Implication of vegetation response to future climate conditions in current potential evapotranspiration methods – a grassland lysimeter study

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Motivation

Measurement data from a unique climate change experiment (ClimGrass) offered an opportunity to observe the ability of evapotranspiration (ET) models to estimate evapotranspiration of managed mountain grassland in ambient and future climate conditions.

To separate climate forcing and management effects from vegetation response, a corrected Penman-Monteith (PMcy) equation was tested, combining:

- a corrected Penman-Monteith (PMc) model presented by Schymanski
- a surface resistance model presented by Yang, that introduces the vegetation response to elevated CO$_2$ into the Penman-Monteith formalism, targeting the surface resistance ($r_s$).

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Methodology

- Calibration of the PM and PMc model to best fit daily lysimeter ET data at ambient conditions. Calibration parameters included $r_l$, $a_s$ and $a_{sh}$ (see page 9).

- Evaluation of model performance at ambient conditions.

- Assessing the impact of elevated $\left[ \text{CO}_2 \right]$ on stomatal resistance:
  - using the original Penman-Monteith equation;
  - using the corrected Penman-Monteith equation accounting for two-sided leaf stomata cover.

- Ability of the PMcy model to estimate ET under elevated $\left[ \text{CO}_2 \right]$.
Research background

The **ClimGrass** experiment (Herndl, Pötsch, Bahn, Schaumberger) allows testing for effects of warming, elevated CO\(_2\) and drought events on grassland productivity and biogeochemical cycles.

**ClimGrassHydro** - analyze effects of warming, elevated CO\(_2\) and extreme climatic events on the ecohydrology of managed C3 grassland typical for many European mountain regions.

The **Lysi-T-Face** experiment (Herndl, 2011) combines:

- enrichment with CO\(_2\)
  (+300 ppm; miniFACE Technique)
- heating with infrared heaters
  (+3° C; T-FACE-Technique)
- high precision weighable lysimeters

More information on the project is available here: [https://www.uibk.ac.at/ecology/forschung/climgrass.html](https://www.uibk.ac.at/ecology/forschung/climgrass.html)

(Slawitsch, 2019)
Findings from Slawitsch (2019):

- elevated CO₂ concentrations decrease ET
- warming increases ET
- observing the combined effect of elevated CO₂ and warming on ET revealed that warming prevailed over elevated CO₂ effects in all years except 2018 (dry year)
Comparing lysimeter ET with estimated potential ET:

Potential ET represents the maximum value of ET from a specific crop/vegetation type under conditions of full soil water supply.

\[ ET = ET_{\text{lysimeter}}, \text{ when: } 1. \text{ No water stress occurs (WC at 10 cm < water stress threshold value (Feddes, 1982))} \]
\[ 2. \text{ Time span between the start of the vegetation period and 3.rd cut (available LAI and crop height data)} \]
Corrected Penman-Monteith model by Schymanski:

To use the leaf scale model at canopy/surface level, a leaf to surface scaling was done using the "big-leaf" approach (aggregation of many representative leaves), where the surface resistance $r_s$ corresponds to the stomatal resistance to water vapor and aerodynamic resistance $r_a$ to the boundary layer resistance around a single leaf.

$$\lambda ET = \frac{\Delta (R_{ns} - a_{sh} R_{nl}) + K_{min} \rho_a c_p a_{sh} (e_s - e_a) / r_a}{\Delta + \gamma \frac{a_{sh}}{a_s} (1 + \frac{r_s}{r_a})}$$

$a_{sh}$ is the fraction of projected area exchanging sensible and radiative heat with the air (2 for a planar leaf, 1 for a soil surface)

$a_s$ is the fraction of one-sided leaf area covered by stomata (1 if stomata are on one side, 2 if they are on both sides)

$$r_a = \frac{\ln \left[ \frac{z_{o,h} - d}{z_{o,m}} \right] \ln \left[ \frac{z_{h} - d}{z_{o,h}} \right]}{k^2 u_z}$$

$z_{o,h}, z_{o,m}, d$ – calculated from crop height

$$r_s = \frac{r_l}{LAI_{eff}}$$

$r_l$ – bulk stomatal resistance of a leaf [s/m]
Implication of vegetation response to elevated CO\textsubscript{2} - PMcy

Higher CO\textsubscript{2} drives partial stomatal closure and consequently indirectly increases $r_s$ (Yang, 2018):

$$r_s = r_{r_{s-300}} \times \{ 1 + S_{r_{s-[CO_2]}} \times ([CO_2] - 300) \};$$

$$r_s = \frac{r_{r_{l-300}}}{LAI_{eff}} \times \{ 1 + S_{r_{l-[CO_2]}} \times ([CO_2] - 300) \};$$

$r_{r_{s-300}}$: reference surface resistance when atmospheric [CO\textsubscript{2}] is 300 ppm (roughly equivalent to the 1861–1960 mean).

$r_{r_{l-300}}$: reference stomatal resistance when atmospheric [CO\textsubscript{2}] is 300 ppm (roughly equivalent to the 1861–1960 mean).

$S_{r_{l-[CO_2]}}$: is the relative sensitivity of $r_l$ to $\Delta[CO_2]$. 

Modifying the Yang equation to account for LAI change!

Yang (Nature, 2018)
Model performance at ambient conditions

Table 1: Model configuration and *calibrated parameter values for each scenario

<table>
<thead>
<tr>
<th>Scen.</th>
<th>$r_u$</th>
<th>$r_i$</th>
<th>$a_i$</th>
<th>$a_{ih}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pm0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>pm1</td>
<td>$r_u(\text{croph})$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>pm2</td>
<td>$r_u(\text{croph})$</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>pm3</td>
<td>$r_u(\text{croph})$</td>
<td>17*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>pm4</td>
<td>$r_u(\text{croph})$</td>
<td>40(\text{fix})</td>
<td>1.3*</td>
<td>1*</td>
</tr>
<tr>
<td>pm5</td>
<td>$r_u(\text{croph})$</td>
<td>56*</td>
<td>1.4*</td>
<td>1*</td>
</tr>
</tbody>
</table>

From Kelliher(1993) for grasslands.

Underestimation of the reference PM equation!!

The corrected PMc method from Schymanski produced best fit with the lysimeter data!
Parameter estimation of \( S_{r_l-[CO_2]} \) and \( r_{r_l-300} \) was done with ET data from both the lysimeter at ambient conditions ([CO_2]=400 ppm) and the lysimeter C2T0 with manipulated CO_2 concentration ([CO_2]=700 ppm) and compared using:

- PM equation coupled with the Yang model
- PMcy equation, with \( a_s \) and \( a_{sh} \), taken from estimated values of scenario pm4 (\( a_s=1.3, a_{sh}=1 \))

What is the impact of model structure on the estimation of \( S_{r_l-[CO_2]} \) and \( r_{r_l-300} \)?

Table 1: Calibrated parameter values for each model configuration and calculated \( r_l \) values at each lysimeter plot

<table>
<thead>
<tr>
<th>Scen.</th>
<th>( r_{l-300} )</th>
<th>( a_s )</th>
<th>( a_{sh} )</th>
<th>( S_{r_l-[CO_2]} )</th>
<th>( r_{l-400} )</th>
<th>( r_{l-700} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>12.5</td>
<td>1</td>
<td>1</td>
<td>0.0046</td>
<td>18</td>
<td>35.5</td>
</tr>
<tr>
<td>PMc</td>
<td>38</td>
<td>1.3</td>
<td>1</td>
<td>0.0023</td>
<td>47</td>
<td>73</td>
</tr>
</tbody>
</table>

- neglecting two-sided stomata distribution can lead to an overestimation of the impact of \([CO_2]\) on stomatal resistance \( r_l \), when estimating \( r_l \) from observed ET.
Conclusion

- The corrected PMc method improves the estimation of both the daily and cumulative ET at ambient conditions.

- Neglecting two-sided latent heat flux of amphistomatous leaves can lead to an overestimation of the effect of elevated CO$_2$ on stomatal resistance, when estimating $r_i$ from observed ET.

Future plans and challenges

- Determining $a_s$ and $a_{sh}$ for a canopy/surface.
- Estimating the combined effect of elevated temperature and CO$_2$ on ET.
- Use of a dual-source model or patch model to include functional group characteristics to the ET estimation.
- Distinction between radiative and aerodynamic surface temperatures when estimating the effect of elevated temperature.

All of the used ET equations are implemented in the Python package PyEt: [https://github.com/phydrus/PyEt](https://github.com/phydrus/PyEt)
Acknowledgements:

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