Article

Potential evapotranspiration of managed grasslands - a climate change lysimeter study

Matevž Vremec [1,†,‡], Veronika Forstner [1,,†‡] and Steffen Birk [2,†,*]

[1] Affiliation 1; matevz.vremec@uni-graz.at
[2] Affiliation 2; e-mail@e-mail.com
* Correspondence: matevz.vremec@uni-graz.at
† Current address: Heinrich Strasse 26, Instutue for Earth Sciences, University of Graz
‡ These authors contributed equally to this work.

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Abstract:
1. Evaluate default PET models
- scatter plot of all - maybe tudi gostote - mean monthly maybe - quantile-quantile plots([1]) - changes in median and interquartile range for projected PET series(([1]) 2. Evaluate calibrated PET models - scatter plot - calibration efficiency [1] 3. Implication/evaluation of elevated CO_2 in PET models
4. Implication/evaluation of warming in PET models
6. Implication/evaluation of combined effect of warming and elevated CO_2 in PET models
7. Uncertainty of hydrological model parameter selection 8. Uncertainty in PET model selection [2] 9. sensitivity of uncertainty 10. How large are uncertainties in future projection of reference evapotranspiration through different approaches? [2] [3], [4], [5], [6], [7], [8], [9]
8. Conclusion

Keywords: keyword 1; keyword 2; keyword 3 (list three to ten pertinent keywords specific to the article, yet reasonably common within the subject discipline.)

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0. Objectives

- Evaluate PET calculation methods for the present and future
- Uncertainty in PET methods
- Third bullet

1. Global Radiation data
ZAMG no data from (2018-03-16 till 2018-03-21
BOKU ERROR data for global rad from 2017-

2. Should I take LAI or height for PET calculation as LAI measurement do not fit with the cuting dates

3. In what time period should i observe PET?
3.1 Should I compare whole year or vegetation period?
3.2 Should I compare on same dates or start vegetation period/cuts
3.3 Vegetation period from start of vegetation till end of vegetation?

1. Introduction

[10] - higher PET with managed grasslands and [11]

2. Evaluation of PET models(Materials and methos)

2.1. Previous research

Sensitivity to erros in potential evapotranspiration input [12] [13] and [14](z0 = 1 for meadow grass)(details of computation)(Blaney-Criddle-only mean T, Jensen-Hasie [15]-solar radiation with T) compared 9 PET methods using onsite meteo data (PEnman with empirical wind function applicable to a short grass with rougness coef of 1cm): [16]-sensitivty of PEnman

$$f(u) = 0.35 + 0.0035 * u_2 \tag{1}$$

Search for best PE formula [17], [18]

2.2. Used PET models

Data notations and units

PE	potential evapotranspiration (mm day^{-1})	u	wind speed 2m above soil surface (m s^{-1})
Δ	Slope of vapor pressure curve (kPa $°C^{-1}$)	T_a	air temperature (°C)
λ	latent heat of vaporization (MJ kg^{-1})	T_d	dew point temperature (°C)
ρ	water density (=1000 kg L^{-1})	R_e	extraterrestrial radiation (MJ $m^{-2}day^{-1}$)
γ	psychrometric constant (kPa $°C^{-1}$)	R_g	global short-wave radiation (MJ $m^{-2}day^{-1}$)
e_s	saturation vapour pressure (kPa)	R_n	net solar radiation (MJ $m^{-2}day^{-1}$)
e_a	actual vapour pressure (kPa)	DL	day length (h day^{-1})
r_a	aerodynamic resistance (s m^{-1})	α	surface albedo
r_s	surface resistance (s m^{-1})	J_D	Julian day
k	monthly consumptive use coefficient (=0.85)	p	percentage of total daytime hours

Table 1. PET Computations

PET method	Equation	Coeff. to calibrate
Blaney-Criddle [19]	$PE = kp(aT_a + b)$, with a=0.46, b=8.13	k, a, b
FAO-PM ET_0 [20]	$ET_0 = \frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T_a+273}U_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)}$	/
Hargreaves [21]	$PE = a(T_{max} - T_{min})^{0.5}(T_{mean} + T_x)\frac{R_a}{\lambda\rho_w}$ with a=0.0023 and T_x=17.8	a, T_x
Jensen-Haise	$PE = \frac{1}{\lambda}C_r(T - Tx)R_s$, with C_r = 0.025 and Tx = -3	C_r, T_x
Kimberley-Penman [22]	$PE = \frac{1}{\lambda\rho_w}\frac{\Delta(R_n-G)+K_u\gamma(a_w+b_w u_2)(e_s-e_a)}{\Delta+\gamma}$ with $a_w = 0.4 + 1.4exp - \left[\left(\frac{J-173}{58}\right)^2\right]$ and $b_w = 0.605 + 0.345exp - \left[\left(\frac{J-243}{80}\right)^2\right]$	/
Makkink [23]	$PE = a\frac{\Delta}{\Delta+\gamma}\frac{R_s}{\lambda} - b$, with a=0.61 and b=0.12 or $PE = f * \frac{1}{\lambda\rho}\left(\frac{0.63R_s\Delta}{\Delta+\gamma} - 14\right)$	a, b
Penman [24]	$PE = \frac{1}{\lambda\rho_w}\frac{\Delta(R_n-G)+K_u\gamma(a_w+b_w u_2)(e_s-e_a)}{\Delta+\gamma}$, with K_u = 6.43	a_w, b_w
Priestley-Taylor [25]	$PE = \frac{\alpha}{\lambda}\frac{\Delta}{\Delta+\gamma}R_n$, with α = 1.26	α
Penman-Monteith [26]	$PE = \frac{1}{\lambda}\left[\frac{\Delta(R_n-G)+K_m in\rho_a c_p(e_s-e_a)/r_a}{[\Delta+\gamma(1+\frac{r_s}{r_a})]}\right]$, with k_{min}=86400 with $r_a = \frac{ln\left[\frac{z_w-d}{zom}\right]ln\left[\frac{z_h-d}{z_{oh}}\right]}{k^2u_z}$ and $r_s = \frac{rl}{LAI_{active}}$	r_a, r_s
Oudin [27]	$PE = \frac{R_e}{\lambda\rho}\frac{T_a+K_2}{K_1}$, if $T_a + K_2 > 0$, else $PE = 0$ with K_1=100 and K_2=5	K_1, K_2
Hamon [27]	$PE = \left(\frac{DL}{a}\right)^2 exp\left(\frac{T_a}{b}\right)$, with a=12 and b=16	a, b /

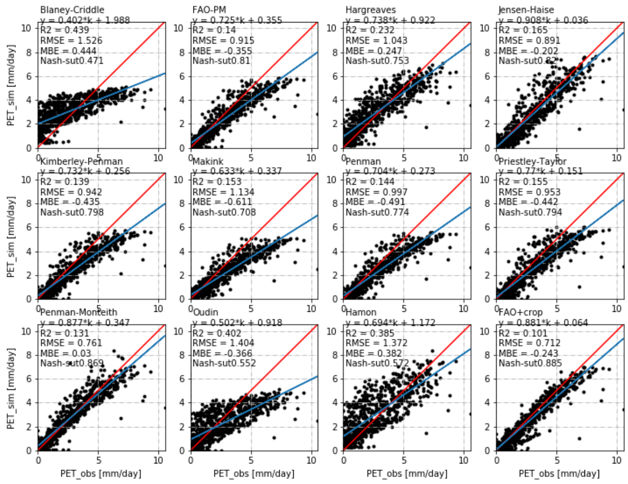

Figure 1. Default PET

Table 2. Effect of LAI and height data to efficiency of the model

n.	LAI	h	RMSE	R2
1	const	const	0.921	0.14
2	meas	const	0.934	0.148
3	const	meas	0.835	0.143
4	LAI from h	const	0.846	0.148
5	LAI from h	meas	0.801	0.148

3. Statistical analyses

Correlation Coefficient

$$r = \frac{\sum_{i=1}^{n}(e_i - \bar{e})(s_i - \bar{s})}{\sqrt{\sum_{i=1}^{n}(e_i - \bar{e})^2}\sqrt{\sum_{i=1}^{n}(s_i - \bar{s})^2} \tag{2}$$

Standard errors of estimates (SEEs) [28]
cRegression coefficient (slope) for regression through the origin of lysimeter versus equation estimate
dCorrelation coefficient for regression through the origin of lysimeter versus equation estimate.
fWeighted standard error of estimate
R_2 [18]

a_w and b_w are wind function coefficients that are usually receive a local or regional calibration. Penman [29] used for clipped grass [26] a_w = 1.0 and b_w = 0.537.

"Jensen and Haise (1963) evaluated 3,000 observations of ET as determined by soil sampling procedures over a 35-year period. From about 100 values for well-watered crops with full cover in the western United States, a linear relationship of a solar radiation coefficient and mean air temperature was apparent. From these data, the constants for the following linear equation were CT=0.025 and Tx=-3 for temperature in C. Rs has the same units as λ ETr."

, where K_min units conversion, equal to 86,400 s d-1 for ET in mm d-1 and equal to 3600 s h-1 for ET in mm h-1. where zw = 2, zh = 2, d = 0.67 * h, zom = 0.123*h, zoh = 0.0123*h, k=0.41, u=wind, h=vegetation height where rl = bulk stomatal resistance of a well-illuminated leaf 100sm-1, and LAI_{active}=0.5 LAI. rs=1/gs

FAO-reference + crop coefficient

4. Evaluation of PET models with original constant values

Priestley-Taylor
Makkink
Blaney-Criddle
Hargreaves
FAO-pm-reference
Kimberley-Penman
Jensen-Haise
Penman-Monteith
Penman
Oudin
Hamon
FAO-pm-reference + crop coefficient

5. Evaluation of PET models with calibrated constant values

Table 3. PET Computations

PET method	Default	Calibrated
Blaney-Criddle [19]	a=0.46, b=8.13, k=0.5	a=, b=, k=
Hargreaves [21]	a=0.0023 and T_x=17.8	a=, T_x=
Jensen-Haise	C_r = 0.025,T_x=-3	C_r=, T_x=
Kimberley-Penman/Penman	Penman a_w=2.6, b_w=0.536	a_w=, b_w=
	Kimberley-Penman: $a_w = 0.4 + 1.4exp - \left[\left(\frac{J-173}{58}\right)^2\right]$	
	and $b_w = 0.605 + 0.345exp - \left[\left(\frac{J-243}{80}\right)^2\right]$	
Makkink [23]	a=0.61, b=0.12	a=, b=
	or f=1	f=
Priestley-Taylor [25]	α = 1.26	α=
Penman-Monteith/FAO [26]	r_a=, r_s	r_a, r_s
Oudin [27]	K_1=100 and K_2=5	K_1=, K_2=
Hamon [27]	a=12 and b=16	a=, b=

6. Implication of vegetation response to elevated CO_2 concentrations

Aimsworth[30] evaluated data from 12 FACE experiments and discovered that elevated CO_2 reduces stomatal conductance by 20 %, when averaged over 40 different species at the 12 locations.
1. Following [31] for Penman monteith
2. Following [32] for Makkink

7. Evaluation of PET models with calibrated constant values

Priestley-Taylor
α

8. Evaluation of PET models with original constant values/results

9. Evaluation of PET models with calibrated constant values/results

9.0.1. Inputs

R_n net longwave radiation BOKU station/ZAMG station

BOKU station bad data from 2017- ZMG.NAN values = (2015-09-25 - interpolate), (2017-09-20 - interpolate), (2018-03-16 till 2018-03-21 - drop?)

compare years 2015, 2016

R_n net longwave radiation BOKU station/ZAMG station

BOKU station bad data from 2017- ZMG.NAN values = (2015-09-25 - interpolate), (2017-09-20 - interpolate), (2018-03-16 till 2018-03-21 - drop?)

compare years 2015, 2016

$$R_n l = f_{cd}(a_1 + b_1\sqrt{e_a})\sigma T^4 \tag{3}$$

if 24-hour or longer time steps...T^4 transforms to $(T^4_{max} - T^4_{min})/2$.
σ is for daily values 4.901 x 10^{-9} $MJm^{-2}d^{-1}K^{-4}$ with Rnl in $MJm^{-2}d^{-1}$
for hourly calculations σ = 2.042 x 10^{-10} MJm2 $h^{-1}K^{-4}$, Rnl is in MJm^{-2} h^{-1}.
Vegetation date of cuts:

GS-1=GS-2=GS-3=GS-4=GS-5=GS-6
(["2015-05-27","2015-07-28","2015-10-13"], ["2016-05-31","2016-07-26","2016-10-04"], ["2017-05-30","2017-07-25","2017-10-03"], ["2018-05-29","2018-07-24","2018-10-02"])

$$R_n l = f_{cd}(a_1 + b_1\sqrt{e_a})\sigma T^4 \tag{4}$$

if 24-hour or longer time steps...T^4 transforms to $(T^4_{max} - T^4_{min})/2$.
σ is for daily values 4.901 x 10^{-9} $MJm^{-2}d^{-1}K^{-4}$ with Rnl in $MJm^{-2}d^{-1}$
for hourly calculations σ = 2.042 x 10^{-10} MJm2 $h^{-1}K^{-4}$, Rnl is in MJm^{-2} h^{-1}.

Wright and Jensen [22] developed an expression for f_{cd}:

$$f_{cd} = a\frac{R_S}{R_{SO}} + b \tag{5}$$

a and b are empirical coefficients. General a= 1.3, b=0.3, a_1 = 0.39 and b_1=0.158

Bulleted lists look like this:

- First bullet
- Second bullet
- Third bullet

Numbered lists can be added as follows:

1. First item
2. Second item
3. Third item

The text continues here.

9.1. Figures, Tables and Schemes

All figures and tables should be cited in the main text as Figure 1, Table 1, etc.

Figure 2. This is a figure, Schemes follow the same formatting. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel. (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.

Text

Text

Table 4. This is a table caption. Tables should be placed in the main text near to the first time they are cited.

Title 1	**Title 2**	**Title 3**
entry 1	data	data
entry 2	data	data

Text

Text

9.2. Formatting of Mathematical Components

This is an example of an equation:

$$a + b = c \tag{6}$$

Please punctuate equations as regular text. Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

Theorem 1. *Example text of a theorem.*

The text continues here. Proofs must be formatted as follows:

Proof of Theorem 1. Text of the proof. Note that the phrase 'of Theorem 1' is optional if it is clear which theorem is being referred to. □

The text continues here.

10. Discussion

Authors should discuss the results and how they can be interpreted in perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

11. Materials and Methods

Materials and Methods should be described with sufficient details to allow others to replicate and build on published results. Please note that publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited.

Research manuscripts reporting large datasets that are deposited in a publicly available database should specify where the data have been deposited and provide the relevant accession numbers. If the accession numbers have not yet been obtained at the time of submission, please state that they will be provided during review. They must be provided prior to publication.

Interventionary studies involving animals or humans, and other studies require ethical approval must list the authority that provided approval and the corresponding ethical approval code.

12. Conclusions

This section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing–original draft preparation, X.X.; writing–review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y.", please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

Funding: Please add: "This research received no external funding" or "This research was funded by NAME OF FUNDER grant number XXX." and and "The APC was funded by XXX". Check carefully that the details given are accurate and use the standard spelling of funding agency names at https://search.crossref.org/funding, any errors may affect your future funding.

Acknowledgments: In this section you can acknowledge any support given which is not covered by the author contribution or funding sections. This may include administrative and technical support, or donations in kind (e.g., materials used for experiments).

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	linear dichroism

Appendix A

Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text. For example, explanations of experimental details that would disrupt the flow of the main text, but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

Appendix B

All appendix sections must be cited in the main text. In the appendixes, Figures, Tables, etc. should be labeled starting with 'A', e.g., Figure A1, Figure A2, etc.

1. Seiller, G.; Anctil, F. How do potential evapotranspiration formulas influence hydrological projections? *Hydrological Sciences Journal* **2016**, *61*, 2249–2266.
2. Her, Y.; Yoo, S.H.; Cho, J.; Hwang, S.; Jeong, J.; Seong, C. Uncertainty in hydrological analysis of climate change: multi-parameter vs. multi-GCM ensemble predictions. *Scientific reports* **2019**, *9*, 4974.
3. White, J.T.; Fienen, M.N.; Doherty, J.E. A python framework for environmental model uncertainty analysis. *Environmental Modelling & Software* **2016**, *85*, 217–228.
4. Tennøe, S.; Halnes, G.; Einevoll, G.T. Uncertainpy: A Python toolbox for uncertainty quantification and sensitivity analysis in computational neuroscience. *Frontiers in neuroinformatics* **2018**, *12*.
5. Van Daele, T.; Van Hoey, S.; Nopens, I. pyIDEAS: an open source Python package for model analysis. In *Computer Aided Chemical Engineering*; Elsevier, 2015; Vol. 37, pp. 569–574.
6. Herman, J.D.; Usher, W. SALib: An open-source Python library for Sensitivity Analysis. *J. Open Source Software* **2017**, *2*, 97.
7. Pianosi, F.; Beven, K.; Freer, J.; Hall, J.W.; Rougier, J.; Stephenson, D.B.; Wagener, T. Sensitivity analysis of environmental models: A systematic review with practical workflow. *Environmental Modelling & Software* **2016**, *79*, 214–232.
8. Wiecki, T.V.; Sofer, I.; Frank, M.J. HDDM: Hierarchical Bayesian estimation of the drift-diffusion model in Python. *Frontiers in neuroinformatics* **2013**, *7*, 14.
9. Miranda, L.J.V.; others. PySwarms: a research toolkit for Particle Swarm Optimization in Python. *J. Open Source Software* **2018**, *3*, 433.
10. Obojes, N.; Bahn, M.; Tasser, E.; Walde, J.; Inauen, N.; Hiltbrunner, E.; Saccone, P.; Lochet, J.; Clément, J.C.; Lavorel, S.; others. Vegetation effects on the water balance of mountain grasslands depend on climatic conditions. *Ecohydrology* **2015**, *8*, 552–569.
11. Leitinger, G.; Ruggenthaler, R.; Hammerle, A.; Lavorel, S.; Schirpke, U.; Clement, J.C.; Lamarque, P.; Obojes, N.; Tappeiner, U. Impact of droughts on water provision in managed alpine grasslands in two climatically different regions of the Alps. *Ecohydrology* **2015**, *8*, 1600–1613.
12. Parmele, L.H. Errors in output of hydrologic models due to errors in input potential evapotranspiration. *Water Resources Research* **1972**, *8*, 348–359.
13. Parmele, L.; McGuinness, J. Comparisons of measured and estimated daily potential evapotranspiration in a humid region. *Journal of Hydrology* **1974**, *22*, 239–251.
14. McGuinness, J.; Bordne, E. A comparison of lysimeter derived potential evapotranspiration with computed values, Tech. Bull., 1452. *Agric. Res. Serv., US Dep. of Agric., Washington, DC* **1972**.
15. Jensen, M.E.; Haise, H.R. Estimating evapotranspiration from solar radiation. *Proceedings of the American Society of Civil Engineers, Journal of the Irrigation and Drainage Division* **1963**, *89*, 15–41.
16. Andréassian, V.; Perrin, C.; Michel, C. Impact of imperfect potential evapotranspiration knowledge on the efficiency and parameters of watershed models. *Journal of Hydrology* **2004**, *286*, 19–35.
17. Jensen, M.E.; Burman, R.D.; Allen, R.G. Evapotranspiration and irrigation water requirements. ASCE, 1990.
18. Xu, C.Y.; Singh, V. Cross comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland. *Water Resources Management* **2002**, *16*, 197–219.
19. Blaney, H.F.; Criddle, W.D. Determining water requirements in irrigated areas from climatological and irrigation data **1950**.
20. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M.; others. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome* **1998**, *300*, D05109.
21. Hargreaves, G.H. Moisture availability and crop production. *Transactions of the ASAE* **1975**, *18*, 980–0984.
22. Wright, J.L.; Jensen, M.E. Peak water requirements of crops in southern Idaho. *Proceedings of the American Society of Civil Engineers, Journal of the Irrigation and Drainage Division* **1972**, *98*, 193–201.
23. Makkink, G. Testing the Penman formula by means of lysimeters. *Journal of the Institution of Water Engineerrs* **1957**, *11*, 277–288.
24. Penman, H.L. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* **1948**, *193*, 120–145.

25. Priestley, C.H.B.; Taylor, R. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly weather review* **1972**, *100*, 81–92.
26. ASCE-EWRI. The ASCE standardized reference evapotranspiration equation. *Technical Committee Rep. to the Environmental and Water Resources Institute of ASCE from the Task Committee on Standardization of Reference Evapotranspiration* **2005**.
27. Oudin, L.; Hervieu, F.; Michel, C.; Perrin, C.; Andréassian, V.; Anctil, F.; Loumagne, C. Which potential evapotranspiration input for a lumped rainfall–runoff model?: Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *Journal of hydrology* **2005**, *303*, 290–306.
28. Jensen, M.E.; Allen, R.G. Evaporation, evapotranspiration, and irrigation water requirements. American Society of Civil Engineers, 2016.
29. Penman, H.L. Vegetation and hydrology. *Soil Science* **1963**, *96*, 357.
30. Ainsworth, E.A.; Long, S.P. What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *New phytologist* **2005**, *165*, 351–372.
31. Yang, Y.; Roderick, M.L.; Zhang, S.; McVicar, T.R.; Donohue, R.J. Hydrologic implications of vegetation response to elevated CO 2 in climate projections. *Nature Climate Change* **2019**, *9*, 44.
32. Kruijt, B.; Witte, J.P.M.; Jacobs, C.M.; Kroon, T. Effects of rising atmospheric CO2 on evapotranspiration and soil moisture: A practical approach for the Netherlands. *Journal of Hydrology* **2008**, *349*, 257–267.

Sample Availability: Samples of the compounds ...... are available from the authors.