

Allometric relations between DBH and sapwood area for predicting stand transpiration: Lessons learned from the Quercus genus

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Abstract

Catchment-scale transpiration is commonly determined by the use of sap-flow sensors, and its quantification, which is critical for water and forest management, relies crucially on the total catchment's sapwood area (A_s). Species-specific allometric relationships between the trees A_s and the trees diameter at breast height (DBH) are widely used for determining stand or catchment A_s . However, substantial differences between studies challenged the robustness of these relationships between sites displaying various topographical and environmental characteristics. In this study, we aim at comparing these relationships between species of the *Quercus* genus from sites in different parts of the world, and testing the role of topographical factors on A_s -DBH relationship in *Quercus petraea*. Using 145 trees sampled within a 0.455 km² catchment, we showed that topography (slope, flow accumulation, aspect, curvature, topographic wetness index) does not modulate the A_s -DBH relationship in *Quercus petraea*, within our catchment. We compared our curve parameters with the ones from 17 studies on oak trees and found that the A_s -DBH relationship is not only species-specific, but depends on the site's conditions, and likely the stand density, the total radiation and the evaporative demand. In the light of these results, we recommend to build site- and species-specific A_s -DBH relationship for determining stand transpiration, using a minimum of nine, randomly sampled trees, and different methods and azimuthal directions for determining sapwood depth.

1. Introduction

The estimation of catchment-scale transpiration remains critical for forest and water management. To date, a widely applied method is based on the use of sap-flow sensors (Hassler et al., 2018; Tsuruta et al., 2019; Mitra et al., 2020). Different types of sensors exist, but all rely on the measurement of sap-flux density in few trees that is multiplied by the sapwood area of the trees to obtained catchment-scale transpiration (Granier et al., 1996; Flo et al., 2019). Sapwood area plays therefore a crucial role in estimating tree and catchment transpiration (Čermák and Nadezhdina 1998; Hölscher et al., 2005; Meinzer et al., 2005), which motivated numerous studies on sapwood allometric relations. Commonly, stand sapwood area is derived from empirical relationships with the DBH of the stand's trees, because sampling all the trees in a catchment/stand is too resource intense (e.g. Hassler et al., 2018; Tsuruta et al., 2019). These empirical relationships were established for a range of tree species growing under diverse environmental conditions like temperate broad-leaved species (Gebauer et al., 2008), boreal tree species (Quiñonez-Piñón and Valeo, 2017), snow-dependent tree species (Mitra et al., 2020), tropical rain forest species (Granier et al., 1996; Motzer et al., 2005; Horna et al., 2011; Aparecido et al., 2016; Kunert et al. 2015; Moore et al., 2018), Amazonian tree species (Parolin et al., 2008; Aparecido et al., 2019), desert tree species (Lubczynski et al., 2017), mountainous tree species (Vertessy et al., 1995; Tsuruta et al., 2019) or Australian tree species (Wang et al., 2016) among others. The relationships can take the form of linear, exponential, hyperbolic or power law functions (Eq. 1) like most species from the Fagaceae family, including the *Quercus* genus,

$$A_s = B_0 * DBH^{B_1} \text{ (Eq. 1)}$$

where A_s is the sapwood area of the tree (cm²) and DBH is the diameter at breast height (cm).

Various methods were developed for determining these empirical relationships. Some are destructive or invasive methods, such as core analysis (Gebauer et al., 2008; Horna et al., 2011), dye-immersed (Parolin et al., 2008; Aparecido et al., 2019) or thermo-imaged fallen trees (Granier et al. 1994). Non-destructive methods are commonly based on electromagnetic imaging techniques (Čermák et al., 2004; Bieker and Rust, 2010 a,b; Wang et al., 2016; Benson et al., 2019; Salomon et al., 2020). The allometric relations of trees from the *Quercus* genus have been quite extensively studied (Table 1), due to its high natural abundance (Rüther and Walentowski, 2008; Petritan et al., 2012) and a broad range of suitable growing conditions (Mette et al., 2013; Pretzsch et al., 2013). Additionally, the sapwood-heartwood limit from most *Quercus* trees can be distinguished straightforwardly by the darker color of the heartwood (Mosedale et al.,

1996; Taylor et al. 2002), which facilitates the quantification of A_s within this genus by direct inspection after coring. In the field of ecohydrology, these species-specific relationships are widely used within sap flux studies (e.g. Chiu et al., 2016, Hassler et al., 2018). However, different studies on the same species have shown contrasted values for the B_0 and B_1 parameters (e.g. Aranda et al., 2005; Schmidt, 2007; Grossiord et al., 2014), and these studies question the robustness of these relationships between sites (Horna et al., 2011). In the past decades, studies showed that the A_s -DBH allometric relationships of Japanese cedar and Japanese cypress may be affected by topographical factors as they vary with the slope position of the trees (Kumagai et al., 2007; Kume et al., 2016). These topographical effects may explain the inconsistencies of B_0 and B_1 between studies. However, topographical effects on A_s -DBH relationships has never been explored in the *Quercus* genus, despite the wide use of this relationship for quantifying stand-scale transpiration, especially across Europe. To date, most forest transpiration studies at the catchment-scale rely on B_0 and B_1 parameters from the literature. There is an urgent need for testing the robustness of these parameters between sites, specific species of a given genus, and topographical factors, to provide guidance for researchers and practitioners in order to build a strong A_s -DBH allometric relationship.

- Is the A_s -DBH allometric relationship specie-specific and site independent?
- Do topographical factors modulate the A_s -DBH relationship?
- What is the minimum number of samples required for reliably fitting the A_s -DBH power-law function for *Quercus petraea* in a temperate European forest?

2.1. Study site

The Weierbach is a forested catchment of 0.455 km² located in north-western Luxembourg (49°49'38" N, 5°47'44"E). The forest is a mix of European beech (*Fagus sylvatica*) and pedunculate (*Quercus robur* L.) and sessile oak (*Q. petraea* (Matt.) Liebl.) (Fabiani et al., 2021; Schoppach et al., 2021). Catchment's elevation ranges between 458 and 514 m asl and the geology is composed of Devonian slate and phyllites covered by 60 cm of silt and rock fragments (Juilleret et al., 2011). Distributions of the catchment topographical characteristics can be found in Schoppach et al., (2021).

2.2. Measurement of sapwood depth in oak trees and landscape characteristics analysis

Sapwood depth of oak trees was measured directly by coring horizontally and at the breast-height level in 145 randomly selected trees within the catchment (Fig. 1b). Sapwood and hardwood was discriminated based on colour variation (Mosedale et al., 1996; Quiñonez-Piñón & Valeo, 2018). Bark was removed from the cores before the sapwood depth was measured. We assumed that the sap wood depth was constant on all azimuthal directions and the tree trunks was considered as prefect cylinder.

>>>>>>>Fig. 3 Inserted here<<<<<<<<<<

We identified 17 studies in the literature in which the allometric A_s -DBH relationship was determined for oak trees (Table 1). Within these 17 studies, 14 relationships have the shape of a power law function (Fig. 4), while two others were linear and one exponential (Table 1). The A_s -DBH relationship was established for 13 different species from the *Quercus* genus (Fig. 4a - Table 1). Beside our study, four others determined the A_s -DBH relationship on *Quercus petraea* (Aranda et al., 2005; Schmidt, 2007; Jonard et al., 2011; Grossiord et al., 2014). Our study has, on average, seven times more samples than the average of previous studies (138 vs an average of 20). Our A_s -DBH relationship presents a R^2 36% lower (0.65 vs an average of 0.88). The area covered by the sampling is almost a thousand time larger (904) than the mean area of all the other studies.

As topography does not significantly influence the A_s -DBH relationship in our data set, a wider range of topographical characteristics compared to other studies cannot be held responsible for the lower level of R^2 displayed by our data. Other potential reasons for the lower level of R^2 include a much larger sampling area, the higher number of sampled trees, a wider range of tree's DBH, or errors coming from the methodology.

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number of sample most studies on *Quercus* genus used (Table 1). Therefore, Eq. 1 parameters extracted from these studies can be considered as robust for the species and sites concerned.

4. Conclusion

Sapwood area plays a key role for determining sap-flow of a tree and upscaling sap-flow measurements from tree to catchment level. A reliable quantification of sapwood area is therefore crucial for water and forest management. In this study, we showed that the A_s -DBH allometric relationship of the *Quercus* genus is not only species-specific, but depends on the site's conditions, and likely the stand density, total radiation and evaporative demand. We showed that topography does not modulate the A_s -DBH relationship in *Quercus petraea*, within our catchment. In the light of these results, we suggest that each upscaling study should rely on its own site- and species-specific relationship and recommend a minimum of nine, randomly sampled trees, in order to build the A_s -DBH relationship. Due to the potentially high variability in radial proportion of sapwood-heartwood and the caveats related to colour distinction, we recommend coring at different azimuthal locations in the trees and validate the delimitation of sapwood via different methods.

Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

Availability of data and material

The data used in this study are the property of the Luxembourg Institute of Science and Technology (LIST) and can be obtained upon request to the corresponding author, after approval by LIST.

Code availability

NA

Authors contribution

Rémy Schoppach: Conceptualization, investigation, data analysis, data visualization, writing original draft and editing. **Kwok Pan Chun:** Data analysis, reviewing and editing. **Julian Klaus:** Funding acquisition, supervision, reviewing and editing, project administration.

Ethics approval (include appropriate approvals or waivers)

NA

Consent to participate (include appropriate statements)

NA

Consent for publication

NA

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Tables

Table 1. Equation 1 parameters measured on oak trees (*Quercus* genus). “ B_0 ” and “ B_1 ” parameters correspond to Eq.1 parameters. “Covered area (m^2)” indicates the area in which trees have been sampled, using the original papers formulation for clarifying when it is ambiguously or vaguely described. “Trees” indicates the number of sampled trees within each study. “Data” indicates if the equations parameters are provided in the study (Eq.) or if only raw data are provided (Raw), so we calculated B_0 and B_1 parameters.

Study	Common name	Binomial name	B ₀	B ₁	R ²	Covered area (m ²)	Trees	Data
Our study	Sessile oak	<i>Quercus petraea</i>	0.3226	1.872	0.65	Within a 4.55 10⁶ m² catchment	145	Raw
Wullschleger, et al., 2001	Chestnut oak	<i>Quercus prinus L.</i>	0.375	1.751	0.93	Within a 1.92 10⁴ m² plot	46	Eq.
	White oak	<i>Quercus alba L.</i>	0.979	1.514	0.81	Within a 1.92 10⁴ m² plot	45	Eq.
	Red oak	<i>Quercus rubra L.</i>	1.122	1.440	0.75	Within a 1.92 10⁴ m² plot	60	Eq.
Wullschleger and Hanson, 2006*	White oak	<i>Quercus alba L.</i>	0.1021	1.5483	0.89	Within a 1.92 10⁴ m² plot	24	Eq.
	Chestnut oak	<i>Quercus prinus L.</i>	0.1146	1.7154	0.92	Within a 1.92 10⁴ m² plot	24	Eq.
	Red oak	<i>Quercus rubra L.</i>	0.0875	1.5075	0.77	Within a 1.92 10⁴ m² plot	24	Eq.
Meinzer et al., 2005	Oregon oak	<i>Quercus garryana</i>	0.37	1.42	/	/	6	Eq.
Poyatos et al., 2007**	Pubescent oak	<i>Quercus pubescens</i>	4.16	0.66	/	78.5 m² (Within a 10m circle)	10	Eq.
Limousin et al., 2009	Mediterranean oak	<i>Quercus ilex</i>	0.363	2.149	0.97	4.2 10² m² (Taken outside of the three 140 m ² plots)	18	Eq.
Grossiord et al., 2014*	Turkey oak	<i>Quercus cerris</i>	1.843	1.6351	0.90	2.7 10³ m² (Selected right outside the three 30 * 30m study plots)	21	Eq.
	Sessile oak	<i>Quercus petraea</i>	0.3653	1.8483	0.94	2.7 10³ m² (idem)	48	Eq.
Jung et al., 2011	Mongolian oak	<i>Quercus mongolica</i>	0.1846	2.1	0.94	2.0 10³ m² (Taken in the 40 m * 50 m plot)	9	Eq.
Aranda et al., 2005	Sessile oak	<i>Quercus petraea</i>	0.90	1.7	0.92	/ (In a plot near the experimental site)	/	Eq.
Salomon et al., 2020	Mediterranean oak	<i>Quercus ilex</i>	0.682	1.911	/	3.0 10² m² (Within three plots of 10 × 10 m)	20	Eq.
Benson et al., 2019***	Live oak	<i>Quercus virginia Mill</i>	0.1808	0.4788	0.97	/	19	Raw
	Water oak	<i>Quercus nigra L.</i>	2.320	1.995	0.80	/	7	Raw
Martin et al., 1998	Scarlet oak	<i>Quercus. coccinea Muenchh.</i>	0.2544	1.7	0.80	/ (Within the Coweeta Bassin)	5	Raw
	White oak	<i>Quercus alba L.</i>	0.1148	1.973	0.88	/ (Idem)	10	Raw

	Chestnut oak	<i>Quercus prinus L.</i>	1.496	1.372	0.95	/ (Idem)	10	Raw
	Red oak	<i>Quercus rubra L.</i>	0.1876	1.801	0.79	/ (Idem)	9	Raw
Schmidt, 2007	Sessile oak	<i>Quercus petraea</i>	0.0627	2.25	0.97	1.58 10⁴ m² (Within a 1.29 and a 0.23 ha plots)	20	Raw
Other relationship conformation than power law function								
Study	Common name	Binomial name	Equation		R²	Covered area (m²)*	Trees	Data
Bovard et al., 2005	Red oak	<i>Quercus rubra L.</i>	3.24 * DBH - 10.24		0.90	2.3 10³ m² (Within a 0.23 ha-plot)	11	Eq.
Jonard et al., 2011	Sessile oak	<i>Quercus petraea</i>	9.442 * DBH -129.11		0.73	2.5 10³ m² (Within a 0.23 ha-plot)	16	Eq.
Wang et al., 2010	Mongolian oak	<i>Quercus mongolica</i>	$\log_{10}A_s = -1.05(\log_{10} \text{DBH}) + 2.1$		0.95	/	8	Eq.
Zhu et al., 2016	Chinese cork oak	<i>Quercus variabilis Blume</i>	$0.0083 * e^{0.0495 \text{ DBH}}$		0.95	/ (Outside the experimental plots)	10	Eq.

* These studies used Eq. 1 with A_s in m² and DBH in m

** This study used basal area instead of DBH in Eq.1

*** Not measured at breast height but at various heights in each tree (2.2 different heights per tree, on average)

Table 2. Meteorological and stand characteristics of the studies on *Quercus petraea*.

Study	Mean annual Temperature (°C)	Total annual precipitation (mm)	Tree density (Tree/ha)
Our study	8.9	815	301
Aranda et al., 2005	8.1	1105	867
Schmidt, 2007	7.7	800	350 & 636*
Jonard et al., 2011	9.8	1044	468
Grossiord et al., 2014	13.5	950	867

* Two plots with two densities mentioned

Figures

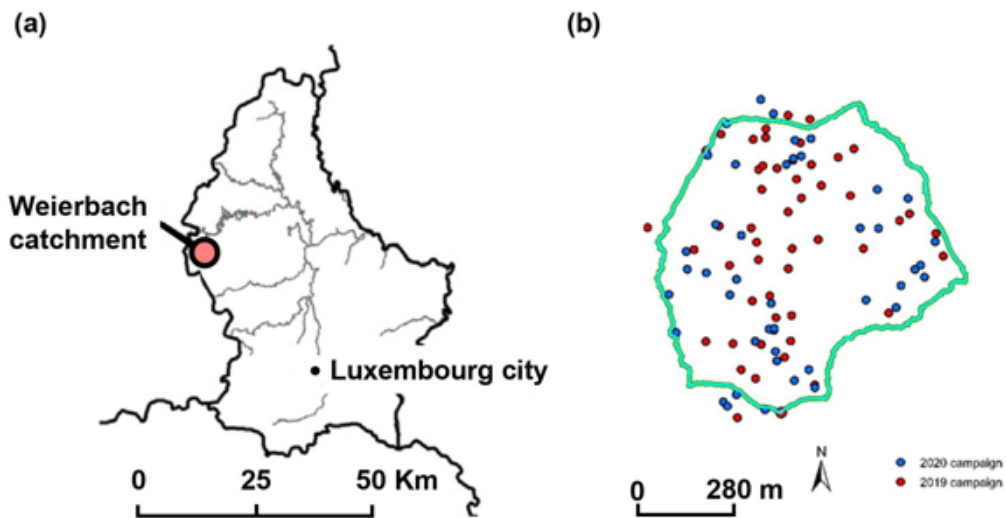


Figure 1

Location of the study site within Luxembourg (a) and location of the wood core samplings within the catchment (b).
Panel B: Red circles represent the location of the trees sampled in 2019 and blue circles represent the location of the trees sampled in 2020. Light green line delineates the catchment boundaries.

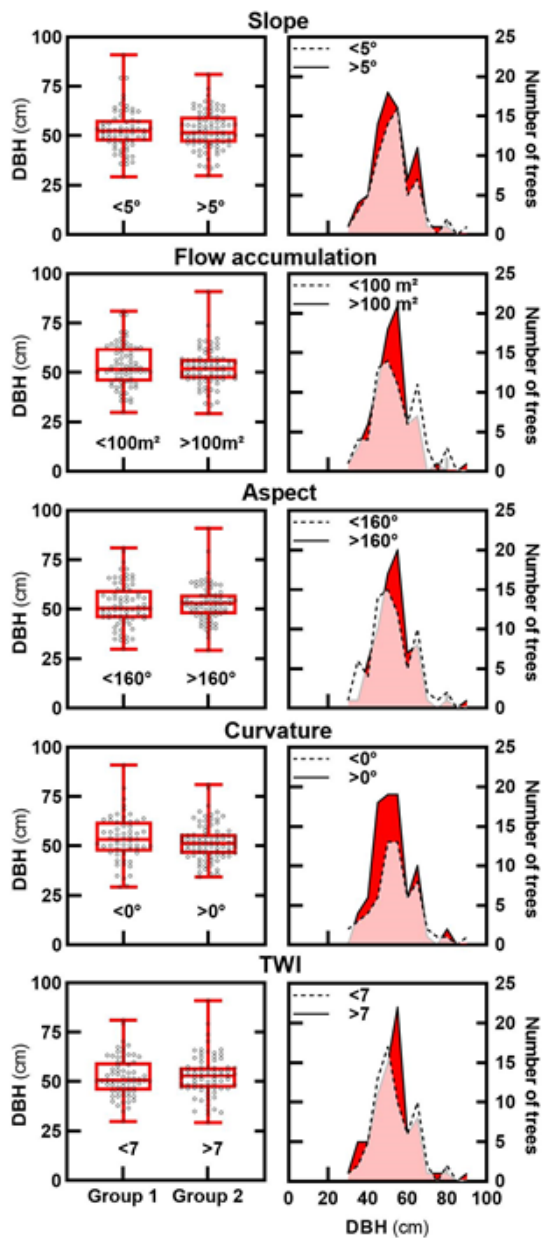


Figure 2

Topographical characteristics associated with each group of tree. Left panels display boxplots of the topographical characteristics with horizontal lines representing the minimum, mean and maximum values of DBH. Right panels display the DBH distribution within each group of trees.

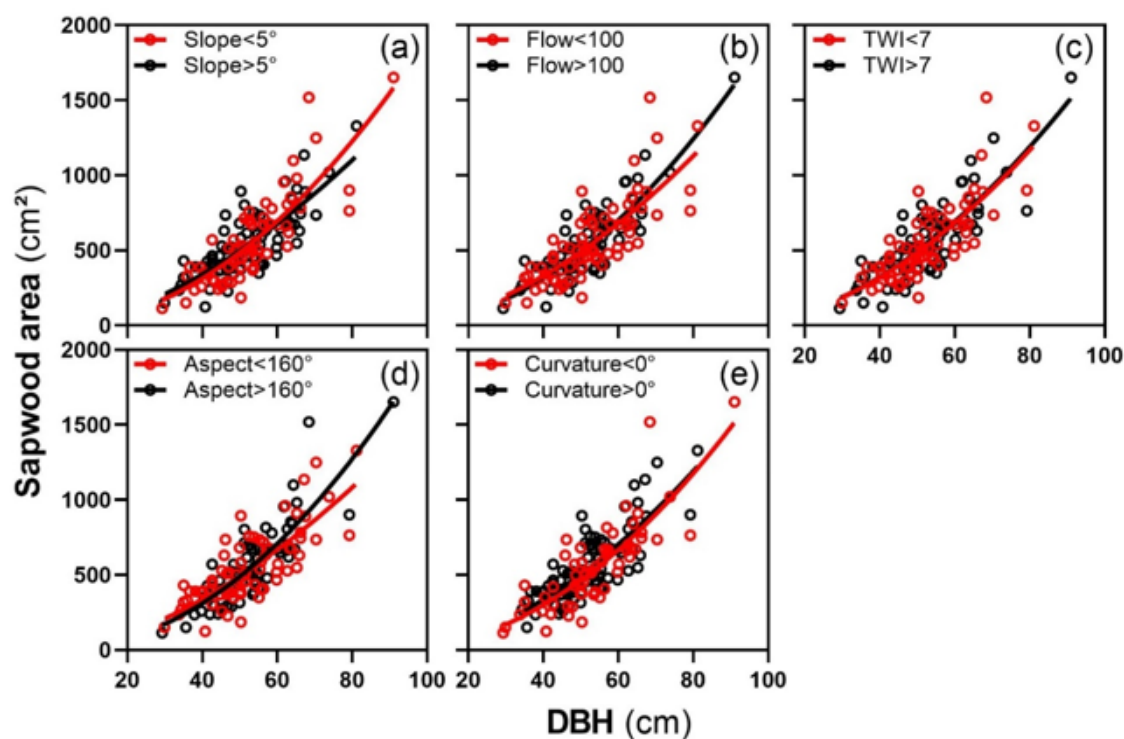


Figure 3

Effect of the topographical characteristics on the A_s -DBH allometric relationship. Each circle represents one tree and the colours denote their group within each topographical characteristic. Black and red curves represent the A_s -DBH allometric relationship (Eq.1) fitted to each group of data.

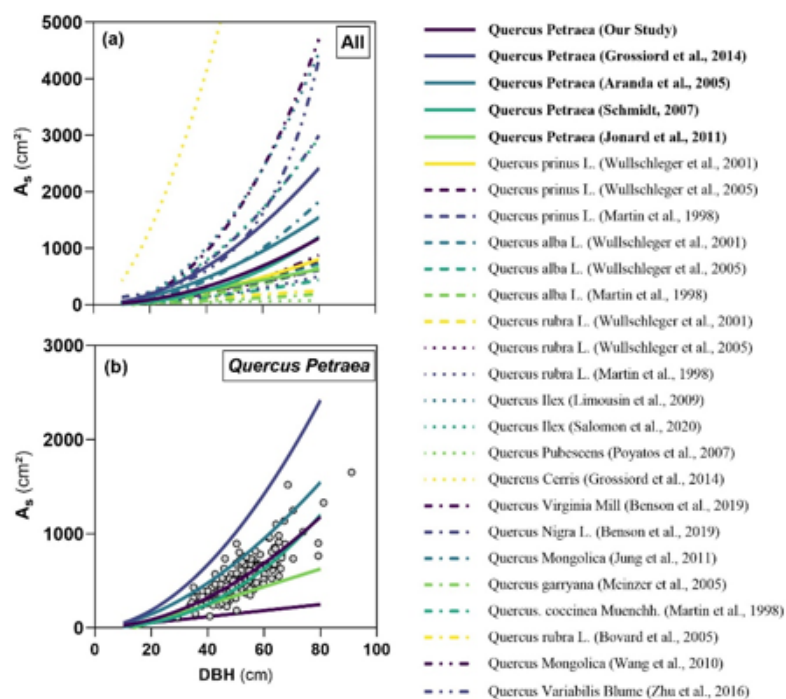


Figure 4

DBH allometric curves determined on *Quercus* trees. Panel (a) displays the A_s -DBH relationships of all *Quercus* species from literature while panel (b) displays the A_s -DBH relationship on *Quercus petraea* only. Different colours represent different studies and species (see legend). In panel (b), each grey circle represents one of our core measurements.