**GEOMATICS CANADA**

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**Woody Area Index and Leaf Area Index Estimates for Selected National Ecological Observatory Network Sites**

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**2024**

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## Abstract

Leaf Area Index (LAI), defined as half the total green leaf area per unit ground area, is an essential climate variable required for monitoring vegetation and as input to land surface models. In this study, LAI was estimated between 20xx and 20xx for xx elementary sampling units at xx US National Ecological Observatory Network (NEON) evergreen forest sites by subtracting representative estimates of woody area index (WAI) from existing estimates of plant area index (PAI). Early spring WAI was derived for between 1 and 6 reference elementary sampling units (ESUs) at each site as the difference between PAI and LAI , estimated with the CANEYE application through visually labelled digital hemispherical photographs. Reference ESU WAI was used to estimate WAI for all dates using site specific relationships between WAI and LAI calibrated assuming constant within ESU WAI . WAI estimates ranged from xx to xx with a median WAI of xx. LAI estimates using site specific values were between 25% and 100% of estimates based on the previously assumed constant ratio of LAI to PAI of 0.84.

## Introduction

Leaf area index (LAI) is an essential climate variable, defined as half the total green leaf area per unit horizontal ground area (GCOS, 2022). Non-destructive in-situ LAI estimates are frequently derived by inversion of measurements of canopy light transmission (xx) or gap fraction (xx) as a function of view angle in the upper hemisphere below the overstory canopy, for overstory LAI, and in the lower hemisphere above the understory canopy, for understory LAI. These approaches will overestimate LAI for canopies with matter other than green leaves. Instead, to the extent measurements are sufficiently detailed and accurate and the inversion theory is correct, these approaches provide unbiased estimates of plant area index (PAI), defined as one half of the total vegetation area per unit horizontal ground surface area. Overestimates of overstory LAI will also result in an overestimate of the fraction of absorbed photosynthetically active radiation absorbed by green foliage (FAPARg).

PAI minus LAI is conventionally termed the woody area index (WAI) although this includes all vegetation surface area other than green leaves. The bias in indirect LAI based can be reduced by subtracting a representative WAI estimate. WAI estimates of evergreen canopies has previously relied on WAI estimates from limited global destructive sampling (Brown et al. xx).). Non-destructive LAI estimates have, for the most part, relied on correcting gap fraction or transmittance based estimates of PAI using the ratio of LAI to PAI based on available destructive sampling studies. LAI to PAI ratios from destructive sampling are limited geographically and in terms of species considered. For example, Brown et al. ([https://doi.org/10.1016/j.isprsjprs.2021.02.020](https://doi.org/10.1016/j.isprsjprs.2021.02.020" \o "Persistent link using digital object identifier" \t "_blank)) used ratios from three sites in the Canadian Boreal forest (black spruce, red pine, jack pine) , one sitka spruce site in the United Kingdom, and one douglas fir site in the United States of America to arrive at a mean ratio of 0.84 and standard deviation of 0.11. However, the theory of tree hydraulics suggests that tree LAI should be proportional to the tree sapwood cross-sectional area in a species dependent manner ([10.1002/ece3.1344](https://doi.org/10.1002%2Fece3.1344" \t "_blank), <https://doi.org/10.1139/x82-086>). As such, the baseline stand level LAI to PAI ratios Brown et al. (xx) could result in substantial biases when applied across a wide range of species and sites as is the case with the NEON PAI dataset.

WAI can be estimated by inversion of angular fraction of non woody viewed area (NWVA) in DHPs (Kucharik et al, xx, Brown et al. xx). Numerical simulations assuming perfect NWVA labelling indicate the uncertainty and bias of WAI estimates using gap fraction inversion theory is similar to that of PAI estimates at the same site (Brown et al. xx). However, quantifying NWVA from in-situ DHP measurements is non-trivial due to the variability in canopy illumination (xx). Previous studies have used cameras with both red and near-infrared bands to increase the contrast between green foliage and other plan matter (Kucharik, xx; Brown etal. Xx). Such cameras are not widely used and often rely on instruments with relatively low (<20Mpixel) resolution that may result in additional NWGA error tall needle leaf canopies (xx).

Qualitative assessment of early season DHP imagery acquired using cameras with high radiometric sensitivity (xx), high radiometric resolution (14 bit), and high spatial resolution (>xxMPixels) suggests it may be possible to visually distinguish green foliage with sufficient accuracy to derive a lower bound on the site WAI at an elementary sampling unit (ESU) within an evergreen forest site. This WAI estimate can then be used to directly to quantify the ESU LAI for the sampling date and, assuming constant WAI over time, for all other dates. Furthermore, assuming similar LAI/PAI ratios for similar overstory canopies within the site, the time series of ratio of LAI/PAI for each measured ESU can then be used to estimate the LAI for ESUs within same sites with the same LAI and species composition.

The proposed approach to WAI correction is applied here to ESUs within xx evergreen forest sites within the US National Ecological Observatory Network. Validation of the proposed approach for WAI correction is beyond the scope of this study. However, strategies for quantifying the uncertainty of this WAI correction approach are discussed.

## Materials

Existing NEON PAI Estimates

2578 verstory PAI estimates were acquired (Brown, L. pers. Comm.) for 180 evergreen forest ESUs across 16 NEON sites (Figure 1). The ESUs were located within a xx mm radius of the site centre and shared similar soils, species composition and microclimate within a site. Up to 3 ESUs were surveyed bi-weekly during the growing season at each site and up to xx ESUs during the peak season. Existing PAI estimates were derived by applying an automated thresholding algorithm to visually quality controlled full frame DHPs, with resolution between xx Mpixel and xx Mpixel, to quantify angular canopy grap fraction and then applying HEMIPy to estimate PAI using the Miller algorithm and the Warren-Wilson algorithm. Miller PAI corresponds to the average of PAI estimated for non-overlapping xx degrees azimuthal field of view by relating the angular gap fraction 0 and 60degrees zenith to PAI assuming random foliage placement. Warren PAI differs from Miller PAI in that only the zenith interval between xxdegrees and xx degrees is used. Both estimates should be equivalent in the absence of measurement errors and with exhaustive sampling of all gaps. Warren PAI is generally larger than Miller PAI for forests as nadir gap fraction is usually overestimated from DHP measurements due to trunks (Leblanc et al., xx)

Figure 1 – Map of sites with esu count as symbol size

Reference ESU DHPs

Between one and six reference ESU(s) were selected for a site so as to span the range of NEON overstory PAI for all evergreen forest ESUs at the site (Table 1). Reference ESU DHPs were downloaded from the NEON Data Site (xx) for the earliest surveyed month after March with preference given to the most recent year on record as NEON cameras have improved over time. The NEON protocol requires sampling during diffuse illumination conditions but approximately half of the DHP surveys were conducted under other illumination conditions.

Data corresponded to NIKON RAW format upward looking DHPs acquired at either 24Mipxels or 36Mpiles. A 15mm fisheye lens was used in all cases resulting in a 180d diagonal, xx degrees vertical and xx degree horizontal field of view. At least 12 DHPs were recorded for each sample date at each ESU.

Table 1. Reference ESUs and CANEYE estimates of PAI, Lai and WAI.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Site | Date | PLOT\_ID | Mean Canopy Height | PAI CANEYE | LAI CANEYE | WAI CANEYE | WAI/PAI CANEYE | PAI  Miller | PAI  Warren | WAIref  Miller | WAIref  Warren |
| ABBY | 17-Apr-19 | ABBY\_067 | 34 | 1.18 | 0.58 | 0.60 | 0.51 | 2.58 | 3.04 | 1.31 | 1.55 |
| ABBY | 17-Apr-19 | ABBY\_068 | 34 | 1.04 | 0.17 | 0.87 | 0.84 | 1.66 | 0.99 | 1.39 | 0.83 |
| ABBY | 17-Apr-19 | ABBY\_069 | 34 | 0.73 | 0.20 | 0.53 | 0.73 | 1.48 | 1.77 | 1.07 | 1.29 |
| BONA | 25-May-22 | BONA\_080 | 8 | 1.08 | 0.44 | 0.64 | 0.59 | 0.60 | 0.81 | 0.36 | 0.48 |
| DEJU | 23-May-22 | DEJU\_052 | 10 | 0.19 | 0.09 | 0.10 | 0.53 | 1.35 | 0.96 | 0.71 | 0.51 |
| DEJU | 23-May-22 | DEJU\_056 | 10 | 0.99 | 0.27 | 0.72 | 0.73 | 0.78 | 0.73 | 0.57 | 0.53 |
| DEJU | 23-May-22 | DEJU\_061 | 10 | 0.45 | 0.12 | 0.33 | 0.73 | 0.31 | 0.46 | 0.23 | 0.34 |
| HARV | 13-Apr-21 | HARV\_041 | 26 | 1.95 | 0.69 | 1.26 | 0.65 | 3.12 | 2.88 | 1.86 | 1.20 |
| JERC | 07-Mar-19 | JERC\_054 | 27 | 0.78 | 0.10 | 0.68 | 0.87 | 1.20 | 1.22 | 1.06 | 0.93 |
| JERC | 12-Apr-22 | JERC\_054 | 27 | 3.52 | 1.42 | 2.10 | 0.60 | 4.82 | 3.69 | 2.88 | 2.20 |
| JERC | 12-Apr-22 | JERC\_060 | 27 | 0.60 | 0.10 | 0.50 | 0.83 | 1.18 | 0.83 | 0.98 | 0.69 |
| JERC | 07-Mar-19 | JERC\_062 | 27 | 0.67 | 0.10 | 0.57 | 0.85 | 0.91 | 0.90 | 0.77 | 0.77 |
| JERC | 12-Apr-22 | JERC\_062 | 27 | 1.26 | 0.24 | 1.02 | 0.81 | 1.20 | 1.12 | 0.97 | 0.91 |
| OSBS | 20-Apr-21 | OSBS\_038 | 23 | 1.09 | 0.19 | 0.90 | 0.83 | 1.13 | 1.08 | 0.93 | 0.89 |
| PUUM | 21-May-20 | PUUM\_010 | 20 | 4.39 | 1.42 | 2.97 | 0.68 | 4.61 | 4.42 | 3.12 | 2.99 |
| PUUM | 21-May-20 | PUUM\_041 | 20 | 4.25 | 1.59 | 2.66 | 0.63 | 4.74 | 4.42 | 2.97 | 2.77 |
| RMNP | 14-May-19 | RMNP\_045 | 20 | 2.06 | 1.14 | 0.92 | 0.45 | 2.15 | 1.99 | 0.96 | 0.89 |
| RMNP | 23-Jul-19 | RMNP\_046 | 19 | 2.85 | 0.66 | 2.19 | 0.77 | 2.66 | 2.10 | 2.04 | 1.61 |
| RMNP | 09-Jul-21 | RMNP\_046 | 19 | 2.46 | 0.86 | 1.60 | 0.65 | 2.88 | 2.00 | 1.87 | 1.30 |
| SJER | 04-May-22 | SJER\_049 | 21 | 0.42 | 0.11 | 0.31 | 0.74 | 0.57 | 0.58 | 0.42 | 0.43 |
| SOAP | 19-Apr-22 | SOAP\_058 | 32 | 0.13 | 0.05 | 0.08 | 0.62 | 0.08 | 0.13 | 0.05 | 0.08 |
| TALL | 13-Apr-22 | TALL\_046 | 25 | 2.70 | 0.88 | 1.82 | 0.67 | 2.37 | 2.50 | 1.60 | 1.69 |
| TALL | 13-Apr-22 | TALL\_048 | 25 | 1.59 | 0.31 | 1.28 | 0.81 | 1.66 | 1.62 | 1.34 | 1.30 |
| TEAK | 25-May-21 | TEAK\_046 | 35 | 3.92 | 1.23 | 2.69 | 0.69 | 3.32 | 3.15 | 2.28 | 2.16 |
| TEAK | 25-May-21 | TEAK\_047 | 35 | 3.11 | 1.03 | 2.08 | 0.67 | 3.31 | 3.32 | 2.21 | 2.22 |
| TEAK | 25-May-21 | TEAK\_057 | 35 | 4.86 | 1.73 | 3.13 | 0.64 | 4.85 | 4.43 | 3.12 | 2.85 |
| UKFS | 05-Apr-22 | UKFS\_051 | 19 | 2.11 | 0.47 | 1.64 | 0.78 | 2.57 | 3.02 | 2.00 | 2.35 |
| WREF | 22-Apr-19 | WREF\_078 | 50 | 3.83 | 0.69 | 3.14 | 0.82 | 4.94 | 4.42 | 4.05 | 3.62 |
| WREF | 22-Apr-19 | WREF\_082 | 50 | 3.53 | 0.97 | 2.56 | 0.73 | 4.45 | 4.82 | 3.23 | 3.50 |
| WREF | 22-Apr-19 | WREF\_088 | 50 | 3.82 | 0.94 | 2.88 | 0.75 | 4.41 | 3.99 | 3.32 | 3.01 |

## Methods

DHPs were enhanced in Nikon NX studio (xx) using default settings (Figure 2) and then tuned to increase the visual separation between green foliage and other vegetation matter. Tuning consisted of adjusting the “shadow protection” setting to maximize the qualitative visual separability of green and non-green vegetation matter, with higher levels of shadow protection increasing detail in shadows but also potential overlap of colours of green foliage and other vegetation. Enhanced DHPs were exported as full resolution highest quality uncompressed JPEG format images for use in CANEYE.

Figure 2 here – NX studio Enhancement

LAI and PAI was estimated from exported DHPs from a single ESU sample date by applying CANEYE (version 4.69, xx). The same camera parameters (Annex x) were used for both LAI and PAI estimation for a reference sample. Three- fold pixel downsampling was applied in horizontal and vertical directions to limit memory demands. PAI was estimated by classifying sky pixels as gaps visually followed by applying the CANEYE inversion algorithms. For simplicity, mixed pixels were not classified as sky (Figure xx) resulting in a potential overestimate in PAI. LAI was estimated by classifying all vegetation pixels as non-gaps using the same criteria for mixed pixels as applied during PAI estimation. Subsequently, vegetated pixels were visually reclassified as non-vegetation if they were visually assessed as not being green foliage. This step included both colour and pattern cues since needles and shadowed leaves could often have similar colour as other vegetation (Figure xx). Where required, large contiguous areas of other vegetation such as trunks was manually masked although this was generally limited to trunks subtending at least approximately 11.25degrees of azimuth. LAI was then estimated using the CANEYE inversion algorithms. CANEYE provides Miller and Warren-Wilson solutions as well as a combined solution (xx). The combined solution is used here since the Warran-Wilson solution tends to oversample vegetation near the horizon and the Miller solution tends to undersample vegetation near nadir and the horizon. Both LAI and PAI were likely overestimated due to the inclusion of mixed pixels as well as commission errors from unmasked other areas. However, the mixed pixel error would be the similar for both LAI and PAI and subsequently cancel out when estimating WAI for the reference sample ( ).

Figure 3 here – Caneye example

CANEYE WAI estimates were not directly used to estimate due to the potential of systematic differences in the gap labelling algorithm. Instead, assuming the ratio of CANEYE PAI to NEON PAI is the same for LAI,

(1)

LAI was then estimated for the NEON PAI measurement at sample date at the reference ESU assuming constant ESU :

(2)

, resulting in between 30 and 100 estimates at each reference ESU.

Assuming similar / ratios for NEON PAI samples within the site with similar overstory LAI as one of the estimates at the site, NEON LAI for samples at other ESUs ( was estimated by scaling NEON PAI by the ratio / for the reference site most closely matching the final estimate:

(3)

### Results

A total of 30 reference ESU DHP sampling dates were reprocessed with CANEYE to estimate LAI and PAI and subsequently (Table 1). Sample months ranged between April and May, inclusive, with the exception of September and October samples at DSNY and July samples at LENO and RMNP due to the lack of spring DHP measurements.

Histograms of CANEYE PAI were similar to NEON PAI Warren with the former being more negatively skewed (Figure 4). Histograms of NEON PAI Miller showed gaps at moderate PAI that CANEYE PAI or NEON PAI Warren. Scatterplots (Figure 4) and Pearson correlation coefficients, r, (Table 2) indicate strong (r≥0.92) linear relationships between all PAI methods and also between each PAI method and WAI CANEYE. Thiel-Sen slopes indicate CANEYE PAI underestimated NEON PAI Miller by ~14% and NEON PAI Warren by ~5% although the 95%ile confidence interval of the slope between CANEYE and NEON PAI estimates always included 1. Thiel Sen slopes between PAI estimates and WAI were 0.68 with 95%ile confidence intervals of ≤+/-0.08. One sample, corresponding to ABBY\_07 resulted in a NEON PAI Warren of 3.04 but a WAI CANEYE of only 0.60. We suspect this is an error in the NEON PAI estimate as a nearby ESU (Abby\_068) had a NEON PAI Warren of 0.99 and CANEYE PAI of 1.04 on the same date.



A collage of graphs

Description automatically generated

Figure 4. Histograms of PAI and WAI from CANEYE and PAI using Miller and Warren algorithms using HEMIPy and pairwise scatterplots of each quantity with 1:1 line.

Table 2. Pearson correlation coefficient ( r) and Thiel-Sen slope and intercept between PAI and WAI estimates.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| X | Y | r | slope | lower 95% c.i. slope | upper 95% c.i. slope | intercept |
| PAI CANEYE | WAI CANEYE | 0.98 | 0.68 | 0.63 | 0.74 | -0.07 |
| PAI Miller | WAI CANEYE | 0.97 | 0.68 | 0.60 | 0.74 | -0.16 |
| PAI Warren | WAI CANEYE | 0.96 | 0.68 | 0.61 | 0.75 | -0.06 |
| PAI CANEYE | PAI Miller | 0.94 | 0.86 | 0.72 | 1.00 | -0.17 |
| PAI CANEYE | PAI Warren | 0.92 | 0.95 | 0.79 | 1.10 | -0.13 |
| PAI Miller | PAI Warren | 0.97 | 1.07 | 0.96 | 1.14 | 0.12 |

The ratio of was proportional to NEON PAI (Figure 5) although the value could at times be negative for some NEON PAI estimates less than 1 due to uncertainty in CANEYE WAI estimation and NEON PAI estimation. However, this issue was eliminated by selecting the maximum ratio between NEON PAI estimation methods for the sample. This strategy will potentially under correct for WAI. WAI estimates using NEON PAI Warren ranged from ~0 to ~4.5 and WAI to PAI ratios ranged from ~0 to 0.9 (Figure 6). Multiple modes were present in histograms of both WAI and WAI to PAI ratios due to differences in sampling frequency at reference ESUs.

A screenshot of a graph

Description automatically generated

Figure 5. Ratio of Lai to PAI versus PAI using (a|) the Warren PAI only or () using the maximum rato calculated for Warren PAI and PAI Miller.

A comparison of a graph

Description automatically generated

Figure 6. Histograms of WAI and Wai to PAI ratio for all ESU measurements.

A diagram of different colored dots

Description automatically generated with medium confidence

Figure 7. Comparison of baseline LAI estimates assuming a LAI/PAI ratio of 0.85 and LAI estimates using site and LAI specific ratios for a) input NEON PAI estimates based on Warren approach and b) input NEON PAI estimates based on Miller approach.

LAI estimates using a baseline LAI to PAI ratio of 0.84 ranged from 100% to 400% of the LAI estimates using sample specific LAI to PAI ratios except for DEJU and SOAP where the baseline LAI was slightly less . The DEJU site at 63degrees North had short overstory canopies (mean height 10m) dominated by black spruce (Picea mariana) that generally has a high ratio of LAI to PAI (Chen et al. xx). The SOAP site had experienced high mortality of the dominant overstory Ponderosa pine (Pinus ponderosa) due to pine bark beetle leaving incense cedar (Calocedrus decurrens) with generally high ratios of LAI to PAI.

## Discussion

Representative LAI/PAI ratios require representative unbiased WAI estimates that could potentially be derived using gap fraction inversion theory applied to DHP images classified first to map canopy gaps and then to map only green foliage. Such a classification was previously enabled by automated classification of visible and NIR imagery to enhance the contrast between green vegetation that both scatters and transmits in the NIR versus woody matter that only scatters in NIR. Here, conventional Red-Green-Blue colour images were enhanced using NXStudio to improve perceptual separability between green foliage and either sky and woody matter and then visually labelled with CANEYE. This strategy relied on two factors not previously exploited when using NIR imagery. Firstly, the cameras used had sufficient spatial resolution, dynamic range and signal to noise ratio to enable colour separation of green foliage and woody matter in all but the darkest shadows. Secondly, the labelling processes relied on an expert visual interpreter who had over a thousand hours of both field measurement experience with digital hemisperhical photography of tree canopies and of CANEYE labelling experience.

The consistency and accuracy of the visual labelling of sky gaps was supported by the high correlation between CANEYE and NEON Warren PAI while the nearly 1:1 agreement of these two estimates at each ESU (Table xx). The consistency of visual labelling of green foliage was also supported by the relatively good agreement between estimate and baseline LAI for sites with species similar to those used for the baseline LAI to PAI ratio (BONA, RMNP in Figure xx). However, the negative LAI/PAI ratios for LAI<1 indicate that the uncertainty in estimates of WAI based on the difference of CANEYE PAI and LAI at an ESU can be as high as 1 WAI. Even so, baseline LAI using a 0.84 LAI to PAI ratio was often larger than estimates using site specific WAI by over 1 unit (Figure xx). As a conservative estimate a +/-0.5 WAI error at one standard deviation should be applied.

## Conclusion

Ratios of LAI to PAI were produced for reference NEON evergreen forest ESUs by using visual interpretation of early season DHPs. These ratios were applied to same site PAI estimates to estimate LAI assuming constant within ESU woody area and similar ratios for ESUs within a site with similar LAI. Visually interpreted PAI estimates were high correlated and almost unbiased in comparison to matching NEON PAI. However, overestimation of current NEON LAI estimates assuming a 0.84 LAI to PAI ratio overestimated LAI estimates from this study ranged from 0% to 400%. LAI to PAI ratios from this study should be used in the absence of new information. Further work is required to quantify the uncertainty in LAI estimates due to the developed approach. Until then a maximum WAI error of +/-0.5 units at 1 standard deviation should be applied.

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