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# Comparison of indirect optical methods for estimating effective leaf area index in young Norway spruce stands

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**Abstract:** Forest canopy structure is crucial for regulating light interception, carbon exchange, and water balance, making accurate estimation of leaf area index (*LAI*) essential for forest ecology and management. This study compared three indirect optical methods (LAI-2200 PCA, LaiPen LP 110, and digital hemispherical photography – DHP) for estimating effective leaf area index ($LAI_e$) in young Norway spruce [*Picea abies* (L.) Karst.] stands. It evaluated the influence of the field of view (*FOV*) and seasonal timing on inter-method agreement. The research was conducted in young, even-aged Norway spruce stands at the Křivina experimental site in the Czech Republic, using three research plots with varying stand densities. Results showed that $LAI_e$ estimates were influenced by the selected *FOV*, with mean values generally decreasing as *FOV* increased, particularly for the LAI-2200 PCA. Narrow *FOV* configurations produced greater local variability among sampling positions, whereas broader *FOV*s resulted in more homogeneous spatial canopy patterns. The strongest agreement among methods was observed between LaiPen LP 110 and LAI-2200 PCA, with correlation coefficients ranging from 0.71 to 0.84 across temporally matched measurements. In contrast, DHP exhibited weaker and more variable relationships with LaiPen LP 110. Differences among research plots were most pronounced between the dense control stand and the heavily thinned stand, indicating that canopy density and structural heterogeneity substantially affected $LAI_e$ estimation. The study demonstrates that indirect optical methods are sensitive to both canopy structure and measurement configuration; therefore, careful instrument selection, *FOV* standardisation, and synchronised measurements are essential for obtaining reliable and comparable $LAI_e$ estimates.

**Keywords:** canopy transmittance; digital hemispherical photography; field of view; gap fraction; LaiPen LP 110; LAI 2200 PCA; *Picea abies*

Leaf area index (*LAI*) is defined as half the total green leaf area per unit horizontal ground surface area (Fang et al. 2019). In non-randomly distributed canopies, indirect optical measurements typically quantify the effective leaf area index ($LAI_e$), which represents the value derived by assuming a simple random foliage distribution within the canopy (Fang et al. 2019; Yan et al. 2019). $LAI_e$ value relates to true *LAI* through the clumping index (*CI*), such that $LAI_e = CI \times LAI$ (Chen et al. 1991). In coniferous stands, this distinction is further complicated by hierarchical foliage aggregation and the contribution

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of woody elements, both of which necessitate specific correction factors to reach true *LAI* (Chen 1996; Bréda 2003; Deblonde et al. 1994). As a fundamental structural attribute, *LAI* characterises the canopy-atmosphere interface, where essential energy and mass exchanges occur (Bréda 2003; Iio et al. 2013; Ye, Zhao 2026). It is a critical determinant of light interception and radiation extinction, which directly drive primary productivity and carbon exchange (Bréda 2003; Parker 2020). Furthermore, LAI governs the forest water balance by controlling transpiration and precipitation interception (Ye, Zhao 2026; Fang et al. 2019). Consequently, accurate *LAI* assessment is essential for evaluating forest stand structure and function, as *LAI* is a key parameter in process-based ecosystem simulations and climate models (Parker 2020; Xu et al. 2020).

Competition for light, determined by relative height and crown position, is a primary driver of young stand development and mortality (King 1990). Vertically stratified canopies can enhance light interception and contribute to stand productivity (Niinemets 2010), supported by morphological plasticity and hierarchical clumping in dense coniferous stands (Cescatti 1998; Bednář et al. 2022). Following canopy closure, increasing competition and self-pruning may result in a continuous decline in *LAI* (Ryan et al. 1997; Pokorný et al. 2008).

Direct *LAI* quantification is labour-intensive, as it requires physical measurement of leaf area through destructive biomass harvesting or the collection and analysis of leaf litter (Bréda 2003; Jonckheere et al. 2004). Although such methods provide the most accurate *LAI* estimates, their destructive and laborious nature often restricts their application in large-scale forest research (Schaefer et al. 2015). As a result, indirect optical methods have become widely adopted because they are non-destructive, relatively rapid, and well-suited for repeated field measurements (Seidel et al. 2011; Olivas et al. 2013). These features make them vital for practical stand-level monitoring and various applications, including ecological and silvicultural assessments and the validation of satellite-based vegetation data (Olivas et al. 2013; Woodgate et al. 2015). Based on radiative transfer theory, these methods estimate canopy structure by measuring canopy transmittance or the gap fraction, i.e. the proportion of gaps visible through the canopy (Bréda 2003; Schaefer et al. 2015). These non-destructive techniques typically use canopy analysers or hemispherical photography to efficiently capture the spatial complexity of foliage across different forest types (Olivas et al. 2013; Woodgate et al. 2015).

Various indirect methods, including the LAI-2200 Plant Canopy Analyser (PCA), LaiPen LP 110, and digital hemispherical photography (DHP), represent distinct methodological approaches. The LAI-2200 PCA measures the gap fraction by capturing diffuse blue-light transmittance across five concentric zenith rings using a fisheye sensor (Welles, Cohen 1996). It offers immediate results but requires above-canopy reference readings for calculation (Jonckheere et al. 2004; Danner et al. 2015). The LaiPen LP 110 also uses blue wavelengths but employs a sensor with a limited field of view (*FOV*), measuring transmittance via an internal inclinometer (Černý, Pokorný 2021; Černý et al. 2018). Conversely, DHP is an image-based method that captures a permanent 180° record of canopy structure, enabling gap fraction estimation without reference readings (Chianucci, Cutini 2012; Jonckheere et al. 2004; Fleck et al. 2020). Still, DHP requires extensive post-processing to binarise images and extract structural parameters (Bréda 2003; Chianucci 2020).

In young, dense Norway spruce [*Picea abies* (L.) Karst.] stands, significant differences between methods often arise from complex canopy structures and hierarchical foliage clustering. Typical *LAI* values in Norway spruce forests usually range from 3.1 to 8.2 (Pokorný, Stojnić 2012), but in young, overstocked stands, *LAI* estimates can reach nearly 15.0 (Konôpka et al. 2016). In these stands, foliage clusters around thin branches, leading to high overlap that breaches the assumption of random distribution and causes significant underestimation of $LAI_e$ (Cescatti 1998; Goude et al. 2019). Additionally, differences between methods are influenced by variations in *FOV* and viewing geometry, as $LAI_e$ is highly sensitive to the sampled zenith-angle range (Chianucci 2020; Yan et al. 2021). Furthermore, the transition from sensor-based measurements to image-based DHP introduces significant post-processing sensitivity. DHP estimates are particularly influenced by the choice of thresholding algorithms and binarisation techniques required to retrieve gap fractions from digital images (Chianucci 2020; Lotz et al. 2026).

These methodological divergences necessitate a rigorous evaluation of instrument performance in dense and structurally complex spruce canopies.

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Consequently, this study aims to compare LAI-2200 PCA, LaiPen LP 110, and DHP for estimating $LAI_e$ in young Norway spruce stands with varying stand density, and to evaluate how the agreement among methods changes across the growing season.

## MATERIAL AND METHODS

Study sites. The study was carried out in young, even-aged Norway spruce stands on permanent research plots (PRPs) managed by the Forestry and Game Management Research Institute, Research Station Opočno, Czech Republic. All PRPs are situated at the Křivina site (50°12'55'N, 16°06'51'E; Černý 2023; Giagli et al. 2026) at an elevation of 402 m a.s.l. (Giagli et al. 2023) within the Natural Forest Area 26 – Předhoří Orlických hor. The plots, owned by Lesy Colloredo-Mansfeld Ltd., were established to investigate how different levels of pre-commercial thinning affect the growth and ecophysiological characteristics of Norway spruce stands close to their ecological limit. The site represents a loamy oak-beech site type (*Querceto-Fagetum illimerosum mesotrophicum*; Viewegh et al. 2003). The soil type is a modal Cambisol. Mean annual air temperature is 9.8 °C, and mean annual precipitation is 570.5 mm for the 2019–2023 period, as measured by a meteorological station located in an open area 500 m from the studied PRPs (Černý et al. 2025). The studied area falls within the Köppen–Geiger Cfb climate zone (temperate oceanic climate), characterised by mild temperatures and evenly distributed precipitation throughout the year (Peel et al. 2007).

The site was artificially regenerated in 2005 after mechanical soil preparation using a disc trencher, with advanced container-grown Norway spruce planting stock initially spaced at about 3 500 trees per ha. In 2018, three PRPs (A, B, C), each measuring 40 × 65 m, were established in 13-year-old stands. During winter 2019/2020 (February 2020), these PRPs underwent varying thinning intensities: Plot A was subjected to mild thinning, which reduced stand density to 2 062 trees per ha. Plot B was left untreated as a control, maintaining 3 512 trees per ha. Plot C underwent heavy thinning, lowering the density to 1 369 trees per ha (Černý et al. 2025). Thinning involved negative selection, primarily removing trees from the lower canopy layer. Downwind stand edges were retained to maintain mechanical stability. All logging residues were removed from the stands after thinning (Černý 2023).

During 2019–2023, annual stand inventories were conducted at the end of September. Diameter at breast height (*DBH*) was measured at 1.3 m above the ground using a calliper with an accuracy of 0.1 cm in two perpendicular directions, and the final *DBH* value for each tree was calculated as the arithmetic mean of the two measurements. Mean plot-level *DBH* was calculated as the arithmetic mean of all trees present on the plot. Tree height (*H*) and green crown base height (*GCBH*; from 2021 onwards) were measured using a Vertex IV hypsometer (Haglöf, Sweden) with an accuracy of 0.1 m (Černý et al. 2025). Basic dendrometric characteristics of the studied stands are summarised in Table 1.

**Measurement of effective leaf area index.** $LAI_e$ was estimated in 2023 using three indirect optical methods: LAI-2200 PCA (LI-COR, USA), LaiPen LP 110 (PSI, Czech Republic) and DHP acquired with a Nikon Coolpix P5100 camera and an FC-E8 lens (Nikon, Japan). Measurements were carried out at 18 regularly distributed below-canopy grid sampling points on each PRP (A, B, C). However, the measurement dates were not identical across methods; specifically, LAI-2200 PCA measurements were taken on 10 August, 29 August, and 20 October; LaiPen LP 110 measurements were taken on 13 June, 29 August, and 20 October; and DHP measurements were taken on 13 June, 4 August, and 20 October. Therefore, the three methods were not available as a fully synchronous dataset across all measurement campaigns. Strict inter-method comparisons were restricted to temporally matched campaigns only, namely LaiPen LP 110 versus DHP on 13 June and 20 October; LaiPen LP 110 versus LAI-2200 PCA on 29 August and 20 October; and DHP versus LAI-2200 PCA on 20 October.

All measurements were conducted under optimal synoptic conditions to minimise errors due to rapidly changing irradiance and canopy movement (Čater et al. 2013). All below-canopy readings and DHPs were taken at 1.3 m above the ground. For LaiPen LP 110 and LAI-2200 PCA in dual mode, reference measurements above the canopy were collected in a large open area adjacent to the studied stands (Fleck et al. 2020). The LAI-2200 PCA was used without horizontal or azimuthal shading, while LaiPen LP 110 was operated with the fixed restrictor provided by the manufacturer, as described by Černý and Pokorný (2021). For LAI-2200 PCA and DHPs,

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Table 1. Basic dendrometric characteristics (mean ± SD) of young even-aged Norway spruce stands at permanent research plots (A, B, C) in 2019–2023

| Year | PRP | Age (years) | Stand density (tree·ha$^{-1}$) | *DBH* (cm) | *H* (m) | *GCBH* (m) |
|---|---|---|---|---|---|---|
| 2019 | A | 14 | 3 569 | 8.5 ± 2.5 | 7.3 ± 1.4 | NM |
| | B | | 3 527 | 7.9 ± 2.4 | 7.0 ± 1.5 | NM |
| | C | | 3 685 | 7.7 ± 2.3 | 6.8 ± 1.4 | NM |
| 2020 | A | 15 | 2 062 | 10.4 ± 2.2 | 9.1 ± 1.0 | NM |
| | B | | 3 519 | 8.5 ± 2.5 | 8.7 ± 1.0 | NM |
| | C | | 1 369 | 10.0 ± 1.8 | 8.7 ± 1.0 | NM |
| 2021 | A | 16 | 2 058 | 11.5 ± 2.4 | 9.4 ± 1.1 | 1.8 ± 0.4 |
| | B | | 3 512 | 9.2 ± 2.8 | 8.4 ± 1.7 | 1.6 ± 0.5 |
| | C | | 1 365 | 11.4 ± 2.1 | 9.1 ± 1.1 | 1.4 ± 0.4 |
| 2022 | A | 17 | 2 058 | 12.2 ± 2.5 | 10.1 ± 1.3 | 2.1 ± 0.6 |
| | B | | 3 492 | 9.6 ± 2.9 | 8.9 ± 1.8 | 2.3 ± 0.7 |
| | C | | 1 362 | 12.5 ± 2.2 | 9.8 ± 1.2 | 1.6 ± 0.4 |
| 2023 | A | 18 | 2 023 | 12.6 ± 2.5 | 10.9 ± 3.9 | 2.8 ± 0.7 |
| | B | | 3 442 | 9.9 ± 3.0 | 9.4 ± 1.8 | 2.8 ± 0.9 |
| | C | | 1 331 | 13.1 ± 2.3 | 10.6 ± 1.2 | 1.9 ± 0.5 |

PRP – permanent research plot; A – mildly thinned PRP; B – unthinned PRP; C – heavily thinned PRP; *DBH* – diameter at breast height (1.3 m above the ground); *H* – tree height; *GCBH* – green crown base height; NM – not measured

data were evaluated separately for five sensor *FOV*s, corresponding to zenith angles of 68°, 53°, 38°, 23° and 7° (LI-COR 2011). In contrast, LaiPen LP 110 was used with a fixed, non-adjustable manufacturer-supplied restrictor with an *FOV* of 16° in the *z*-axis and 112° in the *x*-axis (Černý, Pokorný 2021).

DHPs were taken at the same below-canopy sampling points at the same height as the analyser-based measurements. Within each method-specific campaign, all observations were collected at identical sampling points at each PRP. For this study, all three approaches were evaluated at the $LAI_e$ level. All LAI-2200 PCA data were processed in FV2200 software (LI-COR, USA), LaiPen LP 110 data were processed in the FluorPen software (Version 1.2.0.0, 2026), and DHPs were analysed in WinSCANOPY (Version Pro, 2020).

Statistical analysis. Because each silvicultural variant was represented by only one permanent research plot (PRP), the study lacked true treatment replication. Differences among PRPs A, B, and C were therefore interpreted as case-specific plot contrasts rather than as replicated effects of the thinning treatment.

For each method, sampling date, and *FOV* configuration, $LAI_e$ values from the 18 sampling positions were analysed at the point level. For DHP and LAI-2200 PCA, *FOV*-specific estimates were retained separately for the 7°, 23°, 38°, 53°, and 68° configurations. LaiPen LP 110 was analysed as a fixed measurement configuration corresponding to the Lpfix class.

Differences among PRPs within each method × date × *FOV* combination were evaluated using one-way analysis of variance with PRP as the explanatory factor. Where applicable, post hoc pairwise comparisons among PRPs were performed using Tukey's honest significant difference test. Compact letter displays were assigned to indicate groups that differed significantly at $\alpha = 0.05$.

Direct comparisons of used methods were restricted to temporally matched measurement campaigns. LaiPen LP 110 was compared with DHP on 13 June and 20 October 2023, and with LAI-2200 PCA on 29 August and 20 October 2023. Comparisons were performed separately for each *FOV*-specific DHP or LAI-2200 PCA estimate, without averaging across *FOV*s.

For each paired comparison, $LAI_e$ estimates from identical PRP, date, and sampling-position combinations were matched. Method-to-method relationships were assessed using Pearson correlation coefficients. All analyses were conducted in R (R Core Team 2025). Post hoc comparisons were based on ANOVA and Tukey HSD procedures.

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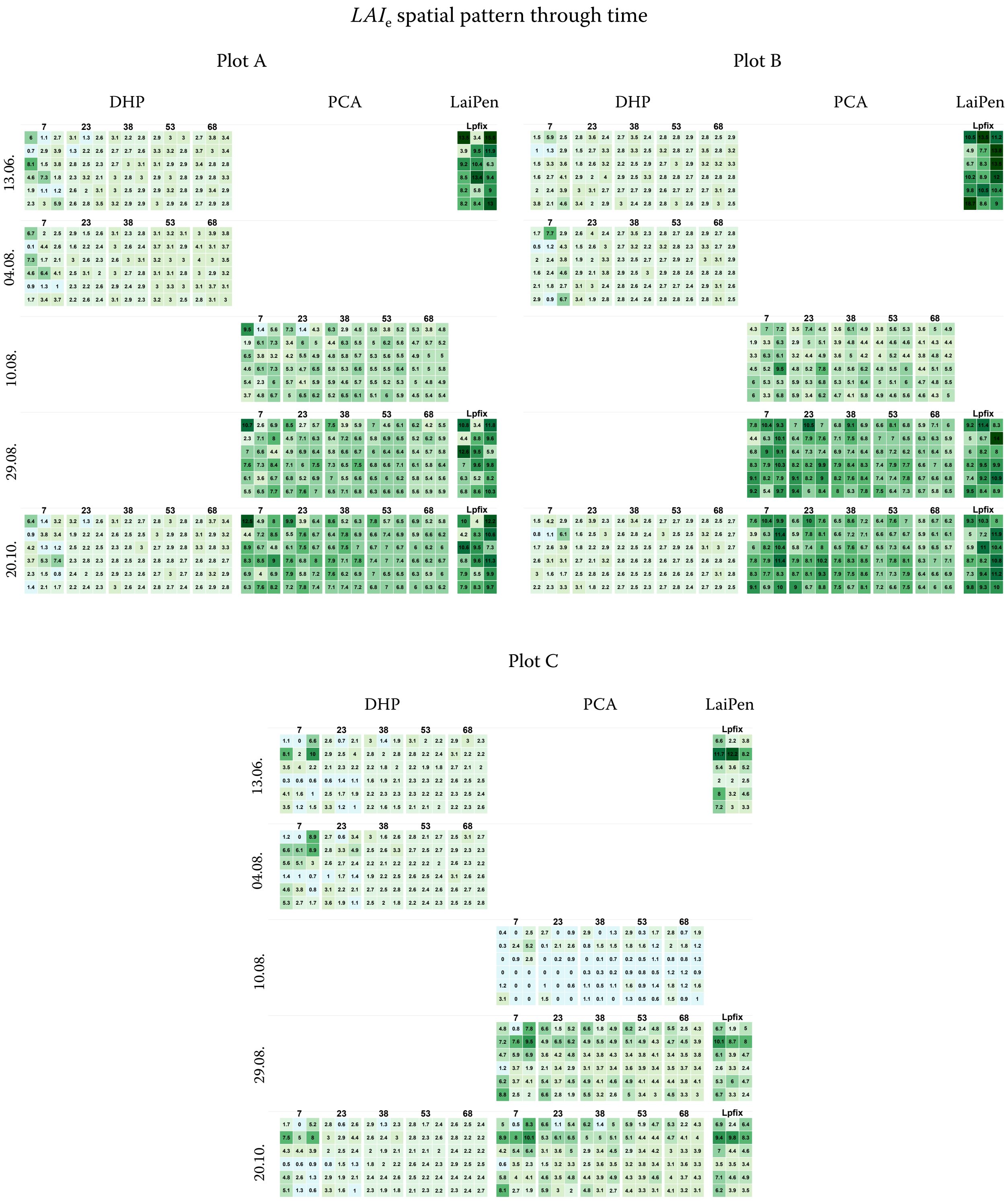

Figure 1. Spatially explicit representation of effective leaf area index ($LAI_e$) estimates obtained at 18 regularly distributed below-canopy sampling positions within permanent research plots (PRPs) A–C during the 2023 measurement campaigns

DHP – digital hemispherical photography; PCA – LAI-2200 Plant Canopy Analyser; LaiPen – LaiPen LP 110; individual panels preserve the spatial arrangement of the sampling grid within each PRP and display point-level $LAI_e$ values as colour-scaled tiles; panels are organised by PRP, measurement method (DHP, LAI-2200 PCA, and LaiPen LP 110), sampling date, and field of view (*FOV*); DHP and LAI-2200 PCA are shown for *FOV* settings of 7°, 23°, 38°, 53°, and 68°, whereas LaiPen LP 110 is represented by the fixed Lpfix configuration

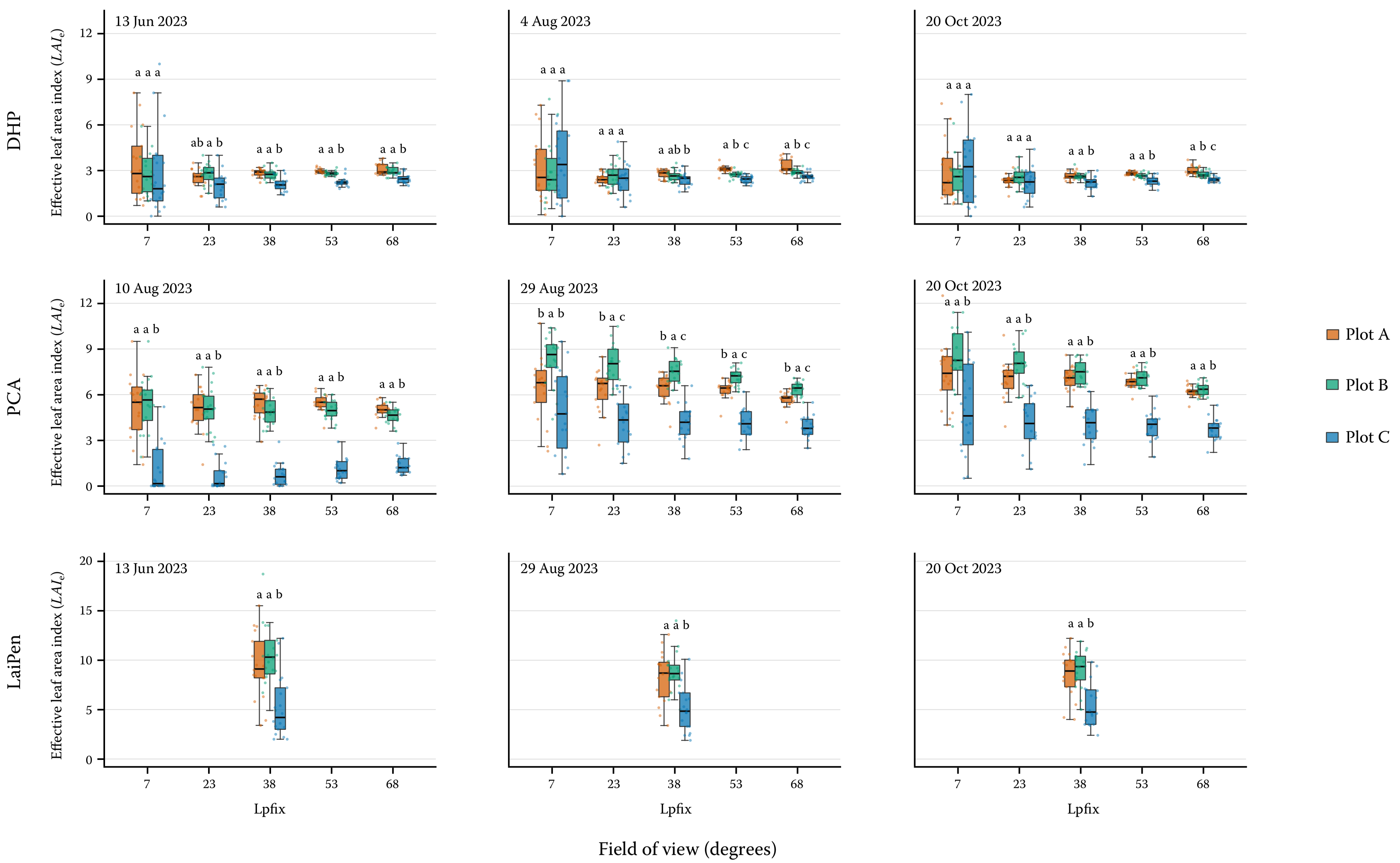

Figure 2. Distribution of effective leaf area index ($LAI_e$) estimates across permanent research plots (PRPs) A–C, measurement dates, methods, and fields of view (*FOV*s)

DHP – digital hemispherical photography; PCA – LAI-2200 Plant Canopy Analyser; LaiPen – LaiPen LP 110; boxplots summarise point-level observations from 18 below-canopy sampling positions within each PRP × date × method × *FOV* combination; overlaid points represent individual measurements; DHP and LAI-2200 PCA are presented for *FOV* settings of 7°, 23°, 38°, 53°, and 68°, whereas LaiPen LP 110 is represented by the fixed Lpfix configuration; different letters above the boxplots denote significant differences among PRPs, as determined by post hoc Tukey HSD comparisons within individual date–method–*FOV* combinations ($P < 0.05$)

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## RESULTS

Spatially explicit patterns of $LAI_e$ (Figure 1) showed that estimates were relatively consistent across *FOV* settings, while spatial variability among sampling positions gradually decreased towards broader *FOV*s (53° and 68°). The overall spatial structure within PRPs remained visually similar across measurement campaigns, indicating relatively stable spatial organisation of canopy openness patterns despite seasonal variation.

In LAI-2200 PCA, narrow *FOV*s produced substantially higher local variability among sampling positions, whereas broader *FOV*s resulted in progressively more homogeneous spatial patterns. Simultaneously, mean $LAI_e$ values generally decreased with increasing *FOV*, most prominently in PRP B, where narrow-angle measurements produced markedly higher estimates than broad-angle configurations. Despite these shifts in magnitude, relative within-plot spatial structures remained partially preserved across *FOV*s.

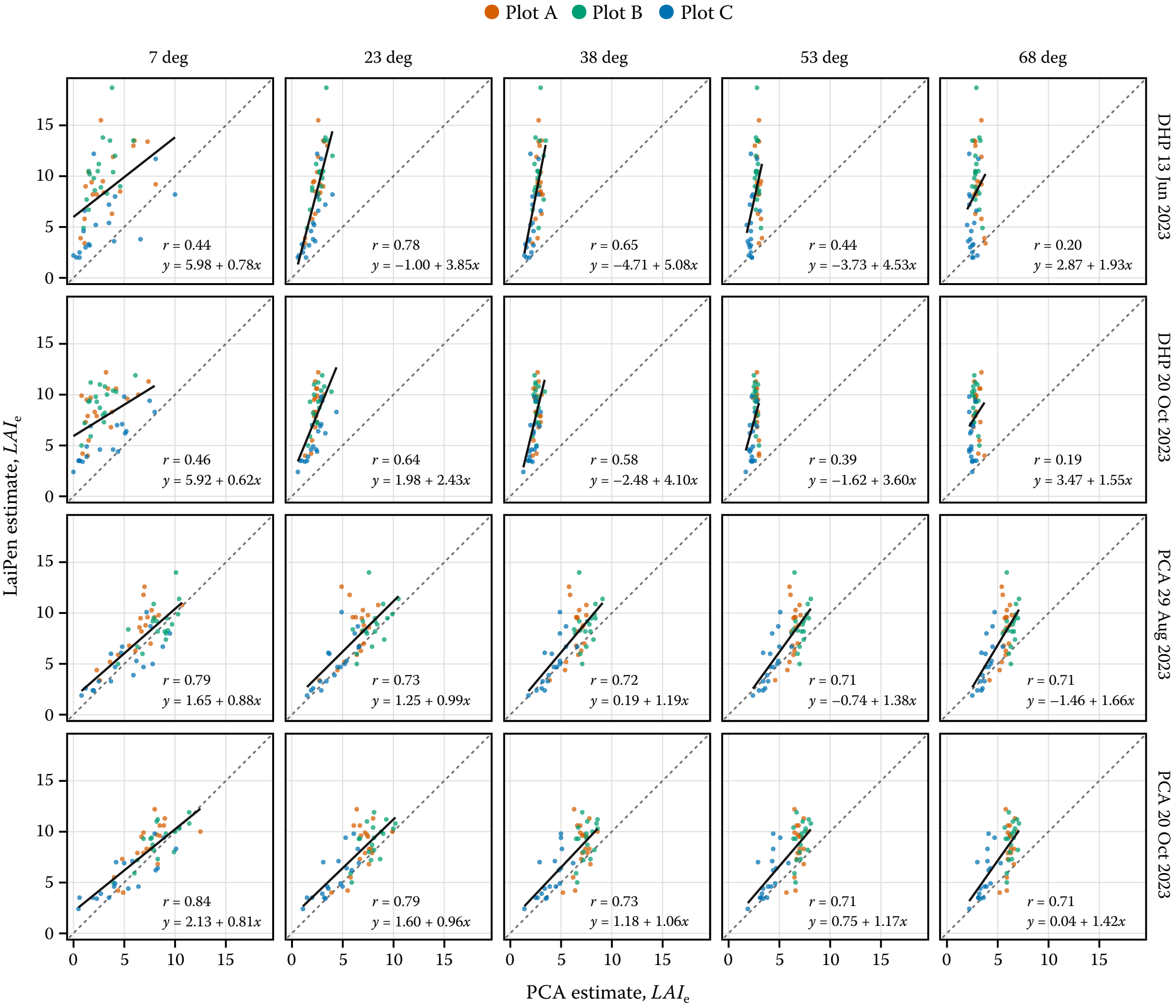

Figure 3. Relationships between LaiPen LP 110 and DHP or LAI-2200 PCA estimates of effective leaf area index ($LAI_e$) in temporally matched campaigns

DHP – digital hemispherical photography; PCA – LAI-2200 Plant Canopy Analyser; LaiPen – LaiPen LP 110; rows show method and measurement date: DHP on 13 June and 20 October 2023, and LAI-2200 PCA on 29 August and 20 October 2023; columns show field-of-view (*FOV*) settings of 7°, 23°, 38°, 53°, and 68°; points are paired observations from corresponding sampling positions within all PRPs (A–C); the solid line shows the pooled regression, and the dashed line indicates 1 : 1 agreement; text annotations report Pearson correlation coefficients ($r$) and fitted regression equations

Post hoc Tukey HSD comparisons indicated significant PRP differences across several method × date × *FOV* combinations, most commonly separating PRP B from PRP C. Differences involving PRP A were less consistent and depended on method, date, and *FOV* configuration (Figure 2).

LaiPen LP 110, operating with a fixed *FOV* configuration, displayed comparatively high variability among sampling positions and clearer differentiation among PRPs. Spatial patterns indicated greater local heterogeneity within plots than in DHP, particularly in PRPs A and B. Across methods, the denser PRP B generally exhibited higher $LAI_e$ values and stronger spatial contrasts than the more open PRP C.

Method-to-method relationships differed substantially between DHP and LAI-2200 PCA (Figure 3). DHP showed relatively weak agreement with LaiPen LP 110, with Pearson correlation coefficients ranging approximately from 0.19 to 0.78 depending on date and *FOV*. The strongest relationships were generally observed at intermediate *FOV*s (particularly 23°), whereas broad *FOV*s frequently deviated from the 1 : 1 agreement line and exhibited pronounced scaling differences. In contrast, LAI-2200 PCA displayed consistently stronger agreement with LaiPen LP 110 across all *FOV*s and dates, with correlation coefficients typically ranging from 0.71 to 0.84 and exhibited lower scatter compared to DHP-derived estimates.

## DISCUSSION

The study showed that although indirect optical methods are useful for evaluating structural features in young Norway spruce stands, estimated $LAI_e$ varied with the specific instrument and measurement configuration. In particular, *FOV* substantially affected $LAI_e$ obtained from both LAI-2200 PCA and DHP, whereas LaiPen LP 110 generally showed closer agreement with LAI-2200 PCA than with DHP. These results indicate that $LAI_e$ estimates from the LAI-2200 PCA, LaiPen LP 110 and DHP frequently differ, highlighting the complex interaction between sensor geometry and canopy structure. Černý et al. (2018) observed that instruments based on similar radiation-transmittance principles can produce comparable results at the stand level, but systematic differences still remain. This highlights the difficulty of ensuring consistency across methods in structurally diverse coniferous stands, where indirect estimates are naturally influenced by spatial layout and optical characteristics (Küßner, Mosandl 2000).

The effect of *FOV* on $LAI_e$ in both LAI-2200 PCA and DHP highlights the angular dependence of gap-fraction measurements in Norway spruce canopies. In this study, the selected zenith angle range was associated with differences in $LAI_e$ magnitude, likely because foliage clumping and multiple scattering effects vary with viewing geometry (Chen et al. 2006). Larger zenith angles are more affected by scattering, which can cause the gap fraction to be overestimated and lead to an underestimation of *LAI* (Rautiainen, Stenberg 2015). This finding is consistent with observations that excluding outer rings from LAI-2200 PCA measurements may improve agreement with independent $LAI_e$ estimates by reducing the effect of non-uniform foliage distribution at the horizon (Thimonier et al. 2010). Thus, these findings show that *FOV* settings are more than just technical details and play an important role in canopy structure measurements.

The greater similarity between $LAI_e$ values from LaiPen LP 110 and LAI-2200 PCA, relative to DHP, may partly reflect that both methods are based on similar spectral sensitivities (see Welles, Cohen 1996; Černý, Pokorný 2021). Both devices use a diffuse blue-light spectrum to maximise contrast between sky and foliage, a principle that reduces some uncertainties associated with image-based binarisation (Černý et al. 2018). By contrast, DHP estimates can be consistently affected by thresholding sensitivities and the 'blooming' effect, in which light saturation close to gaps makes them appear larger than their actual size (Thimonier et al. 2010). This post-processing sensitivity may contribute to lower or more variable DHP-based *LAI* estimates unless exposure and binarisation are carefully standardised. Additionally, the sensor-based method offers a more direct measurement of transmittance, avoiding the pixel-level resolution limitations that can distort DHP outcomes in dense coniferous stands (Chen et al. 2006).

Case-specific differences in stand density and canopy architecture among PRPs A, B and C likely contributed to observed inter-method variation. Norway spruce shows hierarchical clumping at the shoot, branch and canopy levels, which strongly contradicts the assumption of random foliage distribution (Cescatti 1998). In stands differing in stand density and crown spacing, optical sensor bias may increase because the size and angular distribution of canopy gaps change together with crown arrangement (Küßner, Mosandl 2000). This interpretation supports the idea that crown shape strongly affects angular gap profiles, as elongated Norway spruce crowns lead to higher gap fractions at larger zenith angles (Rautiainen, Stenberg 2015). Furthermore, woody components such as branches and stems affect the measured $LAI_e$, which introduces a significant bias (Kucharik et al. 1998).

Variations in inter-method agreement across different measurement dates necessitate caution when analysing seasonal patterns. Although seasonal trends in $LAI_e$ can be consistently monitored using a single method, direct comparisons of LAI-2200 PCA, LaiPen LP 110, and DHP are only valid if the data are collected on the same dates. As Fassnacht et al. (1994) pointed out, optical estimates are closely correlated with true foliage area but can be affected by light conditions and measurement time. Although Norway spruce is an evergreen, small changes in canopy openness or sky conditions over time between non-synchronous sampling dates can introduce variations in *LAI* (Thimonier et al. 2010). Consequently, date-related differences in $LAI_e$ observed in this study should be interpreted with caution, as inter-method comparability may be affected by the lack of full temporal synchrony among measurements. In this context, modern active methods, including laser scanning, are highly useful as they provide detailed three-dimensional canopy information (Disney 2019). However, these approaches tend to provide more accurate results in middle-aged and mature stands than in young plantations (Abegg et al. 2021). In dense stands, nearby vegetation and overlapping crowns may obscure stems and other tree components, leading to omissions or incomplete reconstruction in individual tree segmentation (Chang et al. 2022). These limitations indicate that further methodological and technological development is still needed, mainly for such high-density stands (Wang, Fang 2020).

Each method offers unique benefits for practical forest monitoring. The LAI-2200 PCA remains a widely used benchmark for rapid stand-level evaluations (Chen et al. 2006). Still, it requires accurate manual levelling, which can be compromised by sensor displacement during the combined button press used to log measurements (Černý, Pokorný 2021), and it requires above-canopy reference readings for *LAI* calculation (Jonckheere et al. 2004; Danner et al. 2015). The LaiPen LP 110 offers a more affordable, user-friendly option for rapid field measurements (Černý et al. 2018) and, in this study, showed closer agreement with the LAI-2200 PCA than with DHP. Conversely, DHP offers a permanent, spatially detailed record of canopy structure that enables clumping adjustments during post-processing (Thimonier et al. 2010). However, the accuracy of DHP depends on manual exposure adjustments and strict binarisation procedures, which makes it more laborious than sensor-based methods (Bréda 2003; Chianucci 2020; Lotz et al. 2026). Therefore, selecting an instrument should balance the necessary accuracy with the available resources for both field and office work.

This study has limitations because it did not incorporate direct *LAI* estimation via biomass harvesting, thereby preventing definitive validation of the true *LAI* values. Cescatti (1997) showed that radiative fluxes within Norway spruce canopies arise from complex interactions between shoot architecture and canopy gaps, making it difficult to accurately capture these processes using indirect methods. Furthermore, because indirect methods typically quantify $LAI_e$, accurate extraction of *LAI* remains dependent on rigorous corrections for stems and branches to avoid systematic overestimation (Bréda 2003; Chianucci 2020). Future research should incorporate terrestrial laser scanning or more advanced clumping index models to better estimate the difference between effective and true *LAI*. Despite current limitations, comparing these indirect optical methods offers valuable insights into their sensitivity for monitoring forest structure, highlighting the need for standardisation to improve data consistency across various forest stands.

## CONCLUSION

The study showed that $LAI_e$ estimates in young Norway spruce stands varied with the instrument and measurement configuration used. The results indicate that the *FOV* was associated with differences in $LAI_e$, with mean values decreasing as *FOV* increased, especially for the LAI-2200 PCA. In temporally matched measurement campaigns, the LaiPen LP 110 showed closer correspondence to the LAI-2200 PCA than to image-based DHP estimates, which exhibited greater scatter and weaker correlations. Differences among the case-specific PRPs were linked to variations in stand density and canopy structure, although the lack of destructive *LAI* sampling prevents validation of absolute accuracy. Therefore, these indirect optical methods should not be considered automatically interchangeable. Young Norway spruce stands pose challenges for indirect $LAI_e$ estimation due to their dense, varied canopies, hierarchical clumping, and numerous fine branches. These factors influence light transmission and cause instrument-specific sensitivities. The structural complexity, particularly foliage clumping at the shoot level, is inconsistent with the assumption of a random foliage distribution and can lead to notable methodological differences. Practitioners should consider instrument-specific sensitivities to *FOV* and the lack of full temporal synchronisation across measurement dates.

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