Leaf area index in a forested mountain catchment

Ladislav PALÁN[1], Josef KŘEČEK[1] and Yoshinobu SATO[2]

Abstract

Leaf area index (LAI) belongs among the catchment characteristics widely used in hydrological models but still associated with great uncertainties. In a mountain forest catchment, the leaf area affects retention and evapotranspiration loss, and it could be significantly modified by forestry practices. In this study, LAI in mature stands of Norway spruce *(Picea abies)* and European beech *(Fagus sylvatica)* was analysed in headwater catchments of the Jizera Mountains (Czech Republic) between 2012 and 2016. A comparison evaluation of LAI in harvested site with dominant herbaceous vegetation was taken into account by applying direct ground investigation what was compared with hemispherical canopy photography (Gap light analyser GLA-V2) and satellite remote sensing (Sentinel-2 mission). While the direct ground measurement includes only the foliage (leaves or needles), the Gap light analysis is affected by trunks and branches, and the remote sensing techniques by herbaceous understory. The results of the Gap light analyser underestimated the ground based LAI values by 52–76 per cent, and satellite interpretations by 29–73 per cent. The remote sensing is capable to provide effective information on the distribution of LAI within the time and space. However, in a catchment scale, the satellite detection underestimated average LAI values approx. by 42–62 per cent. Changes in the observed rainfall interception reflected well the LAI variation.

Keywords: mountain watershed, forest canopy, leaf area index, gap light analyser, satellite remote sensing

Introduction

Leaf area index (LAI) belongs to the canopy characteristics often used in hydrological and environmental studies (Jones, H.G. 1992; Cowling, S.A. and Field, C.B. 2003). Leaf area affects the canopy storage capacity (amount of water retained in the canopy), an important parameter of many interception models (Gash, J.H.C. *et al.* 1980). In practical forestry, density of a forest stand is quantified by the number of stems per hectare, the basal area per hectare, eventually, by the crown closure percentage identified at aerial photographs (Watts, S.B. and Tolland, L. 2005). In hydrological models, LAI is used to estimate water budget of the vegetative canopy by calculating the deposited precipitation (rain, snow, fog etc.) (Federer, A. 1993; Allen, R.G. *et al.* 2005; Punčochář, P. *et al.* 2012; Křeček, J. *et al.* 2017). Watson, D.J. (1947) considered the leaf area index as the total one-side area of leaves per unit ground surface. To estimate LAI, both direct and indirect methods were developed (Cowling, S.A. and Field, C.B. 2003). The direct methods are more accurate but laborious and destructive, and representing a patch scale; while indirect methods based on the transmission of solar radiation through the canopy can provide approximates over large areas (Anderson, M.C. 1971). In the last years, several remote sensing algorithms of LAI have been evolved (Weiss, M. and Baret, F. 2016); the European Space Agency (ESA 2017) has developed an algorithm to calculate LAI based on the data of the satellite mission Sentinel 2 and direct ground measurements.

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[1] Department of Hydrology, Czech Technical University in Prague, Thákurova 7. CZ-166 29 Prague 6, Czech Republic. E-mail: josef.krecek@fsv.cvut.cz (Correspondent author.)

[2] Department of Science and Technology for Biological Resources and Environment, Ehime University, 10-13, Dogo-Himata, Matsuyama, Ehime 790-8577, Japan.

Across the large amount of observed data, LAI estimates correlate with the vegetation type, geography and environmental circumstances. Concerning the herbaceous vegetation, Gosa, A.G. *et al.* (2007) reported LAI between 0.7 and 4.5, while Ramiréz-García, J. *et al.* (2012) summarized LAI of meadows between 2 and 3. For higher vegetation, LAI between 1.5 and 5.7 is reported for shrubs and between 4.5 and 10.6 for forests (Gosa, A.G. *et al.* 2007). Lovett, G.M. and Reiners, W.A. (1986) found in spruce stands the surface area index between 5 and 6, Breda, N.J.J. (2003) reported LAI variations in forests between 3.5 (pine) and 7.5 (spruce). However, the specific LAI estimates show relatively high divergences (up to 100%), Brenner, A.J. *et al.* (1995). Therefore, it is evident that the extrapolation of the reported LAI data is limited and for a specific research field it is necessary to estimate the LAI parameter by the existing methodology. The aim of this paper is to compare the direct and indirect methods to estimate LAI values for environmental investigations of the acid atmospheric deposition in headwater catchments of the Jizera Mountains, Czech Republic (Křeček, J. and Hořická, Z. 2010; Křeček, J. *et al*. 2010). This study focused on stands of Norway spruce (*Picea abie*) and European beech (*Fagus sylvatica*), as well as on the herbaceous vegetation growing at clear-cut areas.

Material and methods

This study was performed in the upper plain of the Jizera Mountains located in a humid temperate climate (subarctic region Dfc of the Köppen climate zonation; Tolasz, R. 2007). The analysis of LAI was performed in headwater catchments Jizerka (J-1), Josefův Důl (JD) and Oldřichov (O) in 2012 (*Figure 1*).

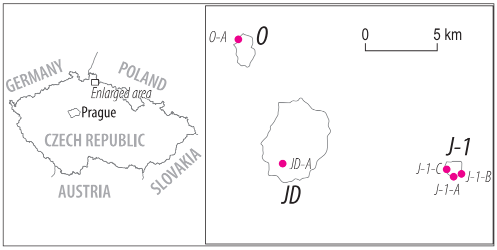

Fig. 1. Investigated headwater catchments of the Jizera Mountains with marked plots of LAI ground observations. – J-1 = Jizerka; JD = Josefův Důl; O = Oldřichov

In five forest plots (J-1-A, J-1-B, J-1-C, JD-A, O-A, squares of 30×30 metres), LAI was estimated by both direct and indirect methods. These studied forest stands are even-aged and single-storied with negligible herb layer, the plot J-1-C represents a harvested area (clear-cutting) with the forest regrowth retarded by a rapid development of herbaceous understory. Common characteristics of the stands were estimated by standard forest inventory according to Shiver, B.D. and Borders, B.E. (1996). The allometric relationship between stem diameter (DBH, measured in the breast height of 1.3 m) and foliage area was used in spruce stands (JD-A, J-1-A, J-1-B, J-1-C) by a destructive sampling of needles at harvested trees (Breda, N.J.J. 2003; Fehrmann, L. and Kleinn, C. 2006). The leaf area was measured on a sub-sample of leaves to calculate the specific leaf area (SLA, m^2 g^{-1}) in ratio to its dry mass. Finally, the total dry mass of leaves collected within a known ground-surface area is converted into LAI by multiplying by the SLA. According to Watson, D.J. (1947), LAI is understood here as a one-sided area of photosynthetically active canopy surface per unit of horizontal ground area.

In the beech forest (O-A), the non-destructive method of collecting leaves below the canopy was applied during the autumn leaf fall (Breda, N.J.J. 2003). Collected litter was dried at 60–80 °C for 48 hours) and weighed to calculate compute the dry mass. The leaf area of herbaceous understory was estimated by harvesting ten 0.25×0.25 m squares per each stand. The surface area of sampled leaves was measured by the portable leaf area meter ELE 470-010/01.

Simultaneously, two indirect methods were applied: the hemispherical canopy photography (Gap light analyser GLA-V2, Frazer, G.W. *et al.* 1999) and remote sensing (Sentinel-2 mission, ESA 2017). The gap fraction – based methods depend on the leaf-angle distribution. According to Campbell, G.S. (1986), LAI may be express by the equation (1):

$$LAI = \frac{1}{G(\theta)} \ln (P(\theta)) \cos(\theta), \tag{1}$$

where LAI = leaf area index, θ = zenith angle of the view, $P(\theta)$ = gap fraction, $G(\theta)$ = G-function corresponding to the fraction of foliage projected on the plane normal to the zenith direction.

Digital hemispherical photographs were collected under different sky brightness conditions. In July 2012, a camera Nikon CoolPix 4500 with FC-E8 fish-eye lens was employed and ten photos were managed in each investigated forest plot (corresponding with the spots of rain collectors installed under the canopy). Photographs were taken skyward from the forest floor with a 180° hemispherical lens to record the size, shape, and location of gaps in the forest overstory. The free imaging software GLA Version 2.0 (Frazer, G.W. 1999) was used to analyse the canopy (to extract the canopy structure and gap light transmission indices from true-colour fisheye photographs), and to estimate LAI values by the zenith angle 0–60° (LAI 4), (*Figure 2).*

For an aerial extrapolation of the ground observations, data of the European Space Agency satellite mission Sentinel 2 with a 10 m resolution (ESA, 2017) were employed. These data might lead to a better result in comparison with the 30 m resolution of the Landsat imagery archive (Křeček, J. *et al.* 2017), particularly, by the strongly non-linear relationship of LAI and reflectance, reported by Garrigues, S. *et al.* (2006). However, the data of Sentinel 2 mission could be easily compared to Landsat mission; Sentinel 2 contains 12 bands (0.43 μm – 2.28 μm). The data of Sentinel 2 – L1C (Level 1C, representing a top of the atmosphere reflectance in cartographic geometry, Mueller-Wilm, U. *et al.* 2016) were collected in the vegetation period 2016 (April–October) and post-processed into L2A (Level 2A, representing atmospheric corrected product and the 'bottom of atmosphere reflectance in cartographic geometry') following procedure of Mueller-Wilm, U. *et al.* (2016) to ensure a correct computation of LAI. However, in this period, only 23 images (with less than 50% cloudiness) were acceptable. Then, the LAI calculation was performed by the Biophysical Processor (S2ToolBox Level 2: estimation of biophysical variables) based on a trained neural network (Weiss, M. *et al.* 2000; Weiss, M. and Baret, F. 2016).

Based on an analysis of a maximal physical range of inputs and outputs, each calculation enables to indicate potentially invalid values of determined LAI (due to the water surface, cloud contamination, poor atmospheric correction, shadow, etc.). To avoid uncertainties in a single point analysis, grids of 5×5 m cells were created in the GIS application on the investigated plots (see *Figure 1*). All gathered LAI values were processed by standard statistical methods, only valid values were kept. Possible changes of the canopy between 2012 and 2016 were controlled by the Landsat imagery according to Křeček, J. and Krčmář, V. (2015).

Additionally, in three two-week periods (June–August, 2012), rainfall penetration within the canopy of investigated stands were registered in daily intervals. Only rain events enough to saturate the canopy storage in days without any significant fog or low cloud occurrence were included in the calculation of canopy interception according to Křeček, J. *et al*. (2017):

$$I = \sum_{i=1}^{n} P - \left(\sum_{i=1}^{n} P_t + \sum_{i=1}^{n} P_s \right), \tag{2}$$

where I = interception storage in mm, P = open field (gross) precipitation in mm, P_t = through-fall under the canopy in mm, P_s = steam-flow, interception loss of the canopy (I), n = number of rainy days.

Three forest stands (J-1-A, JD-A, O-A) were instrumented by ten modified Hellmann rain gauges and stem-flow was collected by plastic tubing (fixed around the stem circumfer-

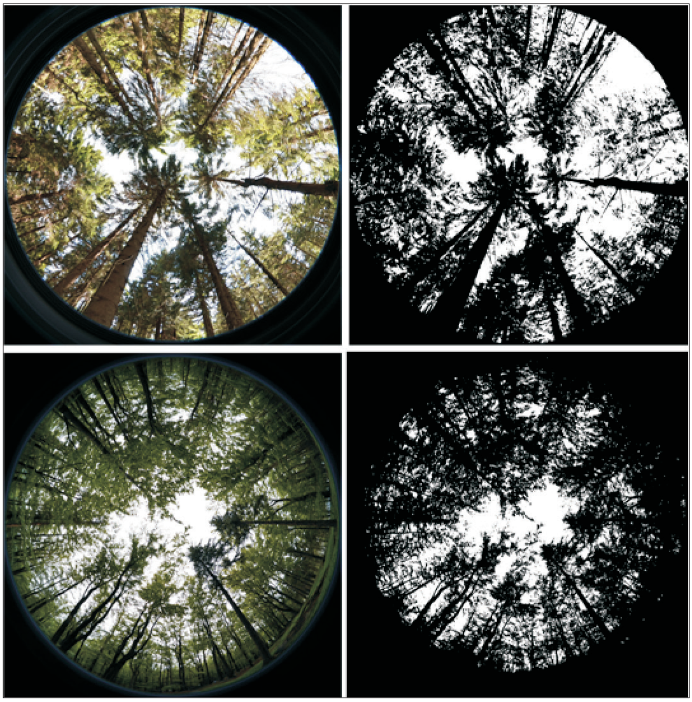

Fig. 2. An example of digital hemispherical photographs taken in investigated plots: Norway spruce (*Picea abies*) – top, and European beech (*Fagus sylvatica*) – bottom. Images registered – left, and processed – right.

ence) at two random tree trunks per each plot (*Figure 3*). The gross precipitation was observed in nearby forest openings (distance between 50 and 200 metres).

Results and discussion

Basic characteristics of the investigated forest stands are given in *Table 1*. From the analysis of sampled trees, the values of specific leaf area (SAI) were found: 17.2, 7.8 and 3.4 m^2/kg for beech, spruce and grass, in a good agreement with data reported by Horntvedt, R. (1993), Breda, N.J.J. (2003), and Liu, Ch. and Westman, C.J. (2009). Regressions between the leaf area LA (m^2) and DBH (cm) in investigated spruce stands were found by $a = 0.74$, $b = 22.8$ (correlation coefficient $R = 0.82$, $R_{crit} = 0.75$, $p = 0.05$, $n = 5$). On the harvested plot (J-1-C), there is a seasonal change in the leaf area described in *Figure 4*. The foliage and LAI values are included in *Table 2*.

Alternatively, LAI values detected by the Gap light analyser are in *Table 3*, and, the seasonal course of LAI provided by the satellite (Sentinel 2) during the vegetation period of 2016 is described in *Figure 5*. Evidently, applications of the Gap light analyser underestimated the ground based LAI of the investigated spruce and beech canopy by 52–76 per cent.

Similarly, Chen, J.M. *et al.* (1991) and Brenner, A.J. *et al.* (1995) reported an underestimation of LAI by hemispherical photographs approx. by 50 per cent (in comparison with the direct destructive methods). Zhang, Y. *et al.* (2005) identified the main LAI errors in just in the automated camera exposure leading to underestimating LAI in a relatively dense canopy and overestimating it in a sparse vegetation cover.

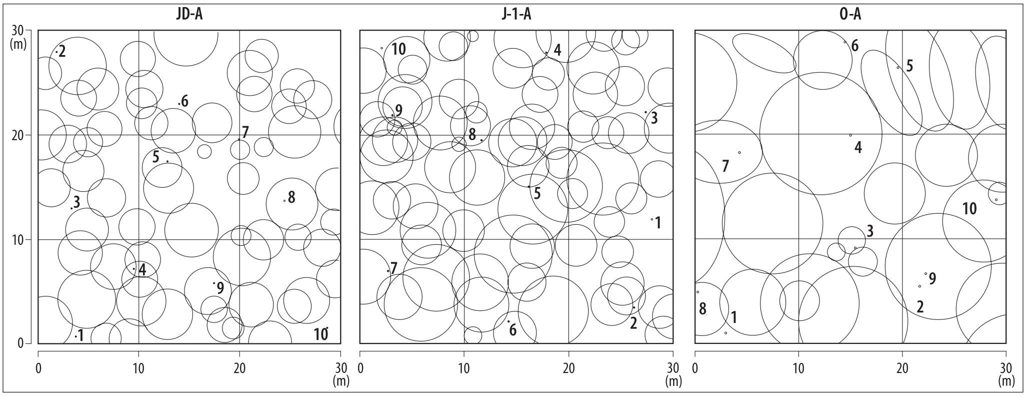

Fig. 3. Crown projection of trees in investigated stands of spruce (JD-A, J-1-A) and beech (O-A) with installed rain collectors (numbers 1–10)

Table 1. Forestry characteristics of the investigated plots

Stand	Dominant canopy	Age class, years	Elevation, m	Number of trees	DBH, cm	Mean height, m
JD-A	Spruce	80–100	745	54	27	24.0
J-1-A	Spruce	80–100	975	68	27	23.0
J-1-B	Spruce	80–100	945	27	36	23.0
J-1-C*	Grass	1–20	918	72	–	0.5
O-A	Beech	>141	506	28	37	25.0

*J-1-C plot represents harvested area overgrown by herbaceous vegetation (*Calamagrostis sp.*); this plot was reforested, but new seedlings still does not create a significant canopy.

Similarly, the satellite estimates underestimated LAI by 29–73 per cent by preferring the herb layers. It is evident that those remote sensing observations are more likely sensitive to an 'effective leaf area index' by reflecting heterogeneity in the leaf distribution. These uncertainties can cause the discrepancies in LAI values, particularly, the differences between the direct ground methodology and remote sensing applications. Chen, J.M. *et al.* (2005) suggested quantifying differences between actual and effective LAI by the clumping index between 0.5 for a fully closed canopy, and 1 for a sparse canopy with randomly distributed leaves.

Remote sensing techniques enable an easy and fast extrapolation of LAI in a catchment scale. However, the comparison of various plots can be affected by possible cloud appearance. The satellite LAI approximation within three selected headwater catchments in the Jizera Mountains is demonstrated in *Figure 6*. It is evident that there are relatively

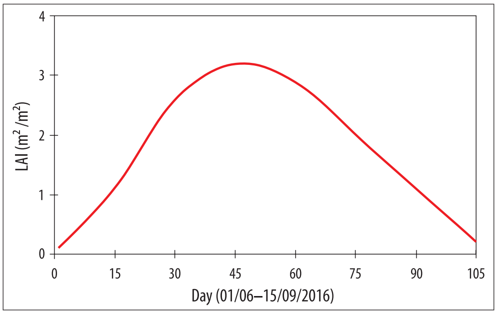

Fig. 4. Seasonal changes of the herbaceous canopy in the stand J-1-C.

Table 2. LAI found by the ground observation (plots of 30 x 30 m)

Stand	Basal area, m^2/ha	Crown closure, %	Dry leaf mass, kg	Foliage area, m^2	LAI
JD-A	41	92	842	6,570	7.3
J-1-A	46	78	773	6,030	6.7
J-1-B	32	61	417	3,253	3.6
J-1-C	–	6	900	2,880	3.2
O-A	41	89	296	5,040	5.6

Table 3. LAI estimated by the Gap Light Analyser (GLA-V2)

Stand	LAI										
	1	2	3	4	5	6	7	8	9	10	Mean
JD-A	1.53	2.39	2.38	1.79	2.77	1.86	2.06	2.08	2.39	2.41	*2.17*
J-1-A	1.69	1.64	1.75	1.81	1.73	1.34	1.27	1.83	2.14	1.22	*1.64*
J-1-B	1.84	1.64	1.77	1.84	1.56	1.68	1.62	1.85	1.72	1.64	*1.72*
O-A	1.59	1.34	1.28	1.54	1.35	1.37	1.55	1.41	1.34	1.78	*1.46*

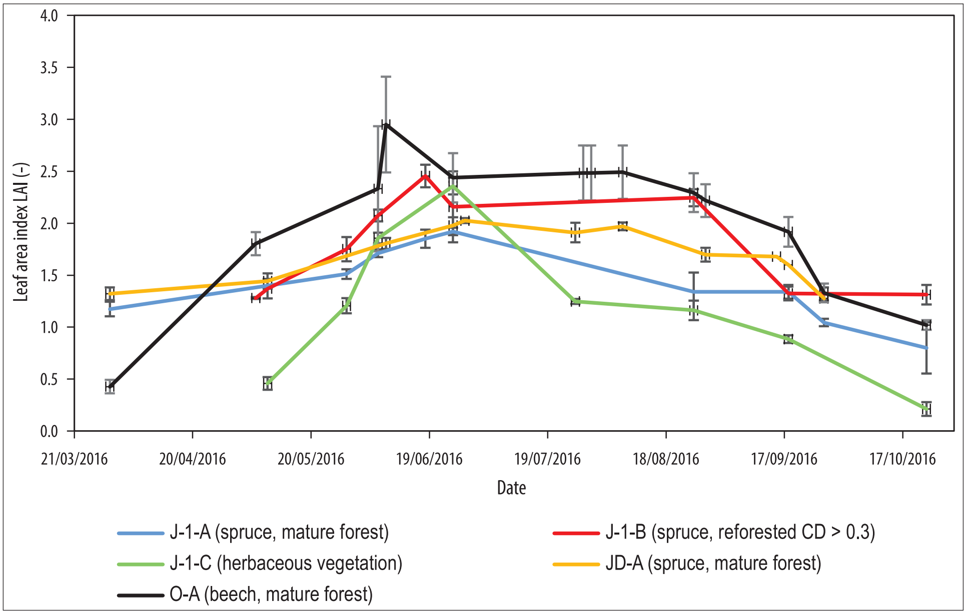

Fig. 5. Satellite estimates of LAI: values provided by the Sentinel 2 mission during the summer months of 2016.

high LAI values in spots of sparse tree occurrence just because of a high sensitivity of the satellite method to the herbaceous canopy. Therefore, the remote sensing method of Sentinel 2 can detect a vegetative surface but not very well the exact density and a foliage area of the canopy. In comparison with the aerial approximation of the direct ground LAI measurements and forest stands detected by LANDSAT imagery (*Figure 7*), the satellite remote sensing underestimates mean catchment LAI values by 42–62 per cent.

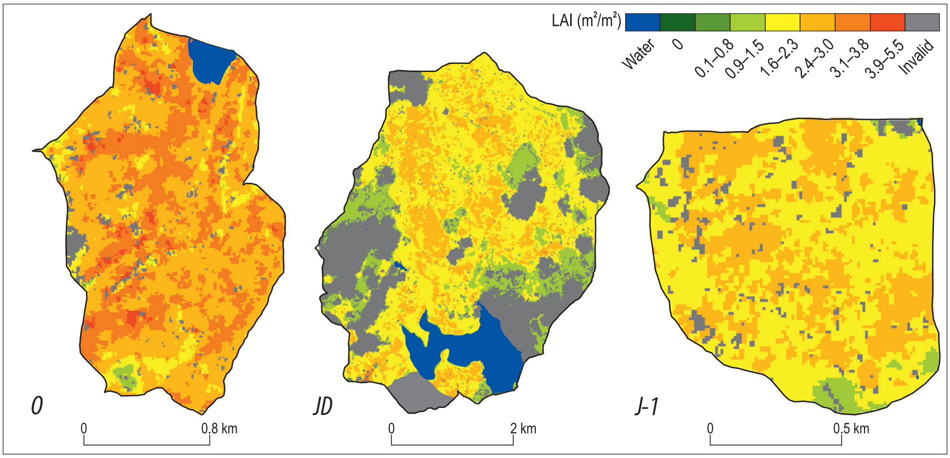

Fig. 6. Satellite LAI values in focused catchments on 25th June 2016. – O = Oldřichov; JD = Josefův Důl; J-1 = Jizerka

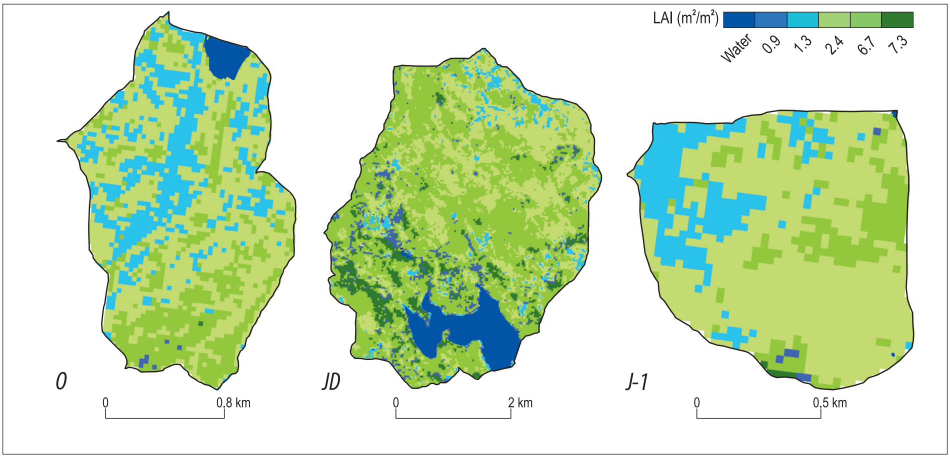

Fig. 7. LAI interpolation according to results of the direct ground observation and detection of forest stands by LANDSAT imagery, 2016. – O, JD, J-1 = for explanation see *Fig. 6.*

In the investigated six-week period of 2012, 16 rainy days without a significant fog occurrence and rainfall enough to saturate the canopy (above the canopy storage capacity) were registered, and the data are presented in *Table 4*.

Both rainfall interception (intercepted percentage of rainfall, *I*) and canopy storage capacity (C_s) correspond well with changes in observed LAI values: correlation coefficient $R = 0.97$ ($R_{crit} = 0.95$, $n = 3$, $p = 0.05$), and we can consider a linear relationship between the canopy storage capacity C_s and leaf area index *LAI*:

$$C_s = 0.395\,LAI - 0.084, \qquad (3)$$

where C_s = canopy storage capacity, *LAI* = leaf area index.

Table 4. Rainfall interception in the studied plots

Indicator	JD-A	J-1-A	O-A
Rainfall interception (I), %	37.0	34.0	26.0
Canopy storage capacity (C_s), mm	2.1	1.7	1.4
Rain to fill canopy storage (R_s), m	3.4	2.8	2.5
Leaf area index (LAI)	7.3	6.7	5.6

With regard to the relatively limited number of interception plots, the relationship (3) has only an informative value, but still can provide us with possible changes in the canopy storage within the extend of investigated LAI values.

Conclusions

The direct ground LAI measurement included the foliage (leaves or needles) of the forest canopy, while indirect LAI estimated are affected also by trunks and branches. Remote sensing techniques reflect all the green parts including the herbaceous understory. In headwater catchments of the Jizera Mountains, the estimates of the Gap light analyser underestimate the ground based LAI values by 52–76 per cent, and satellite interpretations by 29–73 per cent The remote sensing can provide fast and inexpensive information on the distribution of LAI within time and space in focused headwater catchments, and, enables a comparison of relative values among focused plots. However, in a catchment scale, the analysed satellite data underestimated average LAI values approx. by 42–62 per cent. A more valuable output could be considered by the interpolation of direct ground LAI measurements with only a detection of characteristic canopy classes from the both free available satellite imagery Landsat and Sentinel 2. In three plots instrumented with through-fall and stem-flow collectors, there was confirmed a significant relation between the canopy storage capacity and LAI values.

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REFERENCES

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 2005. *Crop evapotranspiration*. FAO Irrigation and Drainage Paper 56. Rome, Food and Agriculture Organization.

Anderson, M.C. 1971. Radiation and crop structure. In *Plant photosynthetic production, manual of methods*. Eds.: Šesták, Z., Čatský, J. and Jarvis, P.G., Hague, Dr. W. Junk, 77–90.

Breda, N.J.J. 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. *Journal of Experimental Botany* 54. 2403–2417.

Brenner, A.J., Cueto Romero, M., Garcia Haro, J., Gilabert, M.A., Incoll, L.D., Martinez Fernandez, J., Porter, E., Pugnaire, F.I. and Younis, M.T. 1995. A comparison of direct and indirect methods for measuring leaf and surface areas of individual bushes. *Plant, Cell and Environment* 18. 1332–1340.

Campbell, G.S. 1986. Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution. *Agricultural and Forest Meteorology* 36. 317–321.

Cowling, S.A. and Field, C.B. 2003. Environmental control of leaf area production: Implications for vegetation and land-surface modeling. *Global Biogeochemical Cycles* 17. 1–11.

ESA, 2017. *Sentinel-2*. https://sentinel.esa.int/web/sentinel/missions/sentinel-2 Accessed on 24.03.2017.

Federer, A. 1993. *BROOK 90: A simulation model for evapotranspiration, soil water and streamflow*. Durham (US), USDA Forest Service.

Fehrmann, L. and Kleinn, C. 2006. General considerations about the use of allometric equations for biomass estimation on the example of Norway spruce in central Europe. *Forest Ecology and Management* 236. 412–421.

Frazer, G.W., Canham, C.D. and Lertzman, K.P. 1999. *Gap Light Analyzer (GLA), Version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, user's manual and program documentation.* Burnaby (British Columbia) – Millbrook (N.Y.), Simon Fraser University – Institute of Ecosystem Studies.

Garrigues, S., Allard, D., Baret, F. and Weiss, M. 2006. Influence landscape spatial heterogeneity on the nonlinear estimation of leaf area index from moderate spatial resolution remote sensing data. *Remote Sensing of Environment* 105. 286–298.

Gash, J.H.C., Wright, I.R. and Loyd, C.R. 1980. Comparative estimates of interception loss from three coniferous forest in Great Britain. *Journal of Hydrology* 48. 89–105.

Gosa, A.G., Schaepman-Strub, G., Kooistra, L., Schaepman, M. and Pellikka, P. 2007. Estimation of leaf area index using optical field instruments and imaging spectroscopy. In *Proceeding 5th Earsel Workshop on Imaging Spectroscopy*. Bruges, Belgium, 1–12.

Horntvedt, R. 1993. Crown density of spruce trees related to needle biomass. *Forest Ecology and Management* 59. 225–235.

Chen, J.M., Black, T.A. and Adams, R.S. 1991. Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand. *Agricultural and Forest Meteorology* 56. 129–143.

Chen, J.M., Menges, C.H. and Leblanc, S.G. 2005. Global mapping of foliage clumping index using multi-angular satellite data. *Remote Sensing of Environment* 97. 447–457.

Jones, H.G. 1992. *Plant and microclimate*. 2nd edition. Cambridge (UK), Cambridge University Press.

Křeček, J. and Hořická, Z. 2010. Recovery of headwater catchments and lakes affected by the acid atmospheric deposition. In *Integrated watershed management*. Eds.: Beheim, E. *et al.* Dordrecht, Springer, 200–207.

Křeček, J. and Krčmář, V. 2015. Landsat imagery applications to identify vegetation recovery from acidification in mountain catchments. *Hungarian Geographical Bulletin* 64. (2): 121–126.

Křeček, J., Nováková, J. and Hořická, Z. 2010. Ellenberg's indicator in water resources control: the Jizera Mountains, Czech Republic. *Ecological Engineering* 36. 1112–1117.

Křeček, J., Palán, L. and Stuchlík, E. 2017. Acid atmospheric deposition in a forested mountain catchment. *iForest* 10. 680–686.

Liu, Ch. and Westman, C.J. 2009. Biomass in a Norway spruce – Scots pine forest: a comparison of estimation methods. *Boreal Environment Research* 14. 875–888.

Lovett, G.M. and Reiners, W.A. 1986. Canopy structure and cloud water deposition in subalpine coniferous forests. *Tellus B* 38. 319–327.

Mueller-Wilm, U., Devignot, O. and Pessiot, L. 2016. *Sen2Cor Configuration and User Manual.* France, ESA.

Punčochář, P., Křeček, J. and Van de Griend, A. 2012. Interception storage in a small Alpine catchment, In *Integrated watershed management*. Eds.: Křeček, J. *et al.* Dordrecht, Springer, 200–207.

Ramiréz-García, J., Quemada, M. and Almendros, P. 2012. Ground cover and leaf area index relationship in a grass, legume and crucifer crop. *Plant, Soil and Environment* 58. 385–390.

Shiver, B.D. and Borders, B.E. 1996. *Sampling techniques for forest resource inventory*. London, John Wiley & Sons.

Tolasz, R. 2007. *Climate atlas of the Czech Republic*. Prague, Czech Hydro-meteorological Institute.

Watson, D.J. 1947. Comparative physiological studies on the growth of field crops: I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Annals of Botany* 11. 41–76.

Watts, S.B. and Tolland, L. 2005. *Forestry Handbook for British Columbia. Vancouver.* Faculty of Forestry, University of British Columbia.

Weiss, M. and Baret, F. 2016. *S2ToolBox Level 2 products: LAI, FAPAR, FCOVER, Version 1.1.* Paris, French National Institute for Agricultural Research (INRA).

Weiss, M., Baret, F., Myneni, R.B., Pragnère, A. and Knyazikhin, Y. 2000. Investigation of a model inversion technique to estimate canopy biophysical variables from spectral and directional reflectance data. *Agronomie* 20. 3–2.

Zhang, Y., Chen, J.M. and Miller, J.R. 2005. Determining digital hemispherical photograph exposure for leaf area index estimation. *Agricultural and Forest Meteorology* 133. 166–181.