

MAPS OF LONG-TERM SOILING LOSSES IN EUROPE CONSIDERING A PARTIAL CLEANING EFFECT BY RAIN

EUPVSEC 2025 (22-26 Sept 2025, Bilbao, Spain)

Elena Ruiz Donoso, Fernanda Norde Santos, Álvaro Fernández Solas, Natalie Hanrieder, Leonardo Micheli, Joaquín Alonso-Montesinos, Jesús Polo, Luis Zarzalejo, Stefan Wilbert, Robert Pitz-Paal*

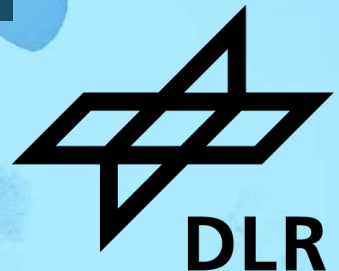


UNIVERSIDAD
DE ALMERÍA

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas



SAPIENZA
UNIVERSITÀ DI ROMA



STRUCTURE

Maps of long-term soiling losses in Europe considering a partial cleaning effect by rain

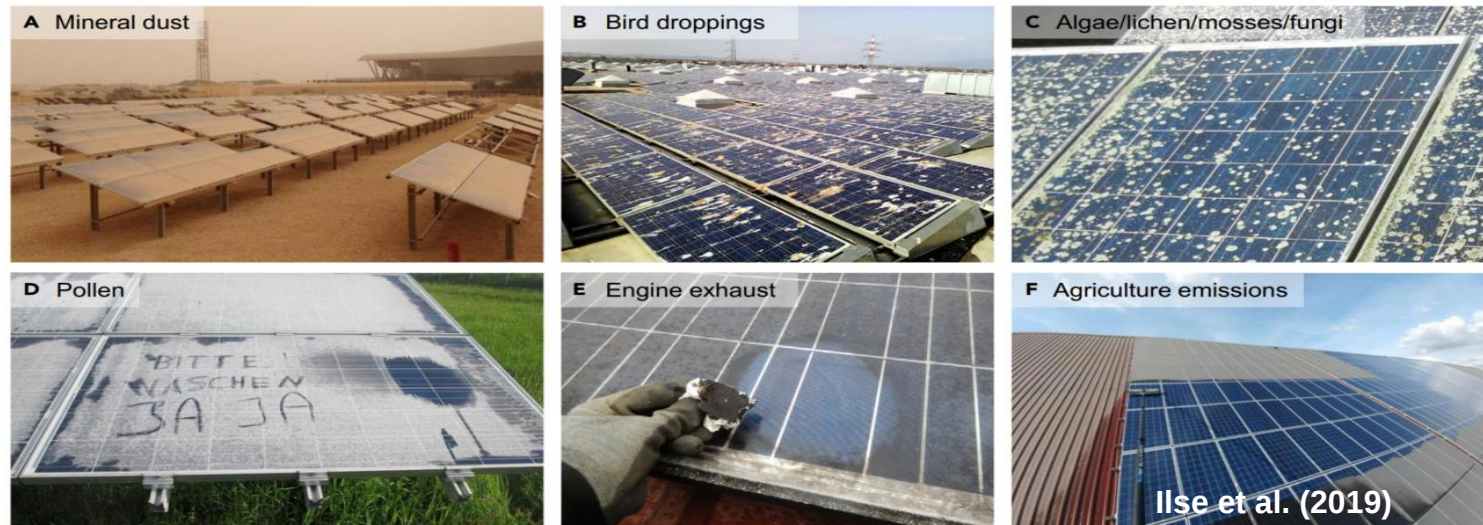


1. Introduction and motivation: Long-term soiling losses and natural cleaning by rain
2. Soiling measurements
3. Soiling models
 1. For soiling easily removable by rain
 2. For incomplete rain cleaning effect and persistent soiling
4. Soiling maps
5. Conclusions

1. Motivation and Introduction

Long-term soiling loss modelling & cleaning by rain

- **Soiling:** pollutants accumulated on PV panels
- **Soiling losses:** Loss in PV energy production due to soiling accumulation
- Importance of **long-term soiling losses** estimation → Are there sites where natural cleaning is sufficient and operator cleaning is not needed?
- **Soiling models** can estimate long-term soiling losses



1. Motivation and Introduction

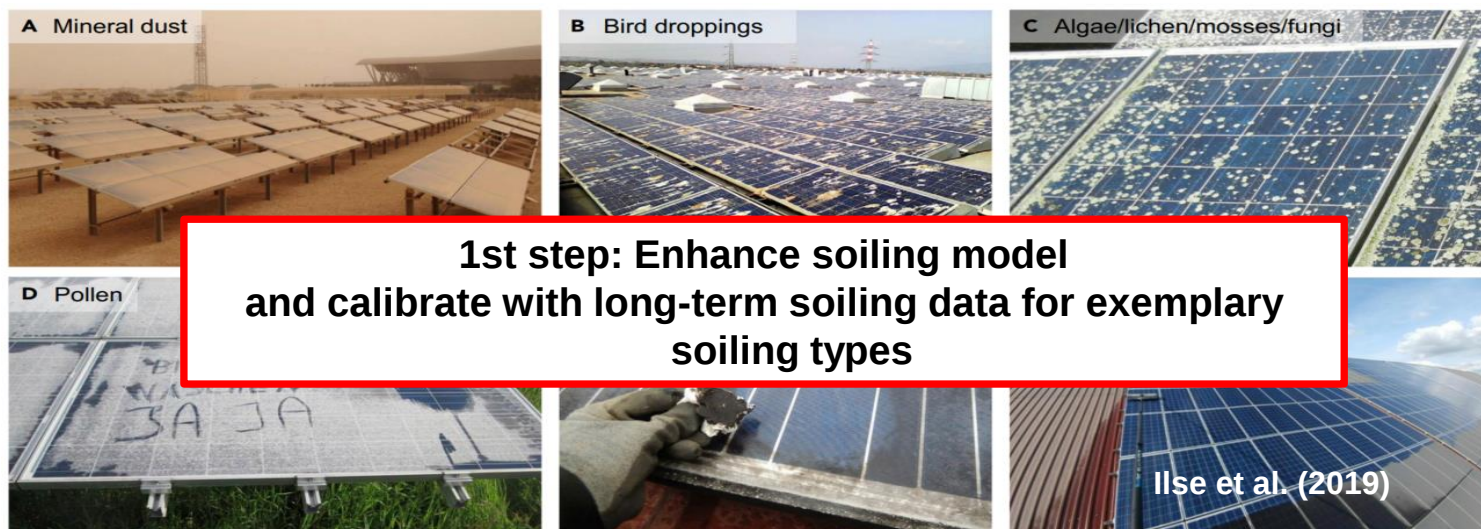
Long-term soiling loss modelling & cleaning by rain

- **Soiling models** can estimate long-term soiling losses

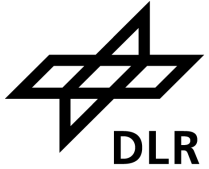
BUT

- Natural cleaning of PV panels by rain normally modelled using a threshold approach
 - Daily rain sum $\geq$ threshold $\rightarrow$ PV panel perfectly cleaned
 - Daily rain sum $<$ threshold $\rightarrow$ No cleaning effect is considered
- Depending on soiling type, rainfall often results in partial cleaning
- Low rain sums can also have a cleaning effect
- Persistent sticky soiling non-removable by rain is not considered
- Long-term soiling also affected by bird droppings, lichen, algae, fungi, mosses
- Soiling models have high uncertainty: World-wide validation of soiling models showed avg. MAD~100% & up to 400% deviations (Pelland et al., 2018)

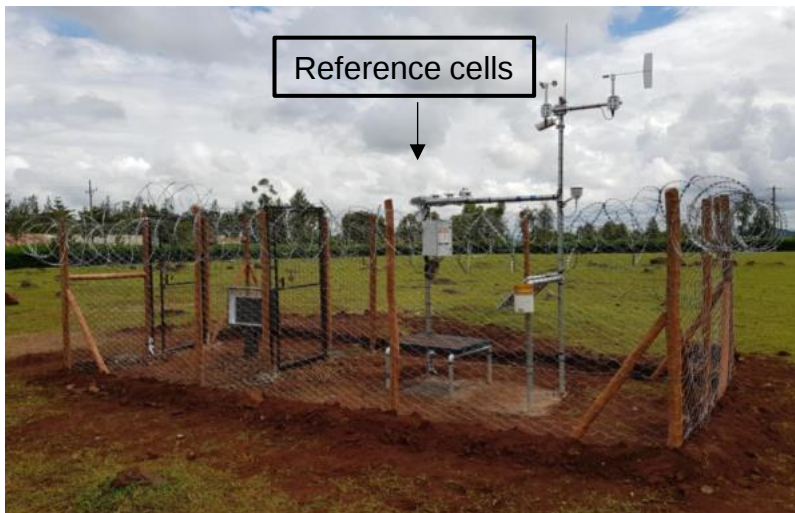
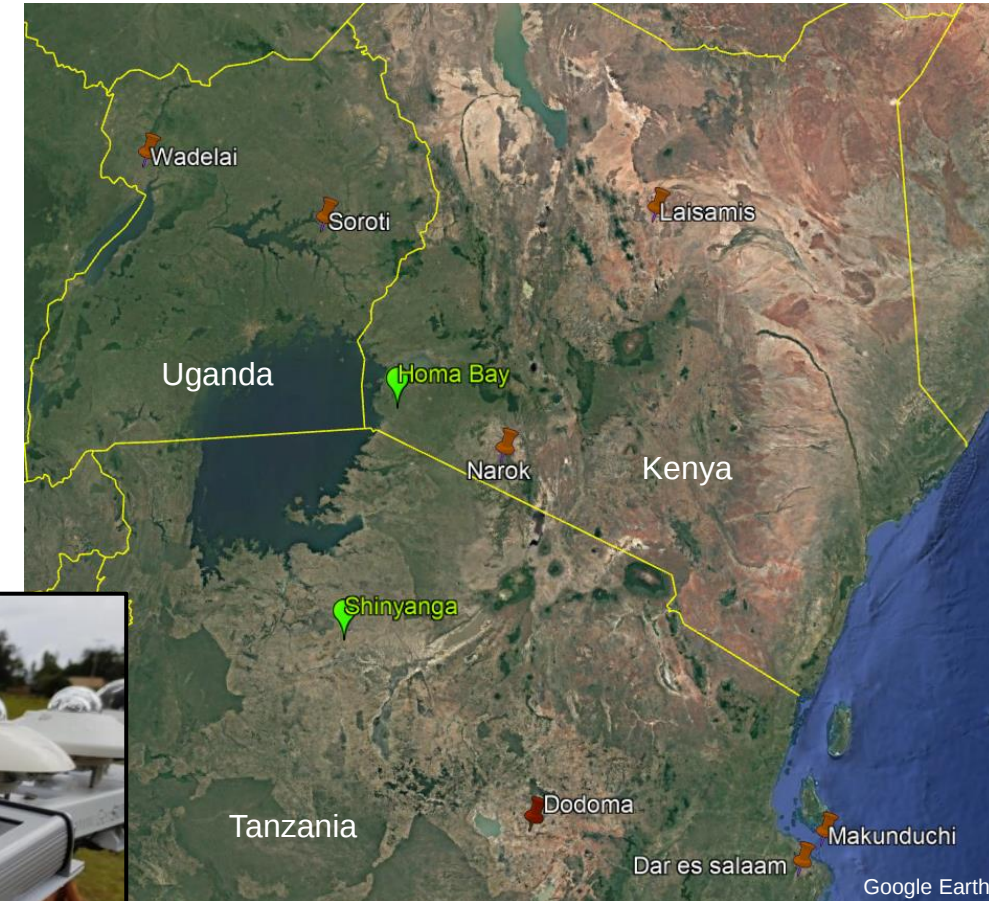
Thresholds in literature: 0.3 to 20 mm/day



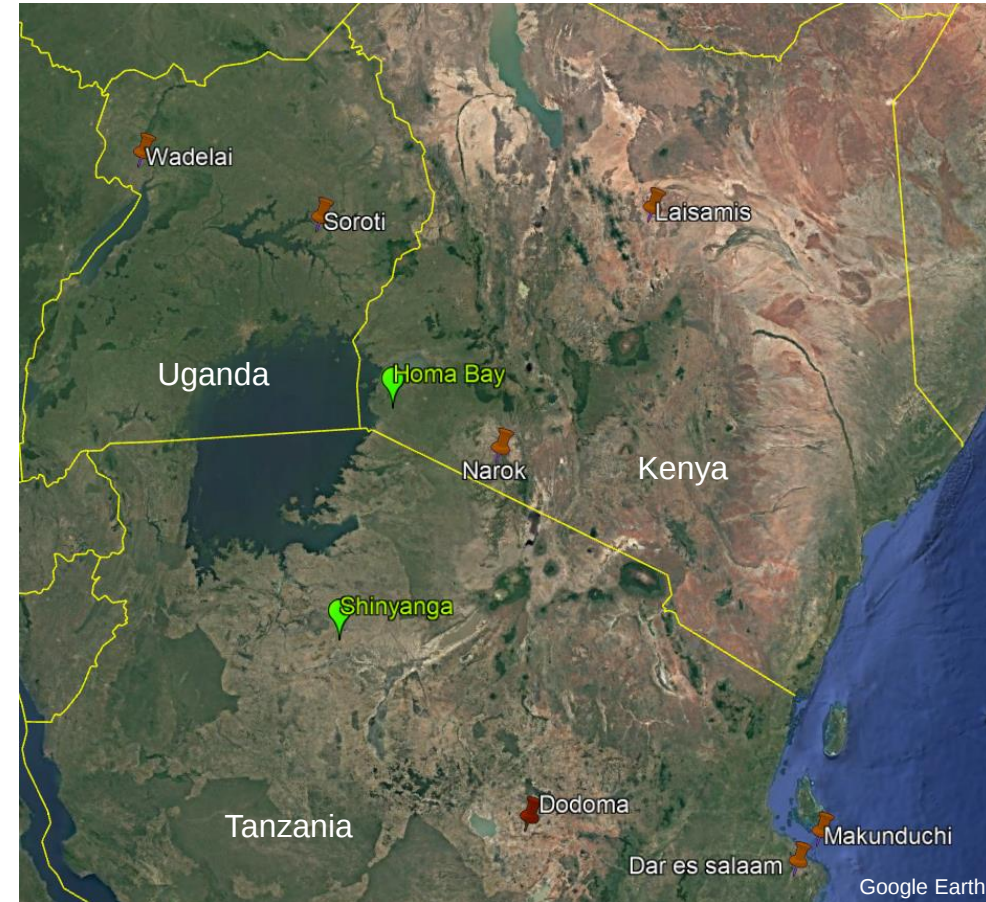
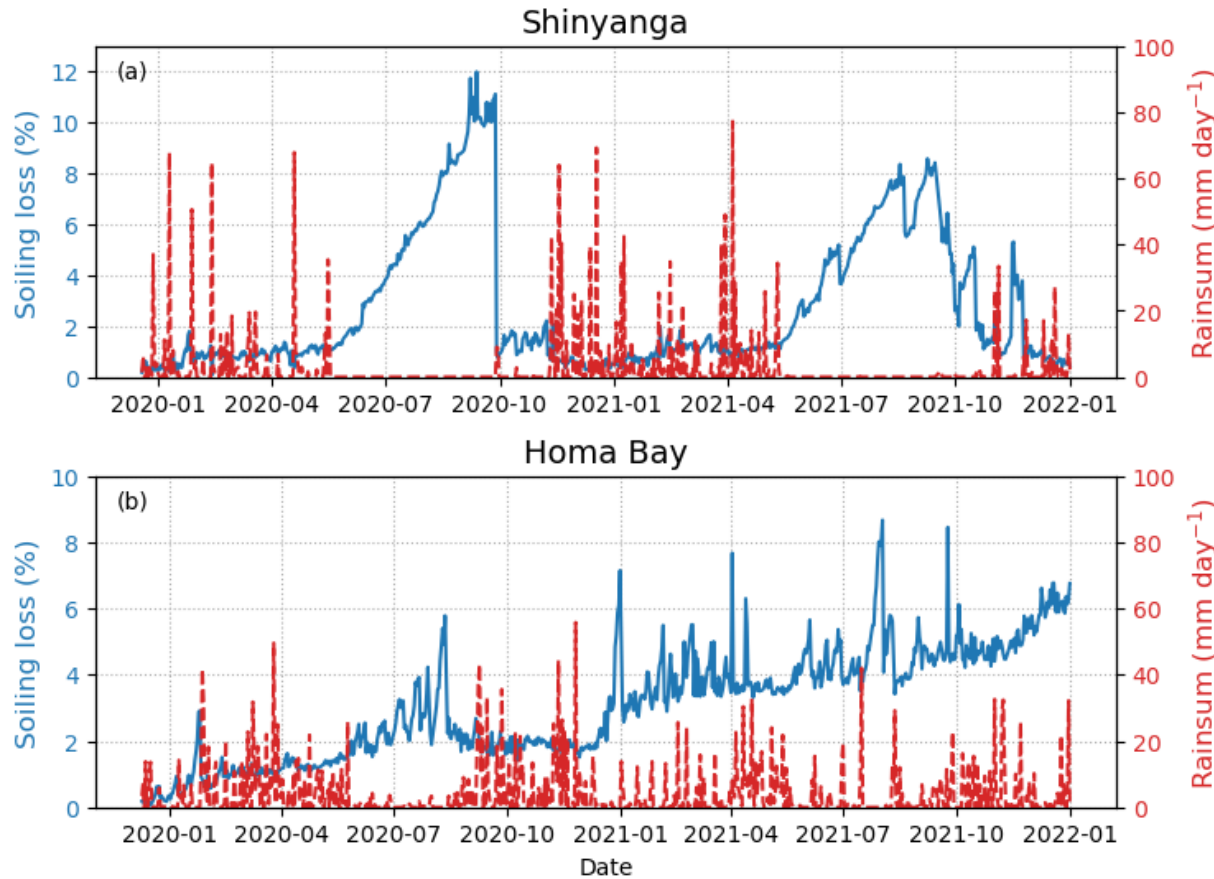
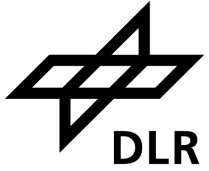
2. Soiling measurements: EAPP meteo stations



- Long-term continuous soiling measurements without cleaning required
- East African Power Pool (EAPP) stations initiated by World Bank with funding from Energy Sector Management Assistance Program (ESMAP)
 - performed by GeoSUN Africa from ~15.12.2019 to 31.12.2021
- 3 tilted reference cells for soiling measurement
 - “clean” reference cell (daily cleaned)
 - “dirty” reference cell (not cleaned during campaign period)
 - “dirty, monthly cleaned” (reference cell cleaned once per month)



2. Soiling measurements: EAPP meteo stations



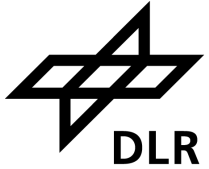
- “Clean” reference cell (daily cleaned) and “dirty” reference cell (no cleaned during campaign period) used to estimate the **natural variability of the soiling losses during the campaign period**
- Observations feature partial **natural cleaning** and **built-in of persistent soiling**

2. Soiling models: Original HSU model

(Coello and Boyle, 2019)

Input variables

- CAMS PM₁₀ concentration
- ERA5 precipitation



- Daily accumulated mass on PV panel

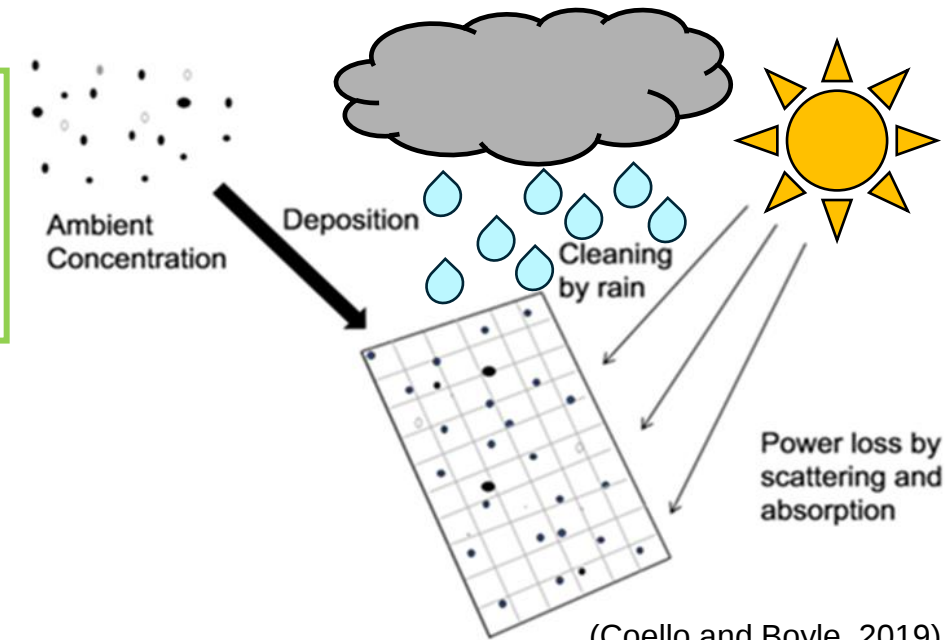
$$m_i = \begin{cases} \sum_{k=i_0}^{k=i} v_d \cdot PM_{10_k} \cdot t \cdot \cos(\theta) & \text{if daily rainsum} < \text{threshold} \\ 0 & \text{if daily rainsum} \geq \text{threshold} \end{cases}$$

- Soiling loss

$$SL_i(\%) = 34.37 \cdot \text{erf}(0.17 \cdot m_i^{0.8473})$$

- Optimizable parameters

- Daily rainsum cleaning threshold (CT)
- Deposition velocity v_d



(Coello and Boyle, 2019)

2. Soiling models: Modified HSU model

- Completeness of natural cleaning

$$CNC_i = \frac{m_{i-1} - m_i}{m_{i-1}} = a \cdot \log(\text{rainsum}) + b \quad (\text{Limited to } 0.97)$$

- Persistent mass (non-removable by rain) accumulated on PV panel

$$\omega_i = \chi \cdot \sum_{k=i_0}^{k=i} v_d \cdot PM_{10_k} \cdot t \cdot \cos(\theta)$$

- Daily accumulated mass on PV panel

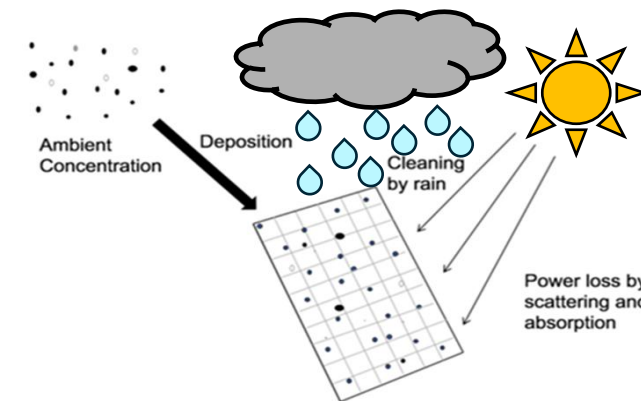
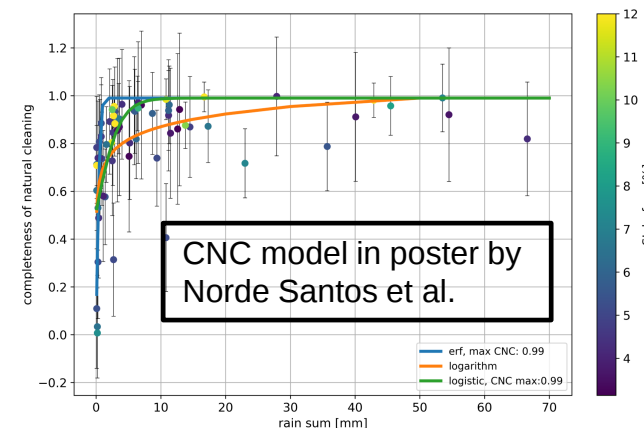
$$m_i = \begin{cases} (1 - CNC_i) \cdot m_{i-1} & \text{if } \text{rainsum} > 0 \text{ and } (1 - CNC) \cdot m_{i-1} > \omega_i \\ \omega_i & \text{if } \text{rainsum} > 0 \text{ and } (1 - CNC) \cdot m_{i-1} \leq \omega_i \\ \sum_{k=i_0}^{k=i} v_d \cdot PM_{10_k} \cdot t \cdot \cos(\theta) & \text{if } \text{rainsum} == 0 \end{cases}$$

- Soiling loss

$$SL_i(\%) = 34.37 \cdot \text{erf}(0.17 \cdot m_i^{0.8473})$$

- Optimizable parameters

- a, b for CNC
- Percentage of daily-accumulated persistent mass χ
- Deposition velocity v_d

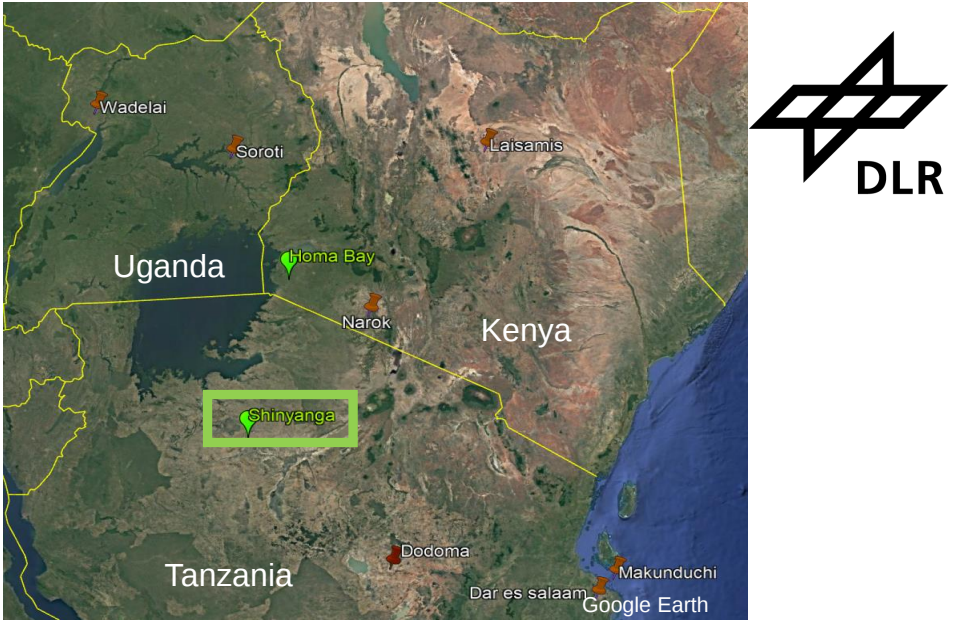
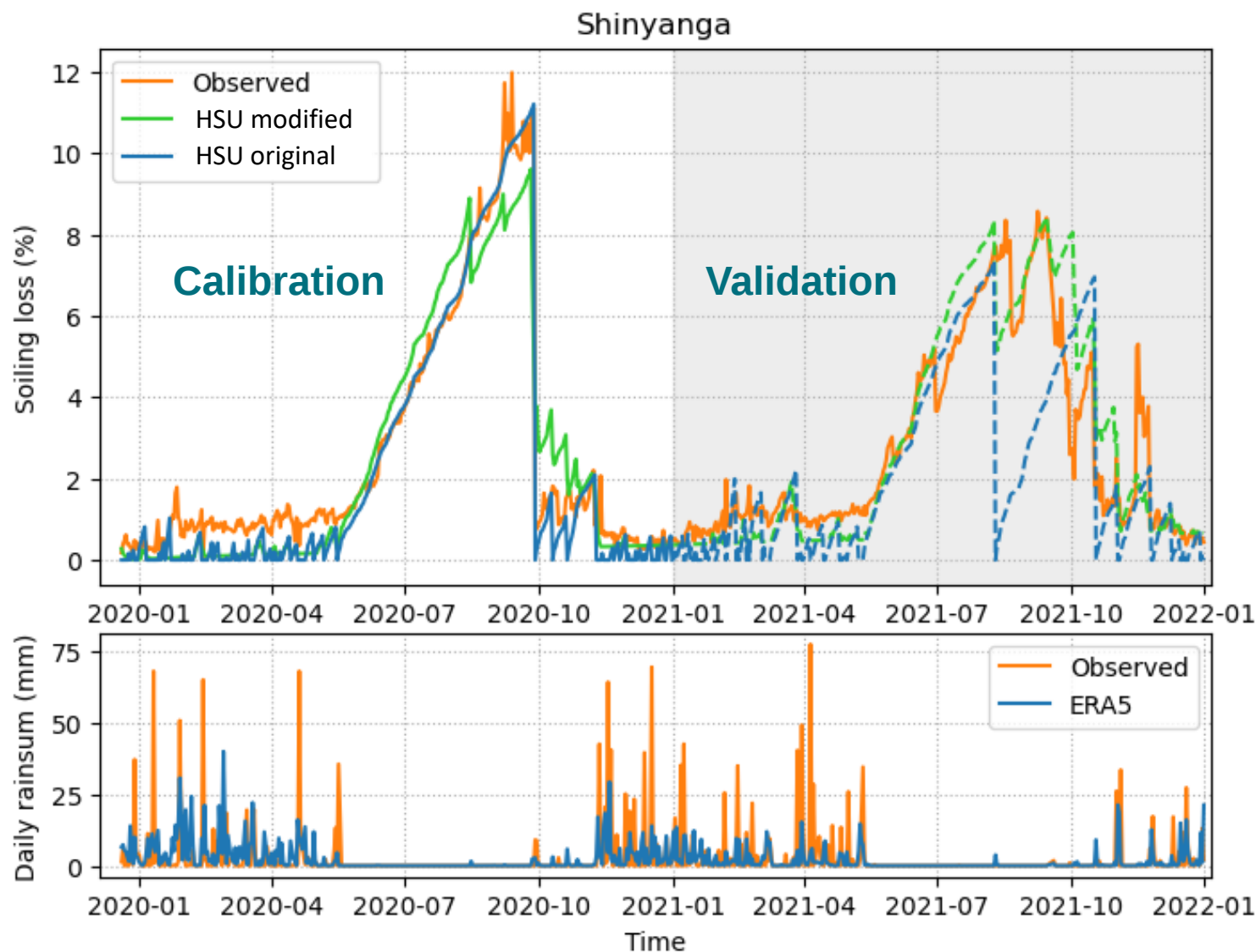


(Coello and Boyle, 2019)

Input variables

- CAMS PM₁₀ concentration
- ERA5 precipitation

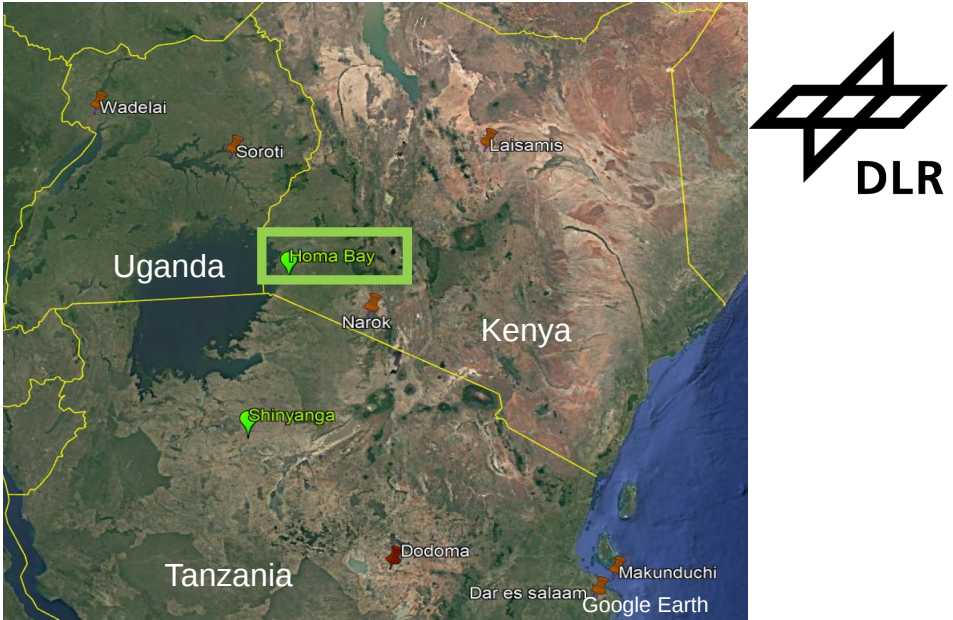
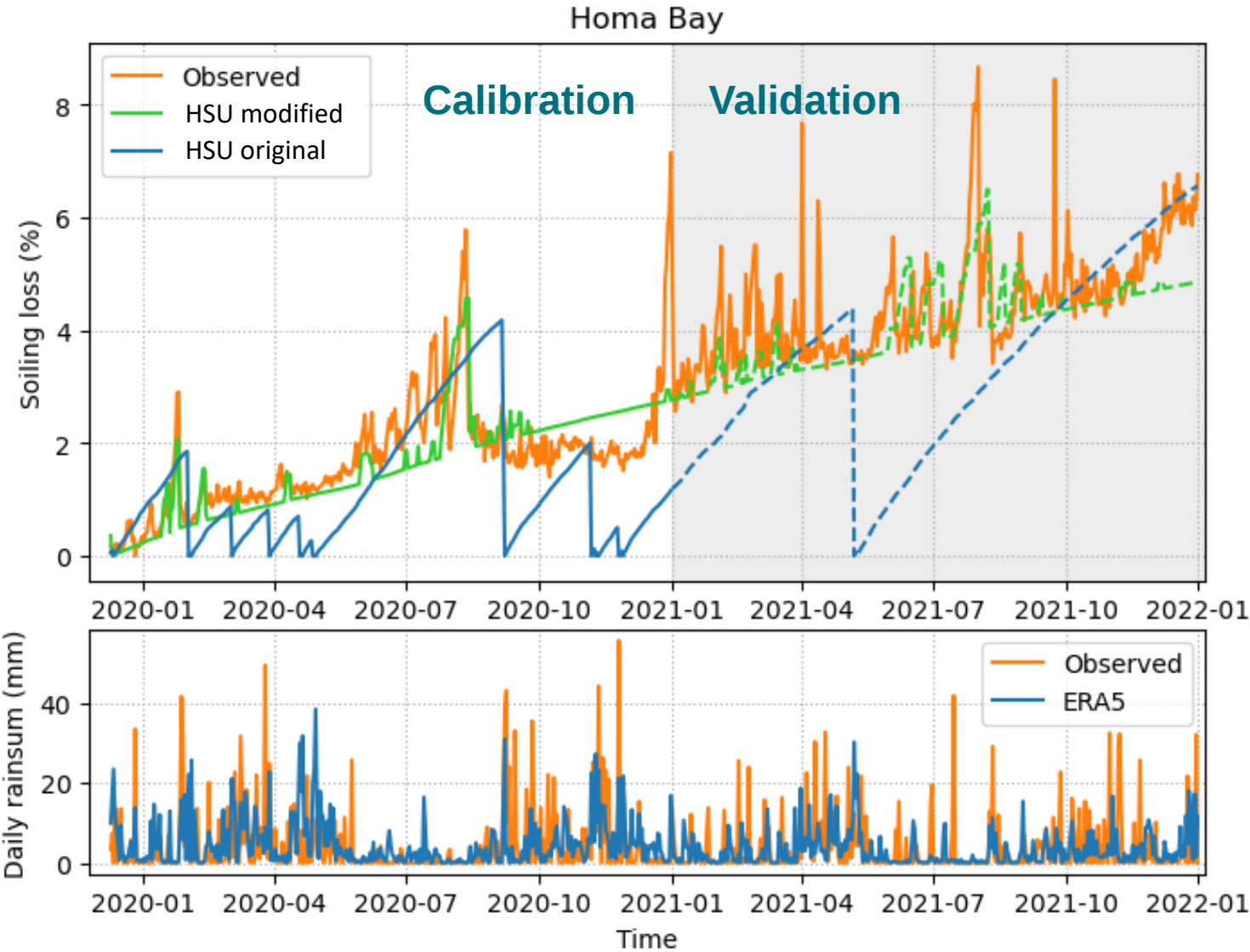
3. Soiling models calibration: Shinyanga Removable soiling type



HSU original			
CT = 2.6 mm/day; $v_d = 0.009\text{m/s}$			
	RMSE (%)	MAE (%)	Bias (%)
Calibration	0.59	0.45	-0.35
Validation	1.89	1.16	-0.72

HSU modified			
$a=0.10$, $b=0.23$, $v_d=0.011\text{m/s}$, $\chi=0.5\%$			
	RMSE (%)	MAE (%)	Bias (%)
Calibration	0.95	0.72	-0.14
Validation	1.13	0.76	0.11

3. Soiling models calibration: Homa Bay Persistent soiling type

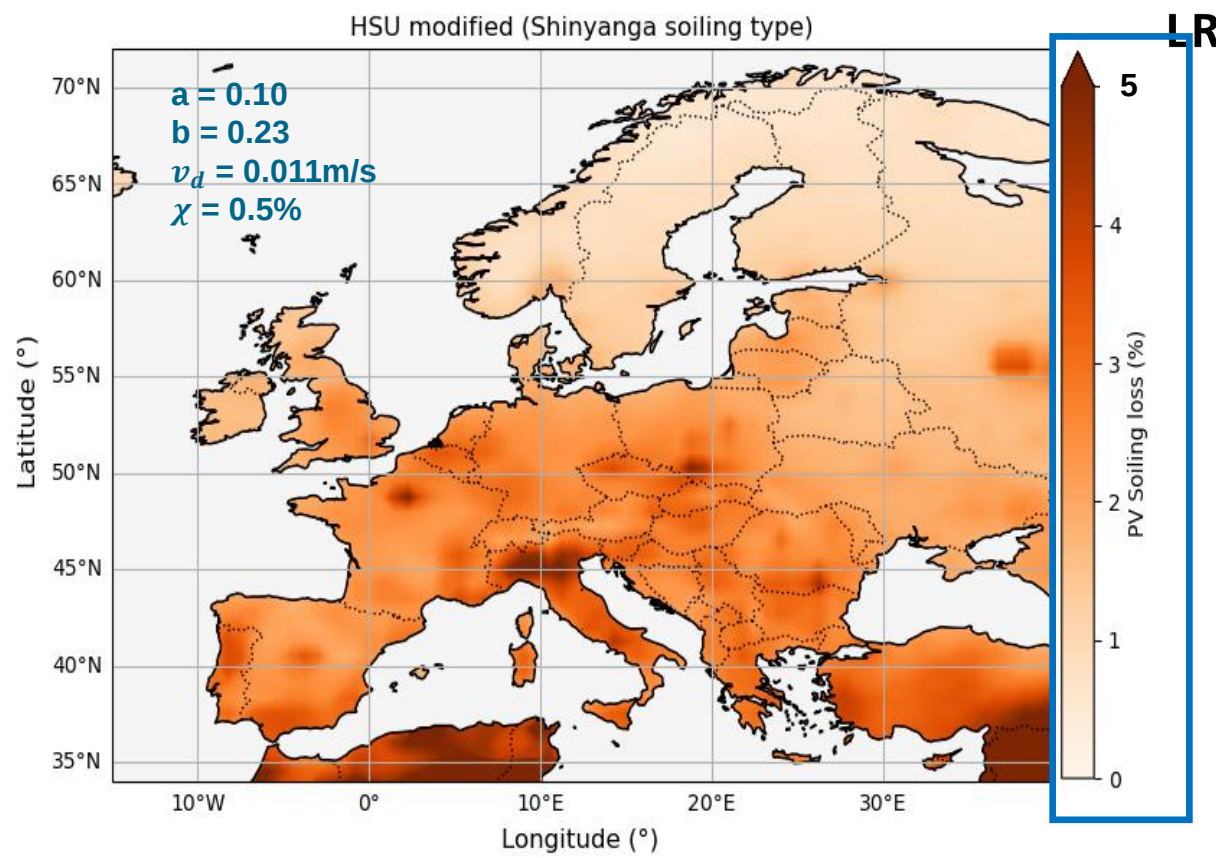
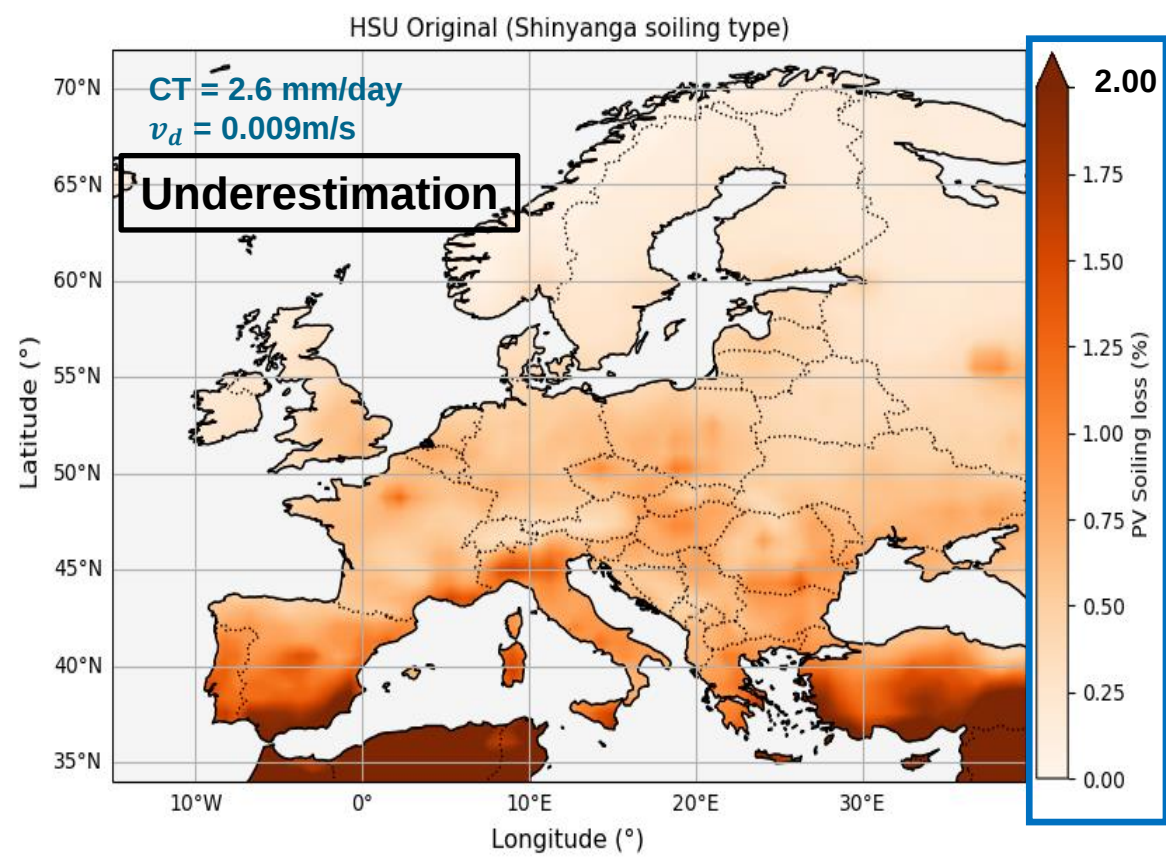


HSU original			
CT = 18.3 mm/day, $v_d = 0.0007\text{m/s}$			
	RMSE (%)	MAE (%)	Bias (%)
Calibration	1.17	0.93	-0.55
Validation	2.08	1.61	-1.41

HSU modified			
$a = 0.3, b=0.08, v_d = 0.007\text{m/s}, \chi=2.5\%$			
	RMSE (%)	MAE (%)	Bias (%)
Calibration	0.67	0.48	-0.09
Validation	0.92	0.60	-0.44

4. European maps

Removable soiling type from Shinyanga 1st year calibration

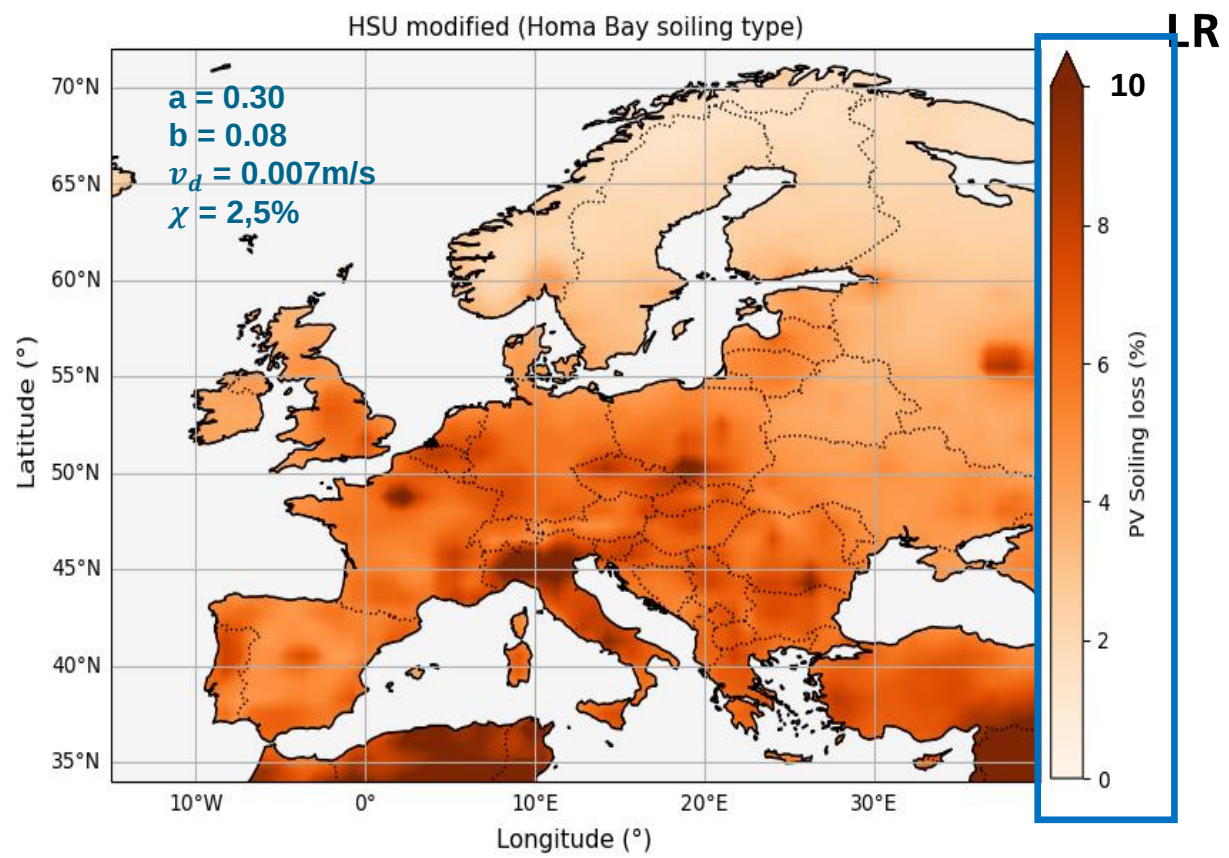
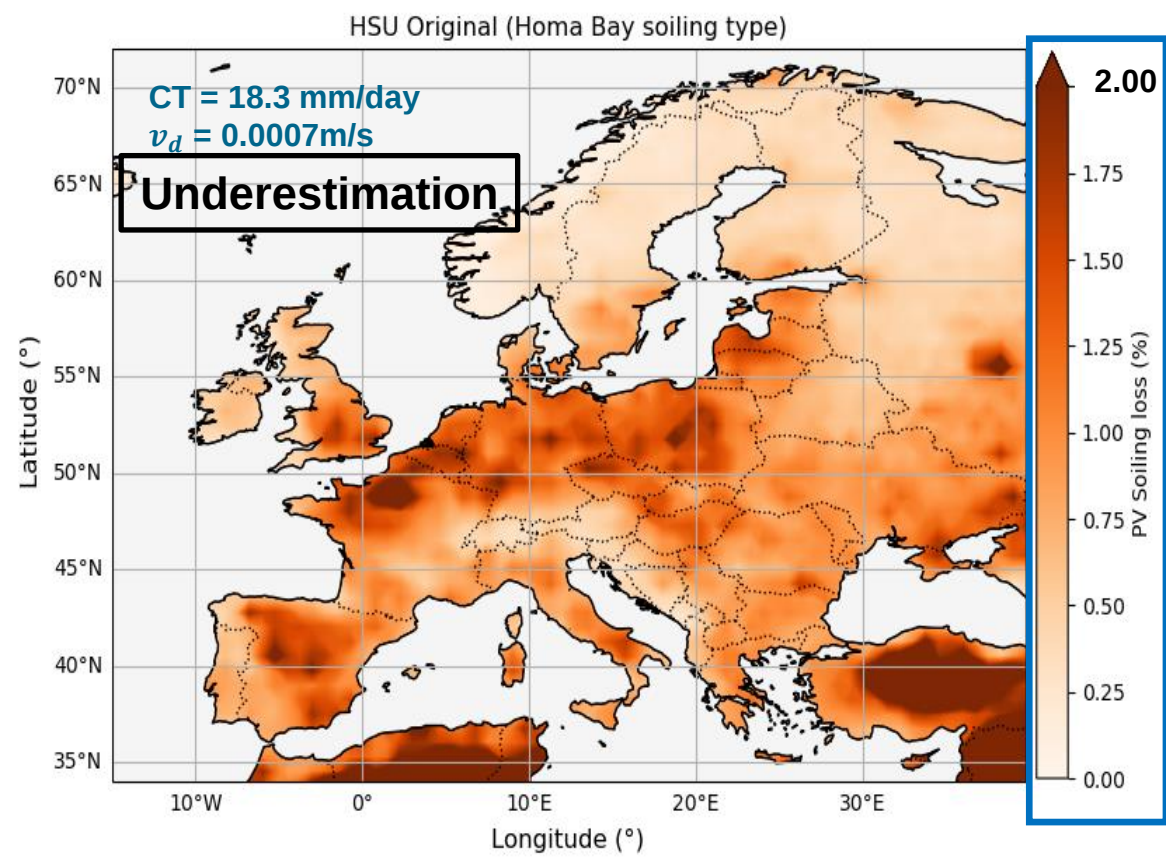


Time-averaged soiling losses in Europe using as input **CAMS PM₁₀** concentrations and **ERA5 daily precipitation** between 2003 and 2023

	HSU original $CT = 2.6 \text{ mm/day}$, $v_d = 0.009 \text{ m/s}$	HSU modified $a = 0.10, b = 0.23$, $v_d = 0.011 \text{ m/s}, \chi = 0.5\%$
European average (%)	0.5	1.9
German average (%)	0.5	2.4
Andalusian average (%)	1.7	3.1

4. European maps

Persistent soiling type from Homa Bay 1st year calibration

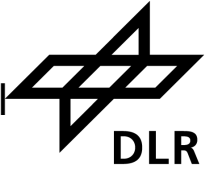


Time-averaged soiling losses in Europe using as input CAMS PM₁₀ concentrations and ERA5 daily precipitation between 2003 and 2023

	HSU original CT = 18.3 mm/day, $v_d = 0.0007\text{m/s}$	HSU modified $a = 0.30, b = 0.08,$ $v_d = 0.007\text{m/s}, \chi=2,5\%$	
European average (%)	0.8	4.5	
German average (%)	1.2	5.9	~2x Shinyanga
Andalusian average (%)	1.1	5.8	

Soiling not well removed by rain → Germany > Andalusia

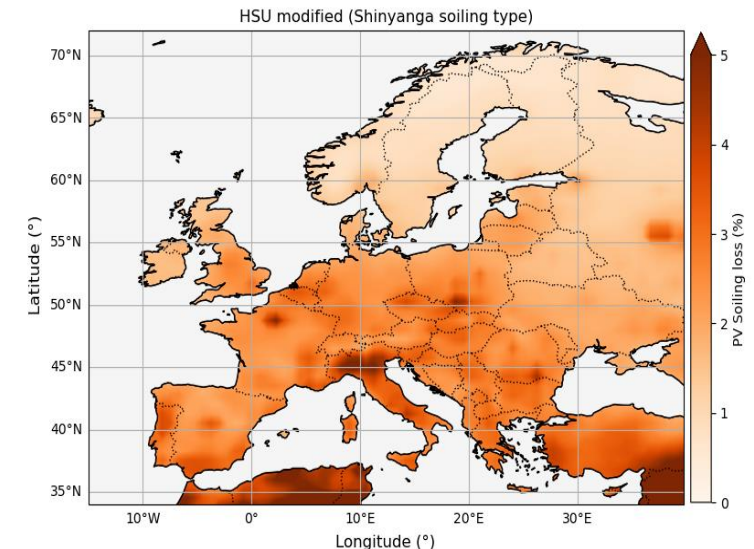
5. Conclusions and outlook



- Soiling models should consider incomplete cleaning by rain and persistent soiling if frequent manual cleaning is not expected
- Current soiling models should be calibrated to the location of interest
- Maps for two soiling types are presented. The deviations of the maps illustrate the uncertainty at European level due to the unknown soiling type, and input data errors
- At locations with expected persistent soiling, soiling losses in Germany can reach similar levels than Andalusia
- Maps can help to estimate the soiling losses for yield analysis (specially in feasibility cases), and decide on mitigation measures
- The uncertainty of modelled long-term soiling losses is high, and introduces a significant uncertainty in yield assessments if low cleaning frequencies are planned → A sufficient manual cleaning frequency can reduce soiling losses and model uncertainty

Outlook

- Further improve soiling model, e.g. consider lichen, moss, algae, fungi, bird droppings better
- Models and maps can be used to estimate the soiling losses for yield analysis, and evaluate the effect of different cleaning frequencies → Optimization of cleaning schedules



Thank you for your attention! 😊

References



- Pelland et al. "Testing global models of photovoltaic soiling ratios against field test data worldwide." 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)(A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC). IEEE, 2018.
- Fernandez Solas, et al. (2025) Photovoltaic soiling loss in Europe: Geographical distribution and cleaning recommendations. Renewable Energy, 239. Elsevier. doi: 10.1016/j.renene.2024.122086. ISSN 0960-1481.
- Bellmann, et al. (2020) Comparative modeling of optical soiling losses for CSP and PV energy systems. Solar Energy, 197, Seiten 229-237. Elsevier. doi: 10.1016/j.solener.2019.12.045. ISSN 0038-092X.
- WAPP, West African Power Pool. URL: <https://www.ecowapp.org/en/news/measurement-summary-solar-development-sub-saharan-africa>. (accessed: January 27 2025).
- Norde et al. (2022), "Soiling Persistence Model as Benchmark for Soiling Forecasts of Solar Collectors", EUPVSEC conference Milan, Italy.
- Kimber et al. (2006), The Effect of Soiling on Large Grid-Connected Photovoltaic Systems in California and the Southwest Region of the United States. Proc. IEEE 4th World Conference on Photovoltaic Energy Conference, Vol. 2, Waikoloa, Hawaii, May 2006.
- NCPRE, (2025) National Centre for Photovoltaic Research and Education. SERIUS Soiling Rate of the World. IIT Bombay. <https://www.ncpre.iitb.ac.in/ncpre/pages/serius-soiling-rate-of-the-world.php> Accessed July 2, 2025.
- Coello and Boyle (2019). Simple model for predicting time series soiling of photovoltaic panels. IEEE Journal of Photovoltaics, 9(5):1382–1387, 2019. ISSN 2156-3381. doi: 10.1109/JPHOTOV.2019.2919628.
- Norde Santos et al. (2024) Cleaning of photovoltaic modules through rain: Experimental study and modeling approaches. Solar RRL, 8(24):2400551, 2024. ISSN 2367-198X. doi:10.1002/solr.202400551. Copernicus Atmosphere Monitoring Service (2021): CAMS global atmospheric composition forecasts. Copernicus Atmosphere Monitoring Service (CAMS) Atmosphere Data Store, DOI: 10.24381/04a0b097 (Accessed on 16.06.2025)
- Abraim et al. (2022). Techno-economic assessment of soiling losses in CSP and PV solar power plants: A case study for the semi-arid climate of Morocco. Energy Conversion and Management 270. 116285. <https://doi.org/10.1016/j.enconman.2022.116285>

Acknowledgements

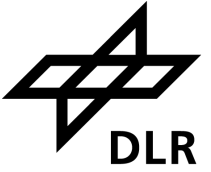
The authors would like to thank GeoSun Africa, the World Bank, the East African Power Pool and the EAPP station responsible for providing the data used in this study. We also thank the European Centre for Medium-Range Weather Forecast (ECMWF), the Copernicus Atmosphere Monitoring Service (CAMS) for providing reanalysis data.

We thank the European Union for funding the CAMEO project (grant agreement 101082125).



Funded by the
European Union

BACK-UP SLIDES



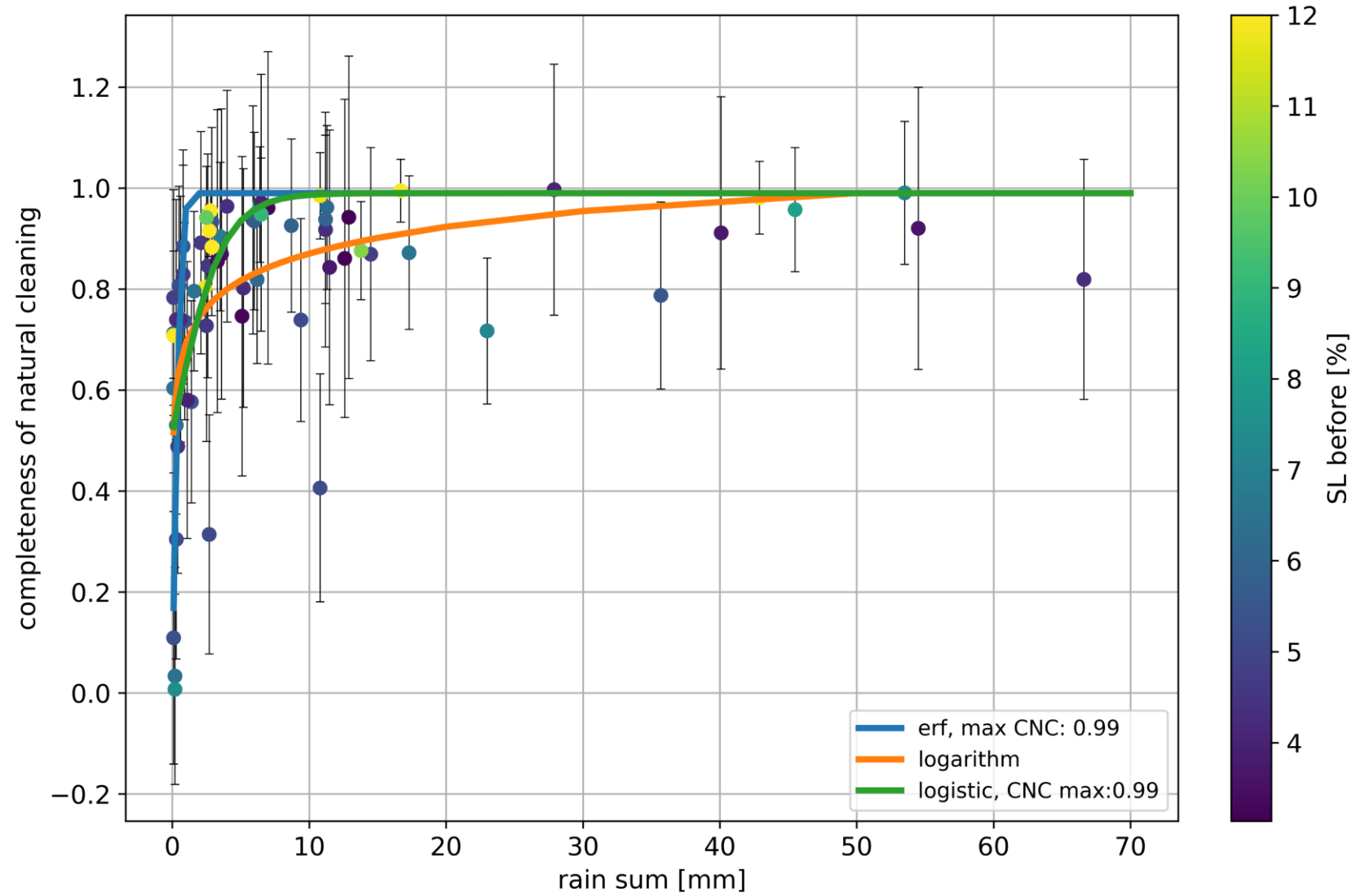
1 Introduction

NOTE: This project occurred during the COVID19 pandemic outbreak. Any impact on the data quality as a result of the pandemic will be recorded in the monthly quality feedback report alongside other noteworthy events for the affected month.

The World Bank initiated a project with funding from the Energy Sector Management Assistance Program (ESMAP) to, amongst others, support the East African Power Pool (EAPP) in doing renewable energy resource assessments. The focus for this particular section of the project is to get high quality bankable irradiance measurements, high quality supporting meteorological measurements and to promote the awareness of the resource potential of solar energy.

The project is orientated around sites considered for large-scale solar power plant development in the near future. The on-site measured data generated from this project for the applicable term is to be used in conjunction with overlapping and historic satellite derived data for the same location in order to generate a bankable data set, subsequently providing enhanced data accuracy for locations where there may be substantial project investments. The data complements the global resource data available for free via the Global Solar Atlas (<https://globalsolaratlas.info>).

GeoSUN Africa has been awarded the contract to execute the on-site measurement related aspects of the project. The assignment for GeoSUN Africa is the following:



Shinyanga vs. Homa Bay territory



Soiling loss in Homa Bay recorded by the monthly-manually-cleaned reference cell

