

A fuzzy-inference system for modelling scenarios involving soil functions and services

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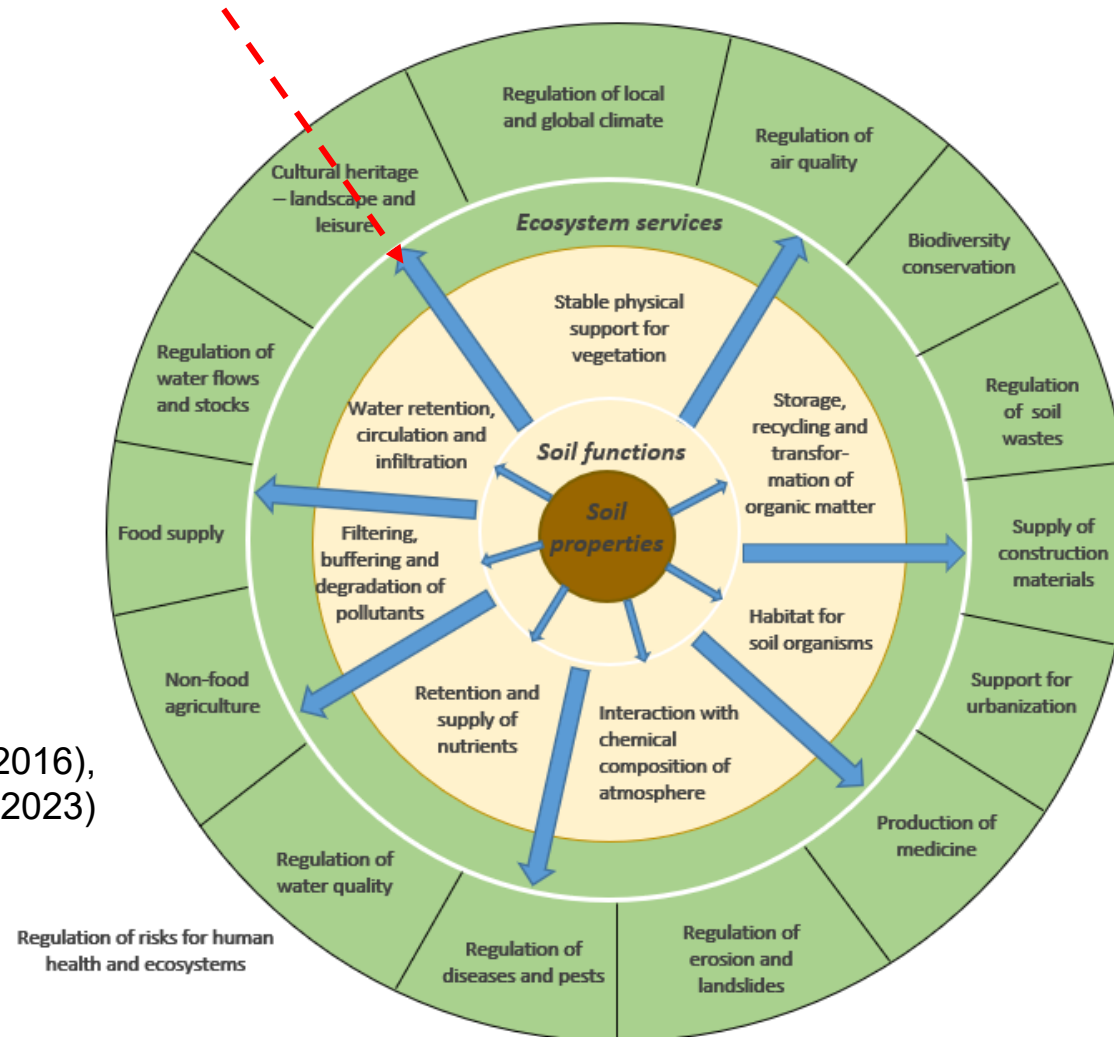


Introduction

- One of the objectives of PHISHES is to improve the quantitative linkage between soil properties, soil functions and associated ecosystem services
- Such linkage is illustrated in the literature in different manners; e.g.:

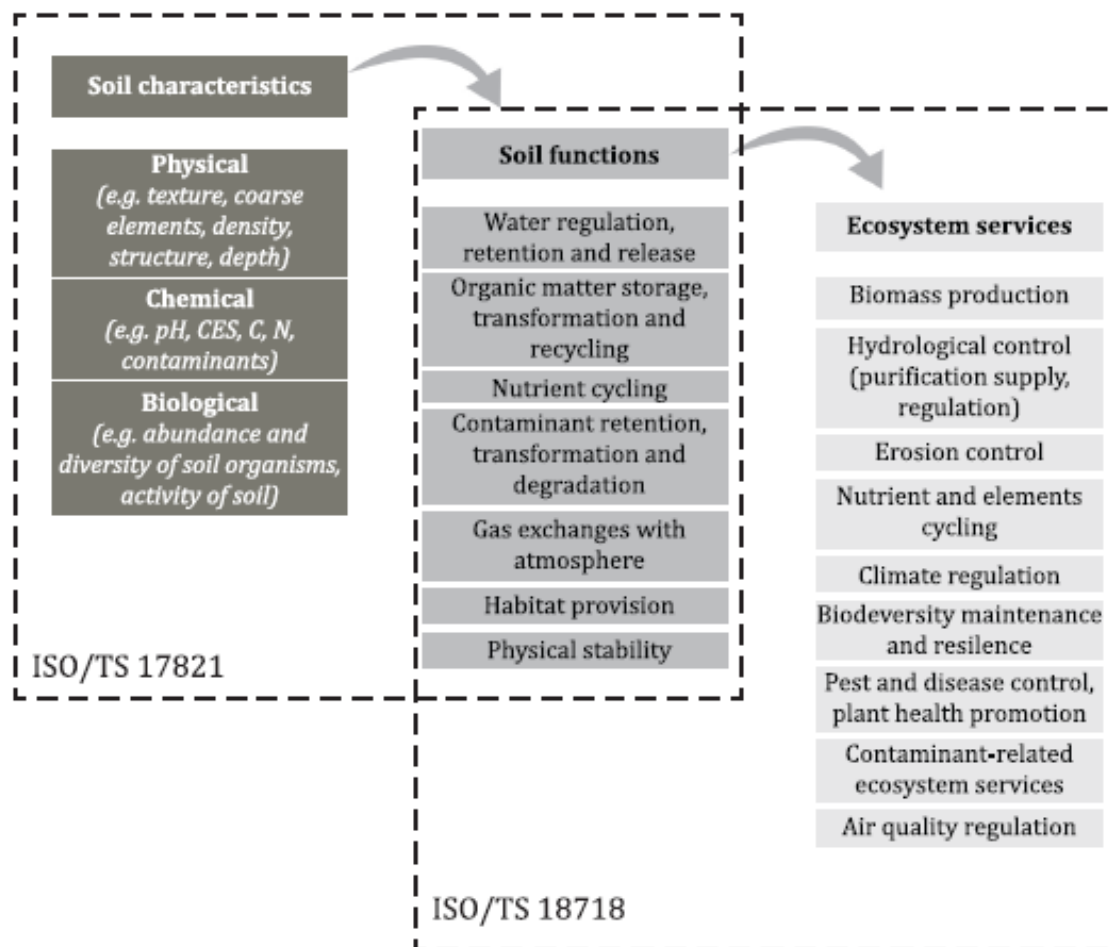
After: Adhikara and Hartemink (2016),
Calvaruso et al. (2020), The Soil Fresco (2023)

In PHISHES we are especially
interested in the arrows





- Other illustrations include recent ISO standards:



ISO/DTS 18721: Ecological soil functions — Characteristics, indicators and methods

ISO/DTS 18718: Soil functions and related ecosystem services — Definitions, descriptions and conceptual framework

Figure 1 — Links between this document (ISO/TS 18718) and ISO/TS 18721 on the soil functions and related ecosystem services



- Needed: quantitative estimation of soil function and ecosystem service indicators
- Several examples exist in literature
- Examples considered to-date in PHISHES:

RESEARCH ARTICLE

European Journal of
Soil Science WILEY

Destisol: A decision-support tool to assess the ecosystem services provided by urban soils for better urban planning

Geoffroy Séré¹ | Maïwenn Lothode² | Anne Blanchart³ | Clémentine Chirol⁴ |
Antoine Tribotte² | Christophe Schwartz¹



Selection of soil health indicators for modelling soil functions to promote smart urban planning

Geoffroy Séré^a, Cécile Le Guern^{b,c,*}, Antonio Bispo^c, Clément Layet^a,
Christophe Ducommun^{d,e}, Margaux Clesse^a, Christophe Schwartz^a, Laure Vidal-Beaudet^{d,e}

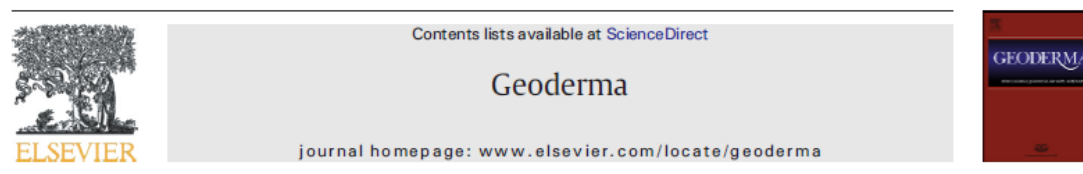
^a Université de Lorraine, INRAE, LSE, F-54000 Nancy, France

^b BRGM, 44000 Nantes, France

^c INRAE, Info&Sols, 45000 Orléans, France

^d Institut Agro, EPHOR, 49000 Angers, France

^e IRSTV, Nantes, France



A methodological framework to assess the multiple contributions of soils to ecosystem services delivery at regional scale



Costanza Calzolari^{a,*}, Fabrizio Ungaro^a, Nicola Filippi^b, Marina Guermandi^b, Francesco Malucelli^b,
Nazaria Marchi^b, Francesca Staffilani^b, Paola Tarocco^b

^a National Research Council, Institute for Biometeorology (CNR Ibiomet), Via Madonna del Piano 10, 50019 Sest F.no, Italy

^b Regione Emilia Romagna, Servizio Geologico, Sismico e dei Suoli, Bologna, Italy



- Soil properties (soil descriptors in the sense of SML) have values that are generally not completely known in practice, due to underlying uncertainties (measurement, heterogeneity, time variations, ...)
- Uncertainty may have different origins (see, e.g., Ferson et al., 1996):
 - ✓ Due to natural variability (stochastic or aleatory uncertainty)
 - ✓ Due to the incomplete nature of our knowledge of the property (epistemic uncertainty)
- Stochastic uncertainty can be addressed using probability theory (provided we have sufficient data to be able to define the probability distributions)
- Epistemic uncertainty can be addressed using fuzzy sets



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0951-8320/96/\$15.00

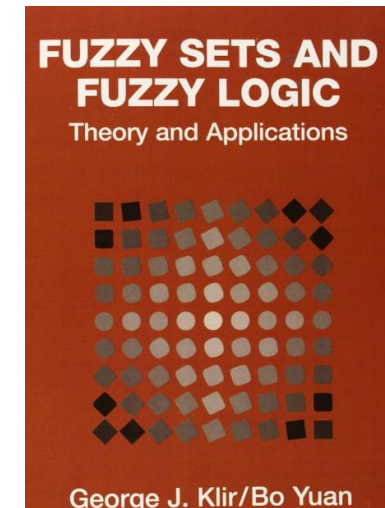
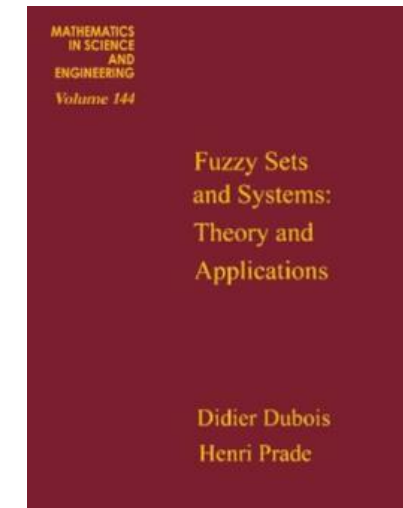
P11: S0951-8320(96)00071-3

Different methods are needed to propagate ignorance and variability

Scott Ferson^a & Lev R. Ginzburg^b

^aApplied Biomathematics, 100 North Country Road, Setauket, New York 11733, USA

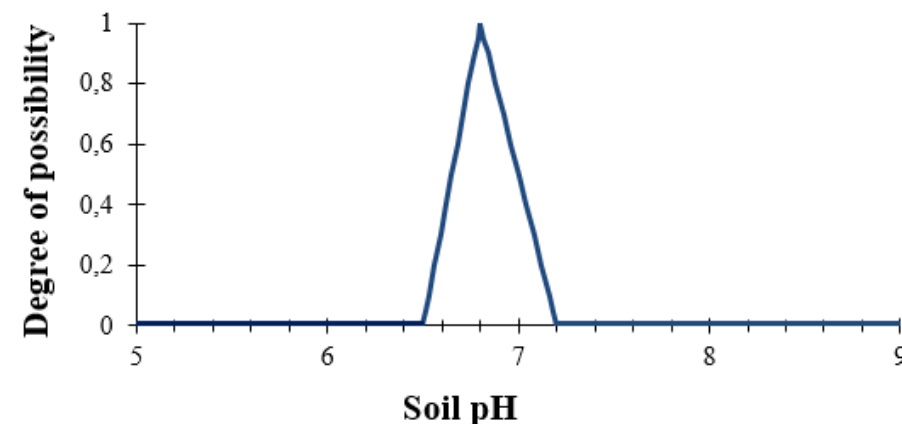
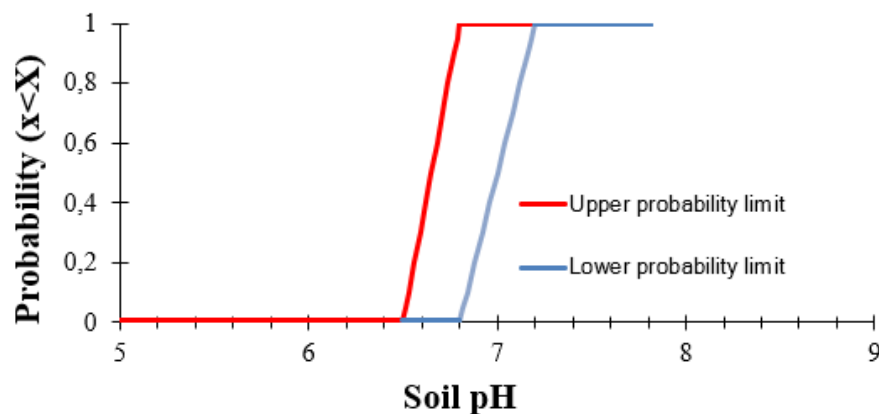
^bDepartment of Ecology and Evolution, State University of New York, Stony Brook, New York 11794, USA





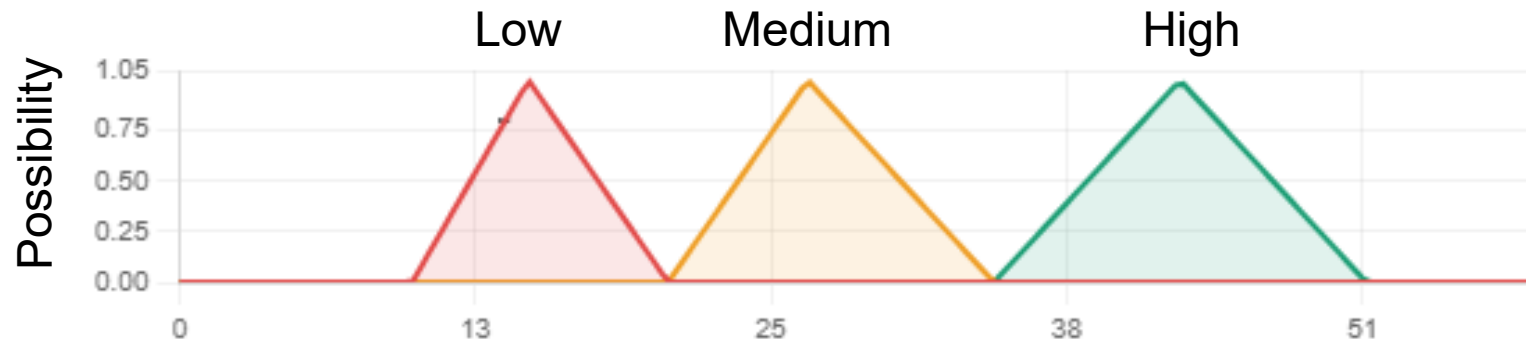
Fuzzy sets

- A fuzzy set is a mathematical set where elements have a partial degree of membership ranging from 0 to 1, rather than strict binary membership
- Fuzzy sets are well suited for representing expert knowledge. For example, let's say we are interested in the pH of a specific soil. A soil scientist or a farmer might say that in his/her view:
 - ✓ The pH of this soil lies somewhere between 6.5 and 7.2
 - ✓ Most likely values are around 6.8
- Such information can be coded in the form of a fuzzy set:
- Such a set defines a “family” of probability distributions:



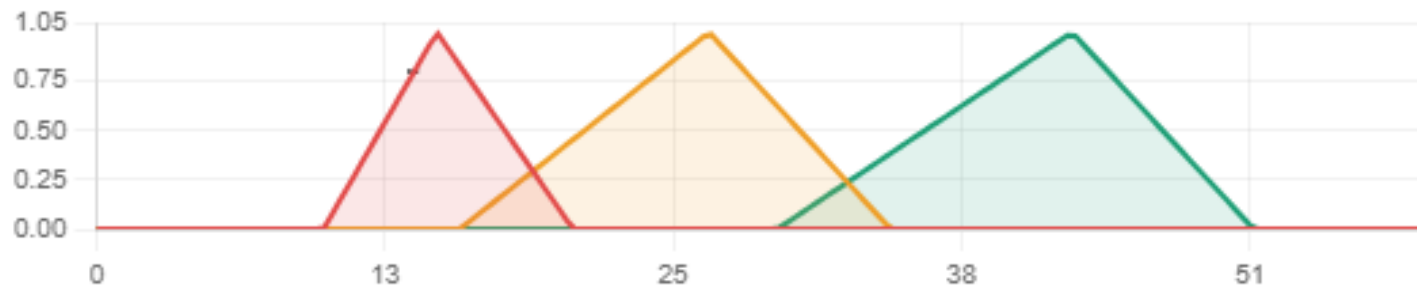


- Fuzzy sets (or fuzzy numbers) can also be used to code linguistic rules regarding soil properties or other parameters
- For example: values of organic carbon in British arable land (g C per Kg soil)



Low: 10 – 20 (15)
Medium: 20-35 (27)
High: 35-50 (42)

- Areas may overlap (limits of ranges are typically imprecisely-known)



- Such information relative to various soil characteristics can be combined using a Mamdani fuzzy-inference engine



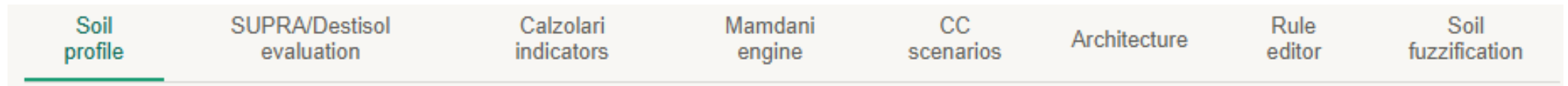
Mamdani fuzzy-inference System (FIS)

- A Mamdani fuzzy-inference system is a human-interpretable fuzzy-logic system that uses linguistic IF-THEN rules, fuzzy sets and centroid defuzzification to estimate results in complex systems.
- Such systems are widely used because:
 - ✓ They are highly interpretable: rules resemble human reasoning
 - ✓ They work well when expert knowledge is available but precise mathematical models are not available
 - ✓ They produce smooth, intuitive control actions
 - ✓ They are most commonly used in industrial control, medical decision support and pattern recognition
- A Mamdani FIS comprises three core components:
 - ✓ (i) a set of fuzzy input variables, each defined by a set of overlapping linguistic terms,
 - ✓ (ii) a fuzzy-rule base linking input conditions to fuzzy outputs, and
 - ✓ (iii) fuzzy output variables, also expressed using interpretable linguistic subsets.
- The essential engine of a Mamdani FIS is its fuzzy-rule base. Each rule is of the form:
If x_1 is A_1 AND x_2 is A_2 AND ... AND x_n is A_n then y is B



PHISH-FIS: a Mamdani FIS prototype

- A Mamdani FIS prototype (called PHISH-FIS) linking soil characteristics, functions and scenarios was implemented to illustrate the potential of the methodology
- The prototype combines information from three soil-evaluation frameworks (SUPRA, Destisol, Calzolari et al. 2016) into a single set of baseline function scores, then uses a Mamdani fuzzy inference engine to predict how these scores vary under different climate-change scenarios
- The main menu



- This menu allows the user to browse through the main components of the tool, including soil parameter inputs, scenarios and rule editions
- The html tool uses formulae coded in R and based on the publications cited previously



- Soil profile: this is a (partial) list of default values from the DESTISOL project used for illustration purposes. Some of the parameters (not all) can be modified in the Fuzzification page
- In a future version, user would enter his/her values

Indicateur	Horizon 1 (0–20 cm)	Horizon 2 (20–55 cm)	Horizon 3 (55–100 cm)
depth_cm (cm)	20	35	45
Slope (%)	3	3	3
Soil_Depth (cm)	100	100	100
Horizon_Colour	brown	brown	ochre
Horizon_Roots_Density (%)	25	8	3
Horizon_Biological_Activity	intermediate	low	absence
Horizon_Structure	fine subangular blocky	coarse subangular blocky	compact
Horizon_Textural_Class	silty	silty	silty
Horizon_Compacity	intermediate	high	high
Horizon_Coarse_Elements_Content (%)	10	20	30
Horizon_Artefacts_Content (%)	2	5	8
Horizon_Hydromorphic_Features	absence	redoxic < 5%	5%
Horizon_pH	7.5	8	8.3
Horizon_OM (g/kg)	28	14	7
Horizon_Ntot (g/kg)	2.5	1.2	0.7
Horizon_CN	11	12	NA
Horizon_CaCO3 (g/kg)	100	200	350



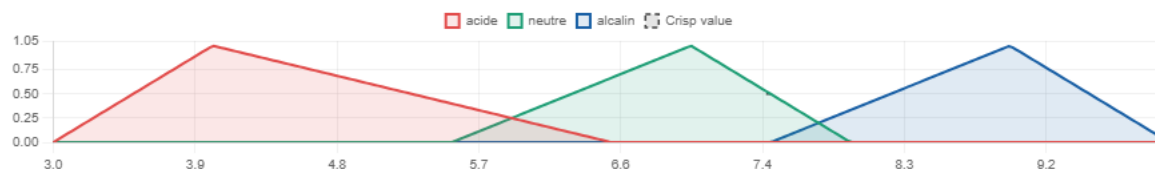
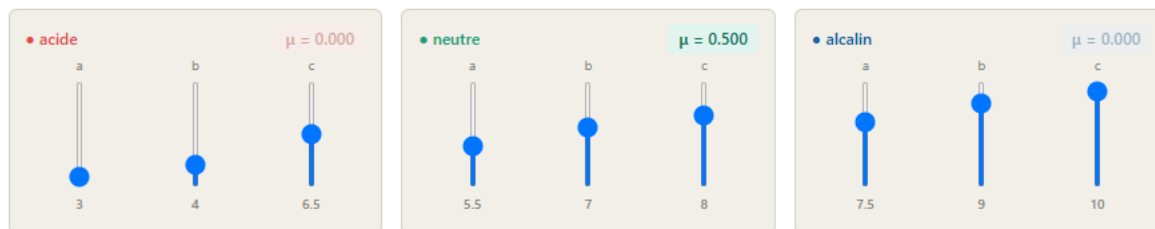
- Parameter fuzzification: can chose parameter boundaries and compare a fixed value

(x) pH (←) (reset)

pH measured on the surface horizon

Crisp value

7.5



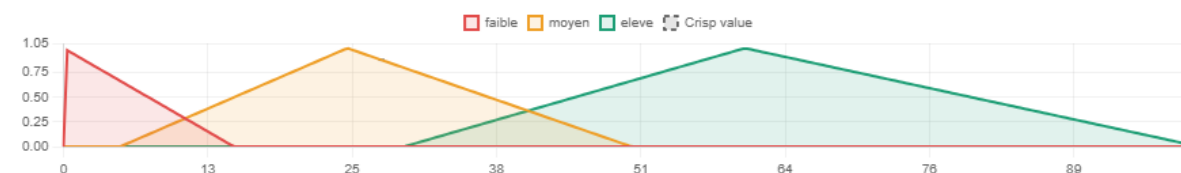
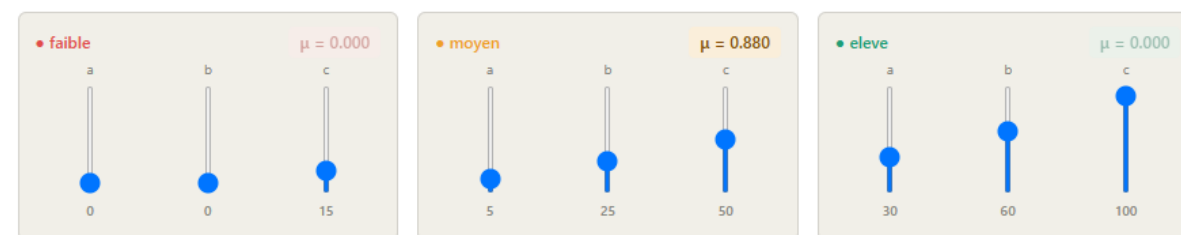
acide : 0.000 neutre : 0.500 alcalin : 0.000

(x) Organic matter (g/kg) (reset)

Organic matter content (horizon 1)

Crisp value

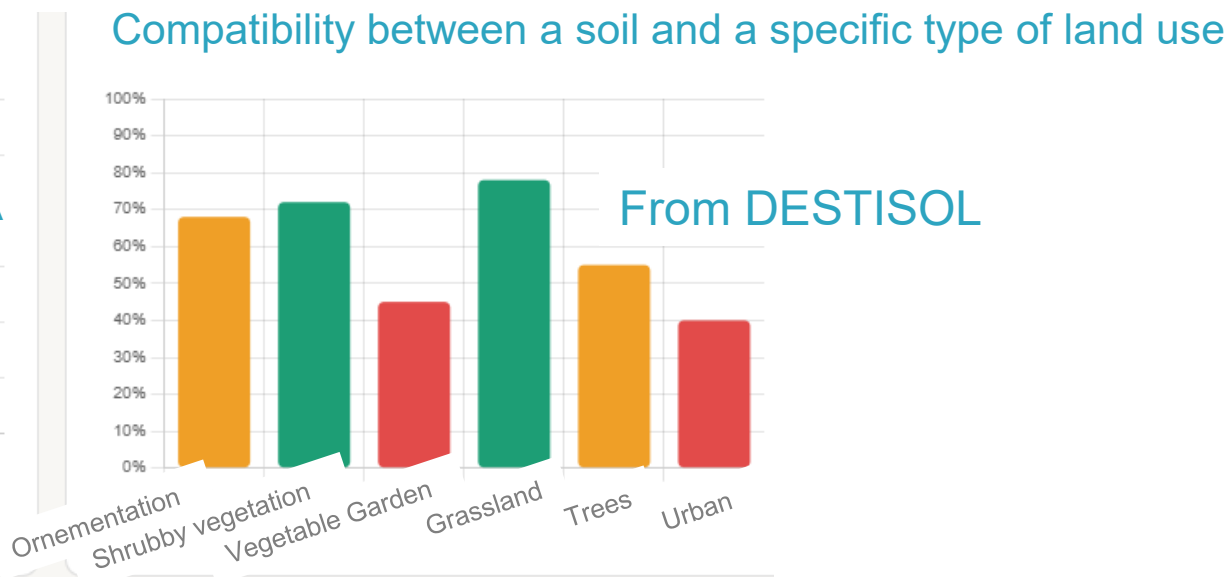
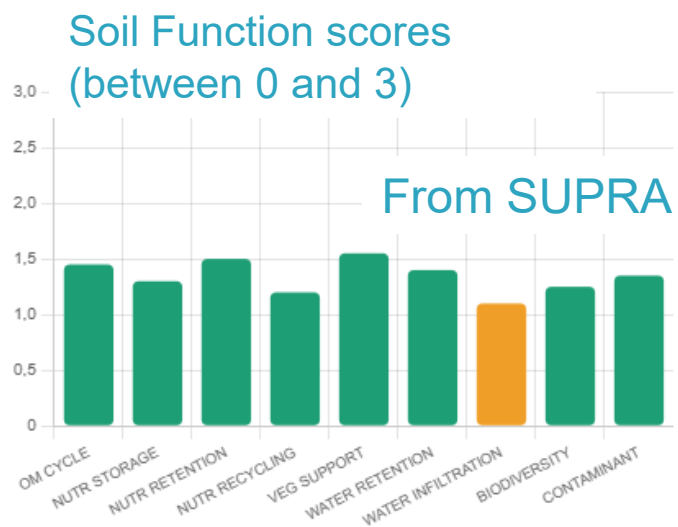
28g/kg



faible : 0.000 moyen : 0.880 eleve : 0.000



- SUPRA/DESTISOL evaluation: this is a check of the Function Scores calculated using the DESTISOL and SUPRA methods



☒ SUPRA × Destisol cross table

SUPRA function	Destisol equivalent	SUPRA score	Destisol score	Gap	Consistency
OM_CYCLE	RECYCLING	1.45	1.50	-0.05	✓ consistent
NUTR_STORAGE	FERTIHERB	1.30	1.45	-0.15	✓ consistent
NUTR_RETENTION	POLRETENTION	1.50	1.55	-0.05	✓ consistent
NUTR_RECYCLING	POLDEGRADATION	1.20	1.25	-0.05	✓ consistent
VEG_SUPPORT	FERTIHERB+FERTISHRUB+FERTIWOOD	1.55	1.45	+0.10	✓ consistent
WATER_RETENTION	WATERRETENTION	1.40	1.35	+0.05	✓ consistent
WATER_INFILTRATION	WATERCIRCULATION	1.10	1.00	+0.10	✓ consistent
BIODIVERSITY	(absent)	1.25	—	—	✓ consistent

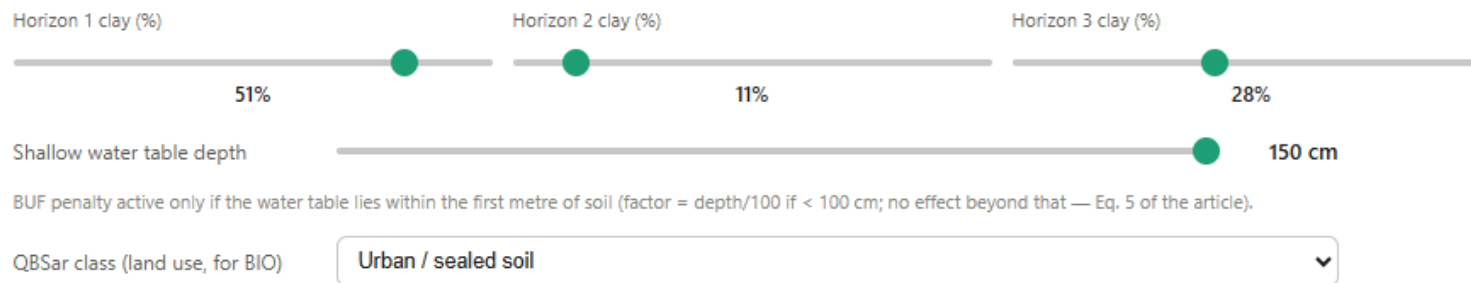
- Good consistency between both methods



- 3 Soil Function/Service indicators from Calzolari et al. (2016) were implemented : BUF (soil buffering capacity), BIO (habitat for soil organisms potential), CSP (soil carbon sequestration potential)

Adjustable parameters — clay, water table & land use

The unified PHISHES profile does not directly provide clay content, water table depth, or the QBSar class (land use). These three parameters drive BUF, BIO and CSP simultaneously — adjust them to explore their effect on the three indicators and on the corresponding triangulated SUPRA baselines.

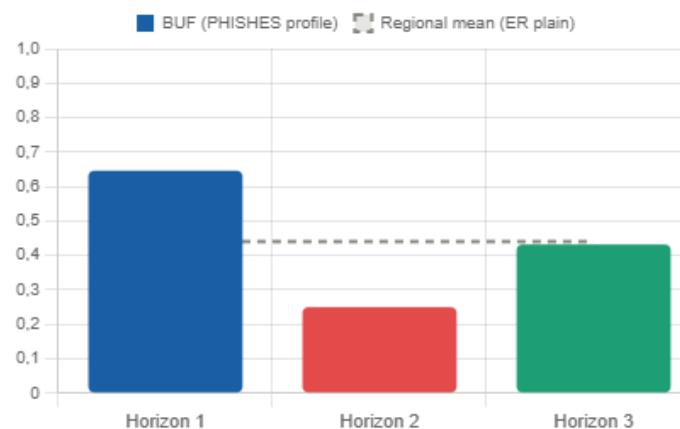


BUF calculation by horizon

Horizon	Clay (%)	Corg (%)	CEC (cmol/kg)	pH	Coarse elem. (%)	BUF [0–1]
H1	51	1.62	29.67	7.5	10	0.65
H2	11	0.81	12.14	8	20	0.25
H3	28	0.41	18.34	8.3	30	0.43

Water table at 150 cm — depth ≥ 100 cm, no penalty applied (Calzolari et al. 2016).

BUF by horizon vs. regional mean



- Lower clay content results in lower buffering capacity

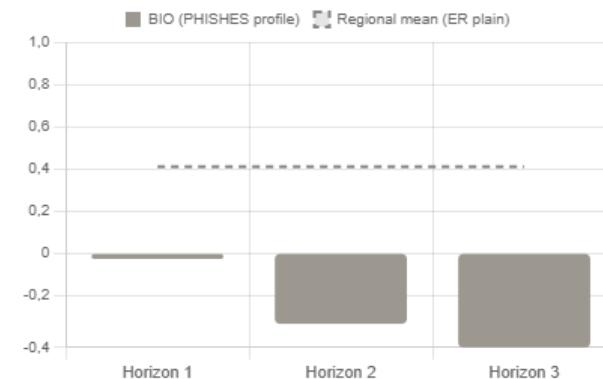


- Habitat for Soil Organisms Potential; BIO

BIO calculation by horizon

Horizon	Corg (%)	Bulk density (g/cm ³)	logOC norm.	logBD norm.	QBSar	BIO [0-1]
H1	1.62	1.35	0.518	0.796	Technosol/sparsely vegetated fallow land (default) (0.25)	-0.03
H2	0.81	1.65	0.404	0.988	Technosol/sparsely vegetated fallow land (default) (0.25)	-0.34
H3	0.41	1.65	0.292	0.988	Technosol/sparsely vegetated fallow land (default) (0.25)	-0.45

BIO by horizon vs. regional mean

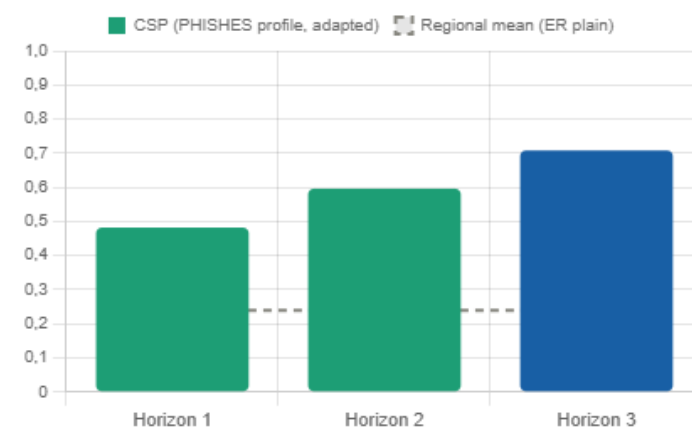


- Carbon Sequestration Potential; CSP

CSP calculation by horizon (adapted)

Horizon	Corg (%)	Normalized Corg (region)	CSP [0-1]
H1	1.62	0.518	0.48
H2	0.81	0.404	0.60
H3	0.41	0.292	0.71

CSP by horizon vs. regional mean





- Rules for the Mamdani engine

(these rules are preliminary and proposed for the purpose of illustration)

f* Mamdani rule base (18 rules)

#	Conditions (AND)	Target function	Consequence	Measure	Intensity
R01	Soil drought= high AND ETP Δ = high	WATER_RETENTION	poor	mulching cover crop	HIGH
R02	ETP Δ = high AND Precipitation Δ = low	WATER_RETENTION	very_poor	reduced tillage water retention	URGENT
R03	ETP Δ = medium AND Precipitation Δ = medium	WATER_RETENTION	good	maintain current practice	NONE
R04	Extreme events= high	WATER_INFILTRATION	very_poor	desealing bioretention	URGENT
R05	Extreme events= medium	WATER_INFILTRATION	moderate	green infrastructure maintenance	LOW
R06	Temperature anomaly= high AND Soil drought= medium	OM_CYCLE	poor	organic amendment compost	MODERATE
R07	Temperature anomaly= high AND Precipitation Δ = high	OM_CYCLE	poor	cover crops no tillage	HIGH
R08	Temperature anomaly= medium	OM_CYCLE	good	maintain current practice	NONE
R09	Soil drought= high AND Temperature anomaly= high	BIODIVERSITY	poor	habitat restoration water management	HIGH
R10	Extreme events= high	BIODIVERSITY	moderate	diversified vegetation buffer zones	MODERATE
R11	Soil drought= high	CONTAMINANT	very_poor	capping phytoremediation irrigation	URGENT
R12	Precipitation Δ = high AND Extreme events= medium	CONTAMINANT	very_poor	drainage control contaminant monitoring	URGENT
R13	Soil drought= high AND ETP Δ = high	VEG_SUPPORT	poor	drought resistant species mulching	HIGH
R14	Temperature anomaly= medium AND Soil drought= low	VEG_SUPPORT	good	maintain current practice	NONE
R15	BUF Calzolari (soil)= low AND Precipitation Δ = high Calzolari et al. 2016	CONTAMINANT	very_poor	buffer amendment clay organic	URGENT
R16	BUF Calzolari (soil)= high AND Soil drought= high Calzolari et al. 2016	CONTAMINANT	moderate	maintain current practice	LOW
R17	BIO Calzolari (soil)= low Calzolari et al. 2016	BIODIVERSITY	poor	soil decompaction organic amendment	MODERATE
R18	CSP Calzolari (soil)= high AND Temperature anomaly= medium Calzolari et al. 2016	OM_CYCLE	good	maintain current practice	LOW



- Rule editor

(+) Build a Mamdani rule

Compose an IF ... THEN ... rule using the drop-down lists. The second factor (AND) is optional. The rule acts on a soil function (SUPRA) and proposes a corrective measure, exactly like the 18 base rules — it is immediately integrated into the inference engine.

IF

Temperature anomaly IS low

AND (optional)

— none — IS low

THEN

soil function OM_CYCLE IS very poor

AND

measure buffer amendment clay organic IS none

+ Add rule

Reset to the 18 original rules

☰ All rules active in the engine

Uncheck a rule to disable it without deleting it. Rules added here carry the identifier Cxx and the badge Custom rule.

#	IF (conditions)	THEN function	Consequence	Measure / intensity	
☒ R01	Soil drought= high AND ETP Δ= high	WATER_RETENTION	poor	mulching cover crop (high)	
☒ R02	ETP Δ= high AND Precipitation Δ= low	WATER_RETENTION	very poor	reduced tillage water retention (urgent)	
☒ R03	ETP Δ= medium AND Precipitation Δ= medium	WATER_RETENTION	good	maintain current practice (none)	
☒ R04	Extreme events= high	WATER_INFILTRATION	very poor	desealing bioretention (urgent)	
☒ R05	Extreme events= medium	WATER_INFILTRATION	moderate	green infrastructure maintenance (low)	
☒ R06	Temperature anomaly= high AND Soil drought= medium	OM_CYCLE	poor	organic amendment compost (moderate)	

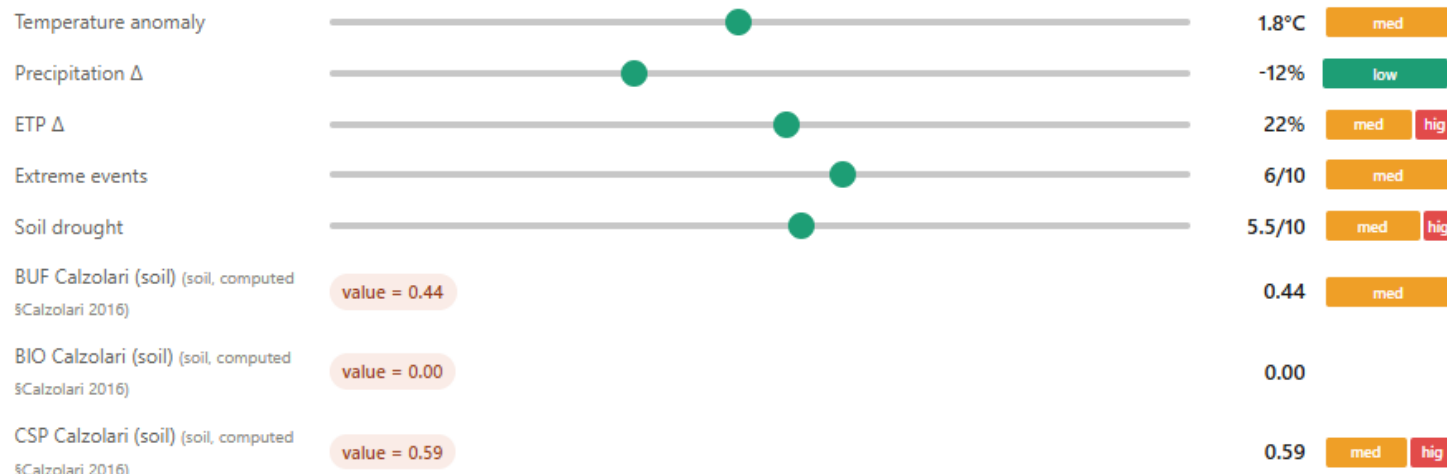


- Scenarios using the Mamdani engine and rules

- ✓ Mild scenario (RCP 4,5)

RCP 4,5 (2050) is a moderate climate change scenario where global greenhouse gas emissions peak around 2040 and begin to decline toward mid-century

Climate drivers — crisp values



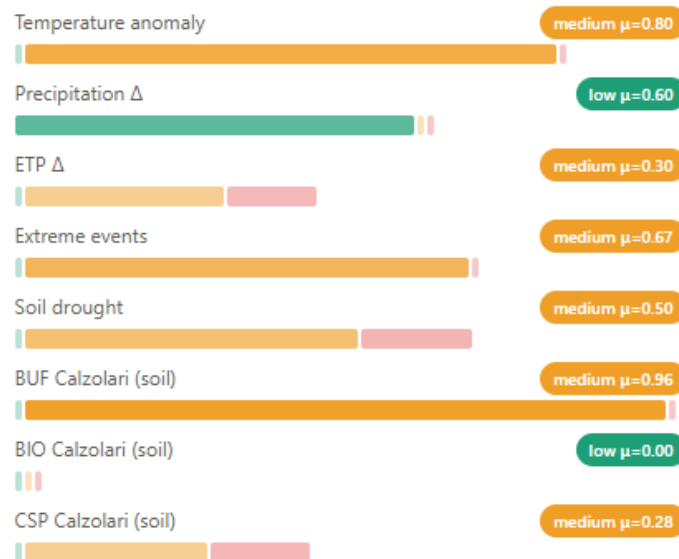
► Run inference

RCP 4.5 (2050)

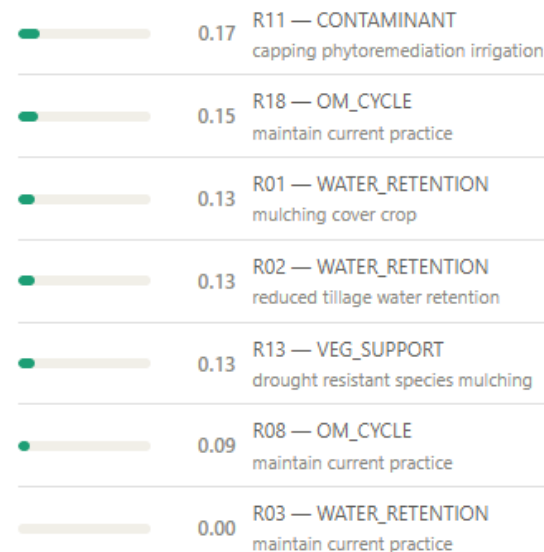
RCP 8.5 (2070)

Baseline

Driver fuzzification



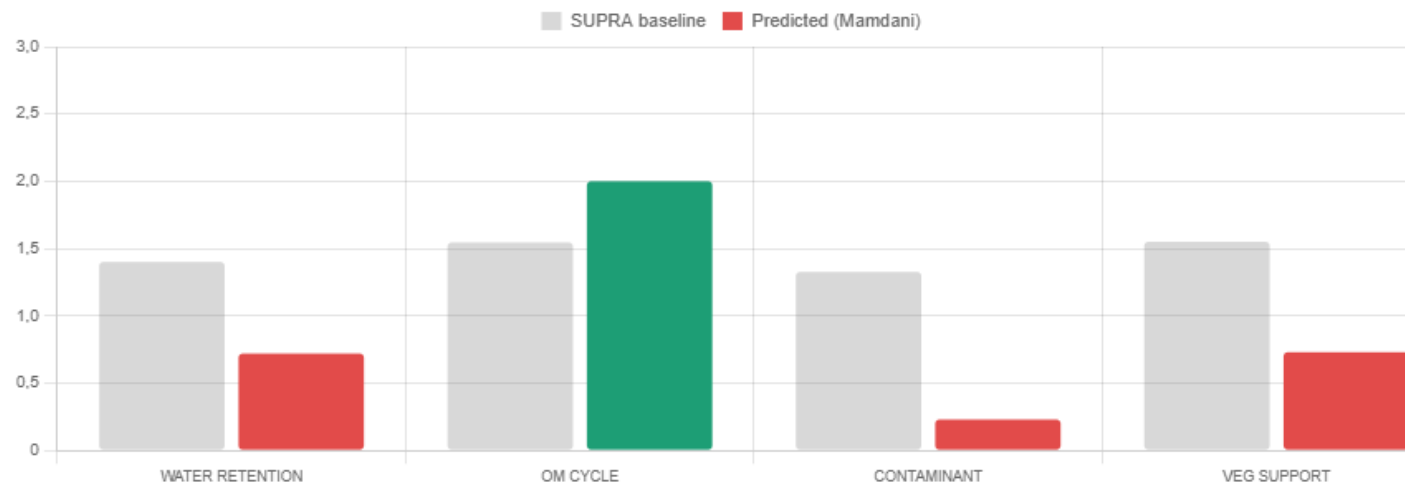
Activated rules





Predicted impact and recommendations

↗ Predicted impact on soil functions



☰ Recommended corrective measures

● capping phytoremediation irrigation

URGENT activation = 0.17 → CONTAMINANT

● maintain current practice

LOW activation = 0.15 → OM_CYCLE

● mulching cover crop

HIGH activation = 0.13 → WATER_RETENTION

● reduced tillage water retention

URGENT activation = 0.13 → WATER_RETENTION

● drought resistant species mulching

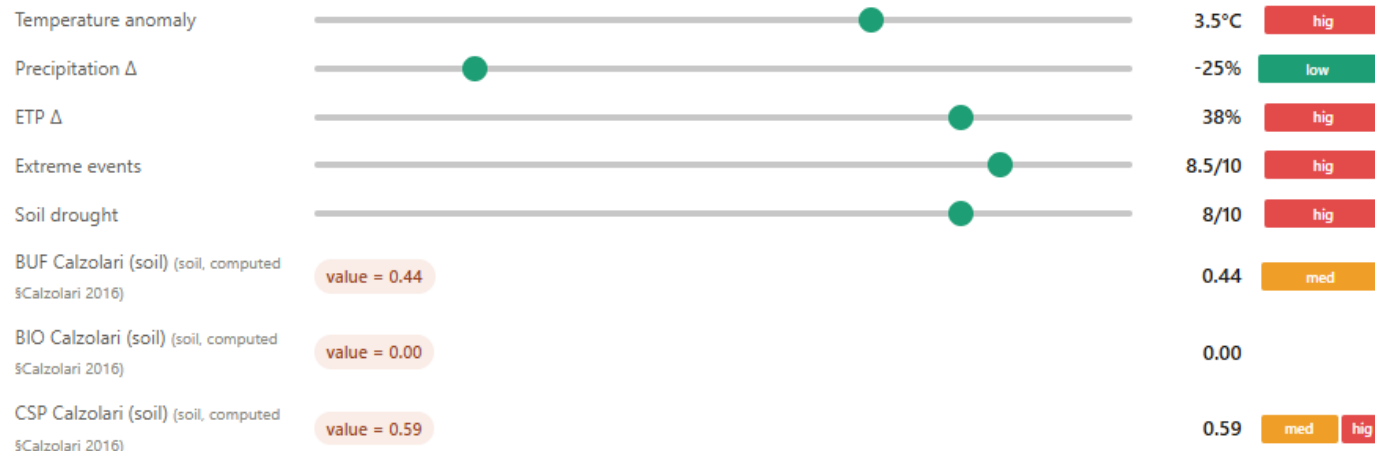
HIGH activation = 0.13 → VEG_SUPPORT



✓ Severe scenario (RCP 8,5)

RCP 8.5 (2070) refers to a high-emissions, "business-as-usual" climate change scenario projected for the year 2070

Climate drivers — crisp values



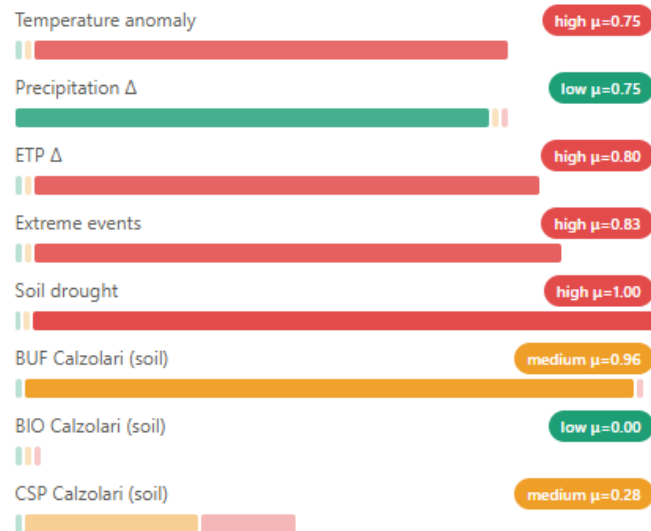
► Run inference

RCP 4.5 (2050)

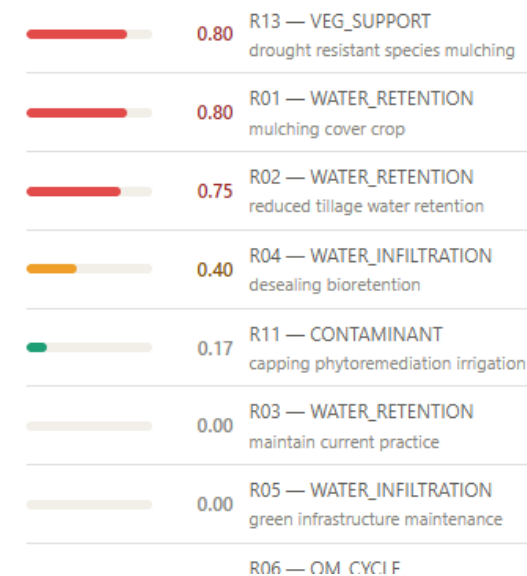
RCP 8.5 (2070)

Baseline

Driver fuzzification



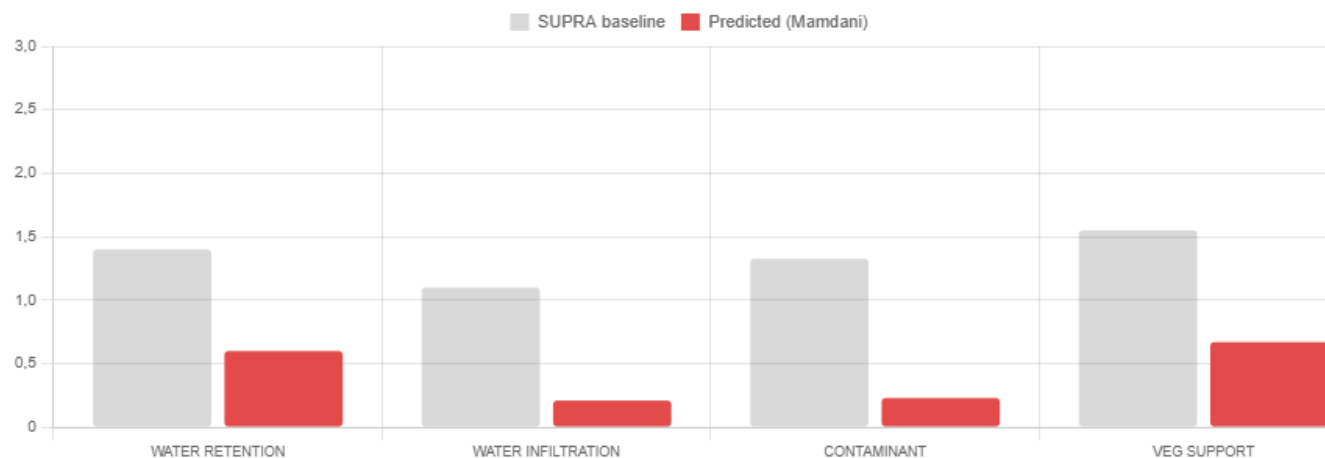
Activated rules





Predicted impact and recommendations

↗ Predicted impact on soil functions



☰ Recommended corrective measures

- **drought resistant species mulching**

HIGH activation = 0.80 → VEG_SUPPORT

- **mulching cover crop**

HIGH activation = 0.80 → WATER_RETENTION

- **reduced tillage water retention**

URGENT activation = 0.75 → WATER_RETENTION

- **desealing bioretention**

URGENT activation = 0.40 → WATER_INFILTRATION

- **capping phytoremediation irrigation**

URGENT activation = 0.17 → CONTAMINANT



Conclusions

- Soil functions and associated ecosystem services are influenced by many parameters that are often incompletely/imprecisely known
- Fuzzy set theory is designed to address this type of uncertainty and help in the decision-making process
- Using data from previous studies, the PHISH-FIS prototype illustrates how:
 - ✓ Soil descriptors can be represented by fuzzy sets
 - ✓ Fuzzy-inference rules can be defined that involve these fuzzy descriptors
 - ✓ A Mamdani engine can combine these rules in scenarios involving, e.g., climate change parameters
 - ✓ Recommendations can be proposed following the outcome of the scenarios
- Further work in PHISHES will aim at linking PHISH-FIS to the outputs of the numerical, mechanistic model trains developed in PHISHES
- For ex. the cation-exchange capacity (CEC), which is calculated in the Hydrus-PhreeqC model train, is an input for the BUF indicator in PHISH-FIS
- Consensus could be sought between different Mission Soil projects regarding Function / Service Indicator calculation methods
- Consensus could also be found regarding Mamdani Engine Rules (IF X1 low AND X2 high THEN Y1 low etc.)

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