



RESEARCH LETTER

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Key Points:

- Leaf area index and aerodynamic roughness length were measured in two sites representing the main northern peatland types
- Linear relationship between the bulk sedge leaf area index and the aerodynamic roughness length was observed
- The finding can be used to estimate the bulk sedge leaf area index solely using the sonic anemometer data

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Relationship between aerodynamic roughness length and bulk sedge leaf area index in a mixed-species boreal mire complex

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Abstract Leaf area index (LAI) is an important parameter in natural ecosystems, representing the seasonal development of vegetation and photosynthetic potential. However, direct measurement techniques require labor-intensive field campaigns that are usually limited in time, while remote sensing approaches often do not yield reliable estimates. Here we propose that the bulk LAI of sedges (LAI_s) can be estimated alternatively from a micrometeorological parameter, the aerodynamic roughness length for momentum (z_0). z_0 can be readily calculated from high-response turbulence and other meteorological data, typically measured continuously and routinely available at ecosystem research sites. The regressions of LAI versus z_0 were obtained using the data from two Finnish natural sites representative of boreal fen and bog ecosystems. LAI_s was found to be well correlated with z_0 and sedge canopy height. Superior method performance was demonstrated in the fen ecosystem where the sedges make a bigger contribution to overall surface roughness than in bogs.

1. Introduction

Leaf area index (LAI) is one of the crucial parameters describing the productivity of an ecosystem and the degree of development of its vegetation. In most ecosystems, LAI is an important parameter governing CO₂ and CH₄ exchange [e.g., *Bolstad et al.*, 2001; *Street et al.*, 2007; *Leppälä et al.*, 2008], evapotranspiration [*Leuning et al.*, 2008; *Bucci et al.*, 2008], and energy exchange [e.g., *Law et al.*, 2001], but its magnitude is not easy to measure.

Boreal peatland vegetation possesses distinctive features that have to be accounted for when estimating its LAI. As in other ecosystems, the peatland LAI is governed by seasonal and interannual variability in phenology of dominant species, weather, and climate. However, unlike in, e.g., tree- or grass-dominated ecosystems, peatland productivity is often composed of commensurable contributions of different plant growth forms (mosses, sedges, and shrubs). While moss LAI remains relatively constant, deciduous sedges and shrubs go through the cycle of green leaf development and senescence, resulting in a LAI peak in the middle of the growing season. Evergreen shrubs and trees, in turn, show a similar but shallower midsummer peak in their seasonal LAI development. Besides, different species within the plant growth forms have their own unique phenologies. Because plant growth forms might differ in their functions—for example, in terms of CH₄ transport—LAI of these growth forms often have to be treated individually. Interannual variability adds yet another degree of complexity. Peatland plant biomass, and thus LAI, reacts intimately to the interannual variation in temperature, water availability, and solar radiation. The result is the peak level of sedge and shrub LAI that varies widely between the years in approximate correspondence with the annual net CO₂ uptake [*McVeigh et al.*, 2014; *Raivonen et al.*, 2015].

The problem of peatland LAI measurement and modeling has received a lot of attention in the recent years, as the data are in high demand by the modeling community. To negotiate the complexity of LAI dynamics, an array of methods have been developed. The most direct is destructive sampling in the field, which is followed by in situ radiation extinction measurement with devices such as LI-2000/LI-2200 (a detailed review is offered by *Breda* [2003]; also *Garrigues et al.* [2008b]). Direct LAI estimation relies on very time-consuming vegetation sampling and the consequent laborious processing of plant material in the lab. Complex sampling strategies were designed to cover the spatial variability in strongly heterogeneous mire landscapes [*Breda*, 2003]. Potential seasonal and interannual variations in LAI necessitate summer-long field campaigns for several years in a row to ensure that all variability is captured. Remote sensing methods based on satellite

products or airborne lidar surveys help avoid the extensive fieldwork but are associated with large uncertainties [Garrigues *et al.*, 2008a; Luo *et al.*, 2015]. All indirect LAI estimates have to be calibrated against direct measurements [Breda, 2003], typically yielding R^2 of less than 0.7. Immediate association with photosynthesis is acknowledged in LAI estimation approaches utilizing photosynthetic potential [e.g., Metzger *et al.*, 2016] and in models based on carbon balance [e.g., Wythers *et al.*, 2003; Raivonen *et al.*, 2015]. Nevertheless, modeled LAI is similarly prone to large uncertainties.

However, what is frequently overlooked in ecological studies is that a number of micrometeorological parameters describing a turbulent flow are naturally related to the vegetation canopy structure. Bulk drag coefficient, zero-plane displacement (d), and aerodynamic roughness length (z_0) all are strong functions of canopy structural features such as average vegetation height and LAI [Raupach, 1992, 1994; Verhoef *et al.*, 1997, and others]. The approaches range in complexity from “rules of thumb” giving z_0 or d as multiples of canopy height [Lettau, 1969] to their computation in large eddy simulations [e.g., Maurer *et al.*, 2015]. The relation between z_0 and LAI is, in theory, much more direct than that with normalized difference vegetation index (NDVI), albedo, photosynthetic potential, or gross primary productivity. The evolution of canopy height and LAI was nearly simultaneous in herbaceous crops like maize [Gao *et al.*, 2013]. Correlation between LAI and short wetland vegetation canopy height was also observed by Luo *et al.* [2015], as well as by Peichl *et al.* [2015] in a minerogenic oligotrophic mire (i.e., poor fen), who used z_0 as a proxy for LAI, obviously expecting a close association.

This study proposes a method that may help avoid the workload of direct LAI measurements while being continuous and representative of the ecosystem-scale LAI. A bulk LAI proxy was developed based on aerodynamic roughness length for momentum, an important micrometeorological parameter obtained from wind measurements. We will first describe the methodology for estimating LAI and z_0 , then show their observed relationships in two pristine peatland sites representing the main open boreal types and, finally, discuss the prospects of LAI derivation from z_0 .

2. Materials and Methods

2.1. Peatland Study Sites

The study sites are located in Siikaneva, a pristine peatland in southern boreal vegetation zone of Finland [Ahti *et al.*, 1968]. The Siikaneva complex features several raised bog cupolas within a wider fen area. Research was carried out at two sites: an oligotrophic fen and an ombrotrophic bog separated by approximately 1.2 km. Compared to the fen, the bog has a better pronounced microtopography in relation to water table (WT) variation (hummock-hollow complex with a few ponds). The hummocks on the drier end of the WT gradient are vegetated with dwarf shrubs and, rather sparsely, some Scots pines with typical heights up to 1.5 m. The opposite extreme is patches of bare peat with sparse sedge cover and no mosses. The intermediate lawn surfaces house a mixture of dwarf shrubs and sedges, whereas the wet hollows have sedge-dominated vascular vegetation. In addition, the ground layer of all communities (except for bare peat patches) is covered by *Sphagnum* moss species typical for the corresponding WT depth. In the fen site, the microtopographical variation, and thus changes in vegetation along the WT gradient, is milder. There, sedges dominate the canopy, with a minor contribution of dwarf shrubs. As in the bog site, the fen species composition of *Sphagnum* moss community reflects the variation in WT. Thus, the sites show significant differences in their microtopography and vegetation cover, causing differences in LAI and, supposedly, in z_0 .

Two field measurement stations, Siikaneva-1 (SI1) and Siikaneva-2 (SI2), are located in the fen and bog areas of the peatland, correspondingly. The stations are equipped with equivalent setups for eddy covariance, meteorological, and auxiliary measurements. Intensive vegetation inventory campaigns have been carried out at both sites to determine the variation in species composition and areal cover along the WT gradient [Riutta *et al.*, 2007; Korrensalo *et al.*, 2017]. The cover fractions of the vegetation community types in both sites were defined by means of vegetation inventory. Inventory sample plots ($n = 341$ in fen and $n = 542$ in bog) were arranged as a regular grid covering the zone of 80% eddy covariance flux footprint. The relative projection cover of each species was visually defined inside the circular 0.071 m² plots. Based on the species cover, the vegetation community types of the inventory plots were defined.

2.2. Measurements of LAI and Canopy Height

Leaf area index (LAI) at both sites was defined 5–11 times per growing season in the years 2004–2007 and 2014–2015 in the fen SI1 and 2012–2015 in the bog SI2. Sample plots of 60 × 60 cm were set up to cover the spatial variation in vegetation ($n = 15$ in the fen and $n = 18$ in the bog). Each vegetation community type had three replicate sample plots (1–7 in 2004–2007 at SI1). For each sample plot, the number of green leaves of each species was calculated biweekly from five 8 × 8 cm subplots during the snow-free season. In the case of *Calluna vulgaris*, *Vaccinium oxycoccos*, *Betula nana*, and *Empetrum nigrum* with small leaves, the lengths of branches having green leaves (cm) were measured instead.

The number of leaves of each species on each measurement day was multiplied by the correspondent average green leaf size to yield sample plot- and species-wise LAI. In the case of species with small leaves, the length of stems was multiplied by the total area of leaves measured per centimeter of stem. From 2012 onward, average green leaf size was defined at both sites by taking samples ($n = 5$ –15) of all recorded species next to the sample plots and defining the average green area of one leaf or leaves attached to a cm of branch using a scanner. In the fen SI1 in 2004–2007 the average green leaf size was defined by calculating green area based on the leaf dimensions measured from tagged individual plants on each measurement day. For each vegetation community type on a certain measurement day, we then calculated the LAI of each species as an average of the measurement plots representing the same community. Ecosystem-level LAI for each species for each measurement day was obtained as an average of the communities weighted by their relative cover within the study site. Finally, the bulk LAI of (i) all species (LAI_{tot}) and (ii) only sedge species (LAI_s) was obtained by log linear fitting to the corresponding LAI values against day number [Wilson *et al.*, 2007]. Fitting was performed for each year individually. A deciduous aerenchymatous forb *Scheuchzeria palustris* was grouped with sedges due to the similarity of growth forms. Owing to the dominance of sedges in the studied ecosystems, LAI_s is primarily used in the following analyses; nevertheless, LAI_s has a clear relation to LAI_{tot} so that conversion is possible.

The canopy structure in both fen and bog sites is largely formed by sedges. The sedge canopy height (h_s) at SI1 was estimated as the average of leaf lengths of the four most prominent canopy-forming species (*Carex rostrata*, *Carex lasiocarpa*, *Scheuchzeria palustris*, and *Eriophorum vaginatum*) but only for 2005–2007 when the required measurements were made.

2.3. Estimation of Roughness Length From Single-Level Anemometer Measurements

If the zero-plane displacement (d) is ignored in the case of low vegetation, z_0 can be estimated from single-level ultrasonic anemometer data as follows:

$$z_0 = z \exp\left(\frac{-\kappa U}{u_*} + \psi_m\right), \quad (1)$$

where z is the measurement height, κ is the von Karman constant, U is the wind speed, u_* is the friction velocity, and $\psi_m = \psi_m(z/L)$ is the stability correction function, where L is the Obukhov length. We also analyzed the effect of ignoring d by assuming it to be two thirds of the vegetation height (a safe assumption, according to Maurer *et al.* [2015]). This produced d values of up to 0.16 m that are small compared with the measurement heights of 3.0 m in SI1 and 2.4 m in SI2. Therefore, it is unsurprising that given the SI1 canopy and measurement height, the introduction of d caused a reduction in z_0 of 5% at most, which is small enough to omit d altogether. The near-neutral stability limits were determined as the interval of the stability parameter $\gamma = z/L$ within which σ_w/u_* remains constant, yielding $-0.002 < \gamma < 0.07$ in SI1 and $-0.004 < \gamma < 0.006$ in SI2. Outside those intervals, the stability correction function was applied for unstable and stable conditions [Paulson, 1970; Webb, 1970]. The periods with z_0 values of over 0.1 m or u_* under 0.1 m/s were excluded from the analysis. z_0 of July 2006 and September 2015 was also excluded for the reason that the gaps in data did not allow reliably determining z_0 .

A change in SI1 setup happened in 2012, when a new anemometer was mounted at a greater height of 3.0 m. As the exact anemometer mounting prior to 2012 is not known, when processing the data of 2005–2007, we used $z = 2.25$ m making the mean z_0 summer maximum of that period match that of 2012–2015. The emerging height of 2.25 m is believed to be close to the actual height. In the view of the above mentioned changes in wind and LAI measurements, we analyzed the 2005–2007 and 2012–2015 SI1 periods separately.

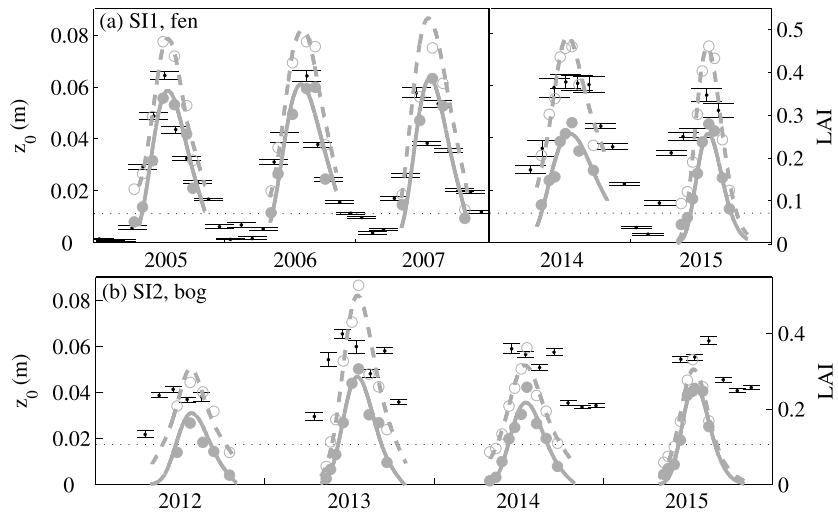


Figure 1. Time series of LAI_s (sedge, bold grey line), LAI_{tot} (total, dash grey line) and z₀ for (a) fen SI1 and (b) bog SI2. The original LAI_s and LAI_{tot} measurements are shown as open and filled circles, respectively. z₀ is shown as monthly bin averages with standard deviation of the mean bars. The LAI curves are log linear interpolants of the original field measurements. The dotted horizontal lines indicate the median April roughness lengths at both sites.

Standard error of prediction (SEP) and relative SEP were calculated as follows:

$$\begin{aligned}
 SEP &= \left(\frac{\sum (LAI_{meas} - LAI_{mod})^2}{n} \right)^{0.5} \\
 SEP_{rel} &= LAI_{mod}^{-1} \left(\frac{\sum (LAI_{meas} - LAI_{mod})^2}{n} \right)^{0.5},
 \end{aligned}
 \tag{2}$$

where the subscript mod stands for modeled and meas for measured.

3. Results and Discussion

3.1. Annual Course of the Measured Quantities

The measured total and sedge LAI and z₀ exhibited similar annual courses and were well matched in phase in SI1 (Figure 1a). The relationship was much less clear in SI2 (Figure 1b). LAI_s reached the maxima of 0.4 in SI1 and 0.3 in SI2 at the peak of the growing season, while the highest z₀ peaks (usually in July) were about 0.06 m in both sites. In SI1, LAI and z₀ began a simultaneous increase after snowmelt, which was followed by a rapid growth corresponding to accumulation of biomass and a decline in late summer due to vegetation senescence. However, it seems that in SI2, z₀ increases already after snowmelt, preceding the increase in LAI, which points at the effect of microtopography revealed under snow cover (Figure 1b). LAI_s made up a major fraction of LAI_{tot}, while their proportion remained approximately constant over the summer (Figure 1). The z₀ in the brief period between snowmelt and initial plant growth represents the base level of site roughness in absence of snow and fresh green biomass. This “base-level” z₀ was 0.017 m in the bog site and 0.011 m in the fen site. z₀ showed a greater seasonal change in the fen than in the bog, which is demonstrated by the fact that the ratio of base-level to peak z₀ was lower in the fen (one fifth) than in the bog (one third).

3.2. Modeling LAI as a Function of z₀

Previous studies proposed a variety of relationships between z₀ and LAI_s, including linear and power function [e.g., Lettau, 1969; Shaw and Pereira, 1982]. The mire canopy is short and homogenous and has a simple leaf area density profile, and the seasonal LAI_s growth is mainly due to the increase in sedge height, with plant spacing and thickness remaining approximately constant. The linearity of the relationship in SI1 (Figure 2a) prompted us to describe the z₀ versus LAI_s relationship with a simple linear function, LAI_s = a*z₀ + b.

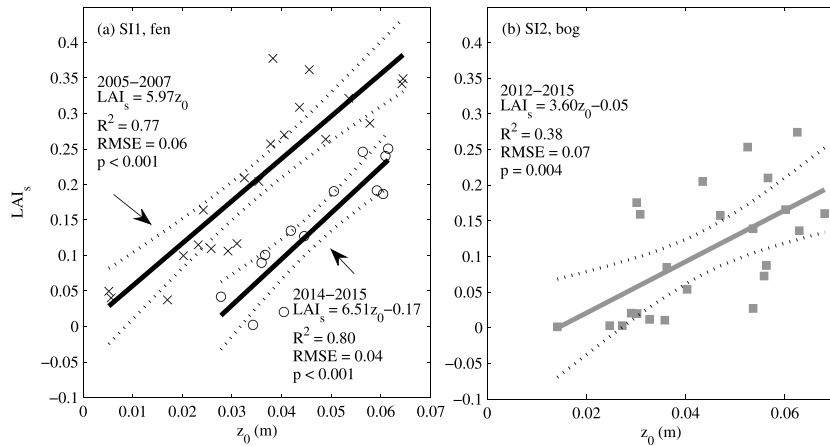


Figure 2. LAI_s versus z_0 monthly averages in the two study sites: (a) SI1 and (b) SI2. The linear regressions are shown with the respective pointwise 95% functional confidence intervals.

In SI2, the correlation was positive but more loose (Figure 2b). The residuals of the regression were normally distributed in SI1 but deviated from normal in SI2 (not shown); however, for consistency, we used the linear regression in SI2 as well. Having a coefficient of determination of 0.77–0.80, the regression was much more significant in SI1 compared with 0.38 observed in SI2 (Figure 2b). Fitting separately to the 2005–2007 and 2014–2015 data sets from SI1, we obtain two lines with similar slopes of 5.97 and 6.51 but a large disparity

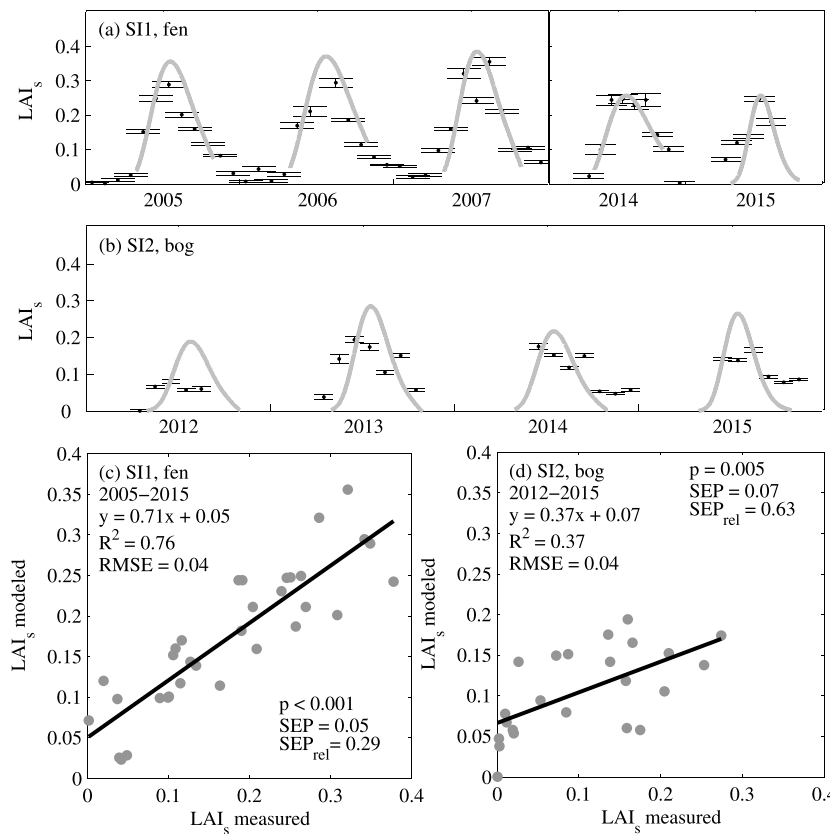


Figure 3. Comparison of the modeled and measured LAI_s time series. (a, b) Solid line: measured LAI_s ; dots with error bars: modeled LAI_s monthly medians. (c, d) Monthly medians of modeled versus measured LAI_s plotted with a regression line. The data of both SI1 measurement phases are combined in Figure 3c.

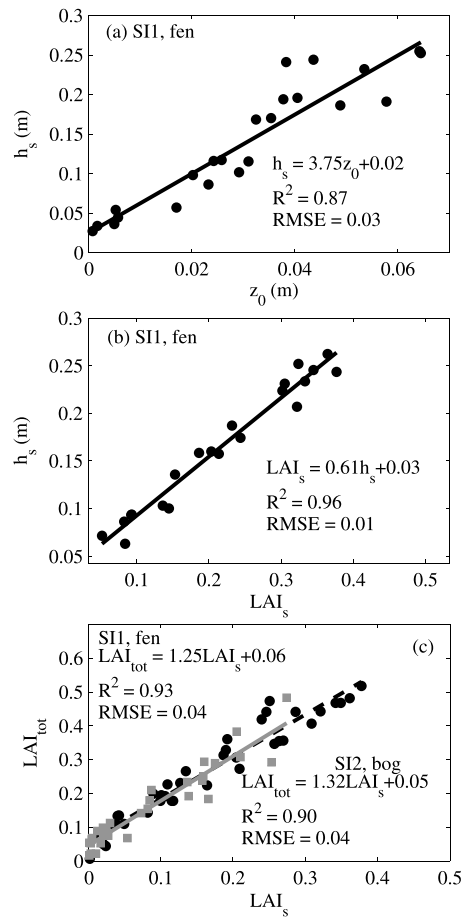


Figure 4. (a) h_s versus z_0 , (b) h_s versus LAI_s , and (c) LAI_{tot} versus LAI_s . The dots are monthly medians and the lines are fits. In Figure 4c, the fen data are in black and the bog data are in grey.

roughness much. In addition, S11 also has a cover of sedge that is somewhat denser than that in S12, which further strengthens the relationship between LAI_s and z_0 . It should be noted that better z_0 data coverage would have improved the predictive power in S12 (Figure 3d). It is curious that the value of z_0 at $LAI_s = 0$ yields zero in the 2005–2007 S11 data set, implying the possibility of a systematic bias in these data, as the surface retains base roughness even at absence of sedges. In contrast, the 2014–2015 S11 data yield $z_0 = 0.028$ at $LAI_s = 0$, a more realistic result. In S12, z_0 approaches a similar value of about 0.02 at $LAI_s = 0$.

The discussed method predicts the seasonal course, i.e., the shape and phase of LAI_s , reasonably well in S11 but rather poorly in S12, in terms of slope, p value and SEP (Figure 3). Simulating the amplitude of LAI_s peak presents a greater challenge. Two reasons might have affected the quality of LAI predictions: first, LAI_s did not seem to vary significantly between the years, precluding any attempts to model its interannual variation; second, there were gaps in z_0 data series, especially in S12.

3.3. Relationships Between z_0 , Sedge Canopy Height, LAI_s , and LAI_{tot}

It would be of interest to examine also the relationships involving sedge canopy height (h_s), an important structural parameter (Figures 4a and 4b). The required combination of z_0 , h_s , and LAI_s was measured in S11 data in the years 2005–2007. In these data, z_0 and h_s showed a linear dependency with R^2 of 0.87 (Figure 4a). Ignoring the small intercept, this allows re-establishing the rule of thumb for this ecosystem as $z_0 = 0.27h_s$.

Similarly, a strong linear relationship is observed between h_s and LAI_s ($R^2 = 0.96$, Figure 4b), as shown for wetlands elsewhere [e.g., Luo et al., 2015]. The fact that h_s is proportional to LAI_s means that the latter changes only via the increment in sedge height, while the other structural parameters (width and spacing of the

in intercept, which is unlikely to be caused by natural interannual variation in the observed quantities. The concomitant reduction in LAI range might have resulted from the change in method or from the natural variation, or a combination of those. In fact, the discrepancy in intercept gives grounds to believe that the change in LAI measurement procedure (see section 2.2.) between the two measurement phases did affect the absolute values of LAI . Measuring the dimensions of tagged individuals (2005–2007) takes more accurately into account the shape of the different vascular plant leaves than using a scanner (2014–2015). On the other hand, collecting a sample of leaves for the scanner measurement results in a more balanced distribution of the leaf size during a certain phase of growing season than when the dimensions of tagged individuals are measured (with inevitably smaller samples).

In general, predicting sedge LAI based on z_0 should be easier in the fen than in the bog—S11 has a relatively flat surface meaning that the “base” roughness does not conceal the contribution of sedges to overall

roughness elements) stay approximately constant throughout the growing season, supporting the statement in section 3.2. Such a simplicity of the sedge canopy structure annual change is consistent with the observed linearity of z_0 versus LAI_s regression.

Furthermore, the findings involving LAI_s can be directly translated to LAI_{tot} as a strong linear relationship is again found between the sedge and total LAI in both the fen and the bog (Figure 4c; $R^2 = 0.93$ and 0.90 , respectively). The equality in the slope and distribution of the data from both sites is notable, with the only difference seen in the LAI maxima (the fen maximum LAI exceeding that in bog by 0.1).

3.4. Performance and Applicability of the Method

Prediction of sedge LAI from z_0 was successful in the fen but generally rather unsuccessful in the bog. Although the predictions of the bog LAI_s suffered extra setbacks due to data gaps, the method may be less suitable for patterned ecosystems also for another reason. In fact, a stable dominance of the annually changing LAI component is a prerequisite for a better performance of the method in question. In this sense, the extra roughness typical of bogs, i.e., due to the developed microtopography, dwarf shrubs, and sparse pine trees, would act as a relatively higher base roughness of the ecosystem. This is likely to conceal the seasonally changing LAI component of sedges and so degrade the performance of the method. However, the method seems to be applicable at SI1, where the contribution of the seasonally growing vegetation to overall roughness is relatively high—which is often the case in fens. At the peak, the seasonal component, LAI_s , comprised 70% of the total roughness at SI2, as compared with 80% in SI1. The method predicts SI1 LAI_s with an R^2 of 0.38–0.80, SEP of 0.05–0.07, and relative SEP of 0.29–0.63. This performance approaches the level of LAI-2000 measurement [Sonnentag *et al.*, 2007] and is better than gross primary product-based modeling [Raivonen *et al.*, 2015], photosynthesis potential and NDVI [Metzger *et al.*, 2016], or satellite products [Garrigues *et al.*, 2008a]. Both phase and annual course of LAI are reproduced well by the method. The close association between LAI_s and LAI_{tot} allows reliable transition between the two, should it be necessary.

Breda [2003] points out that calibration against direct measurement is required for most indirect LAI estimation methods. This certainly concerns the approach under discussion, as peatlands possess a variety of canopies and microtopographies, all inevitably affecting the z_0 -LAI relationship. However, the z_0 -LAI dynamics may be understandable, as shown above. Therefore, we assume that the relations of z_0 with LAI_s and h_s , observed in SI1, with proper calibration, might, with due care, be applicable in the other fens or other short-vegetation ecosystems having similar canopy structure and topography. This, of course, should be confirmed by further studies. However, the evidence of large differences between the two SI1 measurement phases suggests that even the most direct LAI measurement is prone to large uncertainties, presenting an upper limit for the precision of any LAI estimation attempt.

4. Conclusions

This study proposes a method for the bulk sedge LAI estimation exploiting its relationship with aerodynamic roughness length for momentum, z_0 . It is simple, continuous, and more direct than many other noninvasive methods such as airborne lidar survey or satellite-born spectroscopy. The method was tested with the data from two sites: the fen Siikaneva-1 and the bog Siikaneva-2, parts of a mire complex in South Finland. The highest coefficient of determination achieved was 0.77–0.80 when predicting the bulk sedge LAI in the flat environment of a fen, in the absence of extra roughness of microtopography and shrubs. A strong linear relationship between z_0 and h_s allowed updating the rule of thumb for the fen ecosystem as $z_0 = 0.27h_z$.

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