Annals of Forest Science (2018) 75: 50
https://doi.org/10.1007/s13595-018-0730-x

DATA PAPER

A dataset of leaf inclination angles for temperate and boreal broadleaf woody species

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Received: 14 September 2017 / Accepted: 26 March 2018 / Published online: 18 April 2018

Keywords Leaf inclination angle distribution · G-function · Optical canopy instrumentation · Leveled digital photography

1 Background

Angular distribution of leaves is a major determinant of radiation transmittance through the canopy. Leaf inclination angle distribution plays a fundamental role in the leaf projection function (commonly referred to as G-function), which is in turn a key variable for the indirect quantification of leaf area index (Ross 1981).

To date, relatively few measurements of leaf inclination angle have been reported for different tree species; compilation of large datasets has long been hampered due to issues in consistently applying existing methods to tree canopies, difficulty of applying direct methods in the field and unsatisfactory ability of these methods to reproduce measurements and to collect a representative number of leaves.

Recently, Ryu et al. (2010) proposed a robust and affordable method based on leveled photography to provide reliable leaf inclination angle measurements in broadleaf trees, which are comparable to direct measurements (Pisek et al. 2011). Pisek et al. (2013) and Raabe et al. (2015) used this method to compile a dataset of leaf inclination angles for selected temperate and boreal broadleaf tree species.

The dataset presented here integrates and expands the previous measurements to produce the largest existing dataset of leaf inclination angle measurements, covering 138 temperate and boreal broadleaf woody species.[1]

Handling Editor: Marianne Peiffer

Key message Knowledge about leaf inclination angle distribution is essential for determining the radiation transmission within vegetation canopies and to indirectly quantify canopy attributes such as leaf area index and G-function. For this purpose, we measured and compiled an extensive dataset of leaf inclination angles for 138 deciduous broadleaf woody species commonly found in temperate and boreal ecoclimatic regions. We released an R routine to calculate leaf inclination angle statistics, leaf inclination angle distribution type, and G-function from measured leaf inclination angles, which can be used to parametrize optical measurements of light transmittance and for radiative transfer modeling purposes. The leaf inclination angle distribution type can be also used as a plant functional trait to understand light use and photosynthetic plant strategies and to perform functional diversity analyses. Dataset access is at https://doi.org/10.17632/4rmc7r8zvy.2 Associated metadata is available at https://metadata-afs.nancy.inra.fr/geonetwork/srv/eng/catalog.search#/metadata/c1197b55-a582-4ed4-82bc-7008ce9294d9.

Contribution of the co-authors All authors equally contributed to the work.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s13595-018-0730-x) contains supplementary material, which is available to authorized users.

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2 Methods

2.1 Basic theory

For horizontally homogeneous canopy, the probability of light transmittance through the canopy has been commonly described by Beer's law, as firstly introduced by Monsi and Saeki (1953):

$$P(\theta) = \exp\left[\frac{-G(\theta)L}{\cos\theta}\right] \tag{1}$$

[1] For simplicity, we referred to the measured plants as woody species; however, two perennial plants belonging to the *Poaceae* grass family and one fern species were also included in the dataset.

where P is the canopy gap fraction, L is the effective leaf area index, and G is the "G-function" and corresponds to the fraction of foliage area on a plane perpendicular to the view angle θ (Ross 1981). The value of G-function can be calculated by integrating the leaf inclination angle distribution function $f(\theta_L)$ over the leaf inclination angle θ_L, defined as the angle between the leaf surface normal and the zenith (Ross 1981). Assuming an azimuthally symmetric canopy, we can write:

$$G(\theta) = \int_0^{\pi/2} A(\theta,\theta_L) f(\theta_L) d\theta_L \tag{2}$$

A is the projection coefficient for the leaf inclination angle θ_L and the view angle θ (Warren Wilson 1960):

$$A(\theta,\theta_L) = \begin{cases} \cos\theta\cos\theta_L & |\cot\theta\cot\theta_L| > 1 \\ \cos\theta\cos\theta_L[1 + (2/\pi)(\tan\psi - \psi)] & |\cot\theta\cot\theta_L| \le 1 \end{cases} \tag{3}$$

$$\psi = \cos^{-1}(\cot\theta\cot\theta_L)$$

2.2 Digital leveled photographic measurements of leaf inclination angles

The method proposed by Ryu et al. (2010) consists of acquiring leveled images of the canopy using a digital camera. Images shall be taken during calm conditions, to prevent wind effects on leaves (Kimes and Kirchner 1983). As some species may display phototropism, leaves shall be measured in all the azimuth directions and along the vertical profile of the surrounding canopy. Crowns of trees can be observed using towers, extendable poles, ladder, nearby tall buildings, or unmanned aerial vehicles (McNeil et al. 2016). Here we used leveled images for 55 tree species collected by Pisek et al. (2013) and Raabe et al. (2015) at different sites in Sweden, Estonia, and the USA. An additional set of leveled images was also collected for 83 species at various sites in Tuscany, central Italy. The species list is provided in Table 1. The full description of the measurement sites is available as dataset content ("Tab.S1") from the repository URL (see Section 3).

Following Pisek et al. (2013), a minimum of 75 leaf inclination angle measurements have been collected for each plant species, to obtain a statistical representative sample to characterize the leaf inclination angle distribution of each plant species. The measurement of leaf inclination angle requires the identification of the leaf plane, from which the leaf normal is measured (Fig. 1). For this reason, the leaves were selected from those oriented approximately parallel to the viewing direction of the camera (i.e., the leaves shown as a line in the image; Fig. 1), avoiding bended leaves to be measured. The leaf angles of the selected leaves were then measured using the "angle measurement tool" of the freeware program "ImageJ" (http://rsbweb.nih.gov/ij/).

The leaf inclination angle distribution for each species was estimated from measured leaf inclination angles. Wang et al. (2007) identified the two-parameter beta-distribution (Goel and Strebel 1984) as the most appropriate distribution to represent the probability density of θ_L:

$$f(t) = \frac{1}{B(\mu,\nu)}(1-t)^{\mu-1}t^{\nu-1} \tag{4}$$

where $t = 2\,\theta_L/\pi$ and θ_L is expressed in radians. The beta-distribution $B(\mu,\nu)$ is defined as:

$$B(\mu,\nu) = \int_0^1 (1-x)^{\mu-1}x^{\nu-1}dx = \frac{\Gamma(\mu)\Gamma(\nu)}{\Gamma(\mu+\nu)} \tag{5}$$

where Γ is the gamma function and μ and ν are the two parameters of the beta-distribution, which are calculated as:

$$\mu = \left(1-\bar{t}\right)\left(\frac{\sigma_0^2}{\sigma_t^2}-1\right) \tag{6}$$

$$\nu = \bar{t}\left(\frac{\sigma_0^2}{\sigma_t^2}-1\right) \tag{7}$$

where σ_0^2 is the maximum standard deviation with an expected mean $\bar{t}$ and σ_t^2 is the variance of t (Wang et al. 2007).

Following de Wit (1965), leaf inclination angle distributions can be described using six common functions based on empirical evidence of the natural variation of leaf normal distributions and mathematical considerations: planophile, plagiophile, uniform, spherical, erectophile, and extremophile (Fig. 2 and Table 2). In spherical canopies, the relative frequency of leaf inclination angle is the same as for a sphere; planophile canopies are dominated by horizontally oriented leaves; plagiophile canopies are dominated by inclined leaves; erectophile canopies are dominated by vertically oriented leaves; extremophile canopies are characterized by both horizontally and vertically oriented leaves; uniform canopies are characterized by equal proportion of leaf inclination angles for any angle.

As these classical distributions are widely used and easier to interpret than the parameter values of the beta-distribution, all measured leaf inclination angle distributions were additionally classified by assigning them to the closest classical distribution

Table 1 List of plant species available in the dataset

Species name					
1	*Acacia dealbata* Link	47	*Euonymus europaeus* L.	93	*Prunus avium* var. *plena* L.
2	*Acer burgerianum* Miq	48	*Euonymus nikoensis* Nakai	94	*Prunus cerasifera* var. *pissardii* Ehrh.
3	*Acer campestre* L.	49	*Fagus sylvatica* L.	95	*Prunus cocomilia* Ten.
4	*Acer griseum* (Franch.) Pax	50	*Ficus carica* L.	96	*Prunus domestica* L.
5	*Acer miyabei* Maxim.	51	*Fraxinus angustifolia* Vahl	97	*Prunus laurocerasus* L.
6	*Acer monspessulanum* L.	52	*Fraxinus ornus* L.	98	*Prunus serotina* Ehrh.
7	*Acer negundo* L.	53	*Ginkgo biloba* L.	99	*Prunus serrula* Lindl.
8	*Acer platanoides* L.	54	*Gymnocladus dioicus* (L.) K. Koch	100	*Prunus spinosa* L.
9	*Acer pseudoplatanus* L.	55	*Hamamelis virginiana* L.	101	*Prunus subhirtella* Miq.
10	*Acer rubrum* L.	56	*Hedera helix* L.	102	*Pteridium aquilinum* L. Kuhn
11	*Acer truncatum* Bunge	57	*Hibiscus moscheutos* subsp. *palustris* (L.) R.T. Clausen (Newbiscus XXL)	103	*Pterocarya fraxinifolia* (Poiret) Spach
12	*Aesculus hippocastanum* L.	58	*Ilex aquifolium* L.	104	*Punica granatum* L.
13	*Ailanthus altissima* (Miller) Swingle	59	*Juglans nigra* L.	105	*Pyracantha coccinea* M.J. Roemer
14	*Alnus cordata* (Loisel.) Loisel.	60	*Juglans regia* L.	106	*Pyrus communis* L.
15	*Alnus glutinosa* (L.) Gaertner	61	*Laburnum alpinum* (Miller) Berchtold & J. Presl	107	*Quercus cerris* L.
16	*Alnus incana* (L.) Moench	62	*Laurus nobilis* L.	108	*Quercus ilex* L.
17	*Alnus viridis* (Chaix) DC.	63	*Ligustrum vulgare* L.	109	*Quercus petraea* (Mattuschka) Liebl.
18	*Alnus viridis* subsp. *sinuata* (Chaix) DC.	64	*Liquidambar styraciflua* L.	110	*Quercus pubescens* Willd.
19	*Amorpha fruticosa* L.	65	*Lonicera maackii* (Rupr.) Maxim.	111	*Quercus robur* L.
20	*Arbutus unedo* L.	66	*Mahonia aquifolium* (Pursh) Nutt.	112	*Quercus rubra* L.
21	*Arundo donax* L.	67	*Malus domestica* Borkh.	113	*Quercus suber* L.
22	*Berberis aristata* DC.	68	*Malus sylvestris* Miller	114	*Rhamnus alaternus* L.
23	*Betula alleghaniensis* Britt.	69	*Malus yunnanensis* var. *veitchii* Rehder	115	*Rhamnus parviflora* Klein & Willd
24	*Betula pendula* Roth	70	*Mespilus germanica* L.	116	*Robinia pseudoacacia* L.
25	*Buxus sempervirens* L.	71	*Morus alba* L.	117	*Rosa canina* L.
26	*Campsis radicans* (L.) Seem	72	*Morus australis* Poir.	118	*Salix acutifolia* Willd.
27	*Capparis spinosa* L.	73	*Morus nigra* L.	119	*Salix alba* L.
28	*Carpinus betulus* L.	74	*Myrtus communis* L.	120	*Salix caprea* L.
29	*Castanea sativa* Miller	75	*Nerium oleander* L.	121	*Sambucus nigra* L.
30	*Cercidiphyllum magnificum* Nakai	76	*Olea europaea* var. *frantoio* L.	122	*Sorbus aria* (L.) Crantz
31	*Cercis siliquastrum* L.	77	*Osmanthus fragans* Lour.	123	*Sorbus domestica* L.
32	*Citrus limon* (L.) Burm. f.	78	*Ostrya carpinifolia* Scop.	124	*Sorbus hybrida* L.
33	*Clematis vitalba* L.	79	*Parthenocissus quinquefolia* (L.) Planchon	125	*Sorbus rufoferruginea* C.K. Schneid
34	*Cornus mas* L.	80	*Paulownia tomentosa* Steud	126	*Sorbus subarranensis* Hyl
35	*Cornus officinalis* Torr. ex Dur.	81	*Philadelphus sericanthus* Koehne	127	*Sorbus subsimilis* Hedl.
36	*Cornus sanguinea* L.	82	*Phillyrea angustifolia* L.	128	*Sorbus torminalis* (L.) Crantz
37	*Corylus avellana* L.	83	*Phillyrea latifolia* L.	129	*Syringa oblata* Lindl.
38	*Cotoneaster lacteus* W. W. Sm.	84	*Photinia serrulata* Lindl.	130	*Syringa tomentella* subsp. *yunnanensis* (Franch.) Jin Y. Chen & D.Y. Hong
39	*Crataegus monogyna* Jacq.	85	*Phyllostachys bambusoides* Siebold & Zucc.	131	*Syringa villosa* subsp. *wolfii* C.K.Schneid.
40	*Crataegus rhiphidophylla* Stagg	86	*Pistacia lentiscus* L.	132	*Syringa vulgaris* L.
41	*Diospyros kaki* L.	87	*Pittosporum tobira* (Thunb.) Aiton fil.	133	*Trachelospermum jasminoides* Lindl.
42	*Diospyros lotus* L.	88	*Platanus acerifolia* (Aiton) Willd.	134	*Ulmus minor* Miller
43	*Elaeagnus rhamnoides* (L.) A. Nelson	89	*Populus alba* L.	135	*Viburnum lantana* L.
44	*Elaeagnus umbellata* Thunb	90	*Populus nigra* L.	136	*Viburnum tinus* L.
45	*Eleutherococcus sessiliflorus* (Rupr. & Maxim.) S.Y. Hu	91	*Populus tremula* L.	137	*Zelkova serrata* (Thunb.) Makino
46	*Escallonia rubra* (Ruiz & Pav) Pers.	92	*Prunus armeniaca* L.	138	*Ziziphus jujuba* Miller

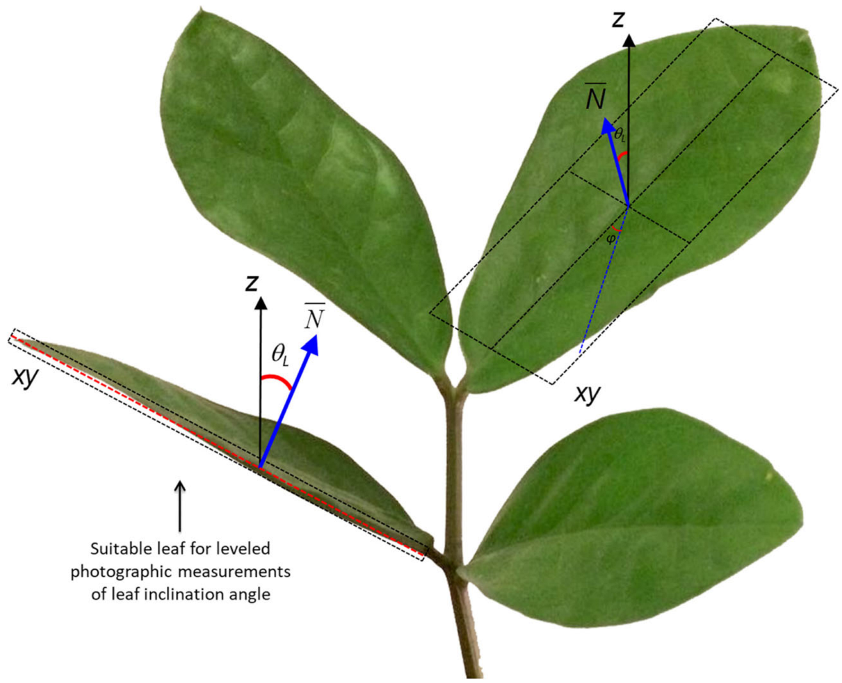

Fig. 1 Example of leaf inclination angle measurements from leveled photography. The measure of leaf inclination angle requires the identification of a hypothetical leaf plane *xy*, from which the leaf surface normal $\overline{N}$ is calculated with respect to the zenith (z). In a 3-D space, calculation of the leaf surface normal requires the knowledge of the azimuth rotation angle φ, which is calculated from the 3-D coordinates of the leaves (right side of the figure). In a 2-D space, such as a digital image, the only measurable leaf normal is that oriented perpendicular to the camera viewing direction, since the leaf inclination plane is parallel to the leaves (the red dashed line on the left side of the figure)

type. For each leaf inclination angle distribution, its deviation from the distributions suggested by de Wit $f_{\text{de Wit}}(\theta_L)$ was quantified using a modified version of the inclination index provided by Ross (1975):

$$\chi_{L}= \min \int_0^{\pi/2} |f(\theta_L)-f_{\text{de Wit}}(\theta_L)|d\theta_L \qquad (8)$$

2.3 Dataset content

The dataset is comprised of four files, consisting of two descriptive tables ("Tab. S1.xlsx" and "Tab.S2.xlsx"), a routine ("Script.r") coded in R (Cran Development Team, Vienna), and the dataset ("dataset_full.csv"), which are available from the repository URL (see Section 3). The latter reports leaf inclination angle measurements obtained for 138 plant species (column "Angle_degree"). The leaf inclination measurements were derived from images collected at a single time over the growing season for some species (130 species; data from Pisek et al. 2013 and this study) and several times during the growing season for some other species (8 species; data from Raabe et al. 2015). In addition, measurements have been conducted at either whole canopy level (i.e., images were not classified according to different canopy height levels but a combination of images from all canopy height levels was used) for some species (126 species), or by dividing measurements into height classes (i.e., the images were taken at several canopy height levels and then grouped into three broad height classes—bottom, middle, and top of canopy—dividing the canopy into three approximately equal parts; 16 species), or by using both approaches (5 species).

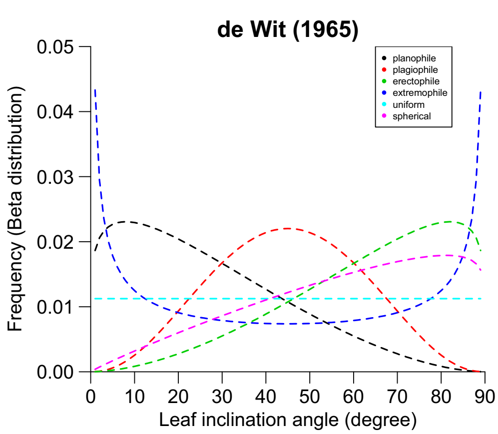

Fig. 2 Beta-distribution for the six theoretical leaf inclination angle distributions by de Wit (1965)

Table 2 Average leaf inclination angle (ALIA, degrees), and μ and ν parameters of beta-distribution for the theoretical leaf inclination angle distributions proposed by de Wit (1965)

Leaf inclination angle distribution	ALIA	μ	ν
Planophile	26.8	2.770	1.172
Erectophile	63.2	1.172	2.770
Plagiophile	45.0	3.326	3.326
Extremophile	45.0	0.433	0.433
Uniform	45.0	1.000	1.000
Spherical	57.3	1.101	1.930

To identify each plant species, four columns were compiled with the following information: UNECE/ICP species code ("ICP_CODE"; available only for European species), Family ("Family"), Genus ("Genus"), Species ("Species"), and Author(s) citation name(s) ("Author_citation"). The column "Canopy_sector" indicates whether measurements have been conducted at whole canopy level or by dividing measurements into bottom, middle, and top of canopy height classes. An additional column ("Date") was reported for the analysis of repeated measurements conducted during the growing season by Raabe et al. (2015).

The additional "Script.r" R routine file allows the user to (i) characterize the leaf inclination angle distribution by fitting the beta-distribution (Eq. 4), (ii) determine the leaf inclination angle distribution type, according to de Wit (1965) (Eq. 8 and Table 2), and (iii) calculate the G-function from the measured leaf inclination angles (Eq. 2). Summary statistics (average leaf inclination angle ("ALIA"), standard deviation ("SD"), μ, ν parameters of beta-distribution ("mu", "nu"), number of leaf inclination angle measurements ("NR"), leaf inclination angle distribution type ("Distribution"), and date of image acquisition ("Date") of the collected data can be also generated from the routine. These summary statistics are also reported in the "Tab.S2" available at the repository URL (see Section 3). Finally, the file "Tab.S1" (available at the repository URL) contains a full description of the measurement sites.

3 Access to data and metadata description

The dataset can be downloaded using the following reference and doi: Chianucci et al. (2017). A dataset of leaf inclination angles for temperate and boreal broadleaf woody species. Mendeley Data, V2, [Dataset] https://doi.org/10.17632/4rmc7r8zvy.2 under the Creative Commons Attribution—Non Commercial 4.0 License. The repository contains four files associated with the dataset, as described in Section 2.3 above ("dataset_full.csv"; "Script.r"; "Tab.S1.xlsx"; "Tab.S2.xlsx"). The metadata description ("metadata.xls") is available at the repository URL and https://metadata-afs.nancy.inra.fr/geonetwork/srv/eng/catalog.search#/metadata/c1197b55-a582-4ed4-82bc-7008ce9294d9.The metadata description reports information about data coverage and access (e.g., geographic range, temporal coverage, data provider, accessibility of collected data), data context (material, methods, and measurement protocols used for data collection, and analytical perspectives), and technical information (description of all tables, variables, and fields available from the dataset content).

4 Technical validation

The dataset includes 23,882 measurements (records) of leaf inclination angles associated with the 138 broadleaved species. The identification, classification, and naming of plant were performed during field data acquisition by expert botanists. Nomenclature of each tree has been carefully checked. For European species, the adopted nomenclature was set according to UNECE/ICP species code (available at http://icp-forests.net/page/expert-panel-on-biodiversity), which is mainly based on *Flora Europaea* (http://ww2.bgbm.org/EuroPlusMed/query.asp).

Measurements of leaf inclination angles have been conducted by four trained users. For measurements conducted in Italy, all plant species have been measured independently by two expert users to check whether the calculated leaf inclination angle distribution type agreed for each species; we then retained the measurements having higher number of measured leaves per species among users. For the remaining species, Raabe et al. (2015) demonstrated that the method is quite robust in providing the same leaf inclination angle distribution type, irrespective of the user and their previous experience with measuring leaf inclination angles.

5 Reuse potential and limits

Quantification of leaf inclination angle distribution $f(\theta_L)$ and G-function is fundamental for the characterization of radiation transmittance through the canopy and for the indirect estimation of leaf area index (Campbell and Norman 1989; Myneni et al. 1989; Ross 1981). As such, the dataset can provide species-specific parameters to retrieve canopy structure from optical measurements of radiation transmittance. From that perspective, the data provided here can fill the following gaps, which exist in the current methods using optical data of the canopies:

i) Hemispherical sensors usually eliminate the influence of leaf inclination angle distribution by either integrating measurements of radiation transmittance at the full hemispherical view range (Miller 1967) or by restricting measurements close to 57° view (Bonhomme and Chartier 1972). However, previous studies indicated that the accuracy of $f(\theta_L)$ calculated from these approaches was affected by actual canopy structure (Chen and Black 1991; Macfarlane et al. 2007; Wagner and Hagemeier 2006).

ii) A commonly adopted alternative approach is assuming a spherical distribution of foliage, because of the difficulty in estimating $f(\theta_L)$. Pisek et al. (2013) demonstrated that the spherical inclination angle distribution is not that frequent in real canopies, which was also verified with measured inclination angles available from the current dataset (only nine species exhibited a spherical leaf inclination angle distribution).

iii) Restricted view angle methods require independent parametrization of G-function. These include most recent optical canopy devices such as smartphones (De Bei et al. 2016), downward-looking cameras (Macfarlane and Ogden 2012), and unmanned aerial vehicles (Chianucci et al. 2016).

In addition, the species-specific parameters provided in this dataset can be used in urban forestry and urban greening to either parametrize optical measurements conducted in single trees (Chianucci et al. 2015b) or to model ecophysiological processes on green roofs (Lazzarin et al. 2005) and vertical greenery systems (Susorova et al. 2013; Wong et al. 2010). Leaf inclination angle statistics can be used to compare measurements performed for the same species by other studies and/or other methods like terrestrial laser scanning (Bailey and Mahaffee 2017; Hosoi and Omasa 2015), LAI-2000 Plant Canopy Analyzer (Zou et al. 2014), and hemispherical photography (Chianucci and Cutini 2013; Chianucci et al. 2015a). The leaf inclination angle distribution can provide information for understanding light use efficiency and photosynthetic strategies of different plant species (Angelini et al. 2015; Niinemets 2010). The leaf inclination angle distribution type can be also used as a plant functional trait, which can be used for functional diversity analyses (e.g., Laliberté and Legendre 2010).

It is worth noticing that measurements for some plant species available from the dataset have been limited to young individuals. The leaf inclination angle measurements in these species may differ from those measured in mature plants, since vegetation canopies may exhibit variation in angular distribution of leaves according to canopy height (Niinemets 1998) and/or plant successional stages (e.g., Hikosaka and Hirose 1997). We plan to include measurements in mature trees and additional plant species in future versions of the dataset, once new measurements will be obtained from future field campaigns.

Acknowledgments We thank the anonymous reviewer and the handling editor Marianne Peiffer for the constructive comments, which improved the original version of the manuscript.

Funding Luca Marchino was supported by the LIFE Project FutureForCoppiceS (LIFE14 ENV/IT/000514)—www.futureforcoppices.eu. Jan Pisek and Kairi Raabe were supported by the Estonian Research Council grant PUT1355 and Mobilitas Pluss MOBERC-11.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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