A Forest Evapotranspiration Paradox Investigated Using Lysimeter Data

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In spite of the large number of studies on the role of forests in affecting local and global water and energy cycles, conflicting reports on even the sign of the change in evapotranspiration over forest compared with non-forest land cover can be found depending on the type of data used. Whereas studies based on closure of the water balance suggest higher evapotranspiration over forests, studies based on turbulent exchange and/or energy balance closure suggest generally higher latent heat flux over non-forest sites. In this study, this forest evapotranspiration paradox was investigated using data from four long-term lysimeter stations in western Europe with contrasting land cover conditions. The results were consistent with evapotranspiration estimates from catchment-scale water balance studies rather than with eddy covariance estimates. They were also found to be largely consistent with a model previously proposed to predict forest cover effects on evapotranspiration. The results of this study suggest that eddy covariance data should be treated with care when used to assess long-term average water balance impacts of land use.

Abbreviations: ET, evapotranspiration.

Forests are known to have a strong impact on hydrological processes and climate (Bonan, 2008; Spracklen et al., 2012; Teuling et al., 2017; Ellison et al., 2017). The evaluation of forest and land cover change effects on the water cycle, however, requires an accurate representation of land cover and vadose zone effects on the terrestrial hydrological cycle in hydrological and land surface models (e.g., Blyth et al., 2010; Williams et al., 2009). In spite of the large number of studies on the role of forests in local and global water and energy cycles (e.g., Sterling et al., 2013), conflicting reports on even the sign of the change in water balance partitioning (in particular of evapotranspiration [ET]) over forest compared with non-forest land cover can be found depending on the type of data used. Thorough knowledge about the impact of forests on evapotranspiration is of key importance to water management because the difference between precipitation and ET is the main control on water availability in streams and aquifers.

Traditionally, the estimation of forest impacts on ET has been performed based on a forced closure of the water balance of a catchment or lysimeter (Senociratne et al., 2010). Based on long-term measurements of precipitation and discharge (or outflow and seepage in the case of a lysimeter), combined with the assumption that storage changes can be neglected over longer time periods (years), ET is usually determined as the difference between precipitation and discharge averaged across multiple years. Based on this principle, Zhang et al. (2001) investigated ET for a large number of catchments across the world, including western Europe. They showed that average precipitation \(P\) and fractional forest cover \(f\) were the main determinants of catchment-scale water loss through ET rather than the potential ET. This is consistent with a study by Shuttleworth and Calder (1979), who questioned the use of potential ET over aerodynamically rough forest ecosystems. Zhang et al. (2001) proposed the following relationship to describe the dependency of ET on precipitation and forest cover:

\[
\text{ET} = \frac{P - \text{ET}_{\text{pot}}}{1 - f}
\]
where $ET_{0,f}$ and $ET_{0,h}$, representing the maximum and constant (potential) ET under conditions of abundant moisture supply for trees and herbaceous plants, respectively, were found to be 1410 and 1100 mm/yr. This model thus predicts higher ET rates for forested areas independent of precipitation, which was also the predominant signal across the available data (see Fig. 1). The Zhang et al. (2001) model is consistent with many other similar studies on the topic (e.g., Bosch and Hewlett, 1982; Brown et al., 2005) and has since been applied in numerous studies (e.g., Sun et al., 2006; Ponce-Campos et al., 2013).

More recently, measurements made by eddy covariance sensors mounted on flux towers have become the primary source of ET observations due to their ability to measure fluxes at the ecosystem level. Many of the towers are part of the global FLUXNET network (Baldocchi et al., 2001). In a synthesis of all FLUXNET data, Williams et al. (2012) reported mean ET rates to be higher for non-forested sites than for forested sites. Also, when separated by mean average precipitation (Fig. 1) following the approach of Zhang et al. (2001), this observation still holds. Similar results have also been reported at a local scale for neighboring flux towers in Germany (Wicke and Bernhofer, 1996) and at regional to continental scales for European summer conditions (Teuling et al., 2010).

The opposing signals from catchment-scale studies and eddy covariance flux towers lead to a paradox: whereas studies based on closure of the water balance suggest a higher ET over forests, studies based on turbulent exchange and/or energy balance closure suggest generally higher ET over non-forest sites (see arrows in Fig. 1). The paradox probably has an origin in problems related to key assumptions underlying the measurement techniques, sampling, and/or analysis. For instance, turbulent exchange measurements might underestimate the true fluxes, while water-balance-based studies at the catchment scale rely on the assumption that all runoff takes place via streamflow. Additional measurement using independent techniques under more controlled conditions might provide additional insight into the paradox and the question whether turbulence-based or water-balance-based observations provide the best estimate for forest water use. In this study, I investigated this forest ET paradox using unique data from four lysimeter stations in western Europe with contrasting land cover conditions and representing some of the longest records worldwide.

**Data**

In this study, I used unique long-term datasets from four lysimeter stations located in western Europe (Fig. 2). Two sites (Castricum and St. Arnold) have multiple very large non-weighing lysimeters with different land cover including different forest types, whereas Rietholzbach and Rheindahlen have smaller weighable lysimeters.

![Fig. 1. Illustration of the forest evapotranspiration paradox, showing the relationship between precipitation and evapotranspiration for forest and non-forest sites using (a) water-balance-based evapotranspiration (ET) estimates from Zhang et al. (2001), and (b) eddy-covariance-based estimates from Williams et al. (2012). Upward triangles indicate observations for forested sites or catchments, and circles indicate non-forested sites or catchments. Curves indicate the Zhang et al. (2001) model for forested (dark continuous lines) and non-forested conditions (light dashed lines). Shaded areas indicate 5 and 95% percentiles of locally weighted scatterplot smoothing (LOESS) as determined by bootstrapping. Black arrows indicate the forest evapotranspiration paradox, with higher ET over forest (+) when catchment-scale water balance studies are considered and generally lower ET over forest (−) when eddy-covariance data are used.](image-url)
These stations were selected based on the length of their records, their great depth (≥2 m), and their size with respect to the cover, measuring ecosystem ET rather than the ET of a single plant or tree. Whereas many other (long-term) stations exist (see discussion by Seneviratne et al., 2012), most do not meet these criteria.

The Castricum lysimeter station started operation in 1943 and is located in the dunes near the Dutch North Sea coast. The site has a mean annual temperature of around 11°C. The station consists of four non-weighing drainage lysimeter basins of 25 by 25 by 2.5 m deep filled with sand. The outflow occurs at the 2.25-m depth, so a groundwater table can develop between the 2.25- and 2.5-m depths (Stuyfzand, 2016). Three lysimeters were covered with coniferous forest (*Pinus nigra* Arnold), mixed deciduous forest, and native bush vegetation (“duinstraweel,” not considered here), while one lysimeter was kept bare. Seeds were sown in 1941. Yearly ET is calculated as the difference between yearly precipitation and lysimeter drainage. The data and reports with more information about the site are available from http://climatexchange.nl/projects/lysimeter/lysimeter.htm.

The German St. Arnold lysimeter station was established in 1965. It has a mean annual temperature of 9.0°C. The station consists of three non-weighing drainage lysimeter basins of 20 by 20 by 3.5 m deep filled with medium-sandy podzol soil. The lysimeters were covered with deciduous forest (*Quercus robur* L. and *Fagus sylvatica* L.), coniferous forest (*Pinus strobus* L.), and grassland. The site and data were described in more detail by Harsch et al. (2009).

The Rietholzbach lysimeter is located in the Rietholzbach catchment, a small (3-km²) headwater catchment situated within the larger Thur basin in northeastern Switzerland. The site has a mean annual temperature of 7.1°C. The Rietholzbach catchment has been a hydrological research site since the mid-1970s. A weighing lysimeter (diameter 2 m, depth 2.5 m) was installed in the catchment in 1976, providing high-resolution estimates of actual ET. The lysimeter is covered by grass, which is cut simultaneously with the surrounding meadows. An overview of all data and a complete description of the area was provided by Seneviratne et al. (2012). The Rietholzbach lysimeter data have been used in numerous hydrological and meteorological studies in the past decades (e.g., Teuling et al., 2009). In this study, I used the monthly values of precipitation and actual ET for the period 1976 to 2007 available from www.iac.ethz.ch/group/land-climate-dynamics/research/rietholzbach/.

The Rheindahlen lysimeter station (www.niederrheinwasser.de/wasserwirtschaft/hydrologische-station/) is located near Mönchengladbach (Germany) and started operating in 1983. The mean annual temperature at the site is typically in the range of 11 to 12°C. The station has several weighing lysimeters consisting of a 2-m-deep soil column (Luvisol), all covered by short vegetation. Lysimeter III had grass cover during the period 1983 to 1994. In this study, I used the observations of yearly ET and precipitation provided by Xu and Chen (2005).

## Results

While time series of ET and precipitation show a large interannual variability of fluxes at all lysimeter stations (Fig. 3), 10-yr average values reveal consistent land-use effects. At Castricum, 10-yr average ET for the coniferous lysimeter is consistently higher than the ET for the deciduous lysimeter. In addition, both lysimeters show consistently lower ET values in the beginning of the observational record (386 vs. 336 mm/yr) than the end of the record (764 vs. 534 mm/yr). In contrast, the bare soil lysimeter shows very consistent averages of just above 200 mm. At St. Arnold, a similar decadal increase of the ET from forested lysimeters can be seen, whereas the ET from the grassed lysimeter remained fairly constant around 300 to 400 mm/yr. It should be noted that the strong decrease in ET after 2007 was caused by damage induced by winter storm Kyrill (Harsch et al., 2009). For this reason, observations after 2007 were not considered. For Rietholzbach, ET makes up a much smaller fraction of precipitation than for the other sites. Because of its humid character, the site has a high sensitivity to changes in available energy, as reflected in a high correlation of 0.7 between yearly global radiation and ET (Teuling et al., 2009). As a result, decadal variability in ET at Rietholzbach has been attributed to decadal changes in incoming radiation (the so-called global “dimming” and “brightening”; see Teuling et al., 2009). At Rheindahlen, ET from the grassed lysimeter is relatively high at 533 mm/yr compared with the moderate precipitation of 795 mm/yr.
Fig. 3. Evolution of yearly precipitation and evapotranspiration, using 10-yr average values (corresponding to horizontal lines), at the three lysimeter stations: (a) Castricum, (b) St. Arnold, (c) Rietholzbach, and (d) Rheindahlen. Colors indicate precipitation (blue), and evapotranspiration (ET) from coniferous vegetation (dark green), deciduous vegetation (light green), grass (orange), and bare soil (yellow).
rather than the eddy-covariance-based estimates by Williams et al. (2012). Figure 4 shows all the selected data from Fig. 3 analogous to Fig. 2. The data points with the highest ET rates are for the most recent periods for the coniferous lysimeters at Castricum and St. Arnold, which generally follow the curve proposed by Zhang et al. (2001) for forest cover with ET0,f = 1410. The deciduous lysimeters at these sites show consistently smaller values of ET, with the most recent points for Castricum and St. Arnold scattered around the curve with ET0,f = 850. The grassland lysimeters at St. Arnold, Rietholzbach, and Rheindahlen all show ET rates lower than the forested lysimeters, except for the initial periods during which tree height was small. The observations at Rietholzbach suggest that a more realistic fit for Eq. [1] under western European climate conditions would be obtained with a value for ET0,h significantly lower than the 1100 mm/yr proposed by Zhang et al. (2001). Here, a value for ET0,h of 700 mm/yr provides a good fit, possibly due to the relatively high altitude, low wind velocity, and strong cloud-cover-induced reduction in summer radiation in the pre-alpine Rietholzbach. The much lower ET values for the bare soil lysimeter at Castricum follow a distinctively different curve, with a near-constant ET that shows little sensitivity to changes in P. While the results seem to confirm the study by Zhang et al. (2001), it should be noted that the precipitation range for most data points is rather limited (700–900 mm/yr) and that only the grassland lysimeter at Rietholzbach has precipitation exceeding 1000 mm/yr.

Vegetation development at the forested lysimeters has led to considerable changes in average ET values even when the average precipitation remained fairly constant, as is evident from Fig. 3 and 4. Clearly, only a fully developed forest canopy will result in high ET rates. In spite of their magnitude, such effects are not included in the Zhang et al. (2001) model. The controlled conditions of the lysimeter observations used here allows reflection on the isolated effect of forest age and height on yearly ET, which would not be possible at the catchment scale where forest stands typically have a variety of species with varying age. To investigate the temporal changes in water balance partitioning for these forest lysimeters and the possible ways in which this effect can be accounted for in the Zhang et al. (2001) model (Eq. [1]), I calculated the apparent forest fraction fapp for each year as

\[ f_{\text{app}} = \frac{ET_{\text{obs}} - ET_{h}(P)}{ET_{f}(P) - ET_{h}(P)} \]  

where ETobs is the observed evapotranspiration, and ETf and ETh are the expected ET rates for non-forested and forested conditions as calculated with Eq. [1] and using f = 0 and f = 1, respectively. Both evapotranspiration and precipitation were first taken as a 3-yr moving average to account for the possible effect of interannual storage variability in the lysimeter. Figure 5 shows the evolution of the apparent forest fraction at Castricum and the relation between tree height and apparent forest fraction at St. Arnold. Figure 5 shows that it might take up to 20 yr or more, or for the trees to develop to a height on the order of 18 to 20 m, before the forest reaches ET rates as high as predicted by the original Zhang et al. (2001) model for full forest cover. The results also suggest that the effect of forest age or height on ET can be parameterized by making f a simple (bi)linear function of either time since reforestation or tree height. This would allow the use of (global) datasets on tree height (e.g., Simard et al., 2011) for improved assessment of the impact of forests on ET and water resources.

Fig. 4. Relation between average precipitation and evapotranspiration for different land use types. Curves show the Zhang et al. (2001) model (Eq. [1]) for coniferous forest (fractional forest cover f = 1; maximum and constant evapotranspiration under conditions of abundant moisture supply for trees ET0,f = 1410 mm, dark green), deciduous forest (f = 1; ET0,f = 850 mm, light green), grassland (f = 0; maximum and constant evapotranspiration under conditions of abundant moisture supply for herbaceous vegetation ET0,h = 700 mm, orange), and bare soil (f = 0; ET0,h = 230 mm, dark green). Data points correspond to the values indicated in Fig. 3, with the symbols for the stations Castricum (square), St. Arnold (downward triangle), Rietholzbach (circle), and Rheindahlen (star) as in Fig. 2. Open symbols indicate early multyear values representative of a growing rather than mature forest.
Discussion and Conclusion

Previous synthesis studies on the forest impact on ET have been inconclusive not only on the magnitude of the difference in ET between forest and grassland but even on the sign of the difference. The dependency of the sign on the method used (i.e., catchment-scale water balance vs. flux tower) can be considered a paradox because both observations cannot be true at the same time. Data from four different lysimeter stations across western Europe with long-term observations are shown in this study to be consistent with ET estimates from catchment-scale water balance studies rather than with eddy covariance estimates. They were also found to be largely consistent with the Zhang et al. (2001) model previously proposed to predict forest cover effects on ET, even though a good fit to the model required some changes in the parameter representing potential evaporation. In addition, the lysimeter data show that an improved representation of forested cover in the Zhang et al. (2001) model is possible for application in (smaller) areas with uniform stand age by introducing an apparent forest fraction that can be parameterized as a function of either time or tree height.

The results suggest that eddy covariance data should be treated with care when used to assess the long-term average water balance impacts of land use. While several studies have addressed the potential shortcomings of flux estimates at tower sites (e.g., Fisher et al., 2007; Hendricks-Franssen et al., 2010), more research into the cause of the apparent underestimation of forest ET by flux towers is needed, taking into account for instance the possible role of advection and interception evaporation during periods of low turbulence. Depending on the forest size, mesoscale circulation might induce convergence–divergence patterns that might influence ET at flux tower sites. A recent study (Teuling et al., 2017) found evidence in cloud patterns over Les Landes forest in France that suggest the existence of a forest-breeze mesoscale circulation.

While the observation that the lysimeter results are in line with the Zhang et al. (2001) model might not be completely unexpected (because both are based on water balance closure), there are several reasons why lysimeter and catchment-scale estimates of ET might differ. Groundwater conditions will typically differ between inside and outside of the lysimeter, which might affect root water uptake under dry conditions. In addition, at the catchment scale, forest cover will never be complete or homogeneous, whereas the forest cover on the lysimeters in Castricum and St. Arnold has been managed to be as homogeneous as possible. The determination of ET will also differ between the lysimeter types. Whereas weighing lysimeters allow determination of ET directly from weight changes, non-weighing lysimeters require additional observations of precipitation. All these factors can potentially influence the fit of the lysimeter data with the Zhang et al. (2001) model.

The fact that different parameters than those reported by Zhang et al. (2001) lead to a better fit with lysimeter data could also be due to local conditions. Castricum, being located close to the coast, has higher wind speeds and a higher frequency of small precipitation events, probably boosting interception evaporation throughout the year. In contrast, the grassed lysimeter at St. Arnold has strongly reduced wind speed due to the wind shadow of the growing forest next to it. This probably contributed to the relatively low ET values. Also, the lysimeter at Rietholzbach might have relatively low ET due to the presence of snow in winter and the frequent presence of convective clouds in summer. While such local conditions might affect the magnitude of the observed fluxes, they are unlikely to affect the sign of the observed land use differences because lysimeter stations were designed to have land use as the only varying factor (in contrast to paired catchment studies where subsurface flow and catchment area are uncertain). However, given the large discrepancies that still exist between lysimeter- and eddy-covariance-based estimates of average ET and the site-specific conditions affecting some of the best and longest lysimeter records available, there is an ongoing need for additional lysimeter measurements of ET across a range of land cover and environmental conditions to help with assessing the impact of land use changes on water resources.
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References


