

Supplement 1: Photosynthesis and fluorescence

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This pdf was generated from an Rmarkdown file, which includes all R code necessary to reproduce the estimations. The Rmarkdown file is available on github (<https://github.com/TTRademacher/Exp2019Analysis>) and is permanently and publicly archived on the Harvard Forest Data Archive.

1 Photosynthesis

Towards the end of the chilling period (i.e., last ten days of chilling; Fig. 1), we measured instantaneous assimilation rates in leaves towards the top (sub-exposed) and bottom (shade-leaves) of the canopy for all eight trees as well as response curves to CO₂ (commonly referred to as A/Ci curves) and light. We conducted those measurements to see if the chilling had affected actual photosynthesis and photosynthetic capacity. All measurements were performed with a LICOR-6400 (Lincoln, Nebraska, USA) from a bucket lift that was parked in between the trees.

1.1 Instantaneous photosynthetic rates at top and bottom of the canopy

For instantaneous rates, the best mixed effects model included only interactive fixed effects of time of day and position in the canopy and a random effect accounting for natural between-tree variability (table S1). This model estimated the time of day and position effects at -0.7 ± 0.3 and $-2.1 \pm 0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively, and their interactions at $2.6 \pm 0.8 \mu\text{mol m}^{-2} \text{s}^{-1}$. This model was only marginally better according to the conditional AIC than several alternative model formulations that included a treatment effect. When the treatment effect was included it was estimated to range from reducing photosynthesis in chilled trees by -0.3 ± 0.7 to $-0.7 \pm 0.9 \mu\text{mol m}^{-2} \text{s}^{-1}$ compared to control trees. However, any difference between chilled and control trees appears to have been larger at the bottom of the canopy (Fig. S1). Overall, there is little evidence for a feedback effect on instantaneous photosynthesis rates.

Table 1: gives the conditions AIC for various formulations of mixed effect models fitted to the instantaneous photosynthetic rates measured in chilled and control trees towards the end of the chilling period. This table was automatically generated from publicly available code and data (data set ID here) on the Harvard Forest Data Archive.

Fixed effect	Random effects	conditional AIC
NA	tree	466.76
time	tree	463.52
position	tree	459.52
treatment	tree	466.36
time + position	tree	459.31
time + treatment	tree	463.22
position + treatment	tree	459.66
time * position	tree	448.87
time * treatment	tree	465.06
position * treatment	tree	461.71
time + position + treatment	tree	459.34
time * position + treatment	tree	448.93
time + position * treatment	tree	461.42
time * treatment + position	tree	461.33
time * position * treatment	tree	452.02

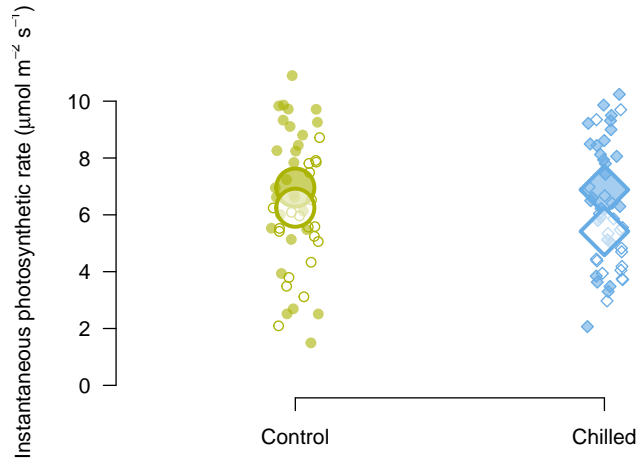


Figure 1: shows instantaneous assimilation rates for chilled (blue diamonds) and control trees (green dots) at the bottom (open symbols) and the top (closed symbols) of the canopy. Treatment group means are displayed with large symbols.

1.2 A/Ci curves

To estimate whether chilling affected the photosynthetic apparatus, we derived maximal rates of photosynthetic electron transport (J_{max}) and RuBisCO carboxylase activity (V_{cmax}), and dark respiration (R_d) from measurements of assimilation in response to varying leaf internal CO_2 concentrations. We estimated photosynthetic parameters by fitting a model using the ‘plantecophys’ package (Duursma, 2015), which showed significant difference in photosynthetic parameters between chilled and control trees (Fig. S2). V_{cmax} was $46.6 \pm 1.5 \mu mol m^{-2} s^{-1}$ for chilled trees instead of $52.1 \pm 1.7 \mu mol m^{-2} s^{-1}$ for control trees, J_{max} was also lower at $85 \mu mol m^{-2} s^{-1}$ for chilled compared to $97 \mu mol m^{-2} s^{-1}$ for control trees, whereas dark respiration increased by 5% in chilled trees relative to control.

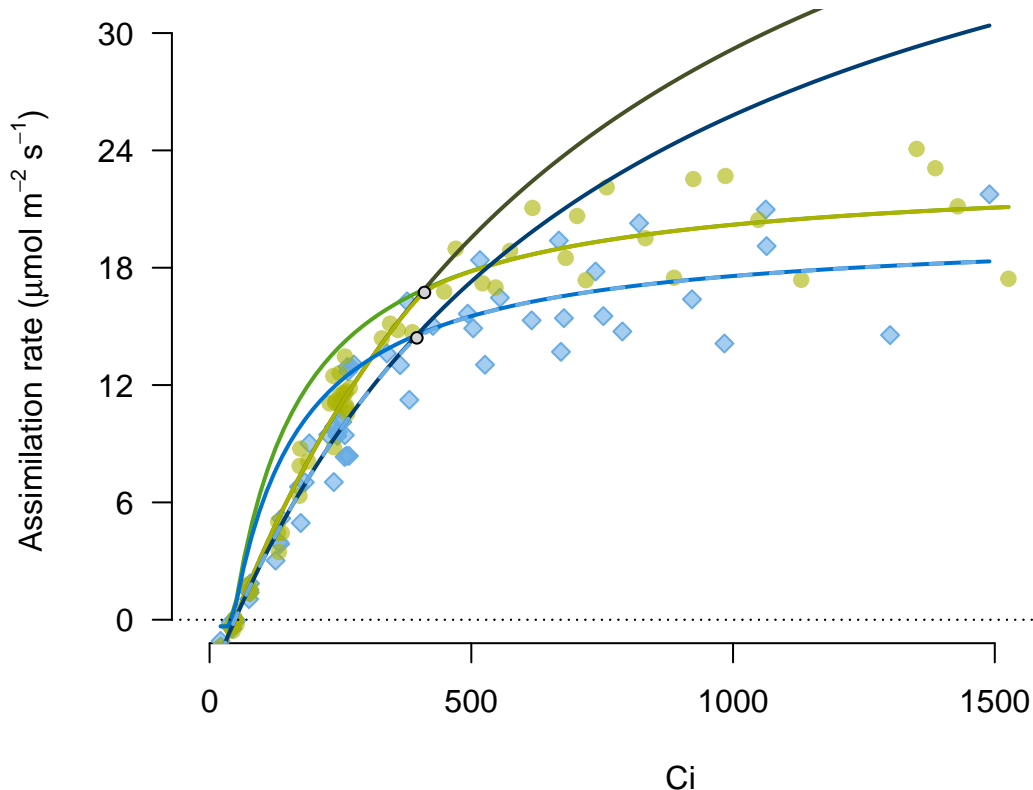


Figure 2: shows photosynthetic assimilation as a function of CO_2 concentration for chilled (blue diamonds) and control trees (green dots). Blue and green lines display the best fitted photosynthetic model using the ‘plantecophys’ R package for chilled and control groups respectively.

1.3 Light response curves

In contrast to the A/Ci curves, light response curves varied seemingly idiosyncratically between trees and there was no clear association between chilling and the light response curves in the leaves in the top of the canopy (Fig. S3). One chilled tree showed the lowest light response curve and saturation level, yet the two highest saturation levels were also found in chilled trees.

2 Leaf fluorescence

Leaf chlorophyll fluorescence in particular the ratio of variable fluorescence over maximum fluorescence (F_v/F_m) in dark-adapted leaves is known to be a reliable indicator of stress to photosystem II (Kitajima

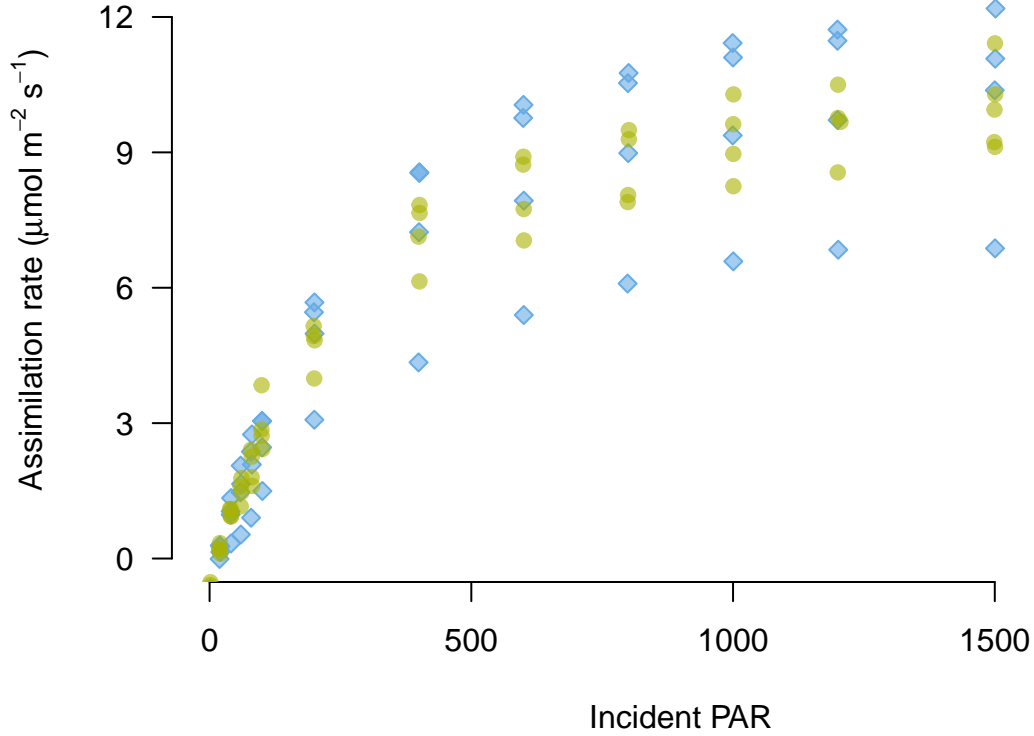


Figure 3: shows the light response curve measurement for chilled (blue diamonds) and control trees (green dots).

and Butler, 1975) and has also been directly linked to low temperature stress (Baker and Rosenqvist, 2004; Groom and Baker, 1992). To test whether photosystem II was stressed by the chilling in our experiment, we measured minimum fluorescence (F_o), maximum fluorescence (F_m) and the ratio of variable fluorescence over maximum fluorescence (F_v/F_m) in light-adapted and dark-adapted leaves during the last 10 days of chilling (Fig. 1). Directly after each photosynthesis measurement, we removed the leaf from the twig and immediately measured chlorophyll fluorescence with a OS-30P chlorophyll fluorometer (Opti-Sciences, Hudson, New Hampshire, USA). Subsequently, we wrapped the leaves in aluminium foil and stored them in a chest cooler with ice, before re-measuring fluorescence of the dark-adapted leaves in the evening of each sampling day (i.e., after several hours of dark-adaptation). Finally, the leaves were weighted, scanned (Epson Perfection V550 Photo Scanner, Long Beach, California, USA), dried at 60°C for 24 hours, and weighted again to obtain leaf area, fresh weight and dry weight for each leaf.

Overall, there were no stark differences in leaf fluorescence between chilled and control trees (Fig. S4 & S5). Dark adapted F_v/F_m were generally close to 0.8, which is close to the assumed optimum for many plant species (Maxwell and Johnson, 2000). However, there was a small difference between F_v/F_m for chilled and control trees (Fig. S4). The estimated treatment effect was -0.14 ± 0.01 , when we fit the mixed effects model containing position of the leaf in the canopy, treatment and their interaction. While this model minimised information loss according to the conditional AIC, it only loses marginally more information than a model that does not contain a treatment effect. Although the estimated effect is comparable to declines in wheat and maize leaves due to cold stress (Andrews et al., 1995; Groom and Baker, 1992), it is also of similar magnitude as normal seasonal changes in F_v/F_m of green summer and green autumn leaves in the closely related sugar maple (Junker and Ensminger, 2016). The lack of a clear difference suggests that the maximum potential quantum efficiency of photosystem II was not strongly affected by chilling here.

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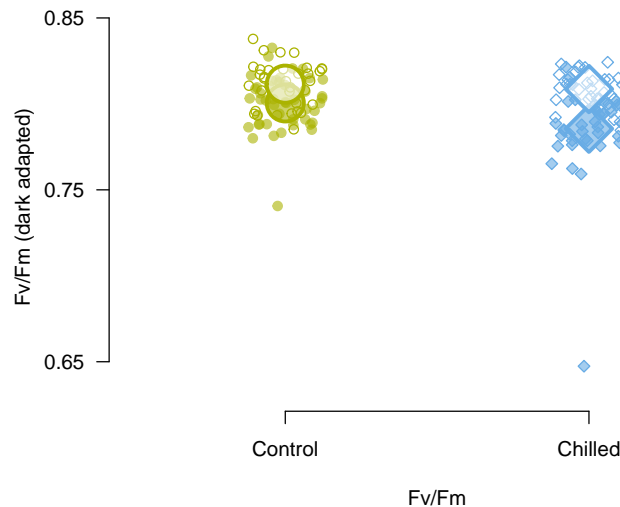


Figure 4: shows F_v/F_m measured immediately after removal and after dark-adapting each leaf for several hours for chilled trees (blue diamonds) and control trees (green dots) for leaves from the bottom (open symbols) and the top (closed symbols) of the canopy.

While there were no differences in minimum and maximum fluorescence between treatments (i.e., chilled versus control), there were differences in the minimum and maximum fluorescence between leaves from the bottom and the top of the canopy, when measured directly after the leaves were removed from the canopy. These differences persist, albeit slightly smaller, once leaves were dark-adapted (Fig. S5). Such differences in fluorescence between sun- and shade-leaves have also been reported for four other temperate deciduous tree species (Lichtenthaler et al., 2007) and are supported by theoretical models (Olmos et al., 1992).

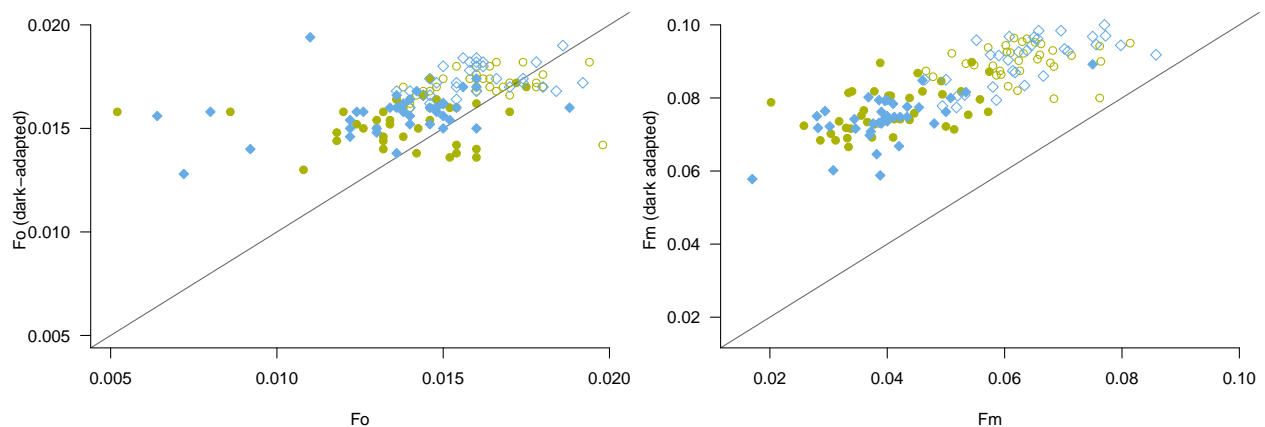


Figure 5: shows minimum (F_0) and maximum fluorescence (F_m) measured immediately after removal and after dark-adapting each leaf for several hours for chilled trees (blue diamonds) and control trees (green dots) for leaves from the bottom (open symbols) and the top (closed symbols) of the canopy.

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