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Estimation of Aboveground Biomass of Acacia Trees in the Hyper-Arid Arava, Israel Using Allometric Analysis

—Allometric Equations for Acacia Trees in the Desert

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Abstract

Biomass is among the most important state variables used to characterize ecosystems. Estimation of tree biomass involves the development of species-specific "allometric equations" that describe the relationship between tree biomass and tree diameter and/or height. While many allometric equations were developed for northern hemisphere and tropical species, rarely have they been developed for trees in arid ecosystems, limiting, amongst other things, our ability to estimate carbon stocks in arid regions. *Acacia raddiana* and *A. tortilis* are major components of savannas and arid regions in the Middle East and Africa, where they are considered keystone species. Using the opportunity that trees were being uprooted for land development, we measured height (H), north-south (C_1) and east-west (C_2) canopy diameters, stem diameter at 1.3 meters of the largest stem ($D_{1.3}$ or DBH), and aboveground fresh and dry weight (FW and DW, respectively) of nine trees ($n = 9$) from each species. For *A. tortilis* only, we recorded the number of trunks, and measured the diameter of the largest trunk at ground level (D_0). While the average crown (canopy) size ($C_1 + C_2$) was very similar among the two species, *Acacia raddiana* trees were found to be significantly taller than their *Acacia tortilis* counterparts. Results show that in the arid Arava (southern Israel), an average adult acacia tree has ~200 kg of aboveground dry biomass and that a typical healthy acacia ecosystem in this region, may include ~41 tons of tree biomass per km^2. The coefficients of DBH (tree diameter at breast height) to biomass and wood volume, could be used by researchers studying acacia trees throughout the Middle East and Africa, enabling them to estimate biomass of acacia trees and to evaluate their importance for carbon stocks in their arid regions. **Highlights:** 1) Estimations of tree biomass in arid regions are rare. 2) Biomass allometric equations were developed for *A. raddiana* and *A. tortilis* trees. 3) Equations contribute to the estimation of carbon stocks in arid regions.

Keywords

Acacia raddiana, *Acacia tortilis*, Carbon Stocks, Desert Ecosystems, Desertification, Allometric Equations

1. Introduction

Biomass is among the most important state variables used to characterize ecosystems. Biomass of an ecosystem is defined as the organic matter resulting from primary production through photosynthesis, minus the consumption through respiration and, if present, harvest [1]. In most forest ecosystems, tree biomass is assessed through allometric relationships between "easily" measurable parameters (e.g., tree diameter at breast height [DBH = $D_{1.3}$] or tree height) and aboveground tree biomass (*AGB*). Indeed, a wealth of allometric equations have been developed during the last 30 - 60 years relating stem volume and biomass of several tree components to $D_{1.3}$ and/or to tree height [2] [3]. Such allometric equations are species-specific as each species has its own physiognomy (*i.e.*, the overall shape or physical appearance of a tree species).

While a wealth of equations has been developed for northern hemisphere and tropical species [3]-[5] rarely have they been developed for trees in arid ecosystems. Indeed, searching the Scopus databases (https://www.scopus.com; accessed 21/02/2017) from 1970 until February 2017 with "allometric equation tree biomass" as keywords resulted in finding 964 related studies. Of these studies, 572 (59%) focused on tropical forest trees, 310 (32%) on temperate forest trees, and 82 (9%) on Mediterranean trees. None focused on desert biomes (Supplementary materials, **Figure S1**).

The trees most often studied and used to formulate allometric equations are from humid (tropical) to relatively humid climates (temperate, boreal), where trees grow in closed forests and develop tall vertical trunks in their efforts to compete for light. However, due to the high irradiance and low precipitation levels that characterize arid regions, local trees do not generally develop closed forest stands but form open and sparse stands and/or savannas where water and nutrients rather than light are the main factors limiting growth. Thus, it is possible that the allometric relationships for trees in arid regions may differ from those developed in other regions.

The reality that many parts of the world are indeed going to become more and more arid in the coming years [6], calls for a better understanding of structure, function and *AGB* biomass of trees in arid climates.

The plant genus *Acacia* is a major component of savannas and open forests in many arid regions of Africa and the Middle East [7]. In the arid Arava valley, along the Syrian-African transform in southern Israel and Jordan, *Acacia raddiana* Savi and *Acacia tortilis* Forssk (Hayne) (Supplementary material **Figure S2(a)-(b)**) are the two most abundant, and in many places the only, tree species present [8] [9]. Here, both *A. raddiana* and *A. tortilis* are considered "keystone species" that support the majority of the biodiversity surrounding them and locally improve soil conditions for other plant species [9] [10]. These drought enduring trees are found mostly growing along "wadis" (ephemeral riverbeds) [10]) (**Figure S2(c)**). Acacia trees vary in shape and size from multi-stemmed shrubs (*A. tortilis*, often called the "umbrella thorn" for its distinctive spreading crown) to trees up to 20 m tall with rounded crowns (*A. raddiana*).

We aimed to develop allometric equations for *Acacia raddiana* and *A. tortilis*, essential for assessing the standing biomass of single trees and open savannas, and beneficial for future ecosystem studies on carbon stocks in desert environments.

2. Material and Methods

2.1. Study Area

Biomass sampling was conducted (17-29/01/2014) in the central Arava region (southern Israel), near Moshav Idan (30˚49'31.3"N 35˚16'30.9"E, altitude −163 m) and Wadi Gidron (30˚47'20.2"N 35˚14'51.5"E, altitude −143 m), with 4.5 km between sites. Like other areas in the region, both of these wadis are dominated by *A. raddiana* and *A. tortilis* trees. While acacia trees in the Arava are now protected, in previous years, clearing land (including the uprooting of local trees) for developing new agricultural land was a common practice. This study is based on an "opportunity" that came up when local authorities let us know in advance that undisturbed land (with acacia trees growing on it) was going to be cleared and trees uprooted. The area planned for clearing was surveyed; trees from both acacia species were counted (more than 15 from each species) marked and their height was measured (details below). To make sure that the selected trees ($n = 9$ for each species) represented the population, we tested the normality of the height distribution as an indicator for tree "size". This preliminary test confirmed that the 18 trees chosen for uprooting and measuring did in fact have a normally distributed size (height) (Shapiro-Wilk, W-Statistic = 0.924, P = 0.172).

2.2. Fieldwork and Acacia Monitoring

For each tree, we measured tree height (H) using a TruePulse 200 laser range finder (Laser Technology, USA), tree crown (canopy) diameters from north-south (C_1) and east-west (C_2) (using a 20 m tape measure), and stem diameter at 1.3 m of the largest stem ($D_{1.3}$ or DBH; using a 1.5 m flexible tape measure). For *A. tortilis* only, the number of trunks was recorded, and the diameter of the largest trunk at ground level (D_0) was taken.

2.3. Tree Felling and Weighing

Trees were either felled directly by chainsaw or lifted out of the ground by a tractor (Supplementary material **Figure S3**). For both species, the main stem of each tree was cut at ground level, where the tree met the ground, so as to measure only the aboveground fresh weight (FW) of the tree. Sampled trees were then cut into smaller pieces that were weighed and summed to obtain the total weight. Cross-sections (~5 cm diameter, n = 3) were taken from both the stems and thick branches of each tree. $D_{1.3}$ and D_0 of the largest stem were measured again after each tree had been felled, for both species.

2.4. Laboratory Work

Cross-sections of each tree (n = 9 trees for each species) were taken back to the lab. Fresh weight (FW) measurements were taken for each section. Cross-sections were then oven-dried (60˚C) until they reached a constant weight, and then weighed again to derive the dry weight (DW).

2.5. Dry to Fresh Weight Conversion

For each sample, the dry- to fresh-weight (DW/FW) ratio was calculated and the dry- to fresh-weight coefficients were calculated for each species. This coefficient (a) was multiplied by the FW to convert fresh to dry weight to calculate aboveground biomass (AGB) (Equation (1)).

$$AGB = a \times FW \tag{1}$$

2.6. Dry Weight to Stem Diameter Algorithm

For each species, dry tree biomass (AGB; calculated using Equation (1)), was then correlated to D (both $D_{1.3}$ and D_0) using a power function obtained with the statistical package available in SigmaPlot 11.0.

$$AGB = a \times D^b \tag{2}$$

2.7. Stem Diameter to Tree Volume Correlation

Aboveground volumetric index (V) of the tree was calculated by multiplying the height (H) of the tree by the north-south canopy diameter (C_1) and the east-west canopy diameter (C_2) (Equation (3)). This gives a box shape similar to the cylindrical pipe-shape volume that is an index of the volume of the tree [11]:

$$V = H \times (C_1) \times (C_2) \tag{3}$$

The relationship between V and D_0 and $D_{1.3}$ was examined to find the correlation between tree stem diameter and the corresponding aboveground tree volume. Dry tree biomass (AGB) for each tree (calculated using Equation (1)) was then correlated to D (both $D_{1.3}$ and D_0) using the power Equation (2). Similarly, AGB was correlated to D using three more equations: linear, exponential and Logarithmic equations (Equations (4)-(6)).

$$AGB = a \times D + b \tag{4}$$

$$AGB = a \times e^{(bD)} \tag{5}$$

$$AGB = a \times LN(D) - b \tag{6}$$

3. Results

Biomass, Volume and Allometry of Acacia Trees

Eighteen trees were measured before felling (supplementary material **Figure S3**). For tree height (H), *Acacia raddiana* trees (average H and SE = 3.09 ± 0.27 m, n = 9) were found to be significantly taller than their *Acacia tortilis* counterparts (average H and SE = 2.41 ± 0.17 m, n = 9, t-test, t(15) = −2.1551, p < 0.05). The average crown (canopy) size ($C_1 + C_2$) was very similar among the two species, with *A. tortilis* (5.55 ± 0.32 m, n = 9) showing slightly, not significantly, higher values than *A. raddiana* (5.08 ± 0.47 m, n = 9) (t-test, t(16) = 0.801, p > 0.05).

Fresh to dry weight conversions performed (Equation (1)) on the thickest branches for both acacia species, showed that dry weight could be highly predicted ($R^2 > 0.99$) from fresh weight ($y = 0.8883x - 3.6346$ for *A. tortilis*, and $y = 0.9202x - 128.46$ for *A. raddiana*).

Correlations between stem diameter and aboveground volumetric index of the entire trees (Equation (2)) were tested for both species. Only *Acacia raddiana* presented a strong correlation both for $D_{1.3}$ ($R^2 = 0.92$) and D_0 ($R^2 = 0.65$), while the correlation was weak for *A. tortilis* ($R^2 = 0.09$ for $D_{1.3}$ and $R^2 = 0.11$ for D_0).

Similarly, the correlations between total plant volume and aboveground biomass (**Figure 1(a)**), proved to be significant for *A. raddiana*, the species with a more "classic" tree-like structure ($R^2 = 0.96$), and again poor for *A. tortilis* ($R^2 = 0.15$).

Aboveground bioma (AGB) correlated positively and significantly with diameter (**Figure 1(b)-(c)**). For both species, the relationship was significant, both using $D_{1.3}$ ($R^2 = 0.79$ for *A. tortilis* and $R^2 = 0.86$ for *A. raddiana*; **Figure 1(b)**) and D_0 ($R^2 = 0.86$ for *A. tortilis* and $R^2 = 0.64$ for *A. raddiana*; **Figure 1(c)**). The parameters of eq. (2) for the two diameters and species are shown in **Table 1**.

The relationship between D and biomass (AGB) was compared for four possible regression types. The results show that the linear relationship performed better for *A. tortilis*, while the logarithmic one was best for *A. raddiana* (**Table 2**).

Table 1. The coefficient values linking DBH ($D_{1.3}$) to volume and biomass for *A. raddiana* and *A. tortilis*.

A. raddiana	Diameter a	Diameter b	Volume a	Volume b
Biomass	0.429	1.555	0.101	1.550
Volume	2.639	0.981		
A. tortilis	Diameter a	Diameter b	Volume a	Volume b
Biomass	4.239	1.166	0.73	0.345
Volume	37.244	0.4297		

Table 2. The relationship between D and aboveground tree biomass (*AGB*) reported for the four possible equations (linear, exponential, logarithmic and power) for *A. tortilis* and *A. raddiana.*

			A. raddiana			*A. tortilis*		
			a	b	R^2	a	b	R^2
Power	Eq. (2)	$AGB = a \times D^b$	0.429	1.555	86%	4.24	1.166	80%
Linear	Eq. (4)	$AGB = a \times D + b$	6.08	75.2	90%	6.96	5.34	89%
Exponential	Eq. (5)	$AGB = a \times e^{(bD)}$	17.97	0.042	84%	49.36	0.044	69%
Logarithmic	Eq. (6)	$AGB = a \times LN(D) - b$	174.3	−354.6	93%	206.7	−553.9	77%

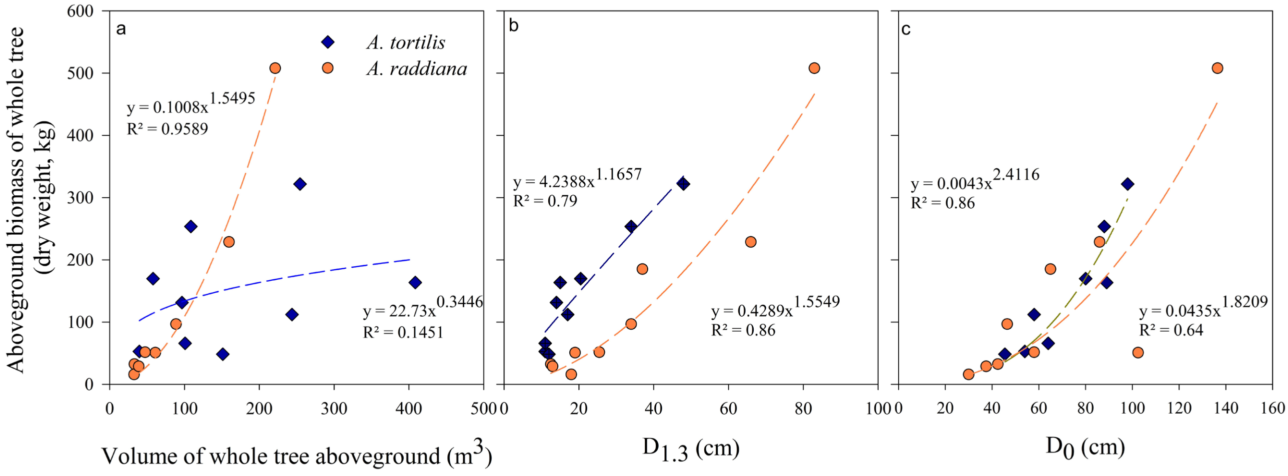

Figure 1. Relationship of aboveground biomass (*AGB*, kg) and volume index (Volume, m³) for *Acacia tortilis* (blue diamonds) and *Acacia raddiana* (orange circles). Lines showing power relationship as equation (2). a) Shown also are the power relationships between aboveground biomass (*AGB*, Kg) and b) diameter of the thickest stem at 1.3 meters ($D_{1.3}$) and c) diameter of the thickest stem at ground level (D_0) in the two acacia species.

4. Discussion

A strong correlation (>79%) was found between trunk diameter at 1.3 m ($D_{1.3}$) and aboveground biomass (*AGB*) for both *A. raddiana* and *A. tortilis.* This is in line with allometric relationships developed for temperate and boreal tree species. Zianis *et al.* [3], using the same equation as our Equation (2) ($AGB = a \times D^b$), reported *a* and *b* coefficients to range between 0.036 and 0.2375 (for *a*) and 2.0291 and 2.785 (for *b*). Our *b*-values (Table 2) were lower than the *b*-values reported by Zianis *et al.* [3] for temperate and boreal tree species, suggesting that for the acacia trees that we measured in the Arava, the relationship between D and aboveground biomass (*AGB*) was linear as opposed to other studies on other trees (where for example D and *AGB* were related exponentially). There was a very weak correlation between the canopy volume of *A. tortilis* and both trunk diameter and biomass, while these two parameters were highly correlated for *A. raddiana*. Trunk diameter at 1.3 m ($D_{1.3}$) had stronger correlation with both tree canopy volume and biomass than ground level diameter (D_0).

For both species and both types of measurements (1.3 m [$D_{1.3}$] and ground level [D_0]), trunk diameter was a good estimate of biomass of acacia trees. The correlation between DBH and biomass shows that DBH is a good allometric variable for biomass estimation of desert acacia trees (**Figure 1(b)**) and therefore can be used to estimate biomass of single trees and ecosystems using the equation parameters formulated in the present study. However, the correlation between volume and biomass (**Figure 1(a)**) is strong only for *A. raddiana* ($R^2 = 0.96$), but not for *A. tortilis* ($R^2 = 0.14$). This is probably due to the different physiognomy of the two species: *A. tortilis* has many stems branching from the bottom, thus DBH only represents one of many branches, while *A. raddiana* has one stem at ground level. Hence, for *A. raddiana*, all measurements of tree sizes are correlated to DBH, while for *A. tortilis* this correlation is weaker.

While allometric equations have previously been developed for acacia trees, those studies included either "new world" tropical acacia species [12] or "old world" African acacia species growing in tropical/subtropical regions [13] [14]. This is the first time that biomass allometric equations have been calculated for *A. raddiana* and *A. tortilis* trees growing in hyper-arid habitats.

Using the algorithm reported in this study, we estimate single acacia trees growing in the Arava desert to weigh an average of around 200 kg of dry aboveground. From a different ongoing study in Wadi Shita (30˚08'14.8"N 35˚07'56.7"E, altitude −223 m; [8]), we estimate tree density in the wadi to be 208 trees per km^2, which in turn suggests around 41 t of aboveground tree biomass per km^2. While this estimation relies on many assumptions, it provides us with a rough calculation of the aboveground carbon storage in this arid system.

Furthermore, the strong correlation found between tree canopy volume and biomass for *A. raddiana* enables replacing field measurements with remote sensing and LIDAR (Light Detection and Ranging) to derive tree canopy size and height in order to estimate ecosystem biomass. This will allow biomass estimation over large areas covered by acacia trees, which could be especially useful in areas where acacias dominate: Africa and the Middle East. This application is particularly valuable for an ecosystem with low stand density and where field measurements are expensive and time-consuming. While it is possible that these allometric equations could also be good for other tree species in the region, this remains to be shown in the future.

Additionally, we learned in this study that the two species do not differ greatly in their biomass, despite the difference in physiognomy. Our recommendation is to use the equations presented here to estimate carbon stocks, biomass and other ecosystem variables using simple field measurements for *A. raddiana* and *A. tortilis*, even though, as expected, the allometric relationships for the latter species are less robust compared to those of *A. raddiana*. The fact that relationships between trunk diameter and Equation (2) ($AGB = a \times D^b$), are associated with the fact that *A. tortillis* is characterized by multiple (10 - 30) "main trunks". For more accurate estimation of biomass of *A. tortilis*, the measurement of DBH could be complemented by additional parameters such as D_0 or more diameters of the multi-stem structure.

5. Conclusion

These are the first allometric equations developed for *A. raddiana* and *A. tortilis* trees growing in hyper-arid habitats. DBH was shown to be a good proxy for tree biomass. Tree volume, based on *A. raddiana* and *A. tortilis* height and canopy width, can also serve as a complementary variable, especially for *A. raddiana*. These equations provide a tool to estimate the biomass of trees in deserts and savannas around the Middle East and Africa, which are dominated by sparse acacia trees. With the growing application of remote and near sensing to surveying forests, whereby tree height and crown diameter are estimated remotely [15], we do belive that using the equations we developed in this study, it is possible to accurately estimate biomass of acacia trees from far. This is probably easier to perform in the arava than in other regions, since in this super arid environment, the two acacaica trees studied here, are the most dominant and sometimes only tress species. With climate change and desertification in mind, we believe that, in the future, these relationships will be useful for understanding tree and carbon dynamics in locations that are at risk of becoming arid**.**

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Winters, Groner and Matteucci designed the fieldwork. Winters and Alexander carried out all the field and laboratory measurements. Data analysis was done by Winters, Alexander and Groner. Thanh Hoai Tran did the literature review. Winters, Matteucci and Groner wrote the paper. We thank Eitan Barnes for the helping out in the field. Wadi Shita is a site of LTER Israel, part of LTER Europe and ILTER networks.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

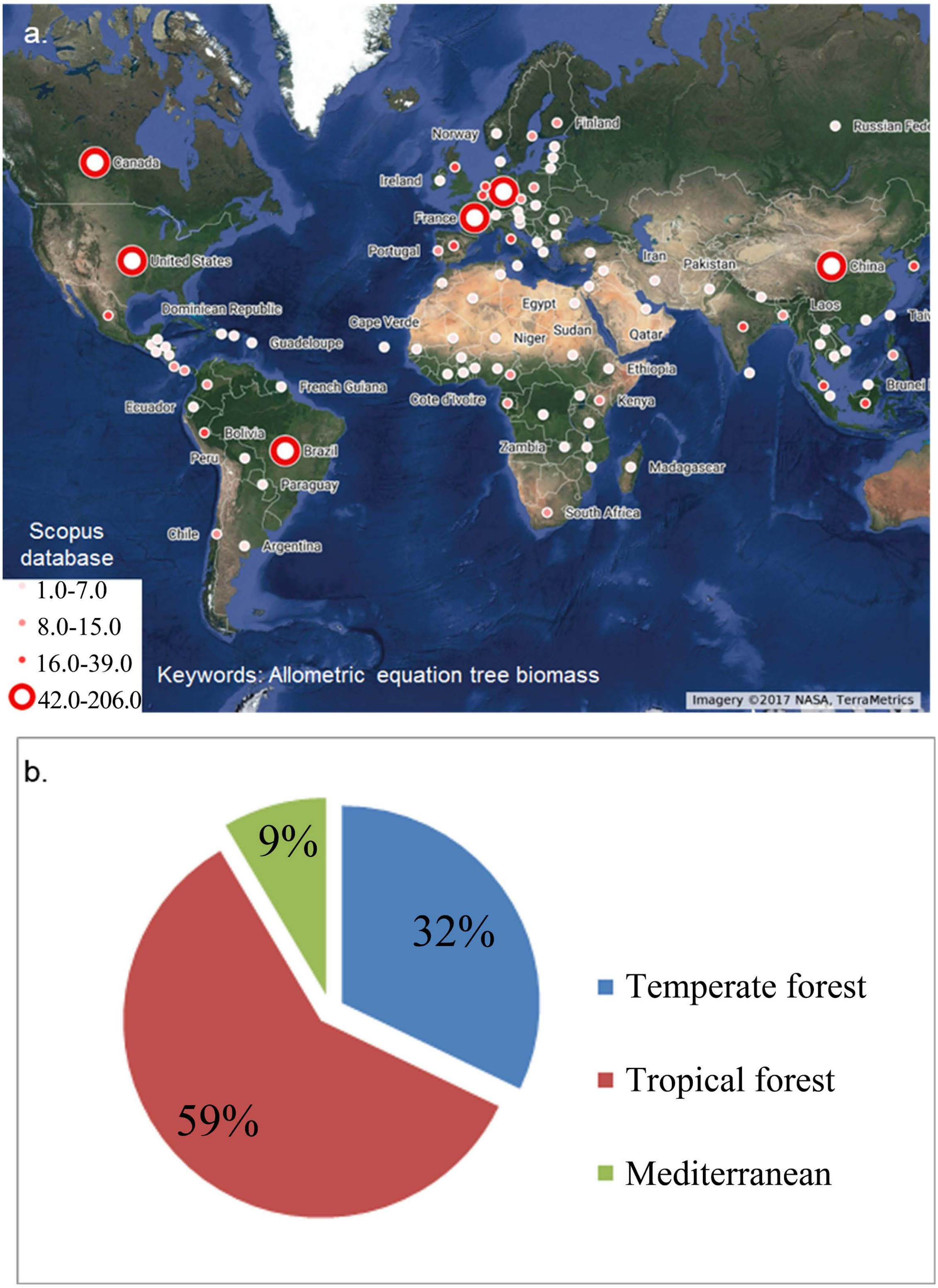

Figure S1. Number of studies related to allometric equations counted from Scopus database website on February 21st, 2017 by using these keywords: "Allometric equation, tree biomass". a) Geographical distribution of the studies and b) Proportion of studies conducted in each biome.

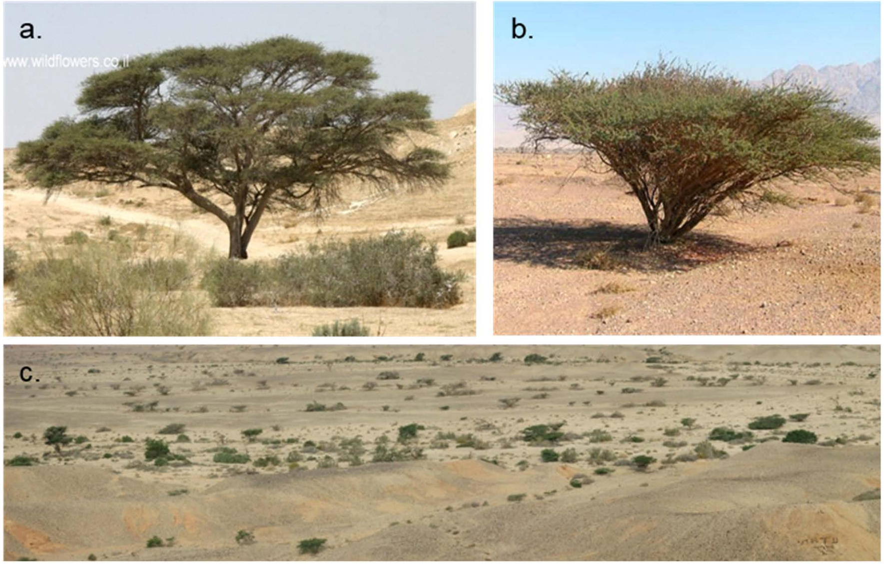

Figure S2. Acacias in the Arava. Species of interest: *Acacia raddiana* (a) and *A. tortilis* (b) (photos: wildflower.co.il). In the arid Arava (southern Israel), these trees are found mostly growing along ephemeral river beds ("wadis", a term from the Arabic; Ward 2010. Shown in this example is Wadi Shahack) (c) (photo: G. Winters).

Figure S3. Tree felling and weighing. Trees were either felled directly by chain saw (a), or for the larger trees, lifted out of the ground by a tractor (b), (c). Trees were then carried and brought to our measuring and weighing station (c), where D_0 was measured (d). Trees were then lifted onto our weighing machine by hand or using a tractor (e).