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Paper:

Kim, J., Hwang, T., Schaaf, C., Kljun, N. & Munger, J. (2018). Seasonal variation of source contributions to eddy-covariance CO₂ measurements in a mixed hardwood-conifer forest. *Agricultural and Forest Meteorology*, 253-254, 71-83.

<http://dx.doi.org/10.1016/j.agrformet.2018.02.004>

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1 **Seasonal variation of source contributions to eddy-covariance CO₂**
2 **measurements in a mixed hardwood-conifer forest**

3
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18 This manuscript will be submitted to *Agricultural and Forest Meteorology*

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20

21 **Abstract**

22 Net ecosystem exchange (NEE) measurements using the eddy covariance technique have been
23 widely used for calibration and evaluation of carbon flux estimates from terrestrial ecosystem
24 models as well as for remote sensing-based estimates across various spatial and temporal scales.
25 Therefore, it is vital to fully understand the land surface characteristics within the area
26 contributing to these flux measurements (i.e. source area) when upscaling plot-scale tower
27 measurements to regional-scale ecosystem estimates, especially in heterogeneous landscapes,
28 such as mixed forests. We estimated the source area of a flux tower at a mixed forest (Harvard
29 Forest in US) using a footprint model, and analyzed the spatial representativeness of the source
30 area for the vegetation characteristics (density variation and magnitude) within the surrounding
31 1- and 1.5-km grid cells during two decades (1993 – 2011). Semi-variogram and window size
32 analyses using 19 years of Landsat-retrieved enhanced vegetation index (EVI) confirmed that
33 spatial heterogeneity within the 1-km grid cell has been gradually increasing for leaf-on periods.
34 The overall prevailing source areas lay toward the southwest, yet there were considerable
35 variations in the extents and the directions of the source areas. The source areas generally cover a
36 large enough area to adequately represent the vegetation density magnitude and variation during
37 both daytime and nighttime. We show that the variation in the daytime NEE during peak
38 growing season should be more attributed to variations in the deciduous forest contribution
39 within the source areas rather than the vegetation density. This study highlights the importance
40 of taking account of the land cover variation within the source areas into gap-filling and
41 upscaling procedures.

42

43 **Highlights**

44 1. The source contribution to eddy-covariance CO₂ measurements differed between leaf
45 development stages.

46 2. The variation in the daytime CO₂ measurements were accounted for by the vegetation density
47 within the source area during the greenup and senescence stages.

48 3. During the maturity stage the land cover within the source area better explained the variation
49 in the daytime CO₂ measurements.

50

51 **Keywords**

52 Eddy covariance flux measurement; Net ecosystem exchange; Spatial representativeness;

53 Footprint model; Landsat EVI

54

55 **1. Introduction**

56 Our understanding of the interactive dynamics between climate change and terrestrial
57 ecosystem processes (Cao and Woodward, 1998; Finzi et al., 2011; Keenan et al., 2014; Nemani
58 et al., 2003) has been remarkably progressed through the use of tower-based eddy covariance
59 (EC) flux measurements (Baldocchi, 2003; Baldocchi et al., 1988; Falge et al., 2002; Law et al.,
60 2002; Schmid et al., 2000). As unique *in-situ* and semi-continuous measurements, these flux
61 tower data have been applied to a wide range of studies, such as statistical analysis for a single
62 site or across multiple biomes (Keenan et al., 2013; Urbanski et al., 2007), and for correlation
63 analysis with other biophysical attributes and processes (Davidson et al., 2006). These tower data
64 have also been used for calibration and validation of mechanical ecosystem models and remote
65 sensing-based estimates at various spatial resolutions (e.g., the Moderate Resolution Imaging
66 Spectrometer (MODIS) gross primary productivity (GPP) product at a 1-km resolution (Heinsch
67 et al., 2006; Schwalm et al., 2010; Verma et al., 2015). The number of flux towers in the
68 FLUXNET network (<http://fluxnet.ornl.gov/>) has increased rapidly, including about 846 sites as
69 of November 2016. Mixed forests are some of the most common land covers in which flux
70 towers have been set up (https://fluxnet.ornl.gov/site_list/IGBPLU/5). Several of the flux towers
71 with the longest records, therefore the towers most frequently used in studies, are located in
72 mixed forests such as Harvard Forest, MA, US (FLUXNET Site ID: US-Ha1, since 1991),
73 Howland Forest, ME, US (US-Ho1,2,3, since 1995,1999,2001), Morgan-Monroe State Forest, IN,
74 US (US-MMS, since 1998), ON-Borden Mixed wood, Ontario, Canada (CA-Cbo, since 1995),
75 Brasschaat, Belgium (BE-Bra, since 1996), and more.

76 Multiple factors have to be considered to determine whether the upwind land surface
77 measured by a flux tower (“*source area*”) adequately describes the characteristics of the

78 surrounding ecosystem (“*spatial representativeness*”; Román et al., 2009; Schmid, 1997). This is
79 especially critical in mixed forests, where temporally varying wind direction and atmospheric
80 stability can change the source weight distribution of fluxes measured at a tower considerably
81 over the heterogeneous land covers, resulting in a large degree of variations in the source area
82 characteristics and therefore in the measured flux (Wehr and Saleska, 2015). This inevitable
83 source area variability has long been recognized as one of the major uncertainties in flux
84 measurements (Baldocchi, 2003). To understand and reduce this uncertainty, a number of studies
85 have focused on developing a source weight function (“*footprint*”; Hsieh et al., 2000; Kljun et al.,
86 2002, 2004; Kormann and Meixner, 2001; Schmid, 1994; van Ulden, 1978) and applying these
87 footprint models for the uncertainty analysis of flux measurements and also for ground-biometric
88 sampling schemes (Amiro, 1998; Chasmer et al., 2011; Griebel et al., 2016; Novick et al., 2014;
89 Oishi et al., 2008; Stoy et al., 2006; Xu et al., 2017). There are also ongoing efforts to
90 standardize the source area estimation at the network levels (Menzer et al., 2015, 2014).
91 However, as of yet, most studies of mixed forests have not fully considered the temporal
92 variations in source areas, but instead have only approximated a fixed area (Turner et al., 2003;
93 Verma et al., 2015) or simply rejected some flux data solely based on wind direction (Daley et al.,
94 2007; Phillips et al., 2010). Such wind-direction based filtering schemes sometimes leave only
95 25% of the total data deemed as appropriate for further analysis (Hadley & Schedlbauer, 2002;
96 Stoy et al., 2006), yet still leaves questions about the representativeness of the flux data for large-
97 scale applications.

98 Furthermore, even those studies that assessed the spatial representativeness of flux
99 measurements for the surrounding landscape using footprint models have usually only performed
100 this assessment for a limited time period, such as for a single season or for only a few years,

101 mainly due to the high computational costs (Chen et al., 2012; Göckede et al., 2008; Kim et al.,
102 2006; Schmid and Lloyd, 1999). In a mixed forest, however, the spatial representativeness of
103 source areas may experience significant seasonal variations, depending on vegetation types and
104 their spatial distributions around the tower. For example, the phenological stage of deciduous
105 trees (greenup, maturity, senescence, and dormancy onsets) can be a primary factor that
106 transforms the entire surrounding landscape and drives the seasonal cycle of flux measurements.
107 Román et al. (2009) showed that the representativeness of tower-based albedo measurements
108 (note: a tower albedometer has a fixed viewing angle) for the evaluation of moderate resolution
109 satellite-derived albedo products is largely dependent on the timing of greenup of deciduous
110 trees, the distribution of conifer trees within the source area, and gridded resolutions of the
111 satellite products (~1-km and 1.5-km). The intrinsic physiological differences among vegetation
112 functional types also contribute to the spatial variations in biophysical attributes over the
113 landscape. Tian et al. (2002) described that 76% of total variance in leaf area index (LAI) within
114 a 15×13 km area in a mixed forest is mostly governed by the spatial variation of vegetation
115 functional types. There are also additional factors driving interannual and long-term changes in
116 spatial landscape characteristics of mixed forests, such as the different sensitivities to interannual
117 climate variability (Welp et al., 2007) and changes in vegetation types and distributions due to
118 ongoing climate change (Battles et al., 2007). Therefore, it is critical to understand long-term
119 representativeness of source areas when interpreting flux measurements in mixed forests and
120 when using these measurements to evaluate ecosystem models and remote sensing-based models
121 across different temporal and spatial scales.

122 In this study, first we calculate hourly source weights for a flux tower in a mixed forest
123 for 19 years (1993-2011). Based on these source weight estimates, we then examine the

124 representativeness of the source area for the surrounding vegetation characteristics (density
125 magnitude and variation) at moderate-spatial resolutions (1-km and 1.5-km) during daytime and
126 nighttime, separately, for each phenological stage. Finally, we investigate how much of the
127 variation in the measured flux can be attributed to vegetation density and land cover based on
128 their footprint-weighted contributions.

129

130 2. Materials and Methods

131 2.1. Study site

132 The Environmental Measurement Site tower (42.537755 °N, 72.171478 °W; US-Ha1) is located in
133 the Harvard Forest Long Term Ecological Research (LTER) site in Petersham, Massachusetts. The
134 topography in this area is relatively moderate, with elevation ranging from 320 to 380 meters
135 above sea level (Fig. 1a). The forest has a cool and moist temperate climate with annual mean
136 temperature of about 8.5 °C (20 °C in July and -7 °C in January) and annual total precipitation of
137 approximately 1100 mm, with winds primarily from southwest and northwest
138 (<http://harvardforest.fas.harvard.edu/research/HF-tract>). The forested landscape is dominated by
139 several tree species, including northern red oak (*Quercus rubra*), red maple (*Acer rubrum*), eastern
140 hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*), and black birch (*Betula lenta*) (Urbanski
141 et al., 2007). Mean ages of northern red oak and eastern hemlock are about 97 and 145 years,
142 respectively (Belmecheri et al., 2014). Canopy height is at about 20-24 meters (Goulden et al.,
143 1996; Wang et al., 2011). Basal area is about 33.5 m² ha⁻¹ (Munger and Wofsy, 1999a). Deciduous
144 trees occupy the southwestern area from the tower with scattered patches of coniferous trees (Fig.
145 1b). In mid-September of 1999, beaver activity caused a flood on the northwest side of the tower,
146 developing a small woody wetland (Savage et al., 2001; Urbanski et al., 2007). Additional beaver
147 activity temporarily flooded an area along the Bigelow brook on the southeast side of the tower in
148 recent years. This forest has been experiencing a hemlock woolly adelgid infestation since late
149 2000s (Orwig et al., 2008), but significant hemlock mortality was not yet been observed close to
150 the tower over the study period (until 2011; Kim et al., 2017).

151 The tower measurements, which began in Oct 1991, provide the longest continuous set of
152 flux measurements in the US (Baldocchi et al., 1988; Goulden et al., 1996; Urbanski et al.,
153 2007). Ground transects were established in 1993 along the prevailing wind directions, southwest
154 and northwest (220-254 and 291-325 compass degrees). Since 1995, biometric and abiotic data
155 has been collected along these transects 20-30 times a year, which include soil samples (water
156 content, temperature and respiration), biomass measurements (leaf area index, litterfall and
157 woody debris), and below-canopy microclimate observations (air temperature and solar
158 radiation). Datasets are publicly available on the Harvard Forest LTER, AmeriFlux and
159 FLUXNET websites (<http://harvardforest.fas.harvard.edu>; <http://ameriflux.lbl.gov>; Munger and
160 Wofsy, 1999a, 1999b).

161

162 *2.2. Data overview*

163 We used the hourly quality-checked NEE data ($\text{g C m}^{-2} \text{s}^{-1}$) of the FLUXNET2015
164 dataset (<http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/>; data quality assessment processes
165 are described in Pastorello et al. (2014)). Micrometeorological and energy flux data such as
166 friction velocity (u^*), wind direction (α), the standard deviations and covariances of wind
167 components (σ_u , σ_v , σ_w , $\overline{u'v'}$, $\overline{u'w'}$), air temperature (T_{air}), photosynthetically active radiation
168 (PAR), vapor pressure deficit (VPD), and sensible heat flux (H), were acquired at the above-
169 canopy 29 m point of the tower as was the NEE data (Munger and Wofsy, 1999b; additional data
170 upon request: tower PI J. William Munger). Only directly measured NEE data was used to avoid
171 any uncertainty or bias in gap-filling procedures, and the u^* threshold was set to 20 cm s^{-1}
172 (Urbanski et al., 2007).

173 At the study site, visual observations of the percentage of leaf size (from April through
174 June) and the percentage of colored leaves on a tree (from September through November) have
175 been performed at every 3-7 days since 1990 (O’Keefe, 2000). We used the observation data of
176 the two dominant deciduous species (northern red oak and red maple) from 1993 to 2011 to
177 determine the phenological stages of the deciduous broadleaf forest (DBF). A piecewise logistic
178 function (Eq. (1) and Fig. 2) was fitted to leaf size and coloration data, respectively, for each
179 year (Fig. S2). The dates when the curvature of the fitted function has the greatest changes were
180 defined as four phenological transitional dates: greenup, maturity, senescence, and dormancy
181 onsets (Hwang et al., 2011; Zhang et al., 2003).

$$182 \quad I(t) = \frac{1}{1+e^{a+t \cdot b}} \quad (1)$$

183 where $I(t)$ is index from leaf data, t is the day of year. The fitting coefficients (a and b) were
184 estimated using a nonlinear regression (*nlinfit*, Matlab R2013a, MathWorks Inc., Natick, MA).
185 The three phenological stages (i.e. greenup, maturity, and senescence) are the periods between
186 the phenological transitional dates (Fig. 2).

187 We collected all available Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced
188 Thematic Mapper Plus (ETM+) scenes from 1993 to 2011 (<http://earthexplorer.usgs.gov/>;
189 Landsat-7 during 1999-2003). Landsat scenes have high spatial- and moderate temporal-
190 resolutions (30 m and 16 day overpass cycle), and they cover the entire study period, which
191 facilitates efficient and consistent assessments of the landscape heterogeneity at the study site.
192 We retrieved surface reflectance data on only cloud-free days using the Landsat Ecosystem
193 Disturbance Adaptive Processing System (LEDAPS; Masek *et al.*, 2006). In this study, we used
194 the enhanced vegetation index (EVI; Eq. (2)) as an indicator of vegetation density (e.g. LAI)

195 because EVI is more sensitive to LAI in a closed canopy forest than other vegetation indices
196 (Gao, 2000; Huete et al., 2002).

$$197 \quad EVI = G \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + C_1 \cdot \rho_{red} - C_2 \cdot \rho_{blue} + L} \quad (2)$$

198 where ρ is the surface reflectance in near-infrared, red, and blue bands (ρ_{nir} , ρ_{red} , and ρ_{blue}), C_1
199 and C_2 are the aerosol resistance coefficients, G is gain factor, and L is the canopy background
200 adjustment. The coefficients are set as follows: $L=1$, $C_1=6$, $C_2=7.5$, and $G=2.5$ (Huete et al.,
201 2002).

202 The land cover in this study is based on three National Land Cover Dataset products at
203 five-year intervals (NLCD 2001/2006/2011; <http://www.mrlc.gov/>). The NLCD 1992 was not
204 included in this study because the land cover definitions in the NLCD 1992 are different from
205 those defined in the others (Trotter et al., 2013). These NLCD products were derived from
206 Landsat imagery, therefore having a spatial resolution of 30 m..

207

208 *2.3. Footprint model and flux source attributes*

209 We calculated the hourly source weights (φ) for the directly-measured and quality-
210 checked hourly NEE data from 1993 to 2011 using the Flux Footprint Prediction (FFP) model
211 (Kljun et al., 2015; <http://footprint.kljun.net>). For the FFP model, the sensor height parameter
212 (z_m) was set to the instrument height minus the zero-plane displacement height ($d = 2/3$ times
213 the canopy height; Stull, 1988). The sonic anemometer is mounted at 29 m on the tower, and the
214 canopy height was set to 21 m in this study. Manual observations in 1992 when the tower was
215 installed (Goulden et al., 1996) and airborne LiDAR measurements in 2003 (Fig. S1; Park et al.,
216 2014; Wang et al., 2011) show no significant differences outside their respective uncertainty and

217 spatial variability. Further input parameters, such the standard deviation of lateral velocity
 218 fluctuations (σ_v), the friction velocity (u_*), and the wind direction were all directly derived from
 219 the EC data. The surface roughness length (z_0) was set to 1.6 m for both deciduous and
 220 coniferous canopies at the study site (Hadley and Schedlbauer, 2002; Wu et al., 2015). The
 221 planetary boundary layer (h) was calculated depending on the atmospheric stability, such as
 222 stable (Obukhov length, $L > 0$), neutral ($L \rightarrow \infty$), and convective ($L < 0$) conditions (Kljun et al.,
 223 2015). It should be noted that the FFP model assumes the upwind domain is spatially
 224 homogeneous, a condition that is complied with at the study site where the topography is
 225 moderate (elevation variation less than 60 m) and the canopy height distribution is mostly even
 226 (Fig. S1; standard deviation (SD) of 2.6 m within the 500-m grid cell; Wang et al., 2011).

227 In this study, we limited the extent of an source area at the 80% source weight (φ_{80}) as
 228 the uncertainty of any footprint model increases for larger extents (Kljun et al., 2015). We then
 229 calculated the geometric mean of the along-wind distance from the tower and the crosswind
 230 distance at the peak location.

231 We focused on two flux source attributes: vegetation density and land cover type. We
 232 calculated the 1-km grid cell mean EVI (\overline{EVI}_{1km}) and footprint-weighted EVI ($EVI_{\varphi_{80}}$ in Eq. (3);
 233 Kim et al., 2006).

$$234 \quad EVI_{\varphi_{80}} = \sum_{i=1}^{N_{\varphi_{80}}} \varphi_{80,i} EVI_i \quad (3)$$

235 where i designates one pixel, and $\varphi_{80,i}$ and EVI_i are the source weight (φ_{80}) and the EVI value
 236 at i -pixel. $N_{\varphi_{80}}$ refers the total number of pixels within the source area. The relative contribution
 237 of each land cover to flux measurements, i.e., the footprint-weighted proportion of each land

238 cover ($P_{\varphi_{80}}$; Eq. (4)), was calculated by summing and normalizing the source weights of the
 239 respective land cover (Chen et al., 2013).

$$240 \quad P_{\varphi_{80,k}} = \frac{\sum_{i=1}^{N_k} \varphi_{80,i}}{\sum_{i=1}^{N_{\varphi_{80}}} \varphi_{80,i}} \times 100 \quad (4)$$

241 where N_k refers to the total number of pixels for each land cover (k) within the source area. Due
 242 to the limited availability of the NLCD for the early 1990s, we did not include the first 6 years of
 243 the study period (1993-1998), and partitioned the remaining study periods to situate each NLCD
 244 at the center year: NLCD 2001 for the 5 years from 1999 to 2003, NLCD 2006 from 2004 to
 245 2008, and NLCD 2011 for the other 3 years (2009-2011).

246

247 *2.4. Quantification of spatial heterogeneity*

248 The semi-variogram model has been recognized as one of the most efficient tools to
 249 describe spatial heterogeneity and autocorrelation in sample measurements (Carroll and Cressie,
 250 1996; Curran, 1988; Davis, 1986; Woodcock et al., 1988a), ranging from abiotic phenomena (e.g.
 251 temperature and precipitation; Haylock et al. 2008) to biophysical attributes (e.g. surface
 252 vegetation albedo; Román et al. 2009). The semi-variance is defined as the average of the half
 253 variances of $N(h)$ pairs of observations at an interval distance (lag distance) of h (Curran, 1988).
 254 The semi-variance estimator ($\bar{\gamma}_{EVI}(h)$; Eq. (5)) here was calculated as half the average-squared-
 255 difference between EVI values at a pair of pixels separated by a distance h .

$$256 \quad \bar{\gamma}_{EVI}(h) = \frac{\sum_i^{N(h)} \gamma_i(h)}{N(h)} = \frac{\sum_i^{N(h)} (Z_{xi} - Z_{xi+h})^2}{2N(h)} \quad (5)$$

257 where Z_{xi} is the EVI value at a pixel (x_i), and Z_{xi+h} is the EVI value at a pixel (x_{i+h}) within a lag
 258 distance h , therefore a multiple of 30 m in this study which is the nominal resolution of Landsat
 259 scenes. The maximum lag distance for a 1-km grid cell is 690 m, half of the length of the
 260 diagonal of the 1-km boundary. The isotropic spherical variogram model in Eq. (6) (Matheron
 261 1963) was fitted to the semi-variance estimators to obtain the variogram parameters: *nugget*
 262 *effect* (c_0), *sill* (c), and *range* (a) in Fig. 1d.

$$263 \quad \gamma_{SPH}(h) = \begin{cases} c_0 + c \left(1.5 \left(\frac{h}{a} \right) - 0.5 \left(\frac{h}{a} \right)^3 \right), & 0 \leq h < a \\ c_0 + c, & h \geq a \end{cases} \quad (6)$$

264 The *nugget effect* is an estimation of the variance at a lag distance of zero, indicating
 265 microscale variability within the smallest sampling distance, uncertainty in the measurements, or
 266 combination of both factors (Noréus et al., 1997). The *sill* represents a horizontal asymptote
 267 value of the variogram model, reflecting absolute magnitude of heterogeneity within the study
 268 grid cell (1-km and 1.5-km in this study). The variogram reaches the *sill* at the lag distance,
 269 *range*, beyond which there is no further spatial covariance between biophysical properties. We
 270 quantified the spatial variation in the vegetation density at moderate resolutions (1 and 1.5-km)
 271 with the semi-variogram model using the Landsat-retrieved EVI from 1993 to 2011 (Román et
 272 al., 2009; Susaki et al., 2007). Examples of the EVI maps retrieved from the Landsat scenes of
 273 the 1-km and 1.5-km grid cells centered at the tower during greenup, maturity, and senescence
 274 stages are shown in Fig. 1c.

275 While a semi-variogram analysis provides information about the spatial variation of the
 276 entire study grid cell, spatial heterogeneity surrounding the tower can be assessed with a window
 277 size analysis (Kim et al., 2006). The vegetation density index (EVI in this study) within a
 278 window centered at the tower was averaged (\overline{EVI}) for increasing size of the window (to a square

279 window). The window-averaged EVI difference from the 1-km grid cell mean EVI (ΔEVI_i ; Eq.
280 (7)) was calculated as the window width increased

$$281 \quad \Delta EVI_i = \overline{EVI}_i - \overline{EVI}_{1km} \quad (7)$$

282 while \overline{EVI}_{1km} refers to the 1-km grid cell mean EVI, and the size of window (i) increases by
283 multiples of 30 m, the nominal resolution of Landsat scenes: $i = 30, 90, \dots, 990$ m (approximate
284 width of \overline{EVI}_{1km}), \dots , 1500 m.

285

286 *2.5. Significant factors of flux variation*

287 We examined how much variation in the hourly NEE could be accounted for by the flux
288 source attributes (i.e. vegetation density and land cover type) during each phenological stage. To
289 minimize the confounding effects of the weather and source weight distributions, the hourly NEE
290 data was classified into a series of classes depending on its meteorological condition (Wu et al.,
291 2013). Each meteorological class is a combination of temperature (equal intervals of 10 °C),
292 PAR ($50 \mu\text{mol m}^{-2} \text{s}^{-1}$), and VPD (100 pascal) classes, resulting in 8405 in total.

293 We applied an ordinary least squares (OLS) regression between NEE and the vegetation
294 density measure ($EVI_{\varphi 80}$) for the meteorological classes when at least 10 observations of both
295 EVI and NEE on the same day with EVI are available (Wu et al., 2013). We also examined the
296 correlation between NEE and \overline{EVI}_{1km} for a meteorological condition when each of temperature,
297 VPD, and PAR was beyond the 75th percentile value of its cumulative distribution function (Fig.
298 S4). We then examined the correlation of the land cover type with a multiple linear regression
299 between NEE and the footprint-weighted land cover proportions ($P_{\varphi 80}$) for each meteorological

300 class. We assumed that the measured NEE were only contributed from the vegetated land covers,
301 therefore the intercept was forced to zero (Hutjes et al., 2010).

$$302 \quad NEE = \sum_{k=1}^n f_k P_{\varphi 80,k} \quad (8)$$

303 where n is the number of land covers ($n = 4$) and f_k is the coefficient for land cover k (deciduous
304 broadleaf forest (DBF), evergreen needleleaf forest (ENF), mixed forest (MF), and woody
305 wetland). A negative f_k indicates a carbon uptake rate per unit land cover proportion ($\text{g C m}^{-2} \text{s}^{-1}$
306 $\%^{-1}$) as a negative NEE means an uptake from the atmosphere in this study. This analysis was
307 carried out for 13 years (1999-2011) due to the limited availability of the NLCD products. The
308 adjusted coefficient of determination (R_{adj}^2) of the OLS regression (against $EVI_{\varphi 80}$) and the R_{adj}^2
309 of the multiple linear regression (against $P_{\varphi 80}$) was then compared separately for daytime (PAR
310 $> 50 \mu\text{mol m}^{-2} \text{s}^{-1}$) and nighttime during each phenological stage.

311 **3. Results**

312 *3.1. Phenological onset timings and stages*

313 The phenological transitional timings have varied every year (Fig. S3), and the greenup
314 stage was from May 10 to June 5, the maturity stage (peak growing season) from June 5 to
315 September 17, and the senescence stage from September 17 to October 19 on average from 1993
316 to 2011. Growing season was defined from the greenup onset to the dormancy onset, therefore
317 from May 10 to October 19 on average.

318

319 *3.2. Footprint extent and distribution variation*

320 At the tower, the prevailing wind directions over the study period were mostly southwest
321 and northwest during both the daytime and nighttime (Fig. S5a; Davidson et al., 2006; Urbanski
322 et al., 2007), but there were variations in the wind speed frequency distribution between the
323 phenological stages (Fig. S5b). Strong northwesterly and westerly winds are noticeable during
324 the greenup and senescence stages (Fig. S5b). Prevailing wind direction and frequency are of
325 high impact to the source weight distribution, therefore the dominant orientation of source areas
326 were mostly toward the southwest (source weight peak locations at 212-236°; Fig. S6) while
327 there were more variations during the greenup and senescence stages. Furthermore, there was a
328 noticeable difference in the source area sizes between the daytime and nighttime (Fig. 3) as
329 source areas had larger extent with larger variation due to the stable atmospheric condition
330 during nighttime (Fig. S6). The geometric mean of along-wind and crosswind distances was
331 mostly different between the daytime and nighttime, while rather similar across phenological
332 stages (163.5-190.6 with standard deviation (SD) of 55.8-70.4 m during the daytime, and 298.9-

333 221.8 with SD of 128.8-159.6 m during the nighttime). The distance between the tower and
334 source weight peak location was also smaller and less variable during the daytime than during
335 the nighttime, 39.4 ± 3.4 and 58.3 ± 30.4 m, respectively (Fig. S6).

336 The 1-km grid cell around the tower from the NLCD 2001 primarily consisted of DBF
337 (Fig. S8). The transition from the NLCD 2001 to the NLCD 2006 shows that there was a slight
338 expansion of the wetland on the northwest side of the tower. There were considerable changes
339 from the NLCD 2006 to the NLCD 2011 due to flooding and draining of the wetlands on the
340 northwest and southeast sides of the tower. The 1-km grid cell consisted of 47.5% of DBF, 22.1%
341 of ENF, 15.0% of mixed forest, and 10.9% of woody wetland in the NLCD 2001, while it
342 consisted of 47.7% of DBF, 16.2% of ENF, 14.8% of mixed forest, and 15.3% of woody wetland
343 in the NLCD 2011. The footprint-weighted land cover proportions ($P_{\phi 80}$; Eq. (4)) were quite
344 different for the daytime and nighttime, relatively similar across the phenological stages (Fig. 4),
345 due to the combined effect of the heterogeneous landscape and the variations in source areas.
346 During the daytime, DBF is the most dominant land cover contributing about 78.3% of measured
347 fluxes on average (SD of 19.0%), which is about 30% higher than the nominal proportion of
348 DBF within the 1-km grid cell in the NLCD. During the nighttime, the $P_{\phi 80}$ of DBF was slightly
349 lower and more variable than during the daytime, at about 71.3% on average (SD of 25.1%).
350 ENF contributed 14.5% and 19.0% during the daytime and nighttime, respectively (SD of 15.9-
351 19.1%). The $P_{\phi 80}$ of other covers (mixed forest, woody wetland, and open space area) were less
352 than 5%, respectively (Fig. 4).

353

354 3.3. Spatial heterogeneity of the study site

355 The *nugget effect* values (Fig. 5a) (indicators of measurement errors or microstructures
356 within the grid cells) were primarily driven by canopy closure (i.e. phenological stage), rather
357 than long-term landscape changes. The *nugget effect* values of the 1-km grid cell were higher
358 than 0.0005 before the entire growing seasons started, and the values substantially declined by
359 the beginning of the greenup stages. As the forest canopy at the sub-pixel scale was almost
360 completely closed during the entire growing seasons, there were almost no sub-pixel scale
361 variations (*nugget effect* values ~ 0), although the values started to increase at the end of the
362 senescence stages as open canopy gaps started to contribute to increased microstructures over the
363 study site. The non-vegetated area and woody wetlands at the northeast corner of the 1.5-km grid
364 cell (Fig. 1b) caused a high level of *nugget effect* values during the maturity and senescence
365 stages (Woodcock et al., 1988b).

366 There were also seasonal and long-term changes in the *sill* values (the overall changes in
367 the spatial heterogeneity within the study grid cells) (Fig. 5b and Fig. S7a). In the early 1990s,
368 the *sill* values of 1-km grid cell were low and nearly constant (around 0.002) throughout the
369 entire growing seasons. Because of the wetland on the northwest side of the tower (Fig. S7b), the
370 spatial variations started to increase during the maturity stage of 2001, although these variations
371 consistently returned to a low level by the end of each senescence stage. The other wetland on
372 the southeast side of the tower has contributed to the gradual increase in spatial variations within
373 the 1-km grid cell during the maturity stages for the last few years (Fig. 5b and Fig. S7a). The
374 flooding and draining of those two wetlands did not have any significant impact on the spatial
375 variation of the 1.5-km grid cell which was already heterogeneous before the wetland expansion
376 (Fig. 5b).

377 The *range* values (the distance limit within which the surface variations are auto-
378 correlated) within the 1-km grid cell were mostly constant during the entire growing seasons (Fig.
379 5c). Most of the *range* values (280 m, 265 m, and 250 m on average during the greenup, maturity,
380 and senescence stages, respectively) were within one standard deviation of the geometric mean
381 of along-wind and crosswind distances during both the daytime and nighttime. The *range* values
382 of the 1.5-km grid cell were higher than those of the 1-km grid cell due to the non-vegetated area
383 at the northeastern corner (Fig. 1b).

384 ΔEVI , the difference between the window-averaged EVI and 1-km grid cell averaged
385 EVI (i.e., the spatial heterogeneity of the tower surrounding area), was mostly negative around
386 the tower during the greenup stage when the canopy of deciduous trees has not yet fully emerged
387 yet (Fig. 6). The ΔEVI slightly increased at a window width of 250 m, including the conifer trees
388 located on the northwest, northeast, and southeast sides of the tower (Fig. 1b), and then gradually
389 converged to zero around a 1-km window width. Overall, the variations in the ΔEVI during the
390 greenup stage were relatively small (less than 0.05) regardless of window widths. Meanwhile,
391 the ΔEVI during the maturity and senescence stages revealed strong spatial heterogeneity
392 around the tower. The ΔEVI values were higher than zero during the maturity stage (i.e. the
393 averaged EVI around the tower was up to 16% higher than the magnitude of \overline{EVI}_{1km}), and then
394 gradually converged to zero at the window widths of 700 and 500 m during the maturity and
395 senescence stages, respectively (Fig. 6). The development of the southeast-side wetland has
396 gradually decreased the ΔEVI at a window width between 250 and 500 m during the maturity
397 stage.

398

399 3.4. Significance of flux source attributes

400 Over an entire growing season, the measured *NEE* was significantly correlated with both
401 vegetation density measures ($R_{adj}^2 = 0.48$ and 0.55 with \overline{EVI}_{1km} and $EVI_{\varphi 80}$, respectively, $p <$
402 0.01 ; Fig. 7). At a seasonal time scale, the correlations were still high for the greenup and
403 senescence stages ($R_{adj}^2 = 0.45$ - 0.61 , $p < 0.01$), but substantially weakened during the maturity
404 stage ($R_{adj}^2 = 0.01$, $p > 0.1$; $R_{adj}^2 = 0.16$, $p < 0.01$). Instead, for most of the meteorological classes,
405 the variation in the daytime *NEE* during the maturity stage was more accounted for by the
406 variation in the footprint-weighted land cover proportions ($P_{\varphi 80}$; Fig. 8b). The R_{adj}^2 values from
407 the multiple linear regression with $P_{\varphi 80}$ were higher than the R_{adj}^2 values from the OLS
408 regression with $EVI_{\varphi 80}$ for a higher number of meteorological classes than the number of classes
409 with the opposite R_{adj}^2 values. On the other hand, the daytime *NEE* during the greenup and
410 senescence stages was poorly correlated with the $P_{\varphi 80}$ ($R_{adj}^2 < 0.4$), and rather strongly driven by
411 $EVI_{\varphi 80}$ (R_{adj}^2 up to 0.7) for some meteorological classes. The nighttime *NEE* was not well
412 correlated with either the $P_{\varphi 80}$ or the $EVI_{\varphi 80}$ ($R_{adj}^2 < 0.4$) regardless of phenological stage for
413 most of the meteorological classes (Fig. 8d-f). The $P_{\varphi 80}$ of DBF was the significant factor for
414 most conditions (median p -value of all classes < 0.01 ; Fig. S10a), except for the greenup daytime
415 (median p -value of all classes = 0.06), even when the correlation was weak. The $P_{\varphi 80}$ of the
416 other land covers, on the other hand, was mostly non-significant. During the daytime, the
417 coefficient of $P_{\varphi 80}$ of DBF was more negative than that of ENF during the maturity and
418 senescence stages, less negative during the greenup stage (Fig. 9). During the nighttime, it was
419 more positive than that of ENF regardless of the phenological stage (Fig. 9).

420

421 **4. Discussion**

422 The study tower is located in a mixed forest where the landscape has gradually changed
423 over the last decades, most noticeably with the expansion of two wetlands on the northwest and
424 southeast sides from the tower (Fig. S7). Our principal goal in this study was to examine the
425 spatial heterogeneity of the two surrounding spatial grid cells (1-km and 1.5-km) and the
426 representativeness of the flux source area in capturing the vegetation characteristics (density
427 magnitude and variation) of the two surrounding grid cells during the daytime and nighttime,
428 respectively, during each phenological stage (greenup, maturity, and senescence). As expected,
429 the study site was mostly homogeneous during the maturity stage in the early 1990s, as the
430 deciduous trees had fully developed to a closed canopy (Lévesque and King, 1999). The
431 expansion of two woody wetlands then began to impact the closed canopy, increasing spatial
432 heterogeneity within the 1-km grid cell, resulting in with up to 3.5 times higher *sill* values than
433 those associated with the canopy in the early 1990s (Fig. 5b). However, their proportion in the
434 flux source areas were still less than 5%. This explains why the flux measurements (i.e., NEE)
435 were not very sensitive to this variability (median *p*-value of all classes > 0.05; Fig. S10). The
436 impact of the changing landscape was also very dependent on its spatial scale. The landscape
437 within the 1.5-km grid cell was already highly heterogeneous in the 1990s, so there was a less of
438 a noticeable change in the seasonal patterns of the *sill* values over the study period (Fig. 5b).
439 Daytime flux source weights mostly peaked along the southwest side around the tower and did
440 not exceed the 1-km grid cell, while the nighttime flux source areas covered larger areas (Fig. 3).
441 Both daytime and nighttime flux source areas were dominated by DBF regardless of the
442 phenological stage, but the proportion of DBF during the nighttime was smaller and more
443 variable than the proportion during the daytime (Fig. 4). Our results suggest that the daytime flux

444 source areas cover a large enough area to adequately represent the vegetation density
445 characteristics (distributions and magnitudes; Fig. 5c and Fig. 6, respectively) within the 1-km
446 grid cell, but not those within the 1.5-km grid cell because of the additional non-vegetated land
447 cover types at the northeastern corner of the grid cell (Fig. 1b). The vegetation density measures
448 (\overline{EVI}_{1km} and $EVI_{\varphi 80}$), therefore, were well correlated with the daytime NEE except during the
449 maturity stage (Fig. 7 and Fig. 8a-c). During the maturity stage, on the other hand, the variations
450 in the footprint-weighted land cover proportions ($P_{\varphi 80}$) accounted for higher proportions of the
451 variations in the daytime NEE for most meteorological classes (Fig. 8b). Meanwhile, the
452 nighttime NEE had little correlation with either vegetation density ($EVI_{\varphi 80}$) or the land cover
453 ($P_{\varphi 80}$) regardless of the phenological stages (Fig. 8d-f), perhaps suggesting that these factors do
454 not account for much of the variation in soil respiration, which is the dominant component of
455 nighttime ecosystem respiration.

456

457 *4.1. Study site spatial characteristics and flux source area representativeness*

458 The *nugget effect* values of the 1-km grid cell reached almost zero during the entire
459 growing season (Fig. 5a), which indicates that the sampling interval (i.e. 30 m of Landsat spatial
460 resolution in this study) is appropriate to resolve the sources of spatial variation within the grid
461 cell. Therefore, the Landsat data used in this study was suitable to assess the spatial
462 representativeness of daytime flux source areas within the 1-km grid cell (Fig. 3). Nighttime flux
463 source areas, however, often extended over a larger area under stable atmospheric conditions
464 (Hadley and Schedlbauer, 2002; Kljun et al., 2002), therefore the 1.5-km surrounding area may
465 be more applicable for the calibration and evaluation of lower resolution remote sensing-based

466 estimates. However, the increased *nugget effect* values of the 1.5-km grid cell during the
467 maturity and senescence stages (almost 10% of the *sill* values) indicate that the spatial
468 representativeness of the 1.5-km grid cell needs be assessed using a higher-spatial resolution data
469 (e.g., higher resolution satellite imagery or aerial photographs) that are able to resolve the finer
470 scale surface structures.

471 The *range* value can be considered to represent the effective size of the heterogeneity
472 attributes (Kim et al., 2006). When a source area size (i.e., in this study, the geometric mean of
473 along-wind and crosswind distances) is larger than the *range* value of the study grid cell, it can
474 be assumed that the source area was large enough to represent the vegetation density variation in
475 the study grid cell, and therefore, the source area is spatially-representative of the study grid cell
476 (Kim et al., 2006). Over the study period, the *range* values of the 1-km grid cell were mostly less
477 than or very close to the daytime source area extent throughout the entire growing season, and
478 consistently smaller than the nighttime source area extent (Fig. 5c). This suggests that both the
479 daytime and nighttime NEE measurements sufficiently reflect the variations in the vegetation
480 density within the 1-km grid cell. The same interpretation can be applied for the 1.5-km grid cell
481 during the daytime, but not during the nighttime when the *range* values mostly exceeded the
482 source area extent.

483 The window size analysis generally corresponds with the semi-variogram results. The
484 vegetation density around the tower is more heterogeneous than the density of the 1-km grid cell
485 during the maturity stage, and smallest during the greenup stage (Fig. 6). The ΔEVI values are
486 less than 5% of the 1-km average magnitudes within the source area during both the daytime and
487 nighttime. This indicates that the source areas are generally large enough to represent the

488 magnitude of the vegetation density within the 1-km grid cell during both the daytime and
489 nighttime.

490

491 *4.2. Significance of footprint-weighted land cover proportion*

492 As stated, the source areas were spatially representative of both vegetation density
493 variations and magnitudes within the 1-km grid cell during both the daytime and nighttime
494 across all phenological stages. Therefore, the 1-km grid cell mean EVI (\overline{EVI}_{1km}), as well as
495 MODIS 1-km EVI (Rahman et al., 2005; Tang et al., 2011; Xiao et al., 2004), can adequately
496 account for the variation in the daytime NEE as much as the footprint-weighted EVI ($EVI_{\phi 80}$)
497 can (Fig. 7). Specifically, the high correlations between the vegetation density measures
498 (\overline{EVI}_{1km} and $EVI_{\phi 80}$) and the daytime NEE were primarily driven by the phenological
499 development of the deciduous trees during the entire growing season and particularly during the
500 greenup and senescence stages (EVI rises/drops by about 0.4). Therefore, the land cover
501 variations within the source area had little effect on the daytime NEE during those periods.
502 However, both \overline{EVI}_{1km} and $EVI_{\phi 80}$ can hardly account for the variation in the daytime NEE
503 during the maturity stage, when both DBF and ENF have similar EVI values (Fig. 1c), and the
504 vegetation carbon uptake primarily depends on its physiological response to meteorological
505 variables, such as solar radiation, temperature, and soil moisture (Gao et al., 2014; Jahan and
506 Gan, 2009; Tang et al., 2012). Yet, however, the mean response functions of a single vegetation
507 functional type (DBF) accounted for only about 50% of the interannual variations in the NEE at
508 the study site (Urbanski et al., 2007). Our results may provide a better explanation of the
509 variation in the daytime NEE especially during foliage maturity (Fig. 8b). It was expected that

510 the $P_{\varphi 80}$ of DBF is the most significant factor in the flux measurements at the study tower, given
511 the dominance of DBF around the study tower (Urbanski et al., 2007), but it hadn't yet been
512 quantitatively assessed for each phenological stage. The stronger contribution of the $P_{\varphi 80}$ of
513 DBF (a more negative coefficient; Fig. 9) than that of ENF corresponds well to the higher carbon
514 uptake rates of deciduous trees than the ones of coniferous trees during the maturity stage
515 (Hadley et al., 2008). Although the $P_{\varphi 80}$ of ENF was not a significant factor on the daytime NEE
516 across the phenological stages, the greater negative coefficient of the $P_{\varphi 80}$ of ENF (representing
517 a stronger contribution) during the greenup stage than that of DBF reflects the higher carbon
518 uptake rates of the ENF than the DBF at the study site at the beginning of the growing season
519 (Hadley et al., 2008). The similar coefficient values of the $P_{\varphi 80}$ for both the DBF and ENF
520 during the senescence stage (Fig. 9) may result from the strong regulation of other factors, such
521 as day length (Bauerle et al., 2012) and soil moisture (Hwang et al., 2014; Urbanski et al., 2007),
522 rather than by leaf presence at the end of growing season.

523 Meanwhile, although the variations in the source area during the nighttime were higher
524 than those during the daytime, the nighttime NEE was only rather weakly correlated with either
525 $EVI_{\varphi 80}$ or $P_{\varphi 80}$ across all phenological stages. This could be largely attributed to the similar
526 rates of soil respiration at both DBF and ENF at the study site (Giasson et al., 2013).

527 Note that the significances and sensitivities of the measured NEE to the footprint-
528 weighted land cover proportions ($P_{\varphi 80}$; Eq. (4)) are subject to uncertainties in the NLCD
529 products and also to the limited NLCD availability (only 3 products over the 13 years study
530 period).

531

532 *4.3. Implication for gap-filling process and upscaling strategies*

533 To date the most common practice for filling gaps in hourly NEE measurements is to
534 derive estimates from mean temperature- and light-response functions (Falge et al., 2001).
535 Uncertainty is therefore introduced because those response functions are not intended to respond
536 to the short-time variations in the meteorological drivers, but to characterize the ecosystem-scale
537 mean response for a certain time period (in days or weeks) (Falge et al., 2001; Stoy et al., 2006).
538 The isotopic eddy covariance flux data also showed that the ecosystem respiration values at the
539 study tower were dependent on the wind direction, the therefore the source area variations (Wehr
540 and Saleska, 2015). Our result indicates the dependence of the daytime NEE on the footprint-
541 weighted land cover variations during the maturity stage, and addresses potential biases resulting
542 from a discrepancy between the spatiotemporally-integrated mean ecosystem and the hourly-
543 varying flux source areas. Therefore, this could cause misinterpretations of ecosystem short-term
544 sensitivity to climate change and to the biome characteristics across multiple sites. In practice, it
545 remains difficult to separate the flux measurements by upwind land cover types because it
546 introduces additional uncertainties as the number of points in each bin available for calibration is
547 substantially reduced. However, our analyses highlight the importance of considering the unique
548 site-specific landscape conditions in the gap-filling process, especially during the peak growing
549 season (i.e. the maturity stage) (Falge et al., 2001; Moffat et al., 2007).

550 Previous studies have investigated the implication of the source area variation on upwind
551 vegetation density and meteorological factors when upscaling the measured flux to regional
552 scales (Fu et al., 2014; Xu et al., 2017). However, vegetation dynamics (such as photosynthesis
553 and respiration) do not necessarily respond linearly to these individual drivers (Urbanski et al.,
554 2007), especially in water-limited ecosystems (Novick et al., 2015), and in dense canopies during

555 the peak growing season when the canopy is fully developed (Fig. 7; Urbanski et al., 2007). The
556 vegetation response to these drivers also varies greatly between the vegetation types (Daley et al.,
557 2007; Hadley et al., 2008). Therefore, in the process of calibrating the upscaling coefficients
558 using flux measurements, the source weight should be applied to the vegetation response (i.e. the
559 flux) depending on its type, rather than on its individual flux source attributes (i.e. vegetation
560 density or meteorological factors). The coefficient of the multiple linear regression, i.e., the NEE
561 rate per unit land cover proportion ($\text{g C m}^{-2} \text{s}^{-1} \%^{-1}$) for the given meteorological class, can be up-
562 scaled using the proportions of the significant land covers within the grid cell of interest (e.g. 1-
563 km).

564

565 **5. Conclusion**

566 We assessed the long-term spatial heterogeneity around the study flux tower using remote
567 sensing datasets, and examined the representativeness of the flux measurements for the
568 surrounding area (1-km and 1.5-km grid cells, respectively) during the daytime and nighttime,
569 respectively, during each phenological stage (greenup, maturity, and senescence). In our study
570 site, the forested landscape had gradually shifted since 2001, resulting in an increase in spatial
571 heterogeneity within the 1-km grid cell centered at the flux tower, especially during the maturity
572 stage. Yet, the daytime flux source area remained spatially representative for vegetation
573 characteristics (both density and type) within this 1-km grid cell over the course of various
574 landscape transitions. We have demonstrated that the relevant flux source attribute, governing
575 more variation in the NEE, differed between phenological stages. The variation in the daytime
576 NEE is highly correlated with the vegetation density (EVI in this study) during the phenological
577 transition stages (greenup and senescence), but the variation during the maturity stage was better

578 captured by the footprint-weighted land cover proportion. The nighttime NEE was hardly
579 affected by the variation in either the vegetation density or the land cover proportion.

580 Our study highlights the importance of accounting for variation in the footprint-weighted
581 land cover in mixed-land cover regions (1) for interpretation of variations in flux measurements,
582 (2) to fill data gaps, and (3) to upscale the flux measurements to larger scales. In this study, we
583 only analyzed flux measurements from a single tower site (the tower that provides the longest
584 flux record in the US) as a case study. Our approach can be further applied to other existing
585 tower sites as there are increasing numbers of flux towers with multi-decadal flux measurements.
586 Our results suggest a consideration of the land cover variations contributing to the measured flux
587 will result in a better understanding of ecosystem response to environmental forcing in a
588 changing climate.

589

590 **Acknowledgements**

591 The authors are grateful for the two anonymous reviewers whose comments have greatly
592 improved the manuscript. We appreciate the efforts of Taejin Park in providing the processed
593 LVIS data. We also would like to thank Dr. Miguel O. Roman for sharing the detailed
594 methodology of semi-variogram analysis using Landsat data and Dr. Kimberly Novick for
595 constructive comments on an earlier version of the manuscript. This study was financially
596 supported in part by the NASA MODIS science team (Grant No. NNX11AD58G), the NASA
597 Carbon Science program (Grant No. NNX17AE69G), and the USGS Science Team (Grant No.
598 ING12PC00072). The Harvard Forest EMS flux tower has been supported by the Office of
599 Science (BER) at the US Department of Energy (DOE) under various sub-programs over the
600 years, and it is now a core site in AmeriFlux network (Grant No. DE-AC02-05CH11231). The

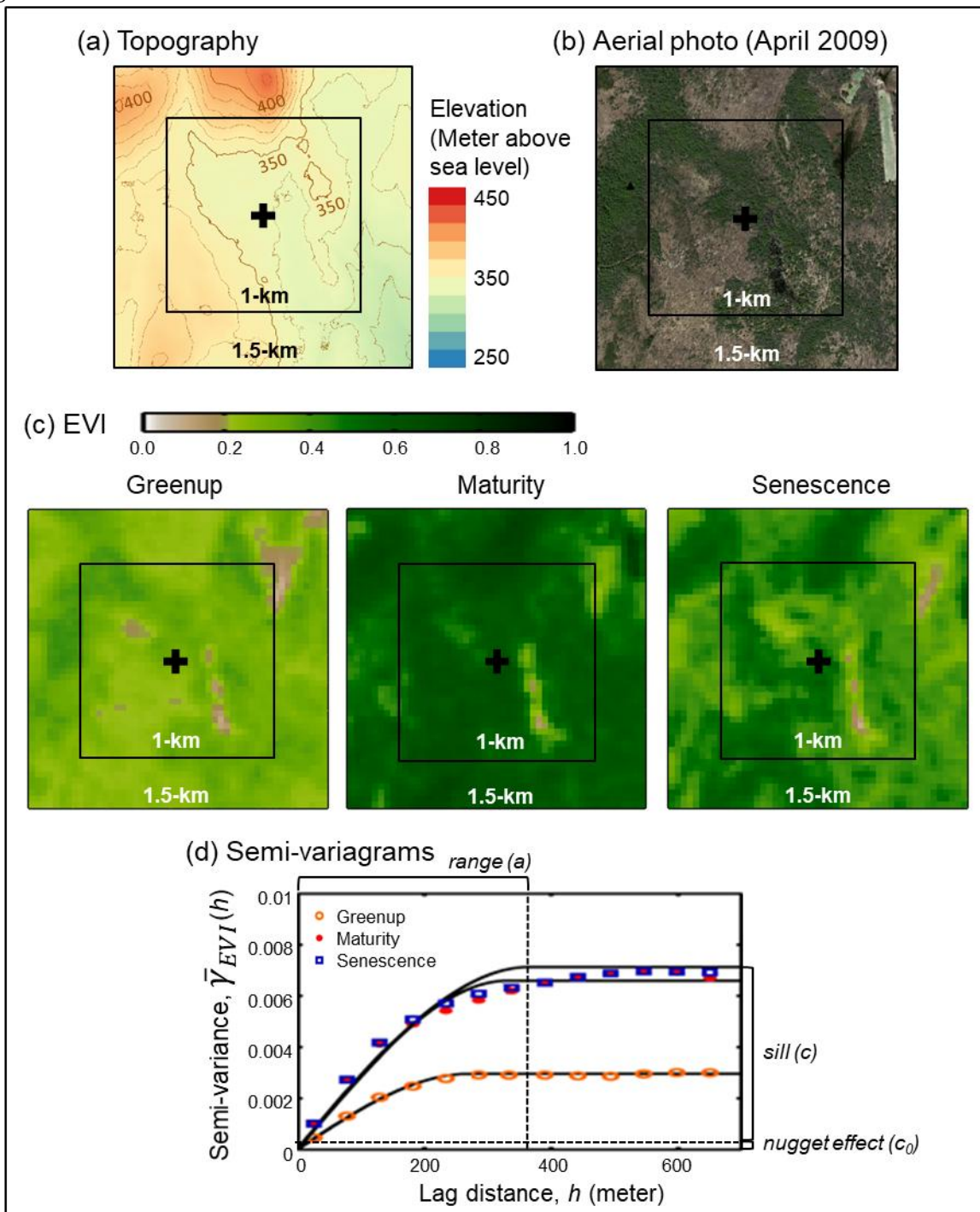
601 long-term meteorological and hydrological measurements at Harvard Forest are also supported
602 through the National Science Foundation Long-Term Ecological Research Programs (Grant No.
603 NSF-DEB-1237491). The Harvard Forest LTER data were obtained from the archive at
604 (<http://harvardforest.fas.harvard.edu/harvard-forest-data-archive>).

605

606 **Appendix A. Supplementary data**

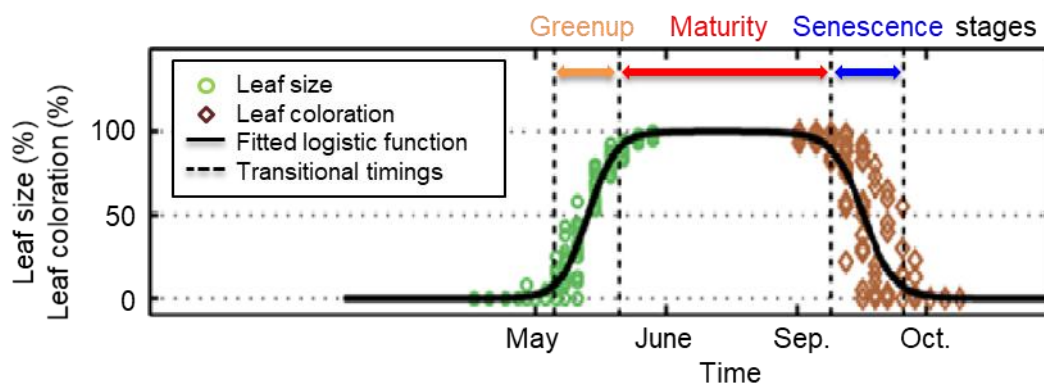
607 Supplementary material related to this article can be found, in the online version, at

608

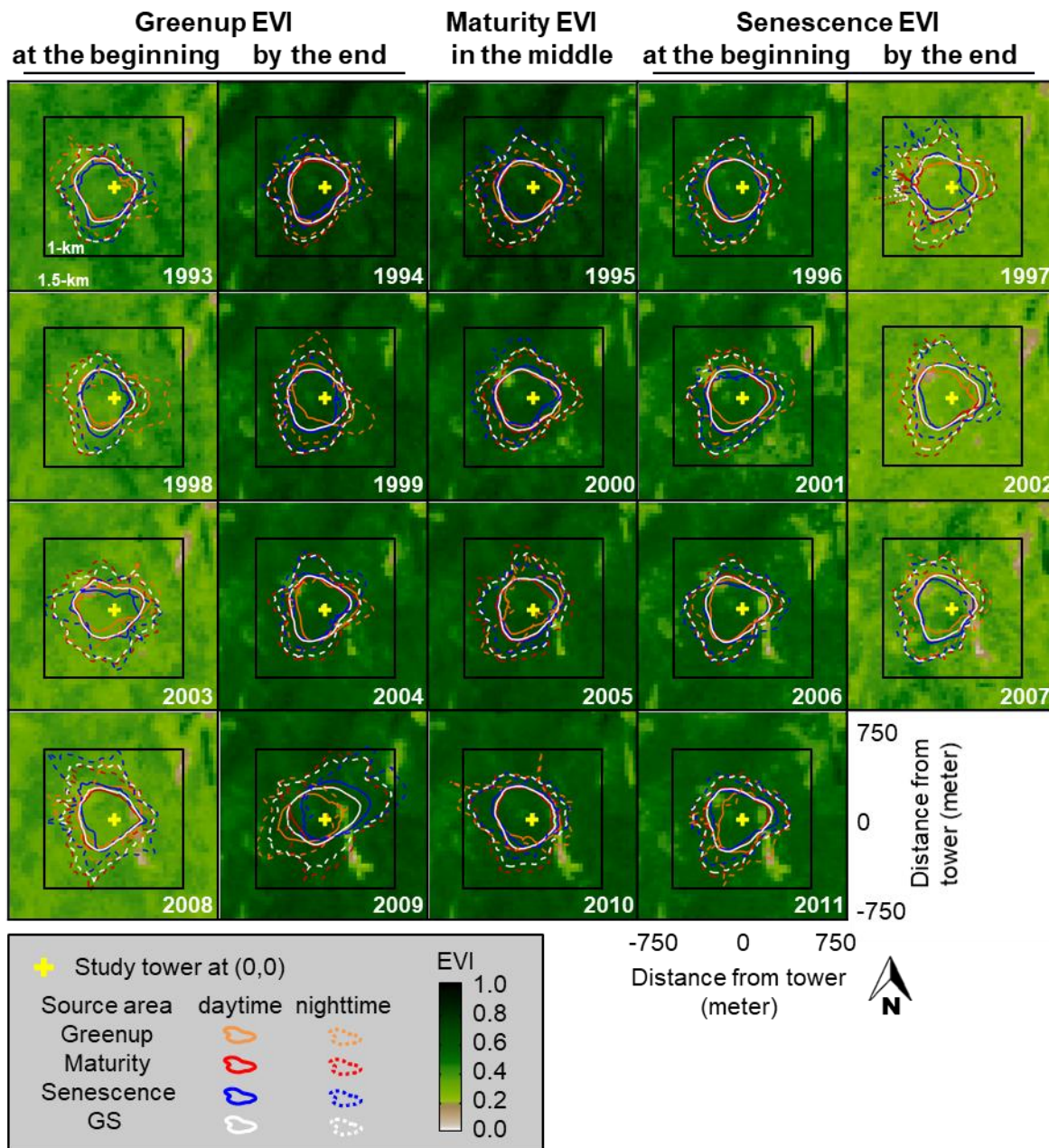


610 **Fig. 1.** (a) Topography of the surrounding area of the study tower (black cross). Elevation above
 611 sea level was retrieved from a LiDAR terrain file (accuracy of 5-35 cm; MassGIS:
 612 <http://www.mass.gov/>) (b) Aerial photo taken on April 2009 (30 cm resolution; MassGIS:
 613 <http://www.mass.gov/>) before the emergence of leaves on deciduous trees. (c) Enhanced
 614 vegetation index (EVI; Eq. (2)) maps retrieved from Landsat TM/ETM+ scenes at each
 615 phenological stage: greenup (5/27/2008), maturity (8/31/2008) and senescence (10/18/2008).
 616

617 Details of the phenological stages are described in the data overview. (d) Schematic diagram of
618 the semi-variogram estimators ($\bar{\gamma}_{EVI}(h)$) calculated from the EVI maps in (c) (orange circle, red
619 dot, and blue square for greenup, maturity, and senescence stages, respectively), and the fitted
620 isotropic spherical variogram models (black solid line), and *ranges* (dashed vertical lines in
621 colors).



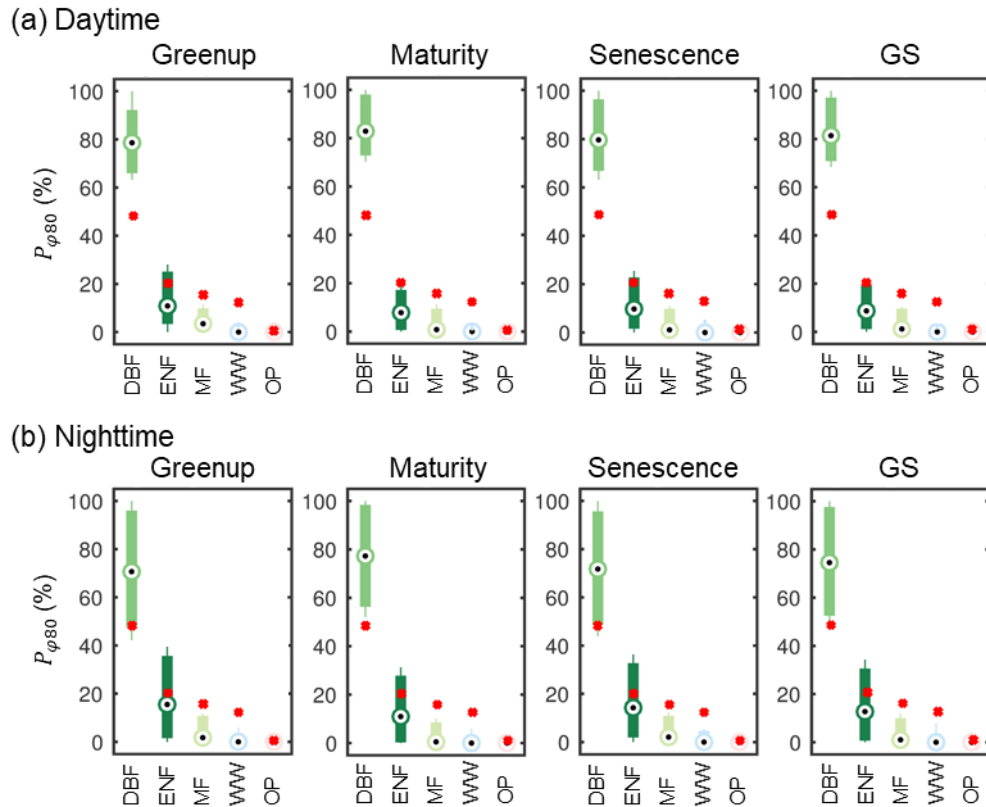
622
 623 **Fig. 2.** Schematic diagram of estimating phenological stages. Leaf size and coloration
 624 (green circles and brown diamonds) are based on ground-based visual observations (O’Keefe,
 625 2000; data shown here is of 2008). A logistic function (Eq. (1)) is fitted to the indices for leaf
 626 size and coloration data, respectively (black solid line). Phenological stages (greenup, maturity,
 627 and senescence) are the periods between the phenological transitional timings (the dates when
 628 the curvature of the fitted function have the greatest changes; vertical dashed line).
 629



631

632 **Fig. 3.** Footprint climatology (i.e., an aggregation of source areas) during the daytime and
 633 nighttime (solid and dashed contours, respectively) during each phenological stage (greenup,
 634 maturity, senescence, and growing season, GS) from 1993 to 2011 overlaid on 1.5-km grid cell
 635 EVI maps centered at the study tower (yellow cross). EVI maps during the greenup stage are
 636 shown in the first and second columns, maturity stage in the third column, and senescence stage
 637 in the fourth and fifth columns.

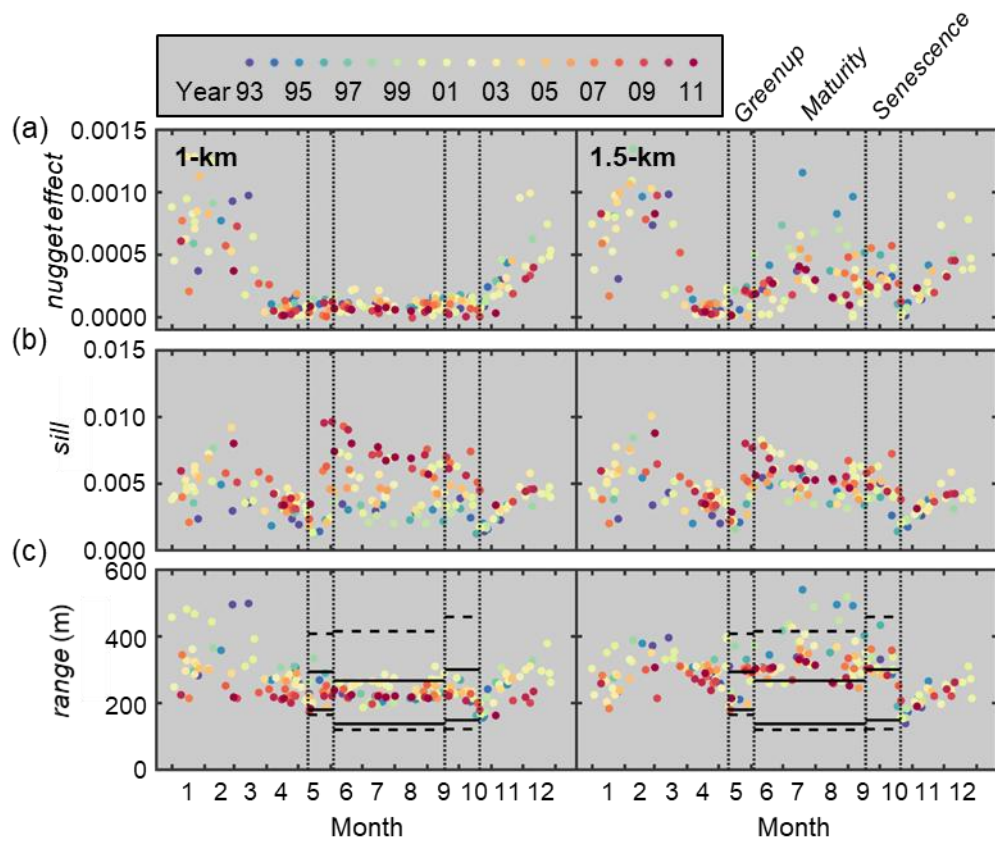
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639

640 **Fig. 4.** The footprint-weighted proportions ($P_{\phi 80}$; Eq. (4)) of each land cover (deciduous
 641 broadleaf forest (DBF), evergreen needleleaf forest (ENF), mixed forest (MF), woody wetland
 642 (WW), and open space area (OP) during the daytime (a) and the nighttime (b) during greenup,
 643 maturity, and senescence stages, and during entire growing season (GS) from 1999 to 2011. The
 644 box shows upper and lower quartile range of the $P_{\phi 80}$ and the black dots represent the median
 645 values. The average value of the nominal proportions of each land cover within the 1-km grid
 646 cell in the NLCD products is marked as a red dot. The hourly $P_{\phi 80}$ during each phenological
 647 stage can be found in Fig. S9.

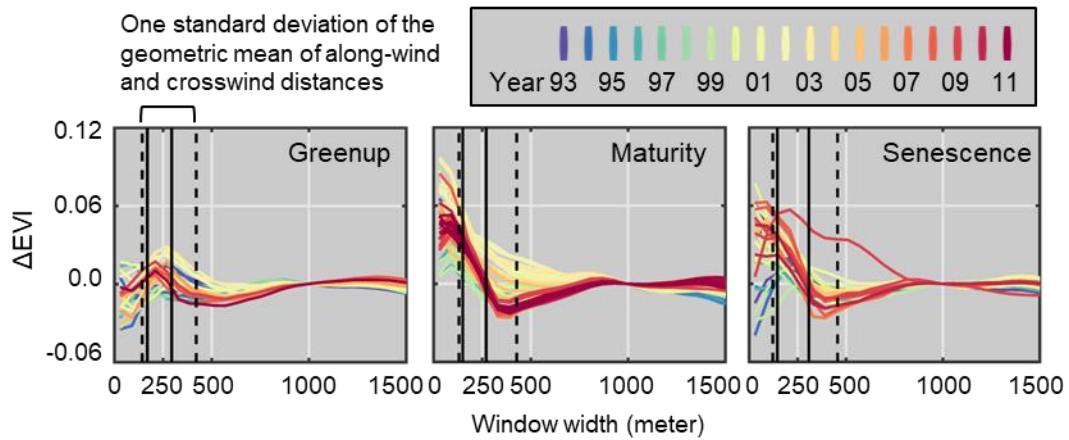
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649

650 **Fig. 5.** Semi-variogram parameters, the *nugget effect* (a), *sill* (b), and *range* (c), derived from
 651 EVI within 1-km (left panels) and 1.5-km (right panels) grid cells from 1993 to 2011 (in
 652 different colors). One standard deviation of the geometric mean value of along-wind and
 653 crosswind distances during the daytime and nighttime (horizontal solid and dashed lines,
 654 respectively) is presented in the *range* plot (c) during each phenological stage (greenup,
 655 maturity and senescence).

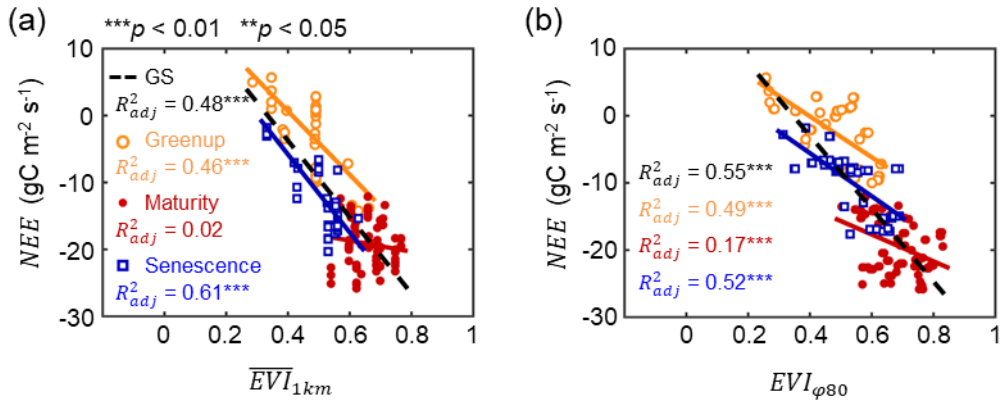
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657

658 **Fig. 6.** The window-averaged EVI difference from the 1-km grid cell mean EVI (ΔEVI ; Eq. (7))
 659 between 1993 and 2011 (in different colors) during greenup, maturity, and senescence stages,
 660 respectively. One standard deviation of the geometric mean of along-wind and crosswind
 661 distances during the daytime and nighttime for each phenological stage is presented in vertical
 662 solid and dashed lines, respectively.

663

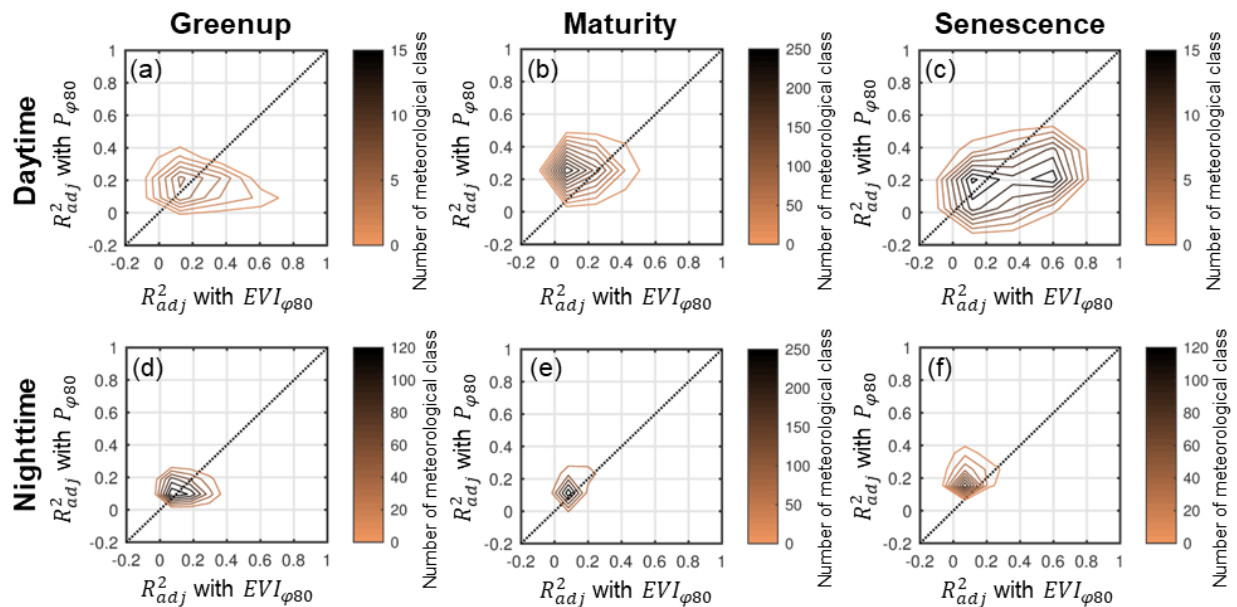


664

665 **Fig. 7.** The ordinary least squares (OLS) regressions between NEE and (a) the 1-km grid cell
 666 mean EVI (\overline{EVI}_{1km}), and (b) the footprint-weighted EVI ($EVI_{\phi80}$) during entire growing season
 667 (GS), and during greenup, maturity and senescence stages for a meteorological condition
 668 (temperature, VPD, and PAR beyond the 75th percentile value of its cumulative distribution
 669 function; Fig. S4).

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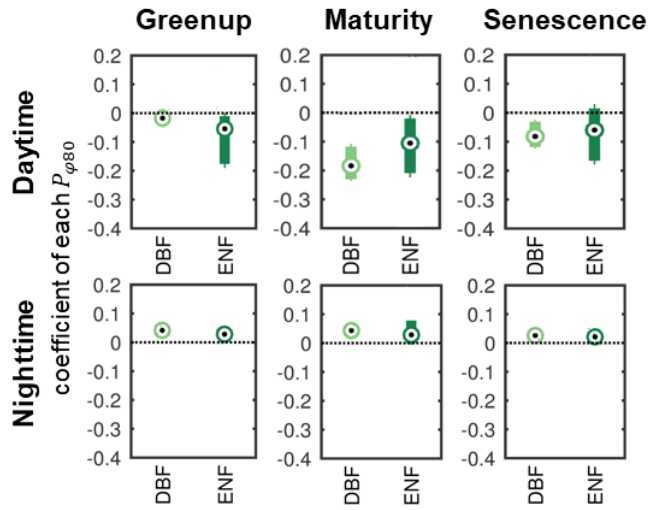
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Fig. 8. Comparison of the adjusted coefficient of determination (R_{adj}^2) from the ordinary least square regression between NEE and footprint-weighted EVI ($EVI_{\phi80}$ in Eq. (3)) versus the R_{adj}^2 from the multiple linear regression between NEE and footprint-weighted land cover proportions ($P_{\phi80}$; Eq. (4)) for the same meteorological class. The number of meteorological class having the R_{adj}^2 values is shown in colored contours for each phenological stage (greenup on the first column, maturity on the second column, and senescence on the last column) during the daytime (a-c; $PAR > 50 \mu\text{mol m}^{-2} \text{s}^{-1}$) and nighttime (d-f), respectively.



682

683 **Fig. 9.** The coefficients (i.e. NEE rate per unit land cover proportion ($\text{g C m}^{-2} \text{s}^{-1} \%^{-1}$)) of the two
 684 most dominant land covers (deciduous broadleaf forest (DBF) and evergreen needleleaf forest
 685 (ENF)) in the multiple linear regression between NEE and footprint-weighted land cover ($P_{\phi80}$)
 686 (Eq. (8)). The coefficients of the non-dominant land covers (mixed forest and woody wetland;
 687 each $P_{\phi80} < 5\%$) are presented in Fig. S10b. The regression was applied on each meteorological
 688 class for each phenological stage (greenup, maturity, and senescence) during the daytime
 689 (photosynthetically active radiation, $\text{PAR} > 50 \mu\text{mol m}^{-2} \text{s}^{-1}$) and nighttime, respectively. The
 690 box shows upper and lower quartile range of the coefficients from all meteorological classes and
 691 the black dots represent the median values.

692

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