection, but infection rate would increase over time.

2. Materials and methods

2.1 Study site

The study site is situated in the Šobes area of Podyjí National Park, which is located in the southern part of the Czech Republic (48°49′32″N; 15°58′21″E), approximately 4 km southeast of the village of Podmoli. The study site is 390 m above sea level. The average slope of the plot is 3°. Land area is 2.37 ha. The border is irregularly shaped. The mean annual temperature is 8.5°C, and the length of the growing period is between 155–165 days. The long-term mean annual total precipitation is 486 mm (Kuchařovice Weather Station 2011). Bedrock is formed by granite.

The study site is located in the core zone of Podyjí National Park where forest ecosystems are left to spontaneous development. The forest stand comprising the research plot has a canopy structure of a single layer, but many trees are multi-stemmed due to coppice origin. However, the forest stand has not been actively coppiced since the end of 19th century and has become over mature (currently, approximately 120 years), undergoing a natural transformation into the high forest (Vrška et al. 2017). The stand is identified as acidophilous oak woodlands. The area is dominated by Quercus petraea (Matt) Liebl. with 1599 individuals (97.7%). The other tree species found on the plot included 34 individuals (2.1%) of Pinus sylvestris L., 2 individuals (0.1%) of Carpinus betulus L. and 1 individual (0.1%) of Larix decidua Mill. The average density of live stems was 634 stems ha⁻¹ (Vrška et al., 2017). Stand density index (Reineke, 1933) was 623.

Mistletoes range from extremely host-specific (e.g., Arceuthobium apachecum) to host-generalist (e.g. Dendrophthoe falcata) (Norton and Carpenter 1998). Mistletoe seedlings may establish more successfully on some host species rather than others (Reid et al. 1995). We avoided this problem by choosing a study plot with the presence of only one hemiparasite – Loranthus europaeus that had only one suitable host – Quercus petraea.
2.2 Data collection

All tree stems with DBH ≥ 7 cm were stem-mapped using Field-Map technology (www.fieldmap.cz), measured and identified to species. The number of stems that belonged to each individual tree was counted (stool). The investigation of the tree infestation by *L. europaeus* at the site was launched (2011) cooperatively with other research by Matula et al. (2015), which primarily focused on the impact of host competition on the intensity of the yellow mistletoe incidence. On the other hand, our investigation continued and rather concentrated on the changes in infestation monitored during a time series (2011–2015). Therefore, each oak stem (1599) was visually checked for the presence of *L. europaeus* in the years 2011, 2013, 2014 and 2015 and the effect of host growth parameters on the intensity of infestation and the differences in dimensions (volume) of the hemiparasite. Observations were made at the beginning of bud growth, so it was easier to spot the hemiparasites in tree crowns. The determination whether the mistletoe is dead or alive was performed on the basis of observations of growing buds and leaves. The number of *L. europaeus* shrubs per stem was counted (abundance) and the diameter of each shrub was estimated with laser rangefinder with a precision of 10 cm. Shrub diameters were used to calculate volume with the formula: \( V = \frac{1}{6} \pi d^3 \), where \( d \) is *L. europaeus* shrub diameter. *L. europaeus* individuals that grew on the same stem were added together to obtain the total volume of *L. europaeus* per stem (volume).

2.3 Data analysis

All analyses were performed in the R environment (R Development Core Team 2015). We investigated the temporal dynamics of abundance and volume of *L. europaeus* infection on individual stems using linear mixed effects models (LME) using the “nlme” package (Pinheiro et al. 2016) in R. The abundance and volume of *L. europaeus* shrubs per stem acted as response variables. The fixed effects of LMEs were DBH, number of stems in a tree, year, and their pairwise interactions. Therefore, the linear predictors had the form of multiple regression and were structured as follows: DBH + Stool + Year + DBH * Stool + DBH * Year + Stool * Year. The terms were removed from the models according to their significance and the rule of marginality (Pekár and Brabec 2016). The volume and abundance values were log transformed, as LME requires a normal distribution of errors (Pekár and Brabec 2012). The *Q. petraea* stem IDs acted as random effects. In addition to the random effects, we included the spatial exponential correlation or the linear correlation of the true residuals using the function ‘corExp’ or ‘corLin’, respectively, to address the spatial autocorrelation problem (Pinheiro et al. 2016).
3. Results

Mean DBH of host trees was 28.8 cm (± 0.401), while mean DBH of uninfected trees was 23.0 cm (± 0.173). The number of infected trees decreased through the monitored years, with the exception of 2013. The rate of infected stems decreased from 9.3% in 2011 to 6.9% in 2015 (Tab. 2). The number of newly disinfected trees was higher than the number of newly infected trees (Tab. 2). The greatest difference was noted in 2014 when 36 trees were disinfected and no newly infected trees were recorded. The number of *L. europaeus* shrubs on sessile oak tree hosts decreased through the monitored years, from 248 in 2011 to 152 in 2015 (Tab. 3). There was a break year in 2014, where 86 hemiparasites died, and only two new individuals were found (Tab. 3).

The largest number of *L. europaeus* individuals recorded on one host stem was between 3-7 (Tab. 3). The average diameter of *L. europaeus* decreased to 63.7 cm (± 3.01) in 2015. The maximum recorded *L. europaeus* diameter was 170 cm. The average number of hemiparasites on one contested stem decreased through the years, from 1.68 in 2011 to 1.38 in 2015 (Tab. 3).

We found no significant relationship between the abundance of *L. europaeus* per stem and the number of stems per tree (LME, F1,176 = 0.2, P = 0.654). The abundance of *L. europaeus* increased with an increase in DBH (LME, F1,177 = 13.3, P < 0.001, Fig. 1, Tab. 1, Tab. 4), year (LME, F1,352 = 8.7, P = 0.004, Fig. 1, Tab. 1), and their interaction (LME, F1,352 = 6.1, P = 0.014, Fig. 1, Tab. 1). At smaller DBH, the abundance of *L. europaeus* slightly increased through the years, but this phenomenon slowed down with increasing DBH. Mistletoe abundance started decreasing over time when the host trees had high DBH (Fig. 1).

There was no significant effect of the number of stems per tree on the volume of *L. europaeus* (LME, F1,176 = 0.9, P = 0.348). The volume of *L. europaeus* decreased over time (LME, F1,353 = 11.6, P < 0.001, Tab. 1) and increased with the DBH of their hosts (LME, F1,177 = 6.3, P = 0.013, Tab. 1, Tab. 4). The total volume of *L. europaeus* shrubs decreased, from 79.79 m³ in 2011 to 43.13 m³ in 2015 (Tab. 3).
Table 1: The estimated coefficients (SE) of the fixed effects of the linear mixed effects models on the abundance and volume of *L. europaeus*. The dash means that the term was not significant in the model. The estimates are for log-transformed abundance and volume.

<table>
<thead>
<tr>
<th></th>
<th>Intercept</th>
<th>DBH</th>
<th>Year</th>
<th>DBH-Year interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abundance</strong></td>
<td>-0.56 (0.23)</td>
<td>0.03 (0.01)</td>
<td>0.10 (0.06)</td>
<td>-0.005 (0.002)</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td>-2.90 (0.61)</td>
<td>0.05 (0.03)</td>
<td>-0.12 (0.04)</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2: Fluctuation of host stem infestation of *L. europaeus*. Number of newly infected stems represents the newly infected host stems compared to findings from the previous year. Number of disinfected stems represents stems with no mistletoes in a given year but were infected in a previous year. Number of surveyed *Q. petraea* individuals was 1599.

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of infected stems</th>
<th>% of newly infected stems</th>
<th>No. of newly infected stems</th>
<th>No. of disinfected stems</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>148</td>
<td>9.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2013</td>
<td>155</td>
<td>9.7</td>
<td>26</td>
<td>19</td>
</tr>
<tr>
<td>2014</td>
<td>119</td>
<td>7.4</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>2015</td>
<td>111</td>
<td>6.9</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>Year</td>
<td>No. of shrubs</td>
<td>Newly grown shrubs</td>
<td>Newly dead shrubs</td>
<td>Max. no. of shrubs per stem</td>
</tr>
<tr>
<td>------</td>
<td>---------------</td>
<td>--------------------</td>
<td>------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>2011</td>
<td>248</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>249</td>
<td>45</td>
<td>44</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>165</td>
<td>2</td>
<td>86</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>152</td>
<td>28</td>
<td>41</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Table 4: Fluctuation of host stem infestation of L. europaeus by DBH classes. The interval of DBH classes was created based on Doležal (1965) design and was adapted to local conditions.


<table>
<thead>
<tr>
<th>DBH class</th>
<th>Range of DBH classes (cm)</th>
<th>% of infested stems</th>
<th>Average no. of shrubs per stem</th>
<th>Average vol. of shrubs per stem (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7–8</td>
<td>0.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>8.1–16</td>
<td>0.54</td>
<td>1.33 (±0.33)</td>
<td>0.02 (±0.01)</td>
</tr>
<tr>
<td>3</td>
<td>16.1–24</td>
<td>6.08</td>
<td>1.23 (±0.05)</td>
<td>0.40 (±0.05)</td>
</tr>
<tr>
<td>4</td>
<td>24.1–36</td>
<td>18.06</td>
<td>1.59 (±0.05)</td>
<td>0.47 (±0.03)</td>
</tr>
<tr>
<td>5</td>
<td>36.1–48</td>
<td>37.21</td>
<td>1.76 (±0.18)</td>
<td>0.56 (±0.07)</td>
</tr>
</tbody>
</table>
4. Discussion

Generally, our study confirmed that mistletoe occurrence and volume increased with DBH, i.e., with size and age of the hosts. Our estimated model showed differences in mistletoe abundance with time. While a slight increase in the number of *L. europaeus* over time was recorded in host trees with a very low DBH (Fig. 1), the number of *L. europaeus* plants declined in trees with a high DBH (Fig. 1) during the study period.
The number of hemiparasites on host trees with intermediate DBH values stagnated over time. The decline in the number of *L. europaeus* on host trees with a greater DBH can be attributed to the natural dieback that occurs as they reach a maximum age, and, as Monteiro (1992), we assumed that larger (older) hosts could be attacked sooner than hosts with a smaller DBH. Some *L. europaeus* individuals died because of the gradual loss of host branches caused by the accelerated ageing of their growth modules. None of the monitored host trees has completely died. The ageing of the modules may be caused by hemiparasite stress on the host, which affects host growth and architecture (Rigling et al. 2010), reduces host photosynthetic efficiency (Dobbertin and Rigling 2006) and alters the respiration rates of the plants (Watling and Press 2001).

Mistletoe haustoria need to overcome the thick bark of host branches to successfully establish on trees. This is easier in places where the host stem tissues are in tension, disrupted or replaced by secondary protective tissues in oak branches, this exchange occurs between ages of 4-6 years (Kubiček, Martinková and Špinlerová 2011). Sargent (1995) found that mistletoe seedlings died more frequently on larger branches than on smaller twigs, probably because they were unable to penetrate the thicker bark of the hosts with larger stem diameters. Young branches are more likely to be attacked by hemiparasites. This can be one factor that explains why the abundance of *L. europaeus* increased more on low DBH trees and why is not as abundant on high DBH trees.

The mean DBH of host trees (28.80±0.401 cm) is comparable with findings of Sayad (2017) – 27.10±1.59 cm. These numbers are higher than mean DBH of all trees.

Over the years included in the study period, 6.9%–9.7% of the *Q. petraea* stems (Tab. 2) were infested with 152–248 *L. europaeus* individuals (Tab. 3). This result can be compared with Idžojtić et al. (2005), who reported a 14.2% infestation rate of *Quercus* trees over 30 years old in the Forest Administration Požega. Sayad (2017) reported an infection ratio of 23% in Oak Zagros forest.

The average number of *L. europaeus* plants detected on one infested tree was 1.4–1.7 pieces (Tab. 3, Tab. 4), which corresponds to the abovementioned research (Idžojtić et al. 2008 report 2 pieces). Sayad (2017) stated that infected trees had an average of 4.08 mistletoes in Oak Zagros forest. The maximum number of individuals (7 pieces per a tree, Tab. 3) was lower than values reported in Croatia (38). There were no sufficient regularities to make a connection between the analysed parameters and the occurrence of mistletoe.

In Albania, Lushaj and Lushaj (2009) conducted two research time series on *L. europaeus* infestation of *Castanea* sp.. Their work mentions an average *L. europaeus* incidence between 3 and 7 (9) individuals per a tree. They determined infestation rates of 4.8% and 5.9% for the first and the second time series, respectively. A gradual in-
crease in infestation was also recorded in our case (Tab. 2), during the first three years of research. However, over the last two years, the percentage dropped quite sharply, and the number of L. europaeus individuals decreased by more than 40% (Tab. 3). The reason for this sudden drop and the increased mortality of the L. europaeus plants can only be hypothesized. L. europaeus death may have occurred naturally, as the individuals reached their maximum age, a hypothesis that is supported by the high volumes of hemiparasites we measured in some cases. According to Úradníček (2009), L. europaeus individuals form branches over 80 cm long, which corresponds to the dimensions we measured (biggest shrub was 170 cm in diameter). We noticed that a few young L. europaeus shrubs died. The low number of newly established individuals can be attributed to the slower growth of new yellow mistletoe, and it is possible that new individuals could not be seen in the high crowns during the five-year research period. Higher mortality may also be associated with worsening climatic conditions - a prolonged dry period (Bartošová et al., 2015), which can cause photoinhibition and affect intrinsic water-use efficiency (Sangüesa-Barreda 2018).

Throughout 5 years of research, we did not detect a relationship between increased L. europaeus incidence and higher within-tree competition caused by the multi-stem growth in the coppice. This supports the short-term results of Matula et al. (2015), who found a small dependency, but noted that the likelihood of L. europaeus infection is more dependent on the host thickness than the competition between the stems. It is also true that the authors who monitored L. europaeus infections in various types of stands that were managed in different ways (Idžojtić et al. 2005, Lushaj and Lushaj 2009) did not note any within-tree differences in competition.

Our data indicate that the abundance of L. europaeus increased with time on host trees with smaller DBH. For this reason, it is important to properly manage in a way that focuses primarily on preventing young trees from drought stress (planting of drought-tolerant species, increasing species diversity, coppicing), which would otherwise accelerate attacks by hemiparasites. The priority harvesting of already infested high DBH trees should help to slow the mistletoe dissemination.

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