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Temporal Dynamics of Aerodynamic Canopy Height Derived From Eddy Covariance Momentum Flux Data Across North American Flux Networks

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Abstract

Aerodynamic canopy height (h_a) is the effective height of vegetation canopy for its influence on atmospheric fluxes and is a key parameter of surface-atmosphere coupling. However, methods to estimate h_a from data are limited. This synthesis evaluates the applicability and robustness of the calculation of h_a from eddy covariance momentum-flux data. At 69 forest sites, annual h_a robustly predicted site-to-site and year-to-year differences in canopy heights ($R^2 = 0.88$, 111 site-years). At 23 cropland/grassland sites,

weekly h_a successfully captured the dynamics of vegetation canopies over growing seasons ($R^2 > 0.70$ in 74 site-years). Our results demonstrate the potential of flux-derived h_a determination for tracking the seasonal, interannual, and/or decadal dynamics of vegetation canopies including growth, harvest, land use change, and disturbance. The large-scale and time-varying h_a derived from flux networks worldwide provides a new benchmark for regional and global Earth system models and satellite remote sensing of canopy structure.

Plain Language Summary

Vegetation canopy height is a key descriptor of the Earth surface and is in use by many modeling and conservation applications. However, large-scale and time-varying data of canopy heights are often unavailable. This synthesis evaluates the applicability and robustness of the calculation of canopy heights from the momentum flux data measured at eddy covariance flux tower sites (i.e., meteorological observation towers with high frequency measurements of wind speed and surface fluxes). We show that the aerodynamic estimation of annual canopy heights robustly predicts the site-to-site and year-to-year differences in canopy heights across a wide variety of forests. The weekly aerodynamic canopy heights successfully capture the dynamics of vegetation canopies over growing seasons at cropland and grassland sites. Our results demonstrate the potential of aerodynamic canopy heights for tracking the seasonal, interannual, and/or decadal dynamics of vegetation canopies including growth, harvest, land use change, and disturbance. Given the amount of data collected and the diversity of vegetation covered by the global networks of eddy covariance flux tower sites, the flux-derived canopy height has great potential for providing a new benchmark for regional and global Earth system models and satellite remote sensing of canopy structure.

Introduction

Vegetation canopy height is a key descriptor of the Earth surface but has not yet been systematically analyzed across observation networks (Simard et al., 2011). Its use is found in many applications, such as land-surface modeling, ecosystem modeling, wildland-fire modeling, estimation of biomass, conservation, and remote sensing (e.g., Garratt, 1993; Giardina et al., 2018; Hurtt et al., 2010; Lindvall et al., 2012; Massman et al., 2017; Tian et al., 2011). Examples of utilization of vegetation height in modeling include output as a diagnostic for plant growth and harvest or key parameters for wind speed profile, plant light competition, biomass/leaf area allocation, and root-stem-leaf water transport. In theory, aerodynamic canopy height (h_a)—the "effective" height of the canopy from the perspective of its effects on the airflow—could be derived from the canopy's momentum absorption characteristics (Nakai et al., 2010; Thomas & Foken, 2007).

Networks of eddy covariance flux sites worldwide have collected ~10^8 hr of turbulent flux data during the last 25 years (Chu et al., 2017). However, long-

term and cross-site studies of momentum flux data are relatively rare. The surface aerodynamic parameters (e.g., h_a, roughness length (z_0), and displacement height (d)—key parameters describing the drag effects of surface on wind speed) are widely utilized to model the effects of the land surface on turbulence and the exchanges of momentum with the overlying atmosphere (Rigden et al., 2017; Thom, 1971; Verma, 1989). These parameters can be evaluated from data collected at flux sites. With the wide spectrum of vegetation types and degrees of surface roughness among the flux sites, momentum-related measurements can provide a unique opportunity to revisit these aerodynamic parameters.

Over the years, studies have proposed different approaches to derive h_a from momentum flux and wind statistics measurements (e.g., Maurer et al., 2013; Nakai et al., 2010; Thomas & Foken, 2007). Common approaches require either detailed vertical wind profile measurements throughout and above the canopy or empirical model assumptions that are rarely tested extensively across sites (detailed discussion in Graf et al., 2014; Maurer et al., 2013; Nakai et al., 2008). Those additional measurements and model assumptions often limit their applicability across a large number of sites. Most recently, Pennypacker and Baldocchi (2015) proposed a simple approach for deriving h_a from single-level eddy covariance data based on the surface layer theory. They suggested that the method was suitable to a broad range of canopy types and demonstrated the potential for calculating h_a on a regular basis (e.g., weekly and annual).

This study adopted the method of Pennypacker and Baldocchi (2015) to calculate h_a and evaluated it for a variety of canopies across the AmeriFlux and Fluxnet-Canada networks. We focused on potential applications in two contrasting cases: tall forests and seasonally dynamic croplands/grasslands. We asked the following: (1) Can h_a adequately represent the actual canopy heights across a wide variety of forests? (2) Is the annual h_a sufficiently robust to detect year-to-year changes of forest canopy heights (e.g., growth trends)? (3) Can h_a adequately represent seasonal variation of canopy heights in croplands and grasslands, where vegetation growth and harvest occur on seasonal time scales? Our motivation is to provide large-scale and time-varying estimates of canopy heights that could be used in Earth system modeling and cross-analyzed with remotely sensed canopy-structure data (e.g., LiDAR and Radar; Simard et al., 2011; Zhang et al., 2017).

Materials and Methods

Theory

The foundation of the Pennypacker and Baldocchi (2015) method is the logarithmic wind profile defined by Monin-Obukhov similarity theory under near-neutral stability conditions (i.e., $|[z - d]/L| < 0.1$, where z [m] is observation height above ground, d [m] is the zero-plane displacement height, and L is Obukhov length [m]; Raupach, 1994, 1995). Monin-Obukhov similarity theory describes the ratio of the mean horizontal wind speed (U_z,

[m s^{-1}]) measured at z, to the friction velocity (u_*, [m s^{-1}]—a generalized velocity scale derived from momentum flux) above the canopy as a logarithmic function of the roughness length for momentum (z_0) and d.

$$\frac{kU_z}{u_*} = \ln\left(\frac{z-d}{z_0}\right) + \Psi_u = \ln\left(\frac{z-d}{z_0}\right) + \ln(\lambda_{rs}) \tag{1}$$

where $k \approx 0.40$ is the von Kármán constant. $\Psi_u = \ln(\lambda_{rs})$ is an influence function associated with the roughness sublayer—a region just above the canopy where turbulence is enhanced (Raupach, 1994, 1995). $\lambda_{rs} = 1.25$ is assumed when z is relatively close to the canopy top (i.e., $z \leq 1.5h_c$, where h_c is the actual canopy height [m]; Massman, 1997; Massman et al., 2017). Otherwise, Ψ_u is assumed to be negligible (i.e., $\lambda_{rs} \approx 1.00$). Details about the roughness sublayer influence are discussed in Texts S1–S3 and Figure S2 in the supporting information.

Both z_0 and d can be expressed as fractions of the effective canopy height, that is, the theoretical height that reflects the canopy's momentum absorption characteristics. We define this theoretical height as the aerodynamic canopy height (h_a [m]), where $z_0 = \alpha_1 h_a$ and $d = \alpha_2 h_a$, and α_1 and α_2 are unitless empirical parameters. Equation 1 is then rearranged as a function of h_a depending on α_1, α_2, z, U_z, and u_*. z is typically fixed at the sites. Given known values of α_1 and α_2, h_a can be calculated from the measured U_z and u_* (Pennypacker & Baldocchi, 2015).

$$\frac{kU_z}{u_*} = \ln\left(\frac{z - \alpha_2 h_a}{\alpha_1 h_a}\right) + \ln(\lambda_{rs}) \tag{2}$$

$$h_a = \frac{\lambda_{rs}z}{\lambda_{rs}\alpha_2 + \alpha_1 \exp\left(\frac{kU_z}{u_*}\right)} \tag{3}$$

α_1 and α_2 are typically parameterized at the site level. Alternatively, "global" approximations for α_1 and α_2 have been proposed, for example, 0.1 and 0.6 (the classical model) used in Pennypacker and Baldocchi (2015). In this study, we propose a more sophisticated approach to account for the uncertainties introduced via the somewhat arbitrary choice of α_1 and α_2 by using an ensemble of randomly generated pairs of values from a bivariate normal distribution ($N = 1,000$):

$$\begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} \sim N\left(\begin{pmatrix} \mu_{\alpha 1} \\ \mu_{\alpha 2} \end{pmatrix}, \begin{pmatrix} \sigma_{\alpha 1}^2 & \rho\sigma_{\alpha 1}\sigma_{\alpha 2} \\ \rho\sigma_{\alpha 1}\sigma_{\alpha 2} & \sigma_{\alpha 2}^2 \end{pmatrix}\right) \tag{4}$$

Three model choices were tested for calculating the distribution means of α_1 and α_2 ($\mu_{\alpha 1}$ and $\mu_{\alpha 2}$). These include the classical model, Raupach (1994; the R94 model), and Schaudt and Dickinson (2000; the SD00 model; Figure S1). Briefly, the classical model assumes fixed values of $\mu_{\alpha 1}$ and $\mu_{\alpha 2}$ across all sites, while the R94 and SD00 models require inputs of site-specific leaf area index (LAI). Model details are provided in Text S1. Our preliminary tests

suggested that the SD00 and R94 models provided the best and representative results for forests and croplands/grasslands (Text S5), respectively. Therefore, results below focus on these model and land surface type combinations. The uncertainties of α_1 and α_2 were propagated via the prescribed variance ($\sigma_{\alpha1}^2$ and $\sigma_{\alpha2}^2$) and covariance ($\rho\sigma_{\alpha1}\sigma_{\alpha2}$) terms (Text S1). For each pair of α_1 and α_2, an estimate of h_a is calculated for each target period (details in section 2.3).

Site and Data

This study included 92 flux tower sites from AmeriFlux and FLUXNET-Canada, including 69 forest sites (Table S1 in the supporting information) and 23 cropland/grassland sites (Table S2) with sufficiently long data sets and information available on canopy heights and date of measurement for these heights (Text S2). Data were downloaded through the AmeriFlux (ameriflux.lbl.gov) and FLUXNET-Canada databases (FLUXNET-Canada Team, 2016), including (half-)hourly horizontal wind speed, wind direction, friction velocity, and Obukhov length. All wind and turbulence data have gone through the standard quality checks adopted by AmeriFlux and FLUXNET (Pastorello et al., 2014, 2017). A series of criteria (i.e., near neutral stability, moderate turbulent intensity, and prevailing wind direction) were applied to filter data following Pennypacker and Baldocchi (2015). Such filtering criteria ensured that only data/periods fulfilling the aforementioned theory assumptions were used (Text S2). On average, most sites retained approximately 7%–26% of data for further analyses (i.e., 300–1,100 half hours per season for forests and 24–87 half hours per week for croplands/grasslands).

Ancillary data, such as actual canopy heights (h_c), instrument heights, LAI, stand ages, and vegetation types, were obtained through the Biological-Ancillary-Disturbance-Management (BADM) database of AmeriFlux and/or by contacting the site investigators. In total, ~111 and ~1,600 records of h_c were acquired for forest and cropland/grassland sites, respectively. h_c at forest sites were determined either using lasers, clinometers, or through visual estimates and were often sampled or reported infrequently (e.g., ~75% of sites only provided one record). h_c at cropland/grassland sites were measured manually throughout the growing season and typically provided weekly or biweekly records.

Data Processing and Statistical Analysis

For the forest sites, we focused on the full-foliage period of each year and estimated h_a at an annual time step. The full-foliage periods were determined as the three consecutive months that had the highest LAI in the multiyear-mean seasonal cycles (i.e., MOD15A2H LAI C6; Myneni, 2015; ORNL DAAC, 2017). This 3-month window was applied to both deciduous (21 sites) and evergreen (48 sites) forests. Our preliminary tests showed that using leafless periods (deciduous forests only) did not substantially improve the results (Text S4 and Figure S3).

At each annual time step, h_a was processed as follows: (1) All postfiltered data for the 3-month full-foliage period of a year were pooled together. (2) One thousand pairs of α_1 and α_2 were generated based on equation 4, using LAI data in the AmeriFlux BADM database. (3) Given each pair of α_1 and α_2, h_a for each (half) hour of postfiltered data was calculated using equation 3. The median of the calculated h_a for the 3-month period was kept as a single estimate. (4) The postfiltered data were resampled with repeats. Steps (3) and (4) were iterated for 1,000 times generating 1,000 estimates of h_a. (5) The median of these 1,000 estimates is treated as the best estimate and used for most of the following analyses, while the 95 percentile range (2.5%: 97.5%) is reported as the uncertainty interval. We interpret the 95 percentile range as propagated uncertainties regarding the choice of α_1 and α_2 and the random measurement errors of wind and turbulent data.

For cropland/grassland sites, h_a was processed at weekly time steps for the entire year. All postfiltered data for a 1-week window were pooled together and used to calculate the 1,000 estimates of h_a following the procedures described above. We did not prescribe site-specific and time-varying LAI for the cropland/grassland sites because weekly LAI data are often unavailable. Instead, we chose a pair of fixed values for $\mu_{\alpha1}$ and $\mu_{\alpha2}$ in equation 4 (e.g., 0.11 and 0.56 for the R94 model). These values were determined based on the model relation of α_1 and α_2 in the low LAI range (i.e., 0–1 $m^2\ m^{-2}$, Figure S1), within which the canopy heights change rapidly and the α_1:α_2 ratio is approximated by a constant.

All calculated h_a were compared against h_c based on matching the years/weeks of estimates and measurements. Thirty-five forest sites that had 5+ years of data were further analyzed for long-term canopy height trends. For trend analyses, h_a and h_c were first normalized by subtracting the site-specific multiyear means, that is, focus on the relative changes ($\Delta h_c = h_c - \overline{h_c}$, $\Delta h_a = h_a - \overline{h_a}$). All data processing and statistical analyses were conducted using the R software (R Core Team, 2017). Specifically, model II linear regression (lmodel2 package) was adopted for comparison of h_a and h_c (Legendre & Legendre, 2012). The Sen's method (trend package), chosen for its robustness to outliers, was adopted to assess the trends of yearly canopy height change in forest sites (Libiseller & Grimvall, 2002; Sen, 1968; Wilcox, 2011). Unless specified, the significance level is set as 0.05 and reported uncertainties are 95 percentile/confidence intervals.

Results

Annual Aerodynamic Canopy Heights at Forest Sites

Across sites, h_a showed good agreement with h_c for the forests (Figure 1, R^2 = 0.88, N = 111). This suggests that h_a is robust for differentiating canopy heights of 1–60 m. The linear regression slope (1.23 ± 0.08) indicates that the calculated h_a was mostly and systematically higher than h_c.
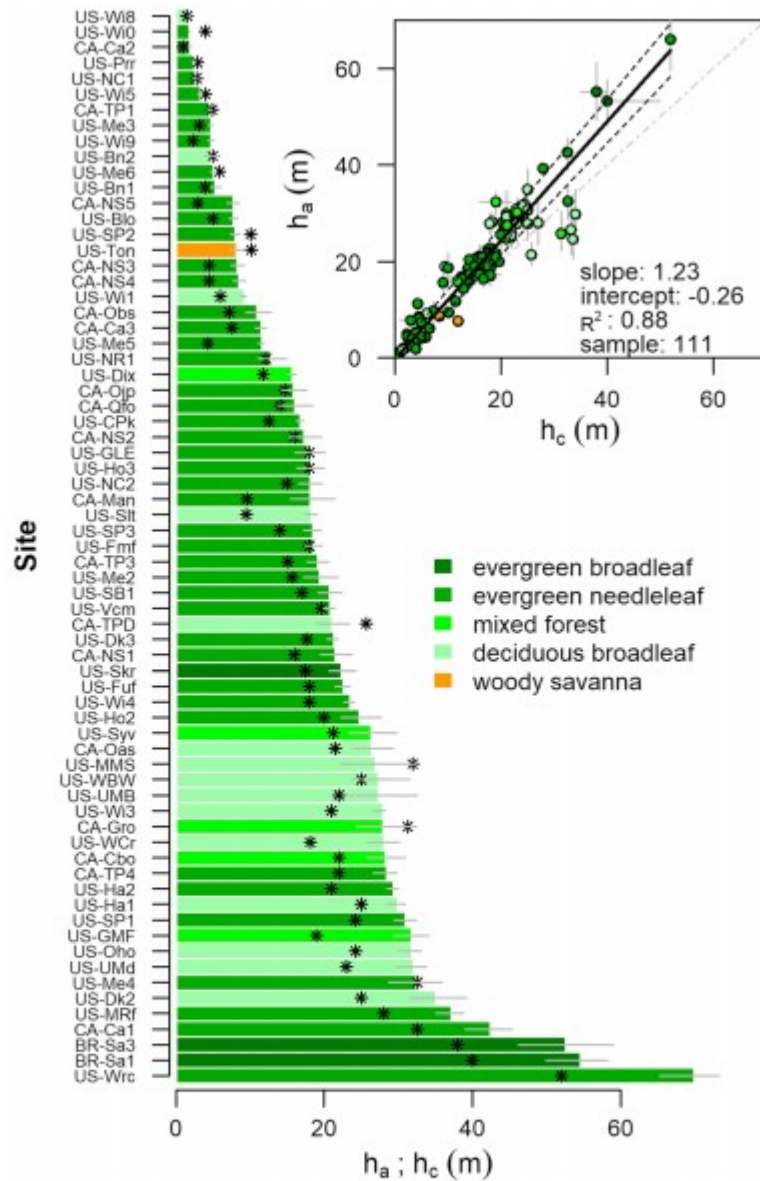
Figure 1. Annual canopy heights across 69 AmeriFlux forest sites (site ID in y axis). The horizontal bars and gray segments indicate the multiyear means of aerodynamic canopy heights (h_a) and the 95 percentile range ($N = 1$–22). The asterisks denote the mean actual canopy heights (h_c) for available years ($N = 1$–5). The colors denote the plant functional types. The inset compares h_a and h_c in all available site-years ($N = 111$). The vertical and horizontal gray segments represent the 95 percentile ranges of h_a and reported upper-lower ranges of h_c, respectively. The black solid and dashed lines denote the linear regression and its 95% confidence intervals. The gray dotted-dash line shows the 1:1 reference line. Please refer to Table S1 for site general information and Table S3 for summary statistics of linear regression.

Only a few sites had routine measurements of h_c over years that allowed us to evaluate the estimated temporal trends. That includes the three plantation sites (i.e., $N \geq 5$; CA-TP4 [Figure 2a], CA-TP3, and US-NC2 [Figure S5]). The trends estimated from h_a were 0.15, 0.25, and 0.49 m yr^{-1} for CA-TP4, CA-TP3, and US-NC2, respectively. While the estimated trends were all significantly positive as expected, the absolute magnitudes were consistently lower than those estimated from h_c (i.e., 0.38, 0.60, and 0.98 m yr^{-1}). For the

other 15 sites that had sparse measurements of h_c (5 > N ≥ 2, Figures S4 and S5), we were unable to obtain quantitatively robust trend estimates for comparison, but we found that the directions of change in canopy heights (i.e., positive, negative, or no change) were generally matched between h_a and h_c. The uncertainty levels in h_a and h_c may still be too large for certain tall canopy sites to allow a robust trend estimate, and thus, our estimates may not always capture the trends observed at the sites (e.g., US-MMS and US-UMB, Figure S4).
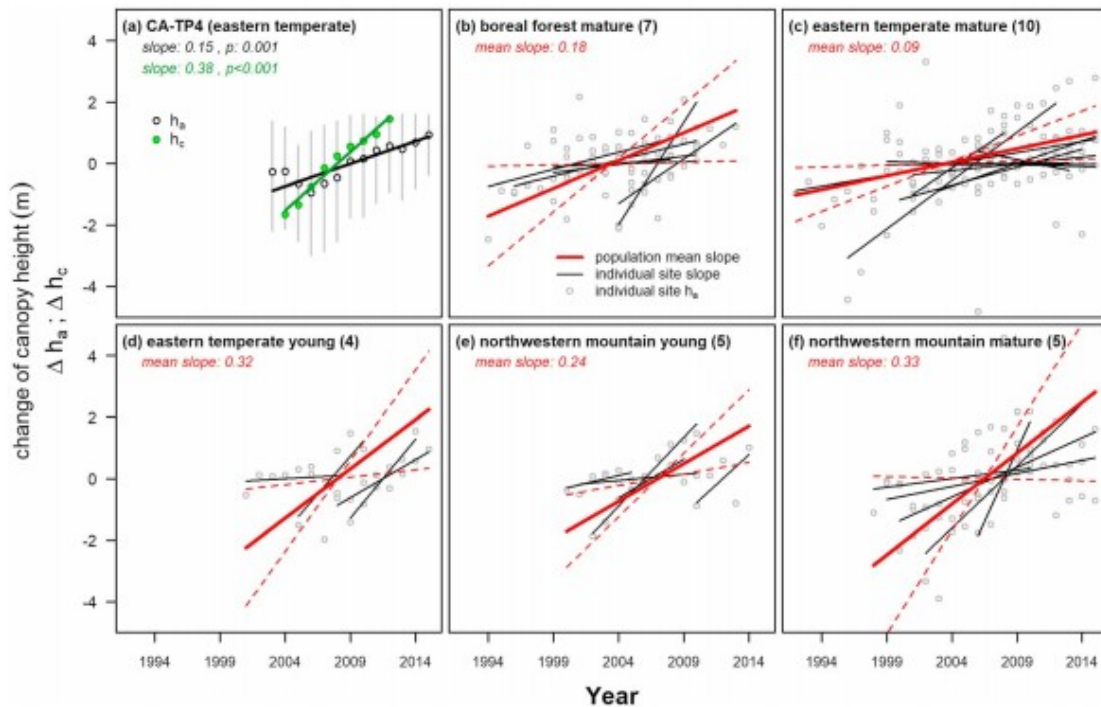
Figure 2. Changes over time in the annual aerodynamic canopy heights (h_a) in the forest sites with long-term (≥5 years) data, including (a) an example of the CA-TP4 site (a needleleaf forest) and pooled results for all the ecoregions. The sites are grouped into (b) mature forests in the boreal region (7 sites), (c) mature forests in the eastern temperate region (10), (d) young forests in the eastern temperate region (4), (e) young forests in the northwestern mountain region (5), and (f) mature forests in the northwestern mountain region (5). In Figure 2a, the black and green colors refer to h_a and actual canopy height (h_c), respectively. The vertical gray segments denote the 95 percentile ranges of h_a. In Figures 2b–2f, the red line represents the mean trend (i.e., slope [m yr^{-1}]) of all sites in the ecoregion, extrapolated over all available measurement years. The dashed lines denote the 95% confidence interval of the Sen's slope. Individual site-year h_a and trends are shown as gray circles and black lines, respectively. Please refer to Figures S4 and S5 for separate plots of individual sites and Table S4 for summary of trend analyses.

We found temporal trends of increasing h_a when pooling the long-term sites without known disturbances in the same ecoregion, an indication of canopy growth over time (Figure 2). The region-average trends were around 0.18 and 0.09 m yr^{-1} for the mature forests in the boreal and eastern temperate regions (Figures 2b and 2c). The trends were higher (0.32 and 0.24 m yr^{-1}) for the young forests in the eastern temperate and northwestern mountain regions (Figures 2d and 2e). The mature forests in the northwestern mountain region showed large site-to-site variation in the temporal trends (Figure 2f).

Finally, four sites reported disturbances during the measurement periods (Table S1), including US-UMd (stem-girdled treatment in 2008), US-Slt (Gypsy moth outbreak in 2007 and 2008), US-CPk (pine beetle outbreak since 2008),

and US-GLE (spruce beetle outbreak since 2008). These four sites showed trends of decreasing h_a (Figures S4 and S5), which were −0.27, −0.07, −0.27 (2009–2012), and −0.32 (post-2008) m yr^{-1}, respectively.

Seasonal Changes in Aerodynamic Canopy Heights at Cropland/Grassland Sites

Weekly h_a effectively captured the seasonal dynamics of h_c across a variety of short vegetation sites (Figure 3). Overall, the regression slopes of the 1:1 comparison were 0.94 ± 0.05, 0.88 ± 0.08, 1.02 ± 0.10, and 0.71 ± 0.06 for corn, soybean, grass, and other vegetation types, respectively. The overall good relationships ($R^2 = 0.56–0.77$) suggest that h_a is robust in capturing the seasonal dynamics of canopy heights (e.g., growth and harvest, Figure 3a).
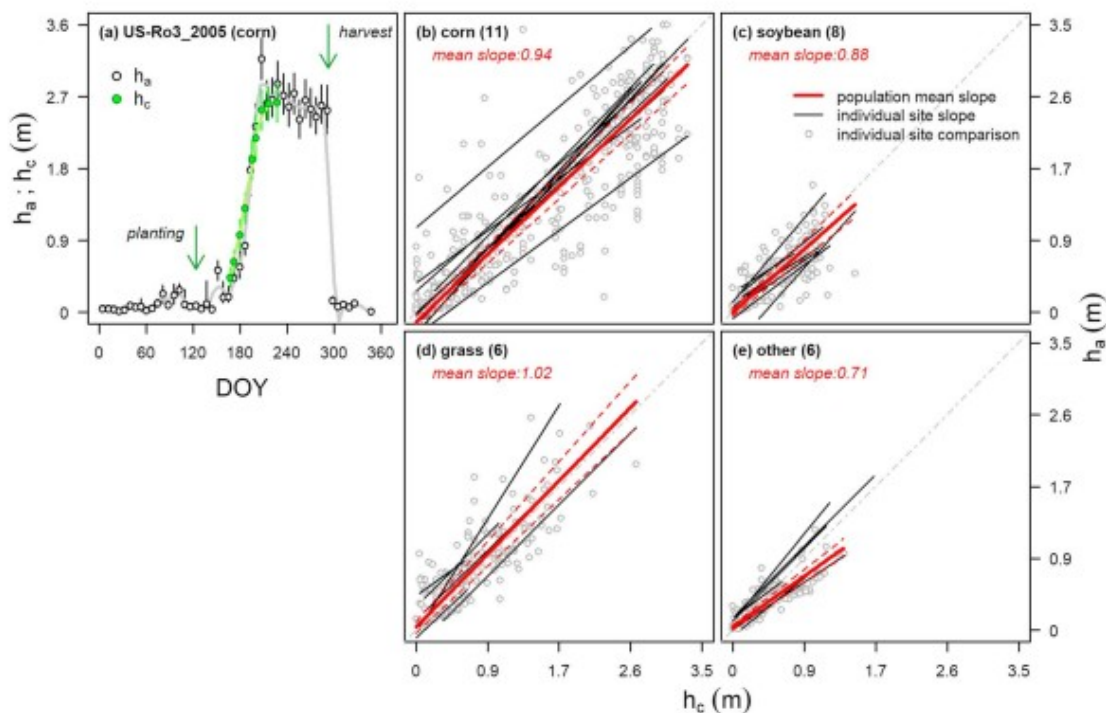
Figure 3. Comparison of weekly aerodynamic canopy heights (h_a) and actual canopy heights (h_c) across cropland/grassland sites, including (a) a 1-year time series example from a corn cropland (US-Ro3, 2005) and pooled comparisons for vegetation types of (b) corn (11 sites), (c) soybean (8), (d) grass (6), and (e) others (6). In Figure 3a, the black and green circles refer to h_a and h_c, respectively. The vertical segments denote the 95 percentile ranges of h_a and h_c, while the light-colored curves show the smoothed temporal trajectories (Savitzky-Golay filter). The green arrows indicate the dates of planting and harvest (DOY = 123 and 293/294). In Figures 3b–3e, the red line represents the linear regression over all site-year data in each vegetation type (95% confidence interval in dashed lines). Individual site comparisons and linear regressions are shown as gray circles and black lines, respectively. Please refer to Figures S7 and S8 for separate plots of individual site-years and Table S5 for summary statistics.

For individual site-years, we found that the majority of years (84%) showed a good linear relation ($R^2 > 0.70$) between h_a and h_c (Figure S6). The majority of site-years had slopes and intercepts of 1.0 ± 0.3 and 0.0 ± 0.3 (Figure S6), respectively. Such consistent agreement suggests that h_a is suitable for capturing the seasonal dynamics of h_c from year to year for short vegetation sites (Figures S7 and S8). For a few of the sites, we found relatively large differences between h_a and h_c in the nongrowing seasons during which the plants either senesced or were harvested (e.g., US-Var and US-KL1, Figure

S8). As the deviations were confined to individual sites that have relatively limited homogeneous fetch, they likely resulted from the site-specific characteristics of the turbulent flux footprint or topography (Figure S9).

Discussion

Aerodynamic Canopy Height as a Robust Proxy of Canopy Height

Aerodynamic canopy height, despite its potential estimation bias at some tall-canopy and fetch-limited sites, successfully captures site-to-site variations of canopy heights across a wide range of vegetation types. Recent research campaigns mapping forest canopy height globally using spaceborne LiDAR (e.g., ICESat GLAS) emphasize the importance and needs of a ground-based canopy height data set for cross comparison with the remotely sensed estimates (Giannico et al., 2016; Lefsky, 2010; Simard et al., 2011). While there is a growing community utilizing ground-based or airborne LiDAR in obtaining detailed canopy structures at flux tower sites (e.g., Beland et al., 2015; Cook et al., 2013), its application is still limited to a small number of sites and sparser, more-recent temporal coverage.

We advocate that h_a could be calculated routinely across the flux networks and be used as a robust proxy of canopy height for sites/years where direct measurements or remote-sensing based estimates are unavailable. The tight linear relationships between h_a and h_c across sites suggest that an empirically corrected data product of canopy height could be derived based on h_a and site-/vegetation-specific h_a-h_c relationships (Figures S10 and S11 and Tables S6 and S7). Future studies should further examine the relations between aerodynamic characteristics (e.g., canopy height and roughness length) and canopy physical structures obtained by low-flying and satellite-based LiDAR (e.g., GEDI). Such relations could be an intermediate method of training satellite algorithms to better represent the canopy's aerodynamic characteristics at the individual site level, or as an approach to scale aerodynamic characteristics from flux tower footprints to a larger spatial extent.

Though it remains challenging to disentangle the probable causes leading to the deviations between h_a and h_c, we can attribute several aspects. First, h_a and h_c are inherently different measures of canopy height. In theory, h_a should be biased toward the effect of the tallest (or aerodynamically rougher) trees comprising the upper canopy (Maurer et al., 2013; Nakai, Sumida, Matsumoto, et al., 2008). Yet strong winds, in contrast, can cause deformation of the canopy for certain moments (e.g., bending over and honami; Finnigan, 1979; Gardiner, 1994). Thus, while it is reasonable to assume h_a scales with h_c, h_a and h_c may not always match. Second, h_c is still infrequently measured using conventional approaches and subject to observer bias. Even when it is reported, it is rarely well defined and/or quantified in a standard way (i.e., across sites/years; see discussion in Nakai et al., 2010). Additionally, measurements of h_c often do not cover the same footprint area (e.g., 10^4–10^6 m^2) and do not match the footprints' spatial

sampling density frequency as the wind measurements used for calculating h_a, adding uncertainties to the comparisons, especially for the tall forest sites, or those with significant spatial heterogeneity in canopy height or ground elevation. Last, the calculation of h_a is dependent on the adequate choice of α_1-α_2 models. The current lack of extensive and time-explicit forest structure data (e.g., leaf area profile, stand density, gap fraction, and nonleaf structure) still hinders further evaluations using more sophisticated α_1-α_2 models (e.g., Maurer et al., 2015; Nakai et al., 2008; Shaw & Pereira, 1982).

Tracking Changes in Aerodynamic Canopy Heights Over Time

The small bias in our estimation, as discussed above, does not preclude the use of h_a for detecting changes in canopy characteristics over time. For sites without major disturbances or structural changes of canopy (e.g., plantation sites), h_a could be a first-order approximation for tracking the canopy height growth. Maurer et al. (2013) was the first study that examined decadal changes of h_a at a broadleaf deciduous forest (US-UMB). Adopting a different approach, they showed that h_a for the leafless seasons tended to better capture growth of the forest canopy than that for the full-foliage seasons. Our preliminary tests found that the estimated trends were mostly compatible using either full-foliage or leafless periods in our calculation (Text S4 and Figure S4). For US-UMB, our estimated trends were 0.12 and 0.11 m yr^{-1} (2000–2014) using the full-foliage and leafless periods, which were similar to 0.12 m yr^{-1} (2000–2011) reported in Maurer et al. (2013). However, the uncertainty levels of our calculations were still too large for this tall forest, and our estimated trends were statistically insignificant. Focusing on roughness length, Keenan et al. (2013) found no significant long-term trend in the midsummer surface roughness at seven AmeriFlux forest sites. Our results generally agreed with their findings for those sites, except that US-Ha1 site showed a significantly increasing trend over a slightly longer time period (1992–2015) than in the previous study (1992–2010).

The unaccounted changes in canopy structure (e.g., total leaf area, leaf area profile, stand density, gap fraction, and composition) are likely responsible for the unexpected interannual variation of h_a at some forest sites, and for the difference between estimated trends from h_a and h_c (Aber, 1979; Maurer et al., 2013; Nakai, Sumida, Daikoku, et al., 2008). As shown in the known disturbed sites (Clark et al., 2018; Frank et al., 2014; Hardiman et al., 2013; Reed et al., 2014), the observed changes of h_a are the consequence of changes in canopy structure (e.g., canopy height, stand density, gap fraction, and leaf area). Some forest sites may have undergone compositional changes (e.g., mortality and succession), which makes it challenging to delineate a physically meaningful trend from the year-to-year variation. In sum, we suggest that the trend analyses of h_a could be treated as a first estimate. For sites that have undergone canopy structural changes, the changes in h_a may need to be interpreted in the context of calculation assumptions or along with ancillary information of canopy structure.

Our analyses show that weekly h_a is a robust estimator of seasonal canopy dynamics at the short-vegetation sites. The need to improve our quantitative understanding of plant phenology has stimulated a growing body of innovative research in recent decades (e.g., Keenan et al., 2014; Toda & Richardson, 2017). Among these, only a few studies focused on the aerodynamic characteristics and canopy structural dynamics (e.g., Graf et al., 2014; Sonnentag et al., 2011). Our evaluations support the applicability and robustness of aerodynamic parameters, which adequately track the transition of fields from bare ground to tall plants over the course of the growing season. Thus, we advocate that h_a should be routinely calculated at the cropland and grassland sites and serve as a continuous canopy structural index (e.g., Alekseychik et al., 2017).

Conclusions

Aerodynamic canopy height derived from routinely collected and underutilized data of momentum flux and wind statistics can serve as a quantitative, rigorous approach to quantify differences in canopy height between sites and over time. We showed its robustness in capturing site-to-site differences in canopy height across a wide range of ecosystems, for example, forest, grassland, and cropland. The annual h_a estimates could be potentially used for detecting long-term growth trends or structural changes at forest sites; however, caution should be exercised in the broader applicability of the method in complex or heterogeneous forest sites. At short-vegetation sites, the weekly h_a estimates provide an innovative and independent approach for tracking the seasonal dynamics of vegetation canopy, such as those induced by harvest, natural disturbances, and land use change. Given the amount of data collected and the diversity of vegetation covered by flux networks, the flux-derived canopy height has great potential for providing a new benchmark for regional and global Earth system models and satellite remote sensing of canopy structure.

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