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

Matevž Vremec[1], Veronika Forstner[1], Markus Herndl[2], and Steffen Birk[1]

[1]University of Graz, Institute of Earth Sciences, Austria (matevz.vremec@uni-graz.at)

[2]Agricultural Research and Education Centre Raumberg-Gumpenstein, Austria

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Institute of Earth Sciences, NAWI Graz Geocenter

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[1]
- a surface resistance model presented by Yang[2], that introduces the vegetation response to elevated CO_2 into the Penman-Monteith formalism, targeting the surface resistance (r_s).

[1]Schymanski, S. J., & Or, D. (2017). Leaf-scale experiments reveal an important omission in the Penman-Monteith equation. *Hydrology and Earth System Sciences*, *21*(2), 685-706.
[2]Yang, Y., Roderick, M. L., Zhang, S., McVicar, T. R., & Donohue, R. J. (2019). Hydrologic implications of vegetation response to elevated CO 2 in climate projections. Nature Climate Change, 9(1), 44-48.

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 [CO_2] 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 [CO_2].

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

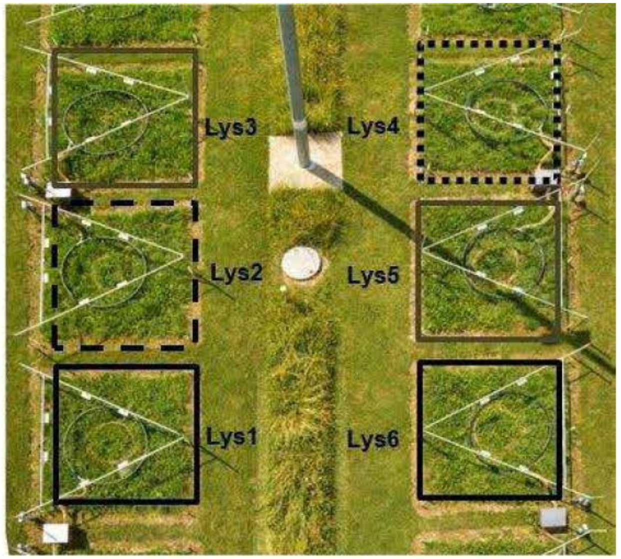
(+300 ppm; miniFACE Technique)

- heating with infrared heaters

(+3° C; T-FACE-Technique)

- high precision weighable lysimeters

C0T2	+ 3ºC
C0T0	Reference plot
C2T0	+300 ppm CO_2 enrichment
C2T2	+300 ppm CO_2 and +3ºC



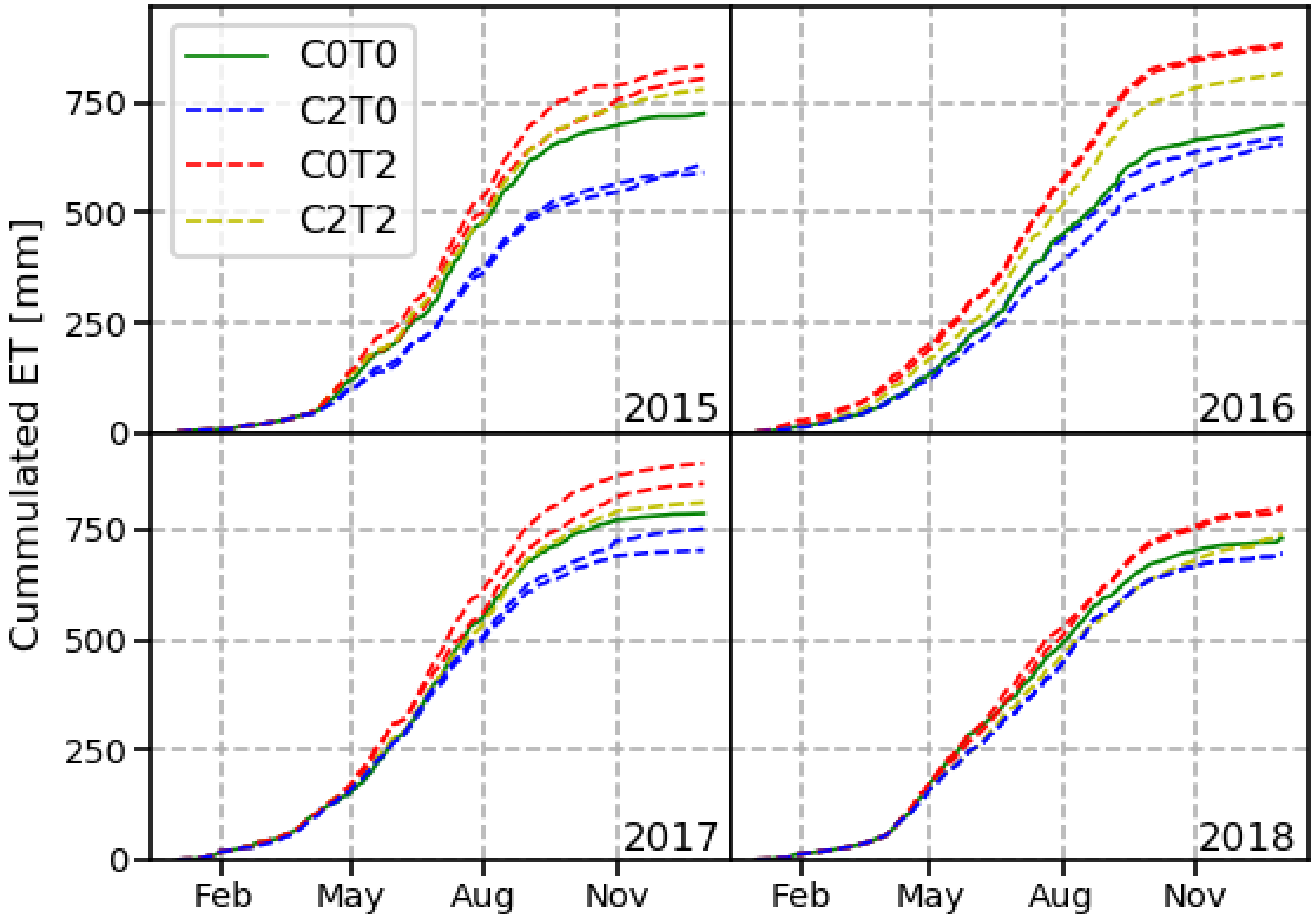
(Slawitsch, 2019)

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

Observed Evapotranspiration at the lysimeters:

Findings from Slawitsch (2019):

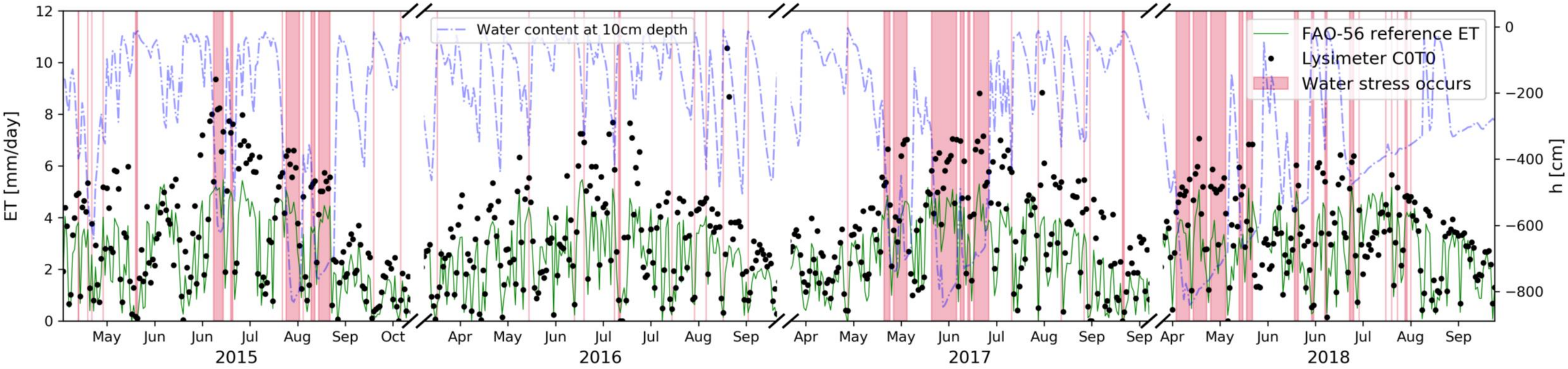
- elevated CO_2 concentrations **decrease ET**
- warming **increases ET**
- observing the combined effect of elevated CO_2 and warming on ET revealed that **warming prevailed** over elevated CO_2 effects in all years except 2018 (dry year)



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.

$ET = ET_{lysimeter}$, when: 1. No water stress occurs (WC at 10 cm < water stress threshold value (Feddes, 1982))
2. Time span between the start of the vegetation period and 3.rd cut (available LAI and crop height data)



Corrected Penmam-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)

$$r_a = \frac{ln\left[\frac{z_m - d}{z_{om}}\right] ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z}$$

z_{oh}, z_{om}, d – calculated from crop height

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

r_l – bulk stomatal resistance of a leaf [s/m]

$$LAI_{eff} = 0.5LAI$$

Implication of vegetation response to elevated CO_2 - PMcy

Higher CO_2 drives partial stomatal closure and consequently indirectly increases r_s (Yang, 2018):

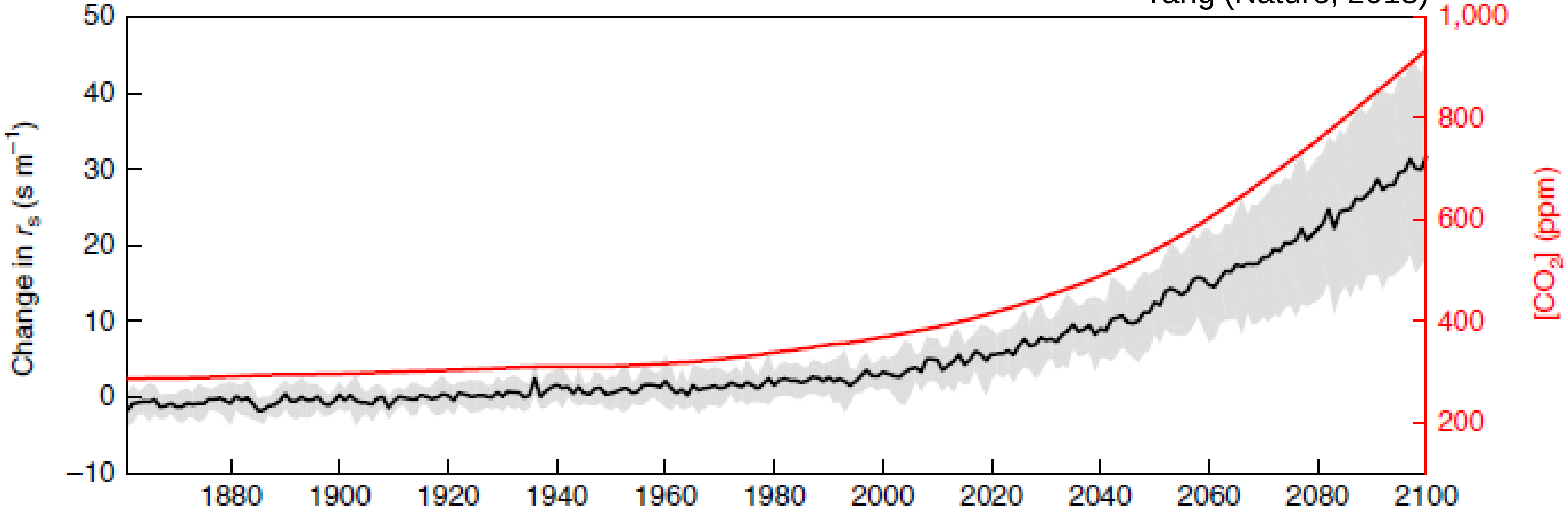
$$r_s = r_{r_s-300} \times \{1 + S_{r_s-[CO_2]} \times ([CO_2] - 300)\};$$

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

Modifying the Yang equation to account for LAI change!

r_{r_s-300}; reference surface resistance when atmospheric $[CO_2]$ is 300 ppm (roughly equivalent to the 1861–1960 mean).
r_{r_l-300}; reference stomatal resistance when atmospheric $[CO_2]$ is 300 ppm (roughly equivalent to the 1861–1960 mean).
$S_{r_l-[CO_2]}$; is the relative sensitivity of r_l to $\Delta[CO_2]$.

Yang (Nature, 2018)



Model performance at ambient conditions

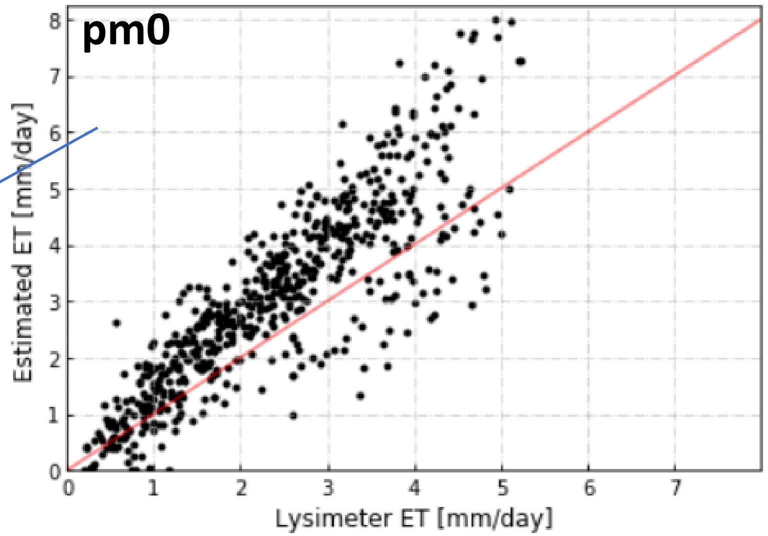
Table 1: Model configuration and *calibrated parameter values for each scenario

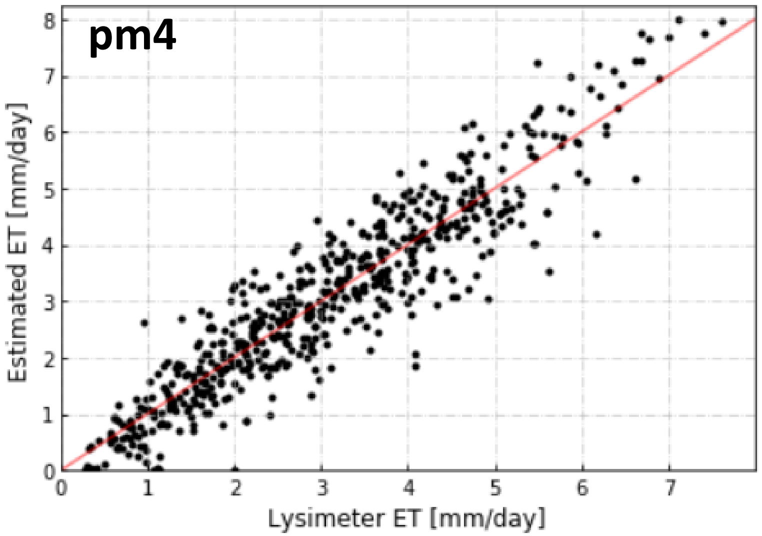
Scen.	r_a	r_l	a_s	a_{sh}
pm0	-	-	-	-
pm1	r_a(croph)	-	-	-
pm2	r_a(croph)	40	-	-
pm3	r_a(croph)	17*	-	-
pm4	r_a(croph)	40(fix)	1.3*	1*
pm5	r_a(croph)	56*	1.4*	1*

From Kelliher(1993) for grasslands.

	Calibration					**Validation**				
	2015,2016		sum (2015,2016)			2017,2018		sum (2017,2018)		
Scenario	RMSE	NSE	obs	sim	$\%Error$	RMSE	NSE	obs	sim	$\%Error$
pm0	1.124	0.611	935.4	714.1	-23.7	1.082	0.429	858.3	675.2	-21.3
pm1	0.916	0.742	935.4	775.1	-17.1	0.921	0.586	858.3	722.2	-15.8
pm2	0.659	0.867	935.4	853.4	-8.8	0.729	0.74	858.3	773.2	-9.9
pm3	0.612	0.885	935.4	907.3	-3	0.697	0.763	858.3	827.8	-3.6
pm4	0.58	0.897	935.4	938.3	+0.8	0.663	0.785	858.3	855.3	-0.35
pm5	0.577	0.898	935.4	937.4	+0.2	0.656	0.79	858.3	847.3	-1.3

Underestimation of the reference PM equation!!





The corrected PMc method from Schymanski produced best fit with the lysimeter data!

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

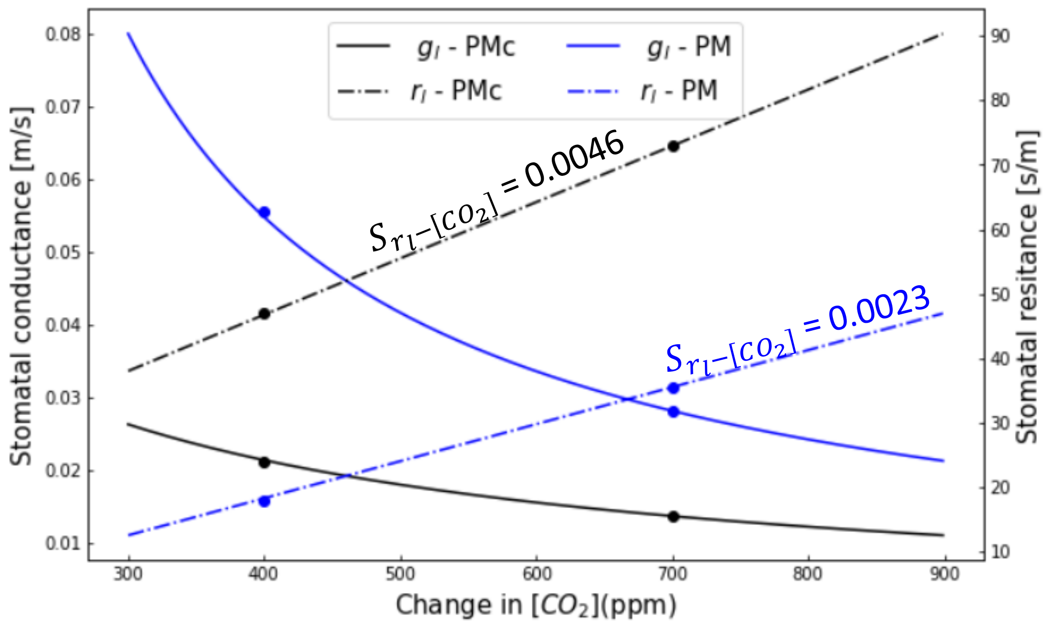
Parameter estimation of $S_{r_l-[CO_2]}$ and r_{r_l-300} was done with ET data from both the lysimeter at ambient conditions ($[CO_2]$=400 ppm) and the lysimeter C2T0 with manipulated CO_2 concentration ($[CO_2]$=700 ppm) and compared using:

- 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)

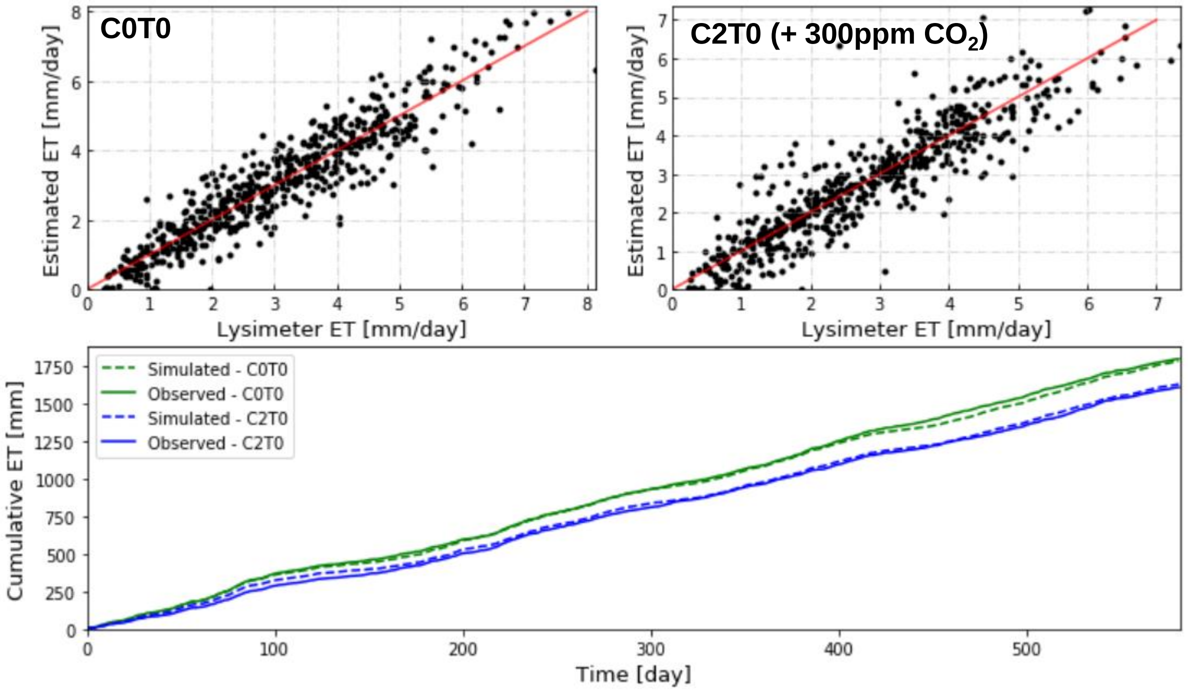
Table 1: Calibrated parameter values for each model configuration and calculated r_l values at each lysimeter plot

Scen.	r_{l-300}	a_s	a_{sh}	$S_{r_l-[CO_2]}$	r_{l-400}	r_{700}
PM	12.5	1	1	0.0046	18	35.5
PMc	38	1.3	1	0.0023	47	73

➢ 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_l 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

Acknowledgements:

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For more information send an email to matevz.vremec@uni-graz.at