Supplementary Information

Simulating Atmospheric Dust Impact on Photovoltaic Performance:

A sensitivity analysis to guide modelling choices in a data scarce region

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NETWAT West African Mineral Dust: a key in the NExus ClimaTe – WATer – Energy
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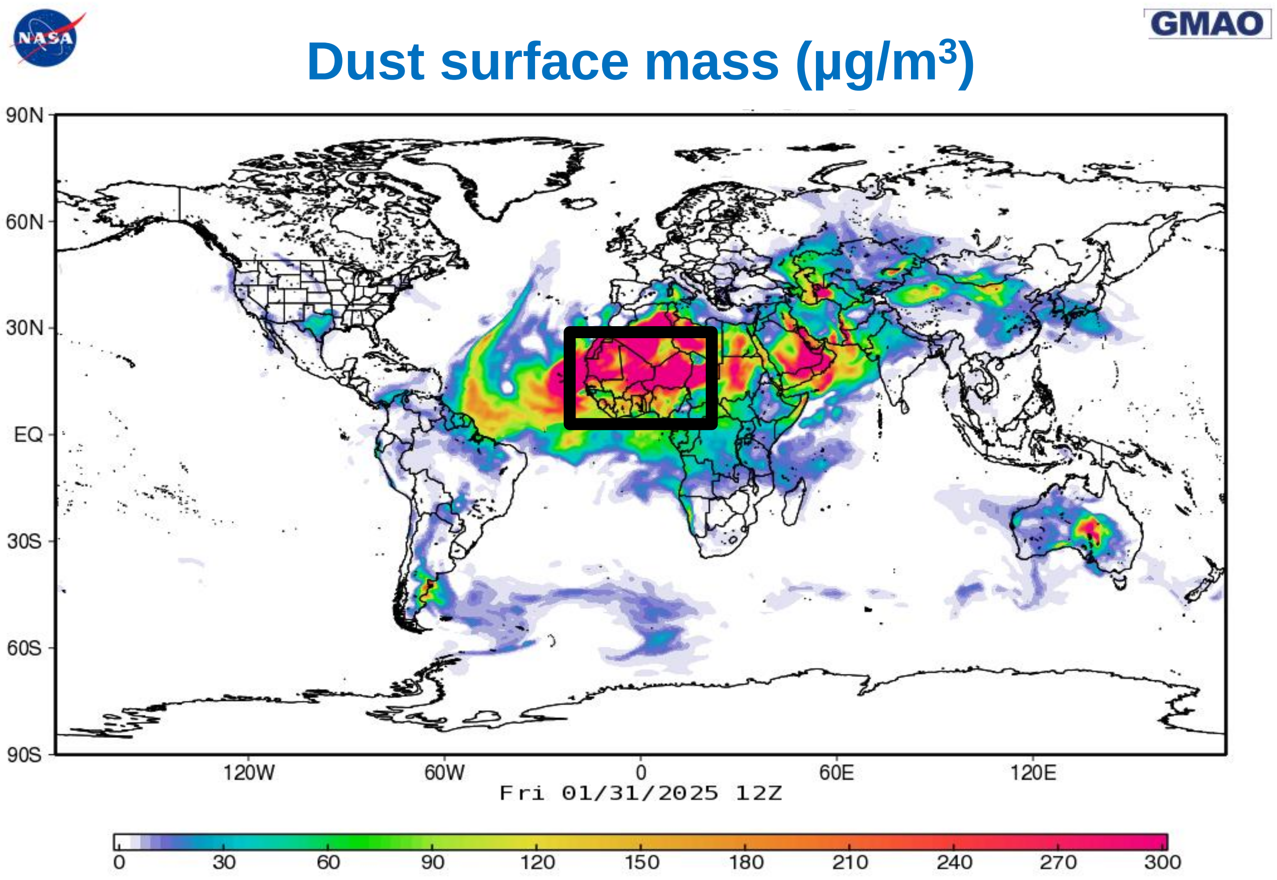
INDAAF

Context

- Atmospheric dust: Potentially critical to PV production.
  1) Reduces incoming solar radiation.
  2) Causes soiling losses.

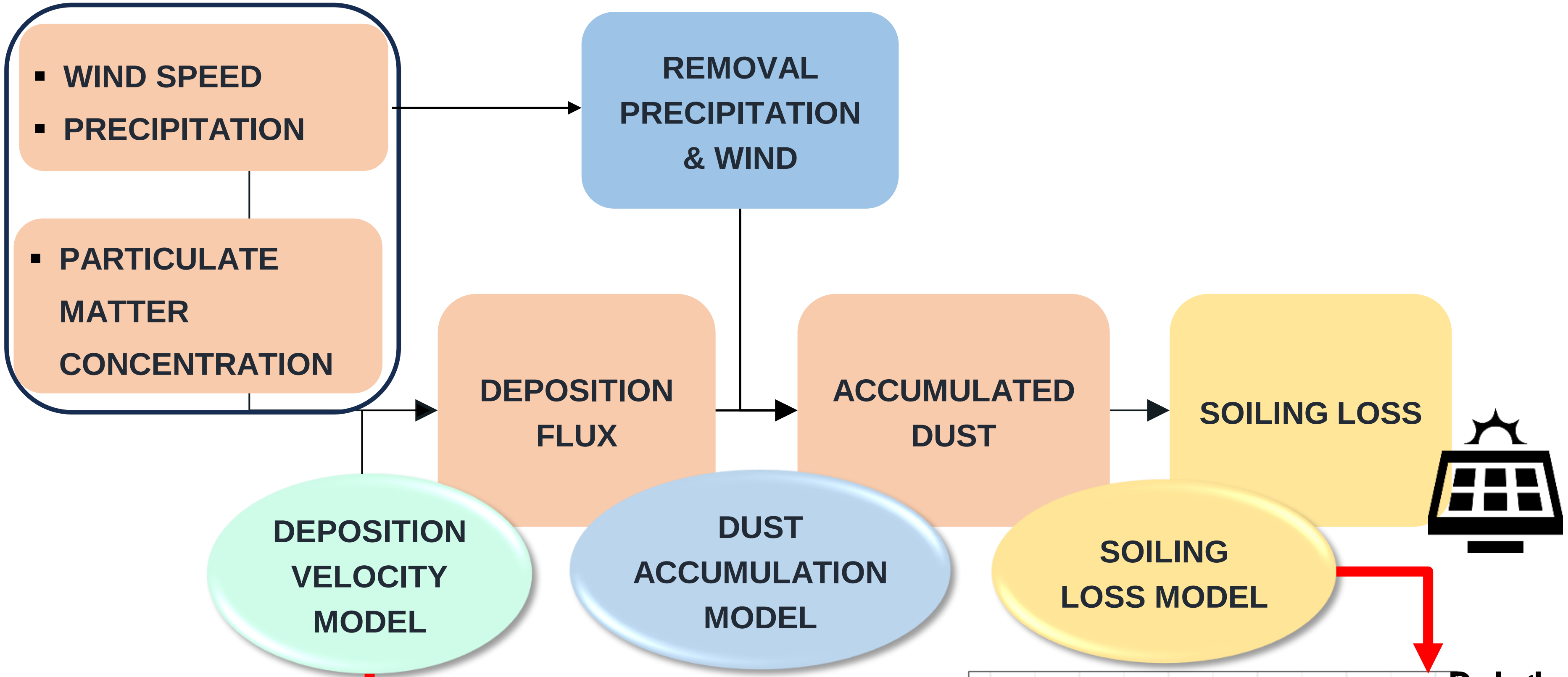


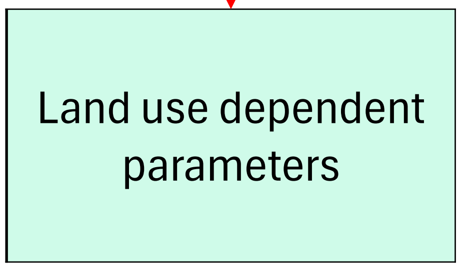
Observations are limited for estimating potential dust impacts.

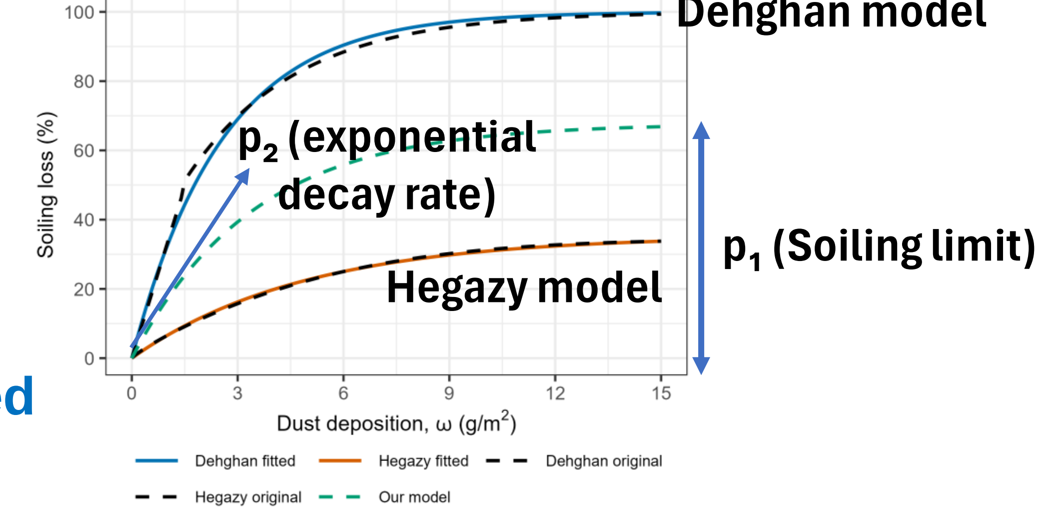
Dust impact estimates can be obtained with simulation models from atmospheric data.

How sensitive are the simulated estimates to data and modelling choices?

Typical Modelling Chain

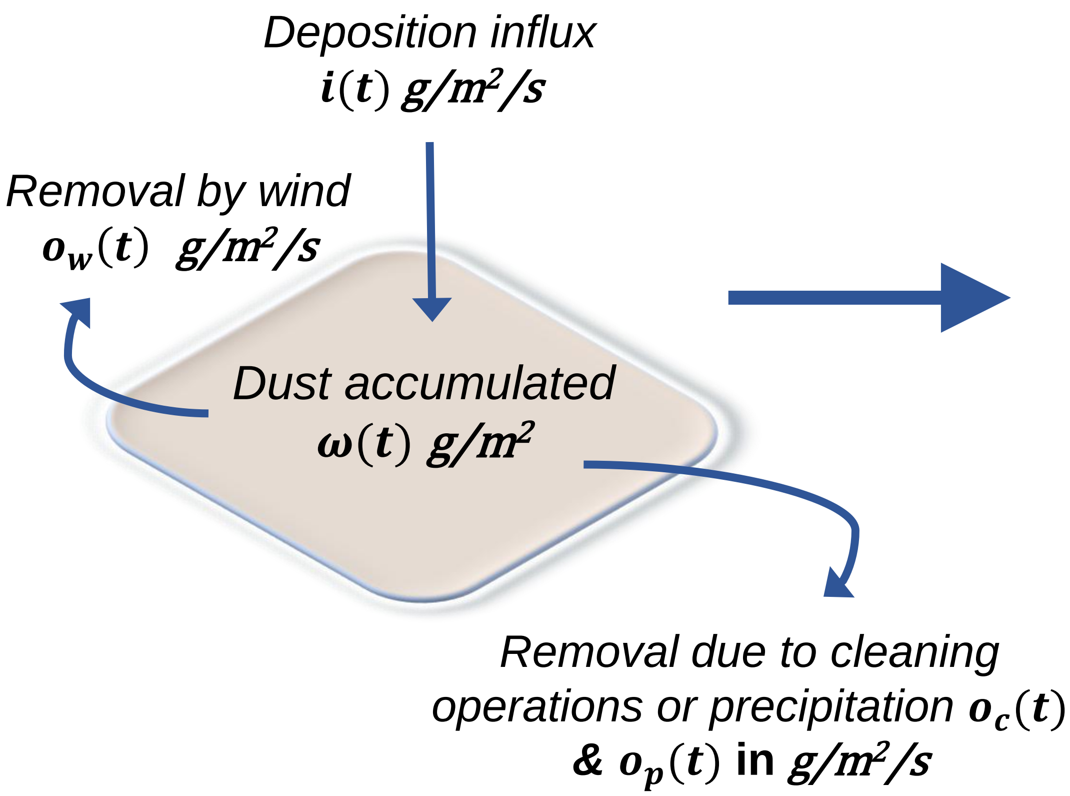






PVWat, the model framework for this study is defined by the modeling choices made in each sub-model.

MODEL DESCRIPTION – PVWat *Dust Accumulation Model*



Mass balance equation

$$\frac{d\omega(t)}{dt} = i(t) - o(t)$$

$\boldsymbol{i(t)}$: **dust deposition influx** estimated from concentration and deposition velocity of different particle size classes.

$$i(t) = C_X(t) \cdot V_{d,X}(t) + C_{Y-X}(t) \cdot V_{d,Y-X}(t) + C_{Z-Y}(t) \cdot V_{d,Z-Y}(t)$$

$\boldsymbol{o(t)}$: **dust outflux** (wind, rain, cleaning).

$$\boldsymbol{o}(t) = \boldsymbol{o_w}(t) + \boldsymbol{o_p}(t) + \boldsymbol{o_c}(t)$$

Deposition velocity model *(Zhang & Shao, 2014; Zhang, 2001)*;

$$V_d = \frac{1}{R_a + R_s} + V_s\, cos\theta$$

$\boldsymbol{R_a}$ = *Atmospheric turbulence resistance term*

$\boldsymbol{R_s}$ = *Surface resistance term*

$\boldsymbol{V_s}$ = *Gravitational settling velocity*

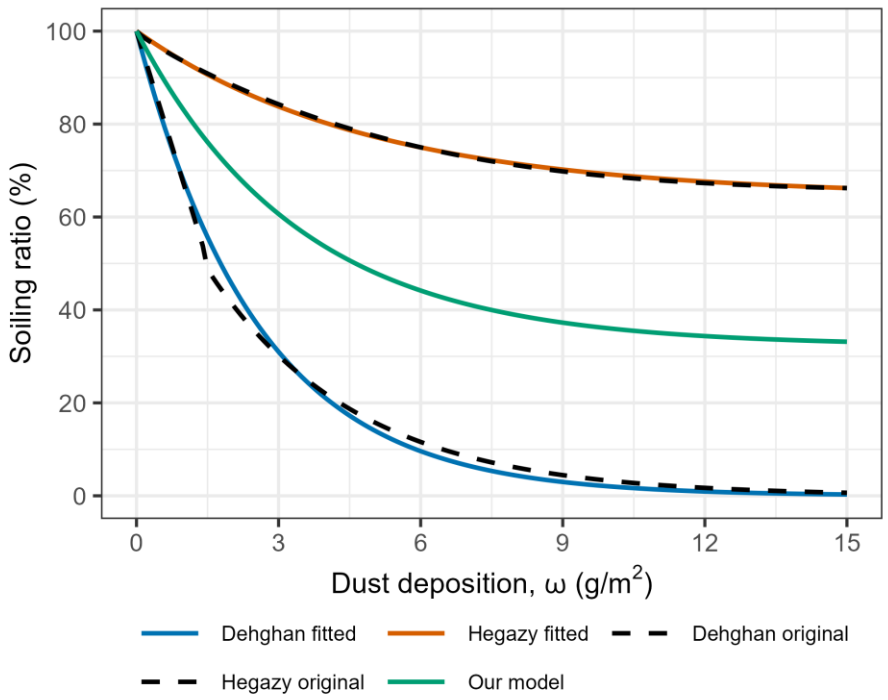
MODEL DESCRIPTION - PVWat *Soiling Loss Model*

- The Soiling loss model in PVWat inspired by Hegazy (2001) and Dehghan et al. (2022).
- Soiling losses are represented by the Soiling Ratio (SR) which describes the PV production efficiency, where 100% SR represents maximum efficiency.

Reformulated soiling ratio models in unified exponential form

Author	Model (ω in g/m^2)	Coefficients	Boundary Conditions	R^2
PVWAT Model	$SR(t) = 100 - p_1 + p_1 \cdot \exp(p_2 \cdot \boldsymbol{\omega}(\boldsymbol{t}))$	$p_1 = 68$ $p_2 = -0.29$	$\omega(t) \to 0, SR(t) = 100\%$ $\omega(t) \to \infty, SR(t) = 32\%$	-
Refined Dehghan	$SR(t) = 100 - p_1 \cdot \exp(p_2 \cdot \boldsymbol{\omega}(\boldsymbol{t})$	$p_2 = -0.39$	$\omega(t) \to 0, SR(t) = 100\%$ $\omega(t) \to \infty, SR(t) = 0\%$	0,99
Refined Hegazy	$SR(t) = 100 - p_1 + p_1 \cdot \exp(p_2 \cdot \boldsymbol{\omega}(\boldsymbol{t}))$	$p_1 = 35.4$ $p_2 = -0.2$	$\omega(t) \to 0, SR(t) = 100\%$ $\omega(t) \to \infty, SR(t) = 65.6\%$	0,99

Comparison of soiling ratio models



DATA

Observational and reanalysis datasets used in this study

Data source	Parameters	Spatial Resolution	Temporal resolution	Reference period
BADOPLU Database	Precipitation (mm)	*Local*	24hr	2000 - 2015
INDAAF/ACTRIS- FR Network	PM_{10} (µg/m^3) Wind speed(m/s) Precipitation (m)	*Local*	1hr	~2006 - 2022
CAMS	PM_1 (kg/m^3) $PM_{2.5}$ (kg/m^3) PM_{10} (kg/m^3) PM_{20} (kg/m^3)	80km	3hr	2004 – 2023
ERA5	Air Temperature(K) Relative humidity (%) Wind speed(m/s) Precipitation (m)	31km	1hr	2004 – 2023
WAPOR 2.1	Land cover classification	250m	Annual	2009 - Present

Observations

Reanalysis

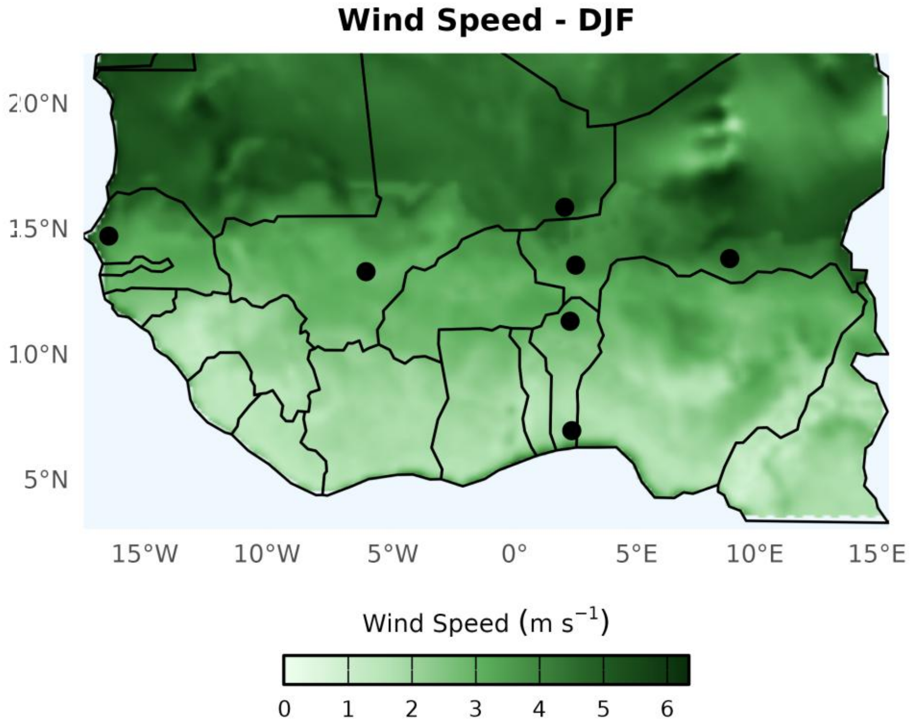
Parameters

INDAAF - International Network to study Deposition and Atmospheric composition in Africa.

BADOPLU - BAse de DOnnées PLUviométriques

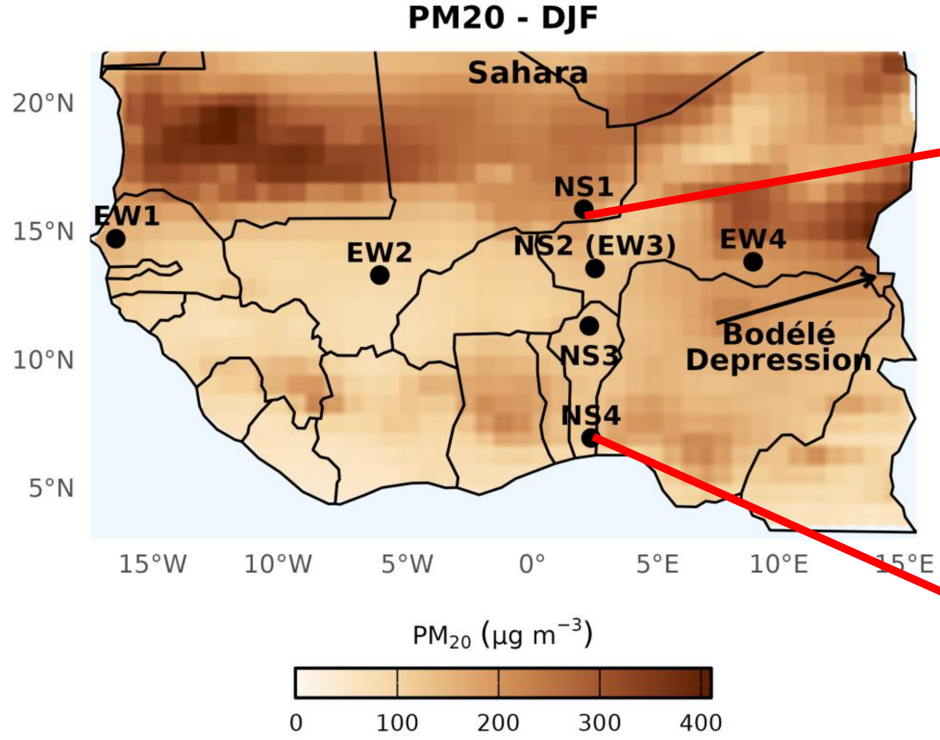
WAPOR - WAter Productivity through Open access of Remotely sensed derived data (FAO)

Eg. Wind speed during dry season (CAMS Reanalysis 2004 – 2023)



Study area and data

PM_{20} during dry season (CAMS Reanalysis 2004 – 2023)

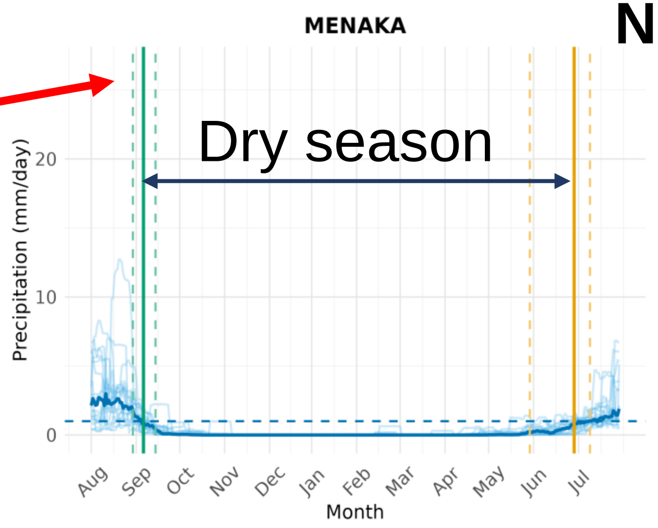


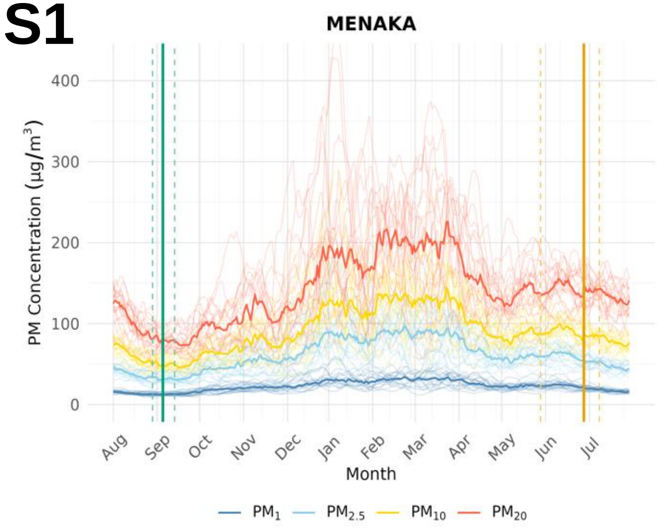
- Sites selected across contrasting atmospheric and land-use conditions.
- PM concentrations peak during the dry season.

Precipitation

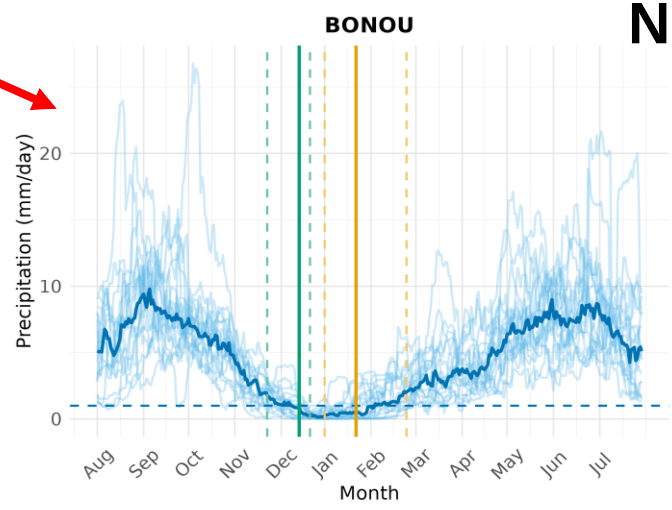
PM concentrations

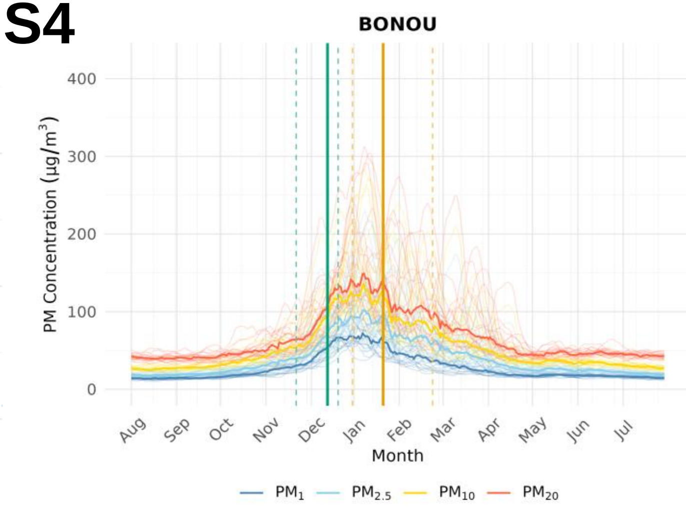
NS1



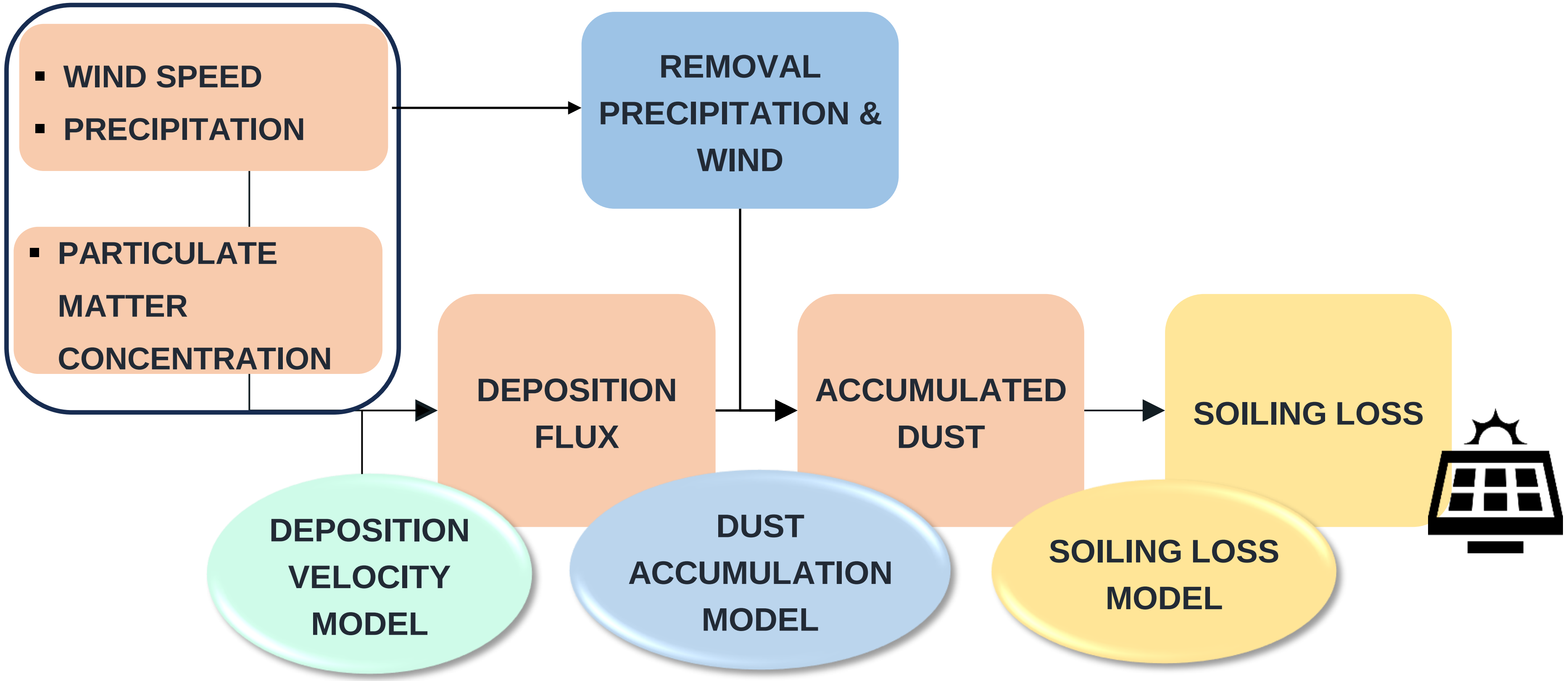


NS4





Sensitivity analysis using elasticity



ELASTICITY:

$$\frac{\%\Delta\, Output}{\%\Delta\, Variable}$$

$$\frac{\%\Delta\, Output}{\%\Delta\, Parameter}$$

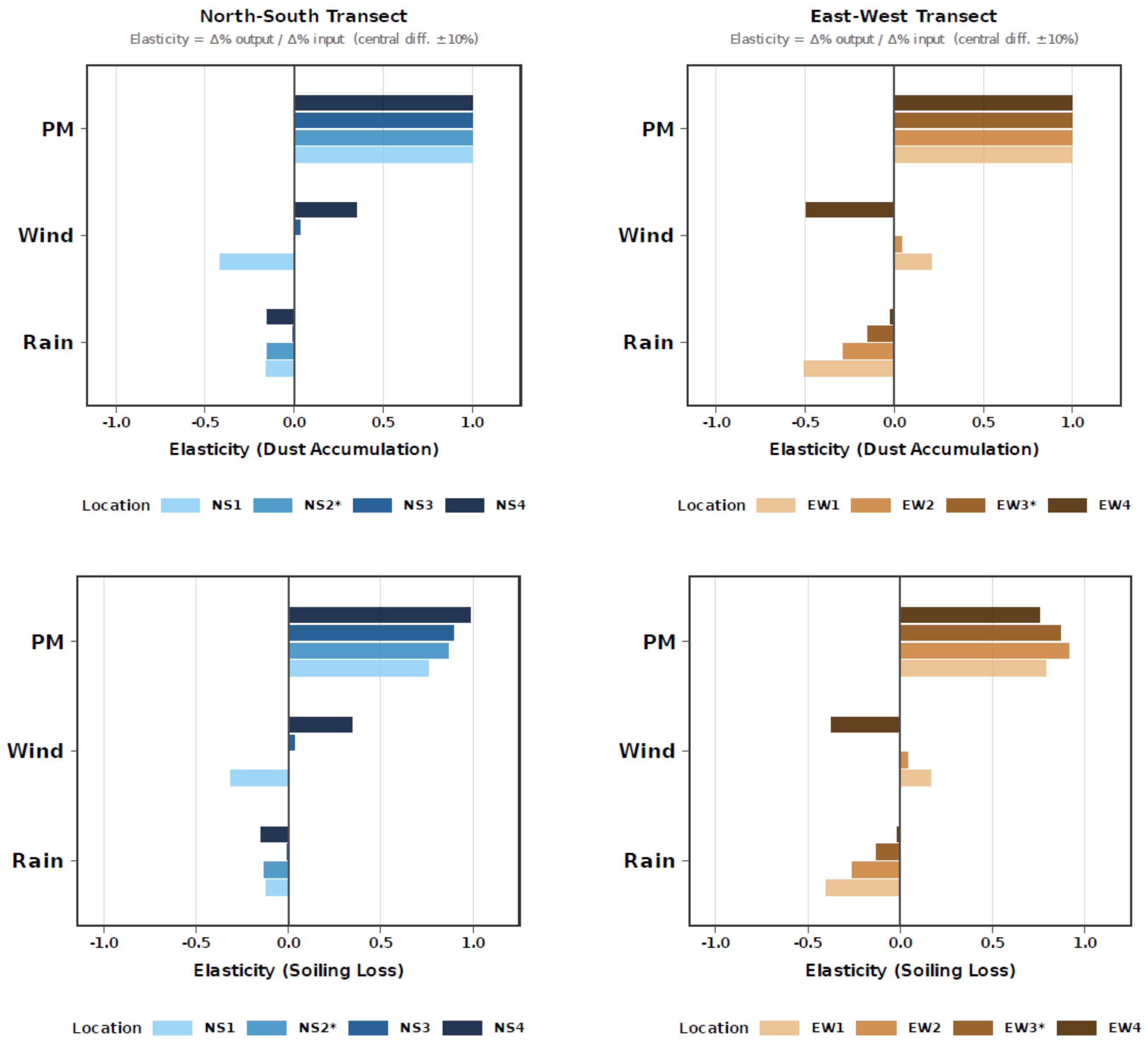
Reference Output: Mean accumulated dust.

Mean soiling loss.

Reference Input Variables: ERA5 & CAMS (20 yrs).

Reference Input Parameters: Literature

Elasticity to input variables



Accumulation

- **Large constant elasticity** to PM concentrations.
- Wind effect; with **competing removal** and **deposition**.
- Relative sensitivity to rain not negligible.

Soiling losses

- Very similar results.

Sensitivity to model parameters

- WIND SPEED
- PRECIPITATION
- PARTICULATE MATTER CONCENTRATION

REMOVAL PRECIPITATION & WIND

DEPOSITION FLUX → DUST DEPOSIT → SOILING LOSS

DEPOSITION VELOCITY MODEL

DUST ACCUMULATION MODEL

SOILING LOSS MODEL

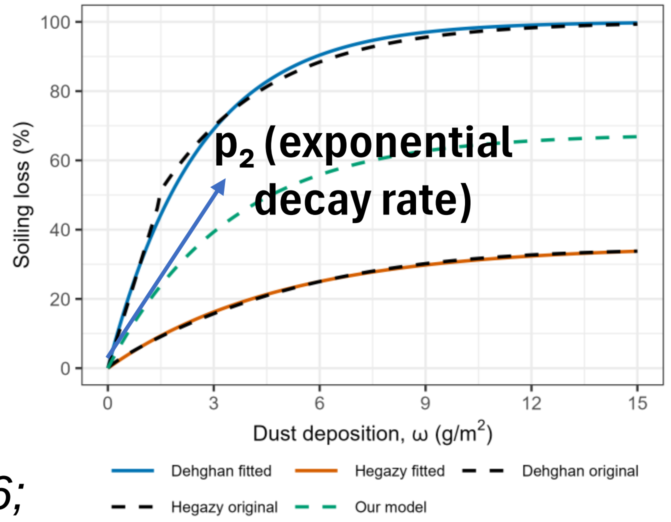
MODELS' PARAMETERS (LITERATURE)

Land use parameter	z_0 (Roughness length)
	A (Characteristic Radius)
	γ (Brownian diffusion exponent)

References:
Zhang & Shao, 2014; Zhang et al, 2001

k (Wind removal constant)
P_0 (Precipitation cleaning threshold)

References:
Figgis et al, 2016; Coello & Boyle, 2019; This work

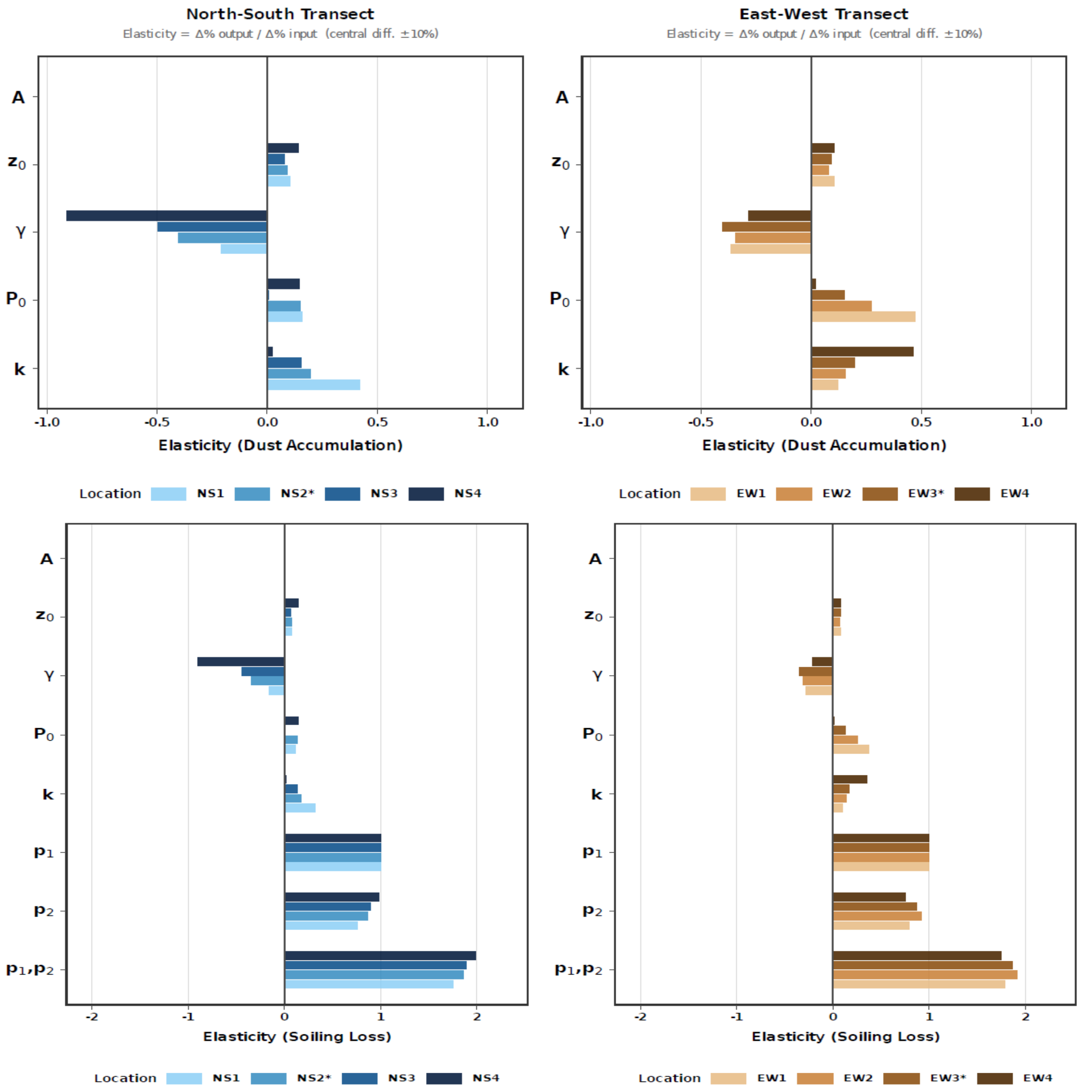


p_1 (Soiling limit)

General expression:

$$SL = p_1 - p_1 \cdot \exp(p_2 \cdot \boldsymbol{\omega}(\boldsymbol{t}))$$

Elasticity to input parameters: soiling loss

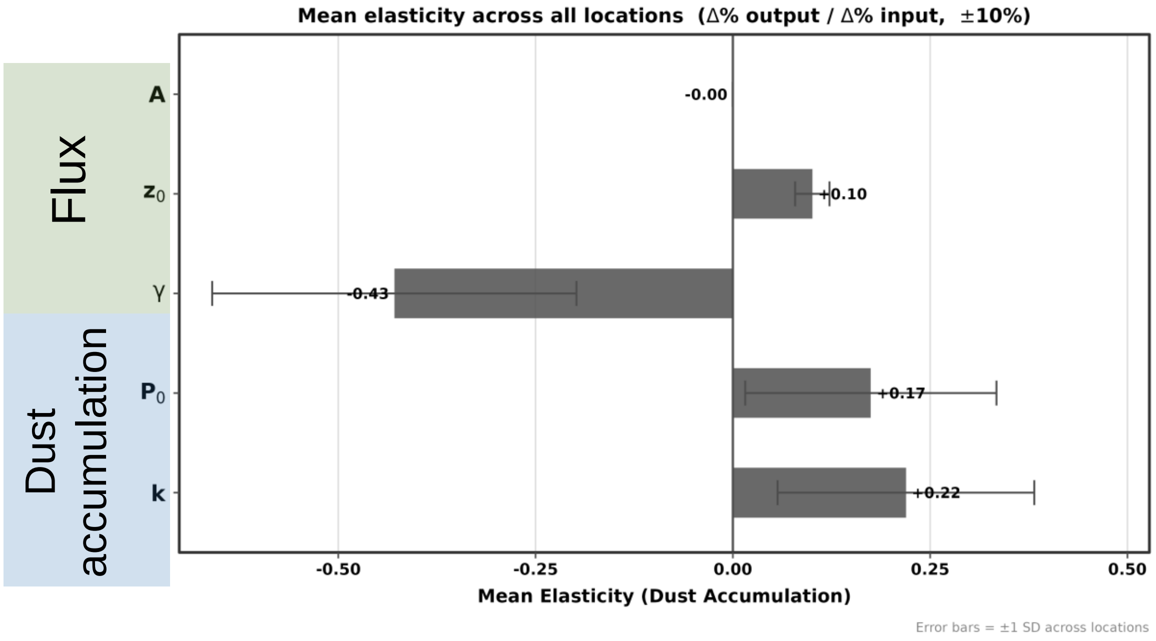


Across all sites:

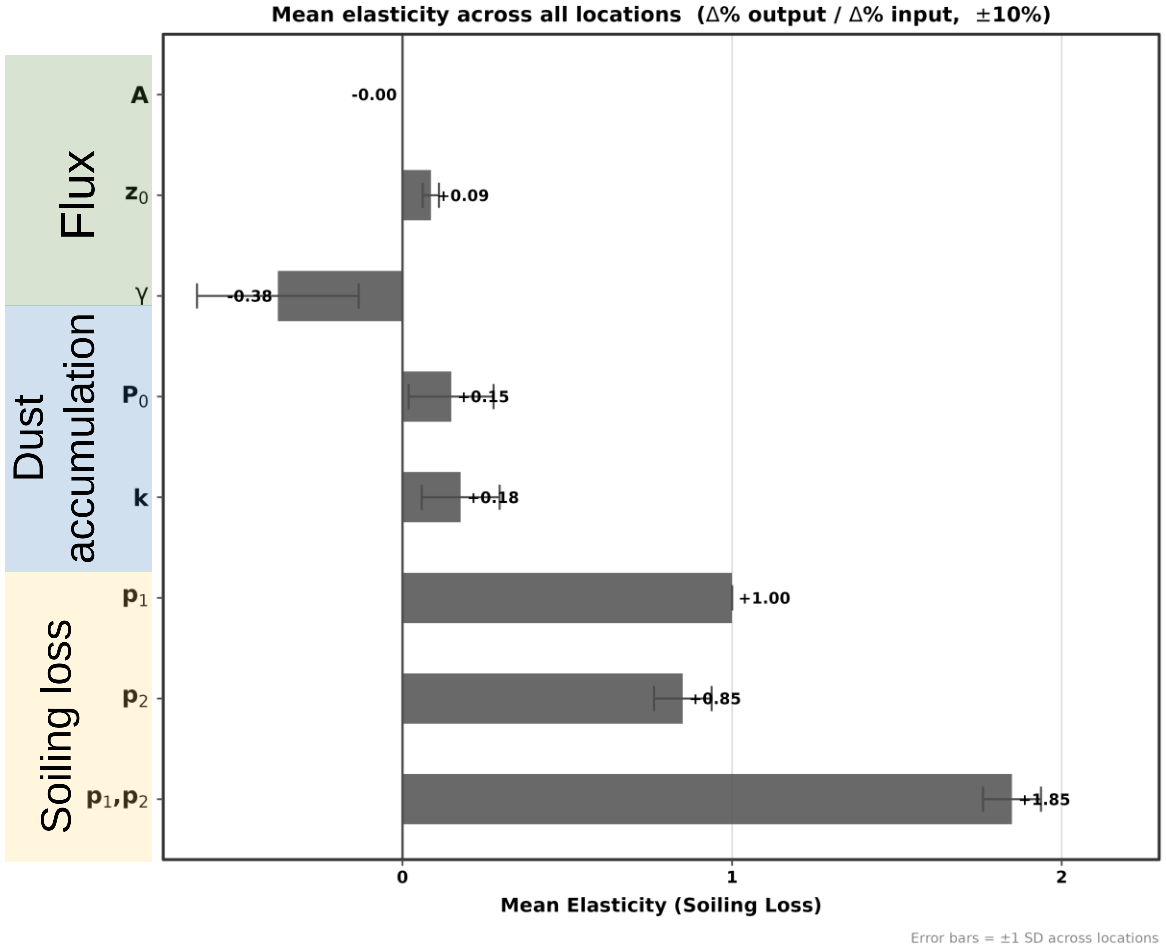
- Significant elasticity to land use and dust removal parameters in accumulation model.
- Very strong elasticity to soiling loss model parameters (p1 & p2).

Elasticity to model parameters

Dust accumulation



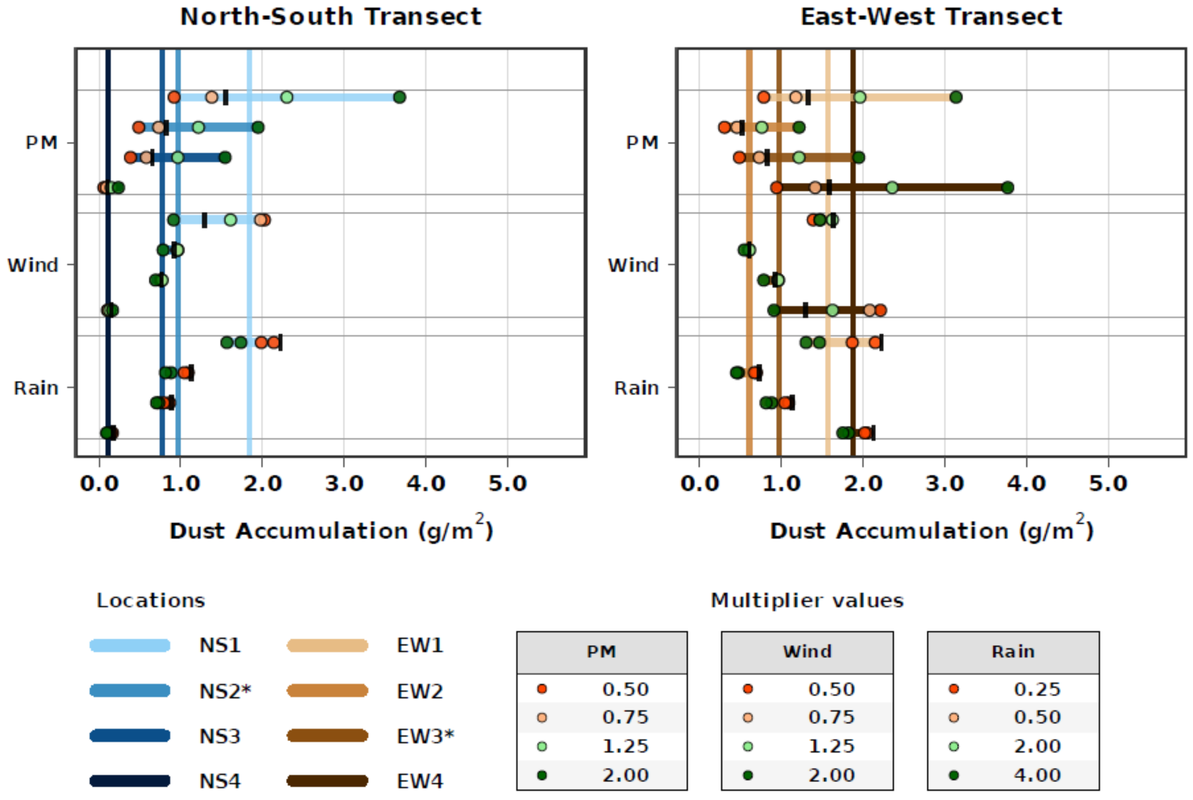
Soiling loss



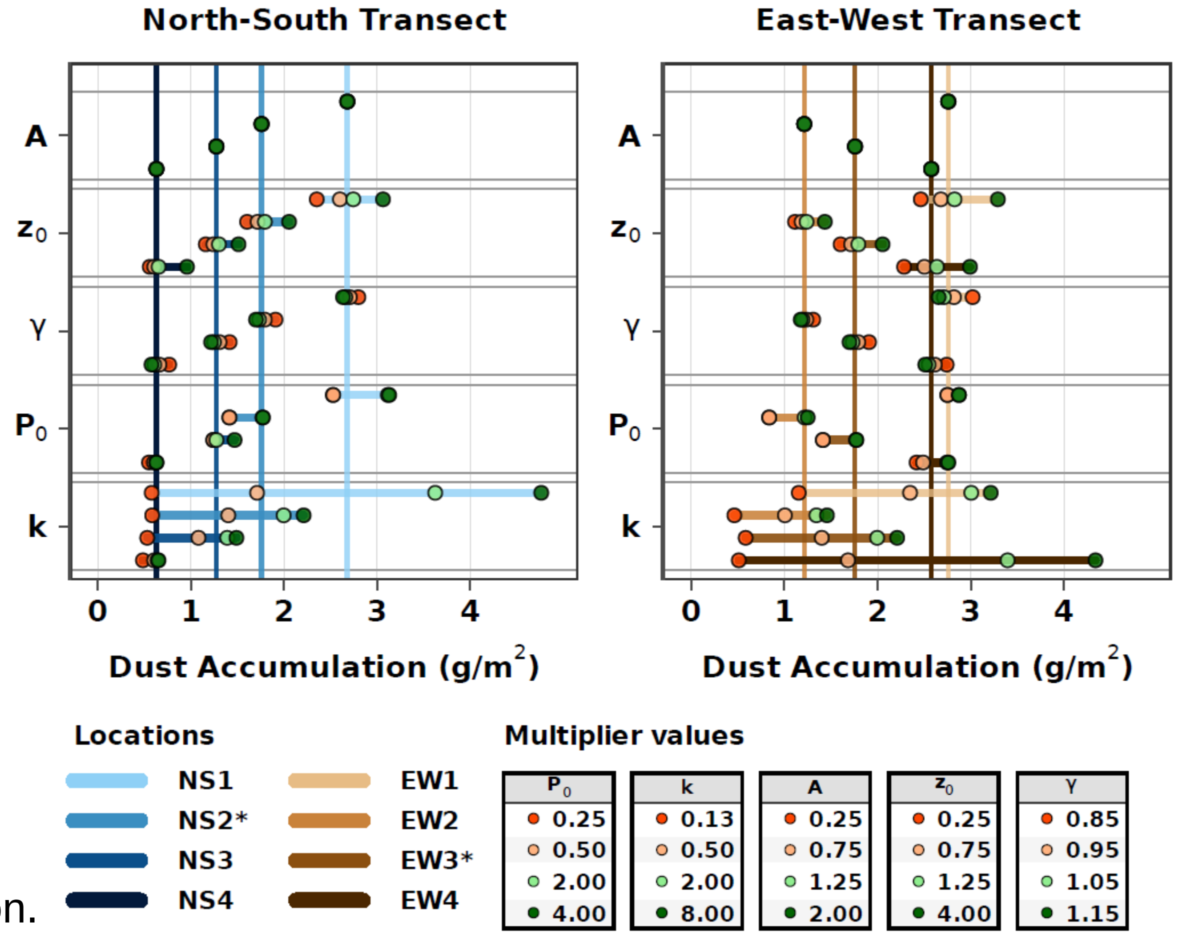
- Significant to strong elasticity to **land use parameters** (e.g. γ Brownian diffusion exponent).
- Significant elasticity to dust removal parameters (precipitation cleaning threshold P_0 & wind removal constant k)
- Very strong elasticity to soiling loss model parameters (p_1 & p_2).

Sensitivity to input variables and parameters (Absolute Sensitivity)

Inputs



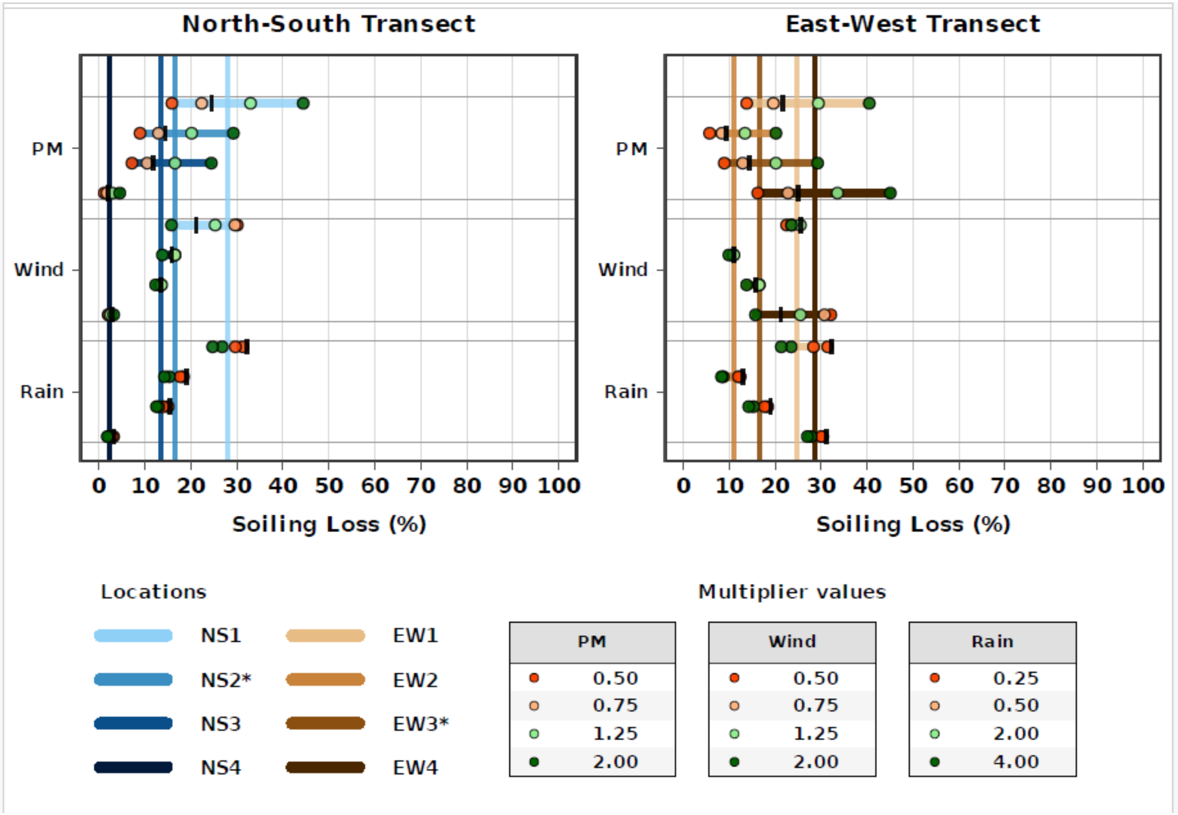
Parameters



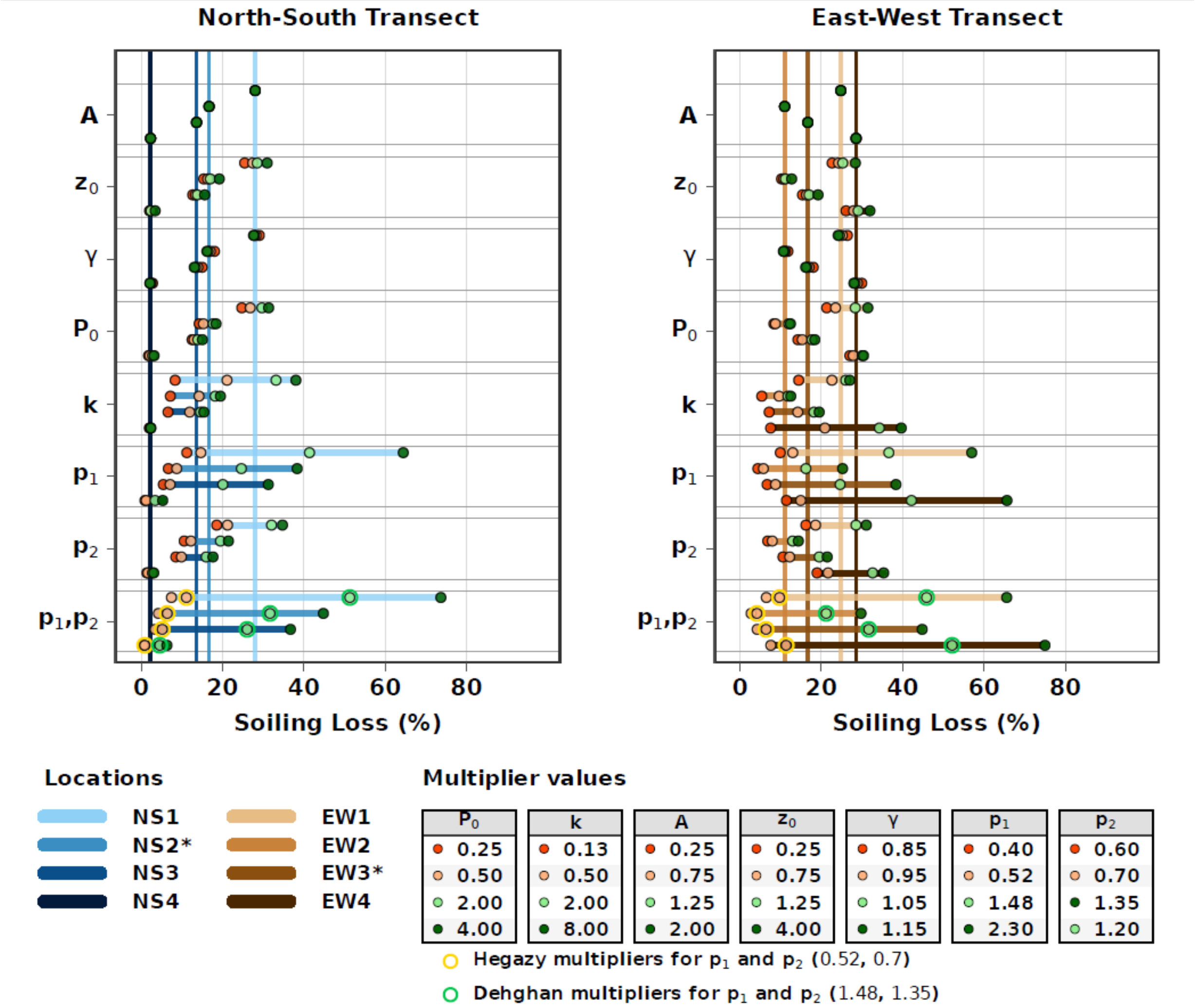
- Dust prone areas drive uncertainty in dust accumulation.
- North - South transect: decreasing dust gradient therefore larger absolute variability in the far North (as opposed to diminishing relative sensitivity which shows nonlinear, saturating behavior in soiling vs PM.
- East - West transect: largest uncertainty at EW4 (Near the Bodélé depression)

Sensitivity of soiling loss inputs vs parameters (Absolute Sensitivity)

Inputs



Parameters



- Inputs: PM and wind dominate uncertainty both accumulation and soiling loss.
- Non uniform uncertainty - it increases in dust-prone regions
- Parameters: Soiling model parameters (p_1 & p_2) drive way larger spread than the bulk wind removal constant (k).

KEY MESSAGES & RECOMMENDATIONS

- **Land use, PM concentrations & wind strongly affect simulated accumulated dust.**
  - Need for improved atmospheric data.
  - Need for high resolution land-use data.
- **Soiling losses are very sensitive** to accumulated dust estimates and to soiling model parameters.
  - **Colocalized observations** of atmospheric data, accumulated dust and PV soiling losses are required to improve and validate models.

The INDAAF* stations are examples in West Africa

* *(International Network to study Deposition and Atmospheric composition in Africa)*

THANK YOU

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For more information, visit netwat.osug.fr.