Commentary

The enduring mystery of differences between eddy covariance and biometric measurements for ecosystem respiration and net carbon storage in forests

Both eddy covariance (EC) and ground-based (biometric) estimates of carbon (C) stocks and fluxes are used to understand current stocks and fluxes of C, their future trajectories, and responses to changing climates. EC measures C fluxes by quantifying the covariance between fluctuations in vertical wind velocity and CO_2 concentrations (Baldocchi, 2003). EC measurements are continuous over a large area (*c.* 0.5 km^2), nondestructive, use a more standardized methodology, and are made at hundreds of locations across different ecosystem types globally. Biometric techniques use chambers to measure respiration fluxes, along with repeated measurements of soil and vegetation C pools, to estimate changes in those pools through time. Biometric measurements in forests have been made at thousands of sites across the globe, though typically only focusing on vegetation change.

Curiously, the two approaches often show differences in flux estimates that are too large to overlook. EC estimates of ecosystem respiration (R_{ECO}) are typically lower than biometric-based estimates, while annual net C storage values (net ecosystem production, NEP) are typically higher (Speckman *et al.*, 2015; Campioli *et al.*, 2016). In an article recently published in *New Phytologist*, Marshall *et al.* (2023; doi: 10.1111/nph.18939) compared C flux and storage estimates from EC and biometric measurements at two simple forest ecosystem sites in Sweden, one fertilized with nitrogen (N) and one not. The simple forests with a single overstory species, low soil organic C, and sparse understory (Fig. 1), combined with a large treatment effect, allowed for robust biometric extrapolation with a large signal-to-noise ratio for the difference between the control and reference sites. The ground-based upscaling provided one of the most rigorous biometric estimates of stocks and fluxes existing, and the EC measurements used the best available technique (Thomas *et al.*, 2013) to select night respiration fluxes by EC.

Fig. 1 Reference stand of Scots pine (*Pinus sylvestris* L.) trees from the Marshall *et al*. (2023; doi: 10.1111/nph.18939), a study recently published in *New Phytologist*, was *c.* 100 yr of age located at Rosinedalsheden *c.* 5 km southeast of Vindeln, Sweden (64°10′N, 19°45′E). Photograph by Dan Binkley.

'…the work of Marshall et al. underscores crucial uncertainties between EC and biometric methods that need to be resolved for confident assessments of forest C monitoring and decarbonization accounting.'

Long-term N addition substantially increased stem wood growth, litterfall, and soil C storage, and reduced total belowground C flux. The two measurement approaches produced similar estimates for photosynthesis (gross primary production, GPP), but differed substantially for ecosystem respiration and net C storage in the forest. Using below-canopy EC sensors to filter night fluxes helped account for some of the discrepancies, but some still remained unaccounted for. Along with other studies, the work of Marshall *et al.* underscores crucial uncertainties between EC and biometric methods that need to be resolved to allow for confident assessments of forest C monitoring and decarbonization accounting.

In contrast to other studies that showed lower R_{ECO} and greater net C storage for EC compared with biometric fluxes, the Marshall *et al.* study found that the discrepancy between the methods differed between the Reference and Fertilized stands. In the Reference stand, EC R_{ECO} was 17% lower than biometric measurements and EC net C storage was 69% (109 g C m^{-2} yr^{-1}) greater, consistent with other EC–biometric comparisons. However, in the Fertilized stand, EC R_{ECO} was 7% higher than biometric measurements and EC NEP was 24% lower. These stand-level differences between methods yielded a −228%

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difference for the treatment change between measurements for R_{ECO} (+102% for EC vs −80% for biometric measurements) and a −89% difference for net annual C storage (25 vs 229 g C m^{-2} yr^{-1}). The measured change between treatments in net C stored in wood and soil C (253 ± 24 (SD) g C m^{-2} yr^{-1}) strongly suggests that EC was unable to accurately measure this change. While using below- and above-canopy, EC coupling to filter night measurements gave a 22% lower NEP than a friction velocity filter (Jocher *et al.*, 2018), in these two stands, the coupling method still gave R_{ECO} and net C storage that differed substantially from biometric measurements.

A mismatch between EC and chamber measurements can arise from many factors, but the persistent directional difference between EC and biometric estimates of NEP and R_{ECO} points to a source of bias that needs to be identified and eliminated. Most of the studies that compared EC and biometric measurements of R_{ECO} show a lower estimate for EC (Speckman *et al.*, 2015). Because of how NEP is estimated with EC, lower estimates of R_{ECO} will inevitably yield a higher NEP. A global analysis found biometric estimates of R_{ECO} averaged 120 g C m^{-2} yr^{-1} more than EC estimates (table 1 in Campioli *et al.*, 2016, $P = 0.06$) (Fig. 2a), which led to a higher NEP of 98 g C m^{-2} yr^{-1} for EC vs biometric estimates (table 1 in Campioli *et al.*, 2016, $P < 0.01$) (Fig. 2b). The strengths of EC measurements are that they are continuous, over a large area, nondestructive, and the methodology is more standardized. Weaknesses of EC are that the method assumes that above-canopy turbulence penetrating a forest canopy provides adequate mixing during the night, that there is no advection that would remove or add air with a different (CO_2) at night, that failure of EC energy exchange measurements to match those of the net radiometer is unproblematic, that the component fluxes of R_{ECO} and GPP are computed, and that NEP is the small difference between two larger fluxes (Fig. 2a).

EC measurements at night are critical for measuring net ecosystem C exchange (net ecosystem exchange, NEE) as they offset C gain from photosynthesis during the light, and EC daily NEP is estimated by summing half-hour values of NEE. Because many measurements of NEE at night (when respiration is not confounded with concurrent photosynthesis) are made under conditions of low vertical transport and advective flows may transport CO_2 to or from the measurement footprint (Aubinet, 2008; Leuning *et al.*, 2008; Yi *et al.*, 2008), filters using friction velocity or coupling of above- and below-canopy fluxes are used to omit NEE measurements taken under poor conditions. The missing fluxes are estimated using a variety of methods. Many EC sites also measure changes in CO_2 stored in the air column below the canopy and add or subtract this from the EC NEE.

A large question for night EC measurements is whether nighttime turbulence provides the same transport of CO_2-rich air from the ground through the air column below the height of (CO_2) measurements, as effectively as they do during the day (Thomas *et al.*, 2013; Speckman *et al.*, 2015). Daytime vertical air transport is provided by heating of the ground and vegetation causing increased air parcel buoyancy and by the penetration of above-canopy wind into the canopy. At night, only penetration of above-canopy wind into the canopy provides transport. The failure of above-canopy wind to adequately transport respired CO_2 to the sensor was documented by Speckman *et al.* (2015), who showed that night EC measurements failed to match biometric estimates of soil and vegetation respiration even with very high friction velocity filters ($u^* > 0.5$). The discrepancy between EC and biometric estimates of respiration decreased as leaf area decreased from bark beetle mortality. The progressively lower leaf area presumably allowed greater penetration of above-canopy wind.

Most EC fluxes are also checked by evaluating the 'energy balance closure', where measurements from a separate instrument (net radiometer) are compared with sensible and latent heat flux (warm air movement and evapotranspiration) and any heat storage. Energy balance estimated from EC is typically 70–90% of that estimated by the net radiometer (Wilson *et al.*, 2002). While EC samples a larger area than net radiometers, the consistent underestimate of EC energy balance compared with the net radiometer across all sites suggests that this lack of energy balance closure remains to be solved for EC measurements.

EC partitioning of NEE into R_{ECO} and GPP also relies on night measurements. EC estimates of photosynthesis or GPP are estimated by summing NEE during light sufficient for photosynthesis plus R_{ECO} estimated at night corrected to the greater temperatures in the daylight, or by fitting NEE to a light response curve to estimate R_{ECO} from the dark portion of the curve and then adding R_{ECO} to NEE during the day.

The strengths of biometric measurements are that they can be made in any terrain, can assess differences in smaller experimental treatments, are comparatively inexpensive, can assess changes in ecosystem C storage over long periods and large areas, and can be assembled with straightforward estimates of variances and precisions. Their weaknesses are that protocols differ among studies, most measurements are not continuous, and they often sample a much smaller area. Measurements might not have been distributed so that a measurement average gives a true average for the ecosystem, and the extrapolation of the short-duration fluxes may not account for all the factors that influence fluxes over the extrapolation period. Changes in soil C and dead wood are difficult to measure accurately on an annual basis because these pools are variable and change slowly. As with EC, photosynthesis is estimated as the sum of the component fluxes: losses to soil and vegetation respiration + C accumulation in biomass + changes in soil C.

How might we work to understand and reduce the differences between EC and biometric measurements? For the EC community, deriving better solutions for estimating night fluxes seems paramount perhaps including measurements of advective fluxes (Yi *et al.*, 2008), although those measurements may not help (Aubinet *et al.*, 2010). Because the Marshall *et al.* study did not find using understory-overstory coupling (Thomas *et al.*, 2013) removed the EC–biometric mismatch, more evaluation of using understory and overstory coupling to screen fluxes should be done. Alternative methods (Van Gorsel *et al.*, 2007, 2008) should also be evaluated at more sites. For the biometric measurement community, using larger chambers for both soil and vegetation fluxes, having more continuous measurements, and combining continuous measurements with periodic broader samples may produce more certain R_{ECO} fluxes.

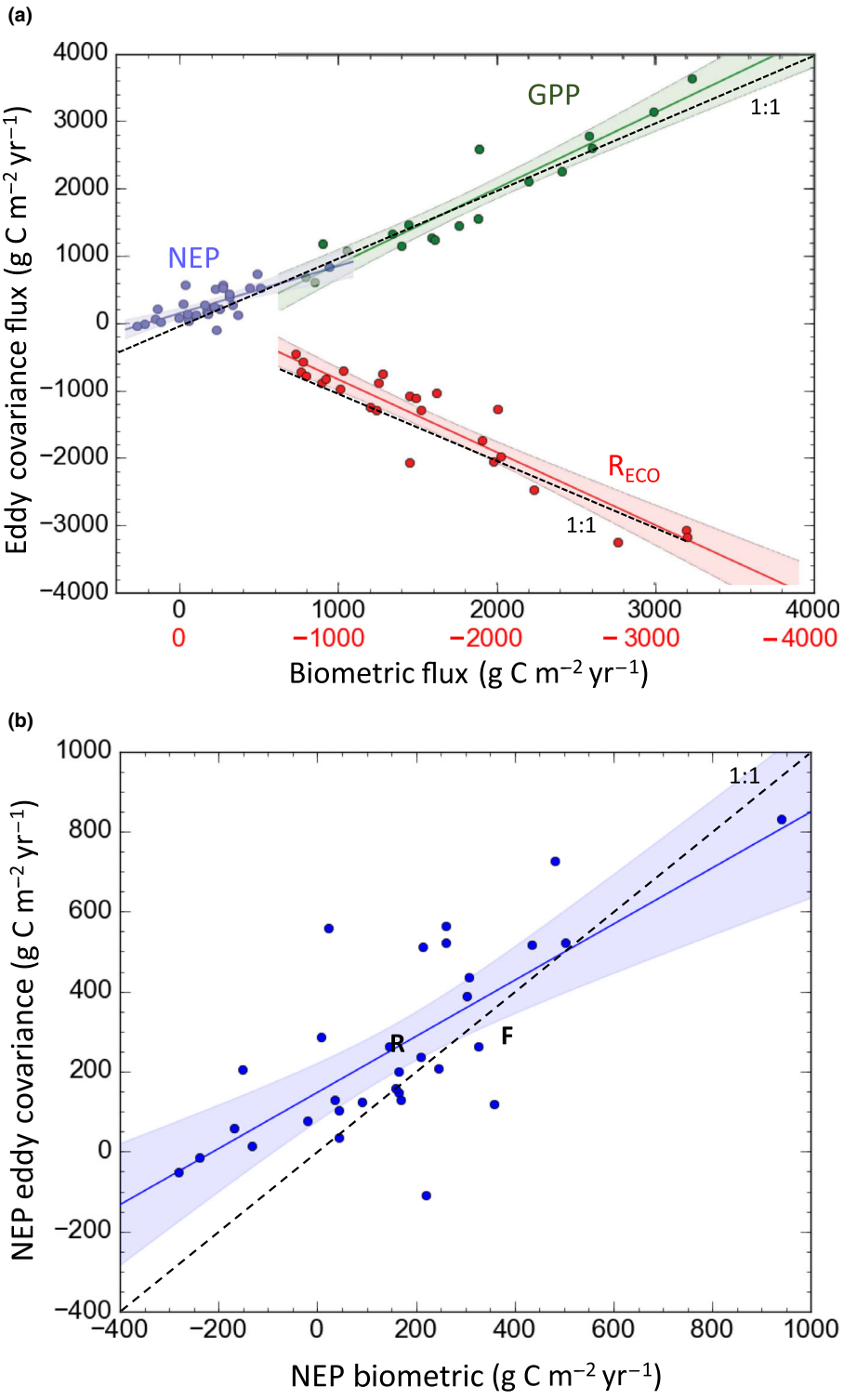

Fig. 2 (a) Data from Campioli *et al*. (2016) plotted with best-fit linear models (colored lines) and 95% confidence intervals (colored, shaded area) and 1 : 1 (dashed black lines) showing that eddy covariance (EC) estimates of gross primary production (GPP) are similar across sites, EC estimates of net ecosystem production (NEP) are higher than biometric estimates and EC estimates of ecosystem respiration (R_{ECO}) tend to be lower than biometric estimates. For EC, NEP is the comparatively small difference between two larger fluxes of GPP and R_{ECO}. (b) Data from Campioli *et al*. (2016) for NEP only plotted with a best-fit linear model (colored line), and 95% confidence intervals (colored, shaded area) and 1 : 1 (dashed black line) showing that EC estimates of NEP are higher than biometric estimates. R, Reference and F, Fertilized are the NEP EC vs biometric comparison from the study by Marshall *et al*. (2023; doi: 10.1111/nph.18939) recently published in *New Phytologist*.

Groups of scientists often rely on one of these two approaches, but collaborations that apply both approaches to the same systems (as done by Marshall *et al.*) may be the most productive path for solving the discrepancies. Both communities would benefit from collaborating to include long-term, large-scale measurements of soil and vegetation C change at every EC measurement site, with repeated measurements every 5–10 yr. For forests, wood C change is the largest annual flux and the simplest to measure over comparatively large areas if robust allometric equations are used (site-specific and including tree height). These measurements can be made annually to compare with EC annual NEE estimates. Both communities ought to be more critical of the shortcomings of their approaches and work together to resolve differences.

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