

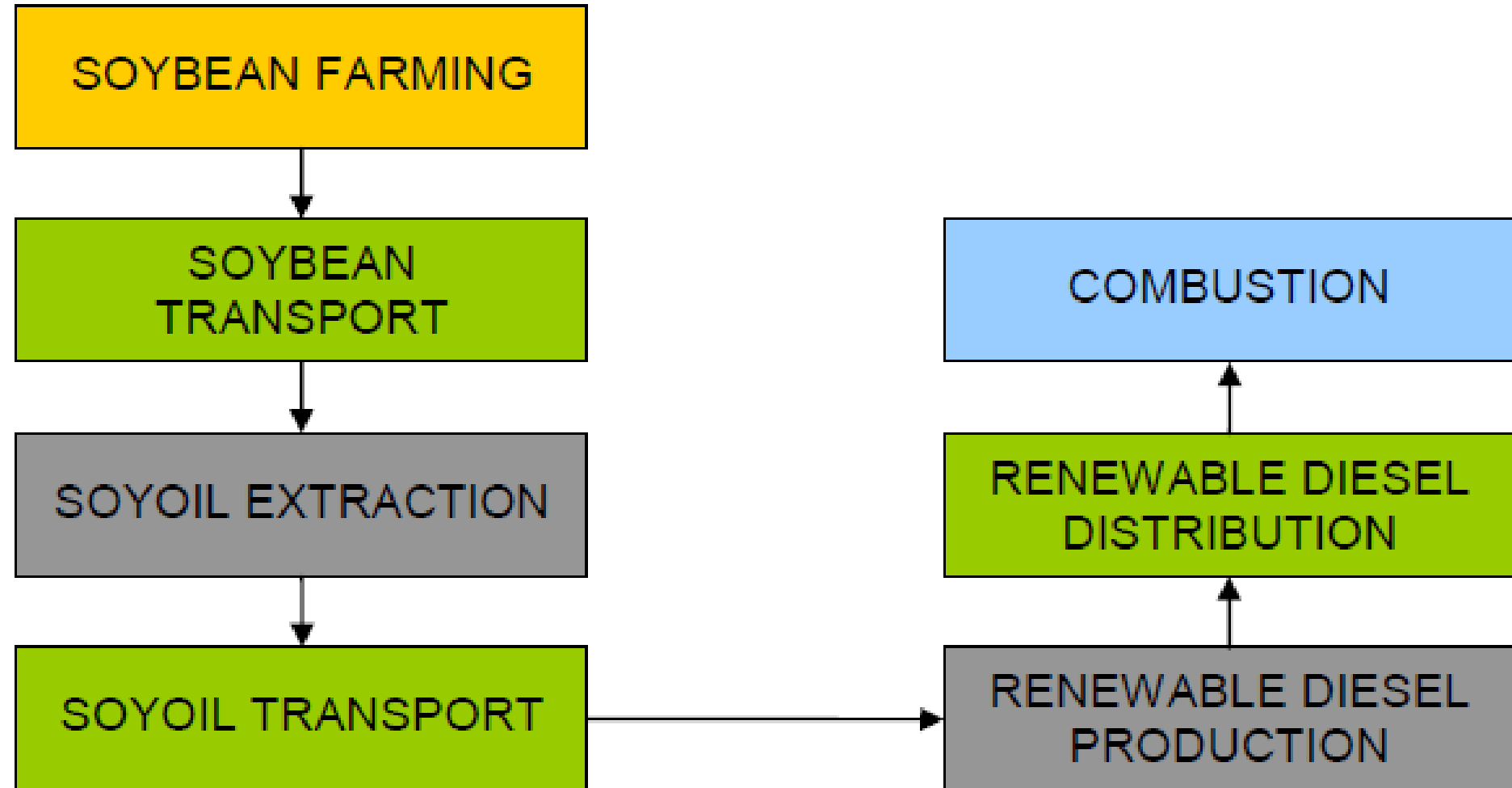
Integrating Hydrological Modeling and Life Cycle Assessment: Assessing the Role of SWAT+ in Soil Organic Carbon Estimation

Mohammad Hadi Bazrkar^a *, Andrea Enriquez^b, Montserrat Núñez^b, Angel Avadi^b, Ariane Albers^b, Tamara Schmidt^b

^a Texas A&M AgriLife, Temple, Texas, USA

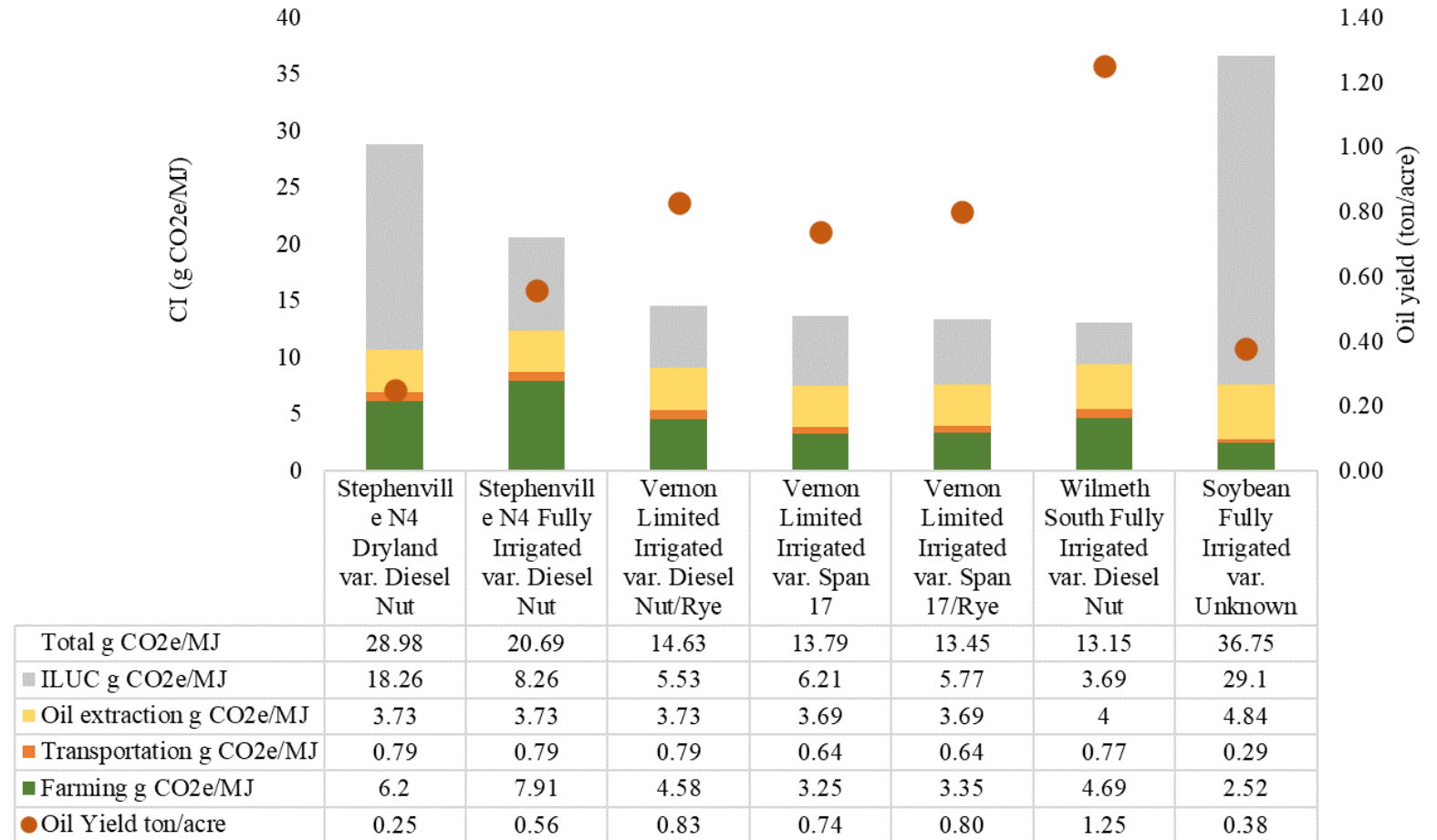
^b Institute of Agrifood Research and Technology (IRTA), Sustainability in Biosystems Program, Caldes de Montbui, Spain

What is Life Cycle Assessment (LCA)?



Carbon Intensity of Peanut and Soybean

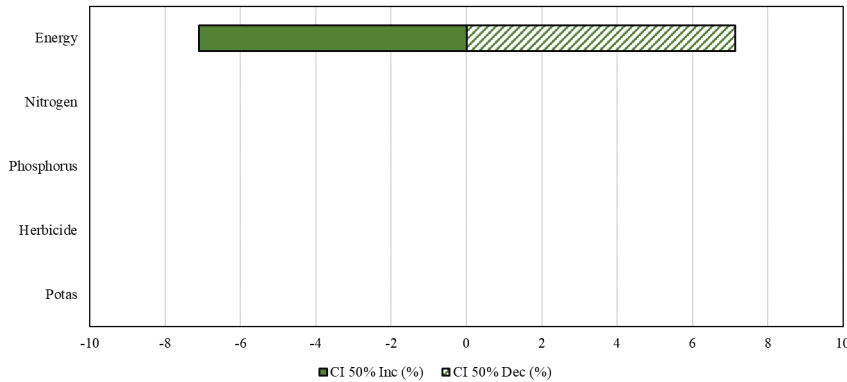
- Estimated CIs for the farming transportation, oil extraction, and ILUC of ‘Diesel Nut’ and edible peanuts in six scenarios and soybean oil production in the GREET model:
 - based on a functional unit of 1 kg
 - 100-year global warming potentials (GWP) (IPCC).
 - The highest CI is estimated in the N4 Dryland scenario, which is still much lower than that of soybean. The lowest CI is in the Wilmeth South scenario.



Hydrologic models can help run sensitivity analysis

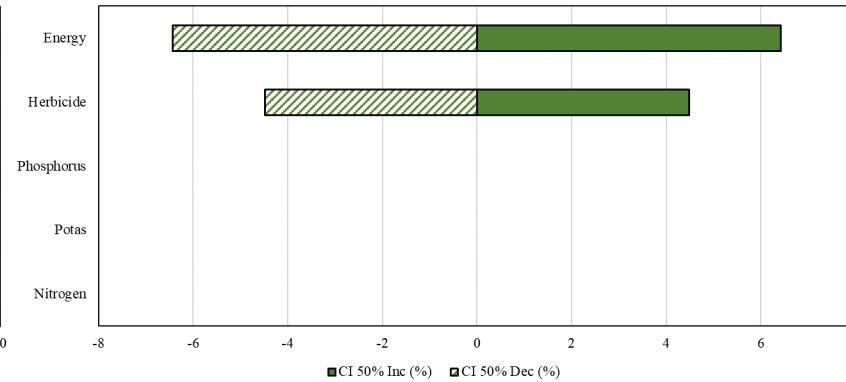
Base: 28.98 g CO₂e/MJ

Stephenville N4 Dryland var. Diesel Nut



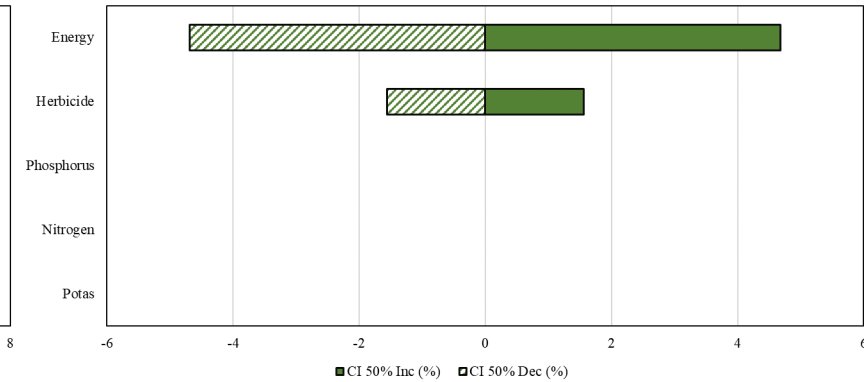
Base: 14.63 g CO₂e/MJ

Vernon Irrigated var. Diesel Nut/Rye



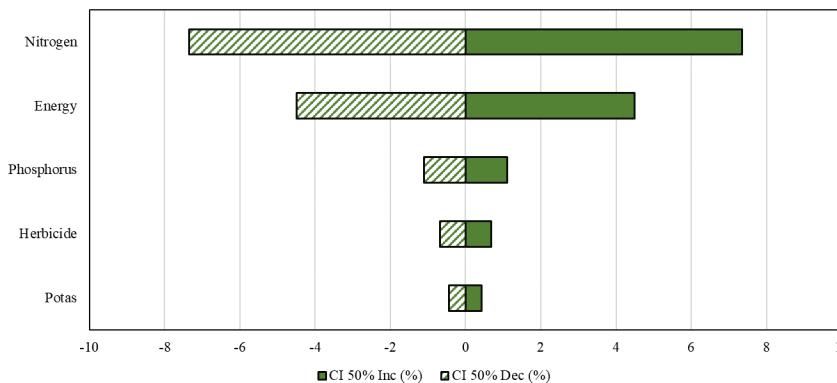
Base: 13.45 g CO₂e/MJ

Vernon Irrigated var. Span 17/Rye



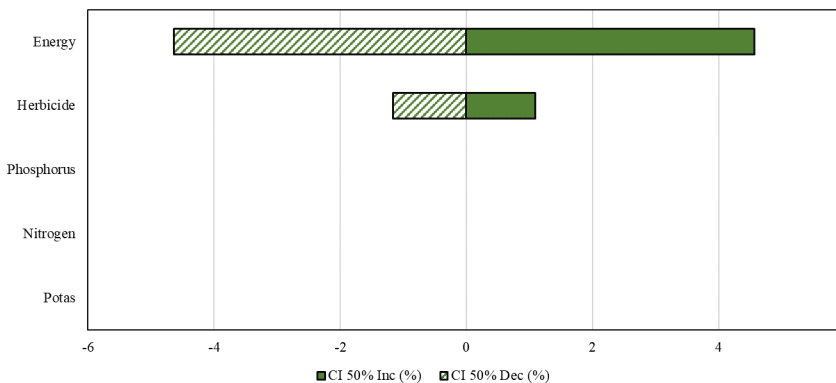
Base: 20.69 g CO₂e/MJ

Stephenville N4 Irrigated var. Diesel Nut



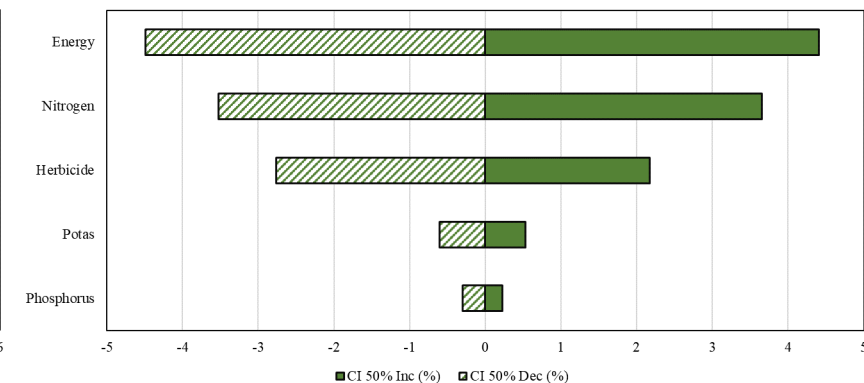
Base: 13.79 g CO₂e/MJ

Vernon Irrigated var. Span 17



Base: 13.5 g CO₂e/MJ

Wilmeth South Irrigated var. Diesel Nut



Research importance



The integration of hydrologic models and life cycle assessment (LCA) is becoming increasingly important due to the growing need to estimate carbon emissions from various production processes, driven by climate change concerns. LCA and, in particular, life cycle impact assessment (LCIA) are key tools for estimating carbon emissions, and they can be used to evaluate and compare best management practices (BMPs) within hydrological models.

LCA and hydrological models

LCA and LCIA analyses are often missing from hydrologic models, and LCA studies frequently lack the data that hydrological models can provide. For instance, hydrological models can aid in estimating water footprint—such as available water in a watershed (blue water) and soil moisture (green water)—which is a common challenge in LCA. Additionally, hydrologic models can provide valuable data on biomass and N₂O emissions, soil organic carbon (SOC) from soil plowing and harvesting, helping to complete life cycle data inventories (LCI). For instance, the required parameters for SOC modeling, are actual evapotranspiration, soil cover, soil humidity, and soil erosion by water that can be simulated using the Revised Universal Soil Loss Equation (RUSLE). This empirical model is a widely used model for estimating long-term average annual soil erosion rates, particularly sheet and rill erosion caused by rainfall and runoff.

SWAT inputs for LCA

Modeling saves time and cost

SWAT Input	Use in LCA
Weather data (precipitation, temp)	Impacts evapotranspiration and crop growth modeling; affects water footprint and yield in LCA.
Soil data (texture, bulk density)	Influences SOC modeling and erosion; affects emissions from soil disturbance and carbon sequestration.
Land use / land cover data	Key for estimating biomass production and soil erosion; helps define system boundaries in LCA.
Management practices (tillage, fert)	Defines scenarios for BMP comparison; input for LCI regarding inputs and operations.
Crop type and rotation	Determines crop yield, biomass, and residue; input for feedstock life cycle inventories.
Fertilizer and pesticide application	N ₂ O emissions estimation; connects to LCIA categories like eutrophication and global warming.
Irrigation data	Defines blue water use; directly feeds water footprint and energy for pumping in LCA.

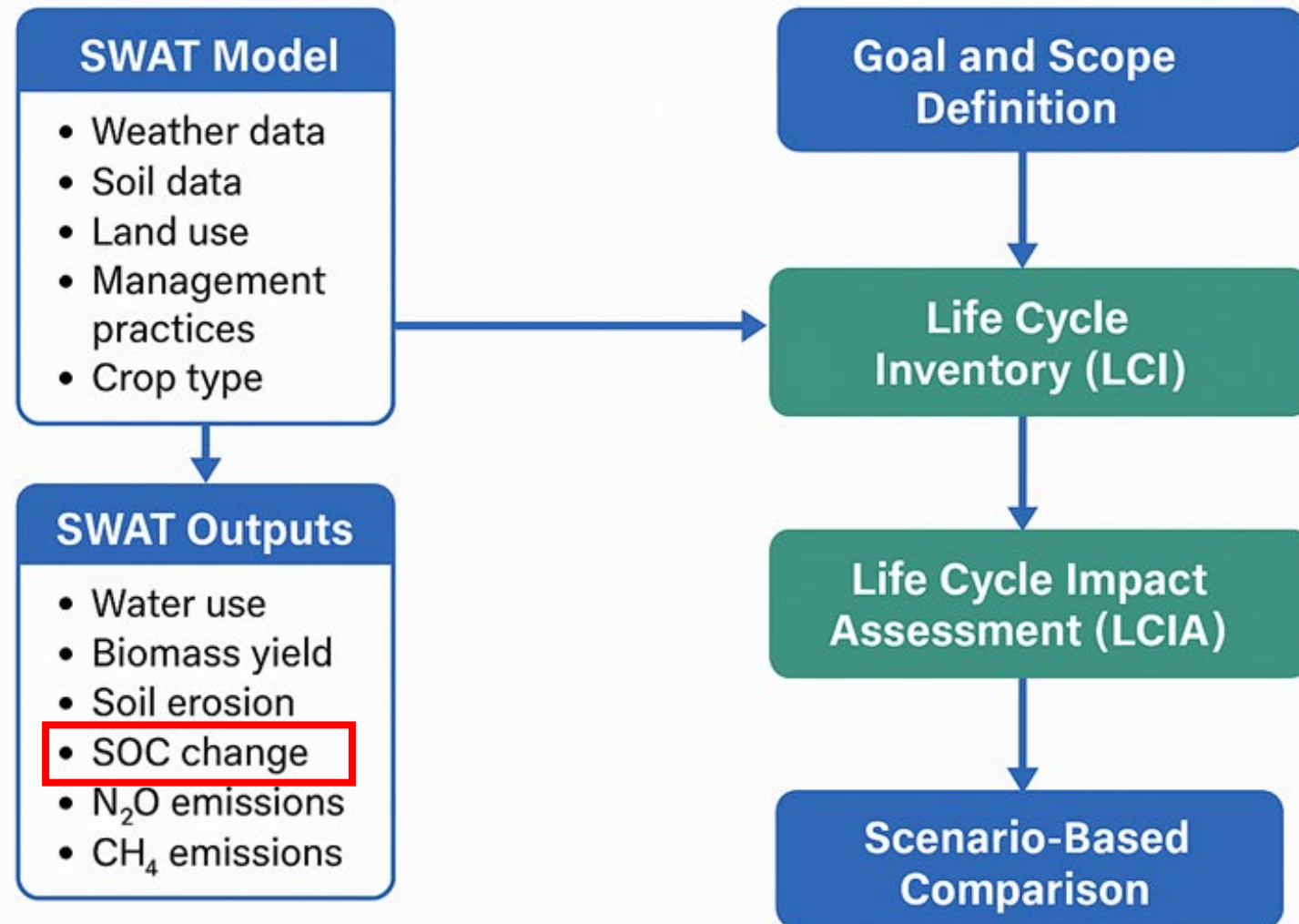
SWAT outputs for LCA

SWAT Output	Connection to LCA
Actual evapotranspiration (AET)	Required for modeling SOC; used in estimating water use (green water footprint).
Soil moisture	Used to estimate water availability; affects water stress impact categories.
Blue water use (stream withdrawal, irrigation)	Critical for water footprinting in LCA.
Green water use (soil water evaporation and transpiration)	Impacts water availability for crops and natural systems.
Soil erosion (via RUSLE)	Needed for LCI related to soil carbon loss; supports erosion impact categories.
Crop yield / biomass production	Direct input for calculating functional units (e.g., per ton biomass) and energy output.
Runoff and nutrient losses	N and P loading impact eutrophication categories in LCIA.
SOC change (if modeled via plugin)	Important for estimating net carbon fluxes; links to GHG emissions.
N ₂ O and CH ₄ emissions (with modifications)	Emissions from soils; direct input to GHG inventories and LCIA climate change category.

LCA components can improve using SWAT

LCA Phase	What SWAT Provides
Goal and scope definition	Helps define BMP scenarios, spatial scales, and temporal boundaries.
Inventory analysis (LCI)	Supplies data for crop yields, input rates, irrigation, erosion, water flows, and emissions.
Impact assessment (LCIA)	Provides emission data for categories like global warming, eutrophication, land use, and water scarcity.
Interpretation	Enables scenario comparison (e.g., BMPs vs. baseline) based on system-level emissions and resource use.

Integrating SWAT and LCA



SWAT+ Model Setup

Study Area:

- Fluvià watershed (Catalonia, Spain) — 97,070.32 ha

Inputs:

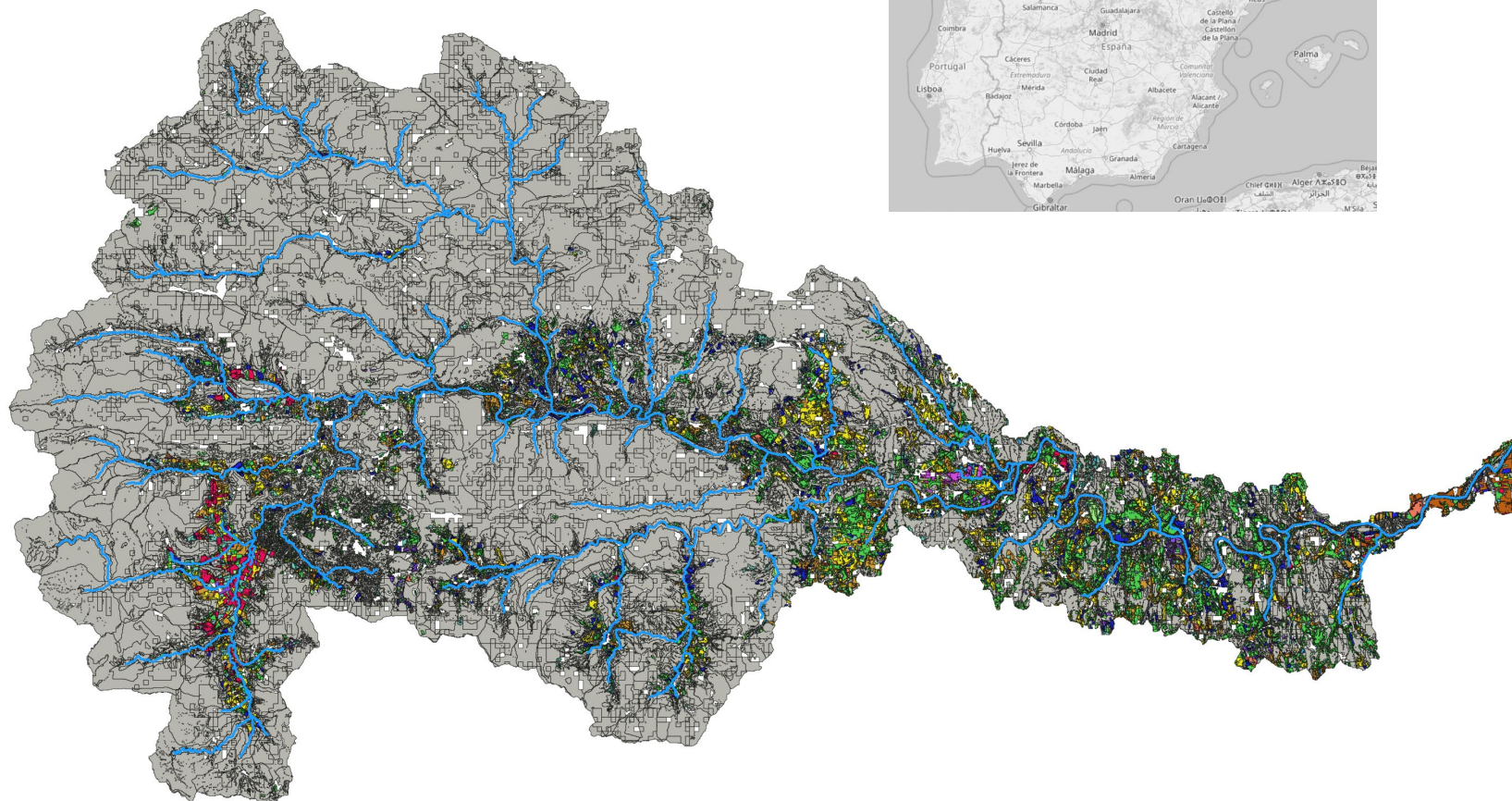
- DEM, land-use and soil maps, weather data (rainfall, temperature, solar radiation, humidity, wind)

Outputs:

- Water balance variables, yields, channels, soil organic carbon

Model Setup & Calibration:

- Simulation period: 2013-2023
- Spatial resolution: Hydrological Response Units (HRU), based on agr. land-uses
- 4820 selected HRUs (out of 9526)
- Crops simulated: wheat, wheat irrigated, barley, barley irrigated, canola, canola irrigated, rye irrigated
- Calibration against streamflow data (2013-2023), satellite ETa data (2019–2023), crop yields



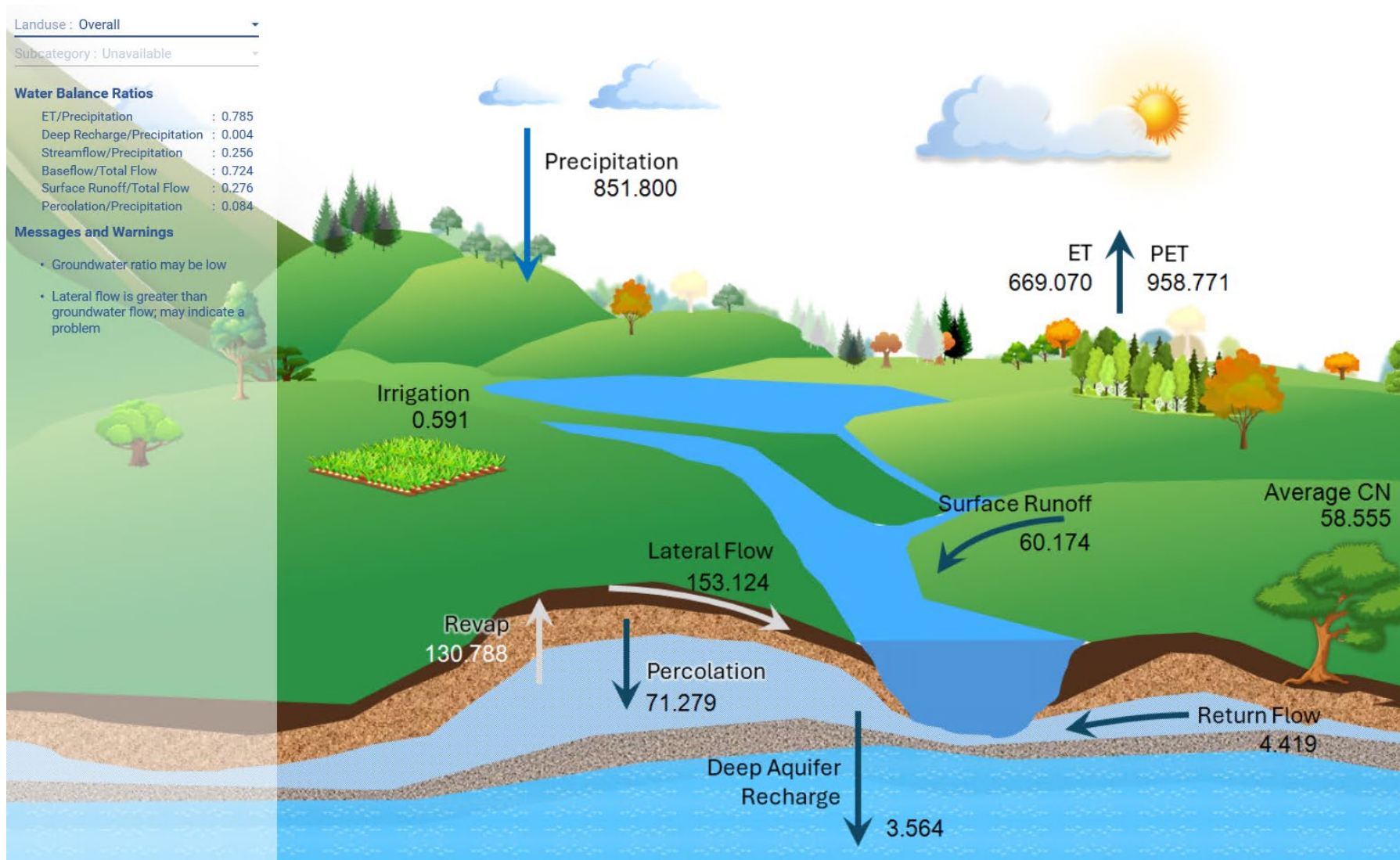
Watershed

Channel reaches (rivs1)

— Channel

Actual HRUs (hrus2)

- AGRL
- ALFA
- ALMD
- BARL
- BARN
- CANA
- CLVR
- CSIL
- FRST
- GRAS
- OATS
- OLIV
- ORCD
- PAST
- RNGB
- RYE
- RYEG
- SUNF
- URMD
- UTRN
- WATR
- WWHT

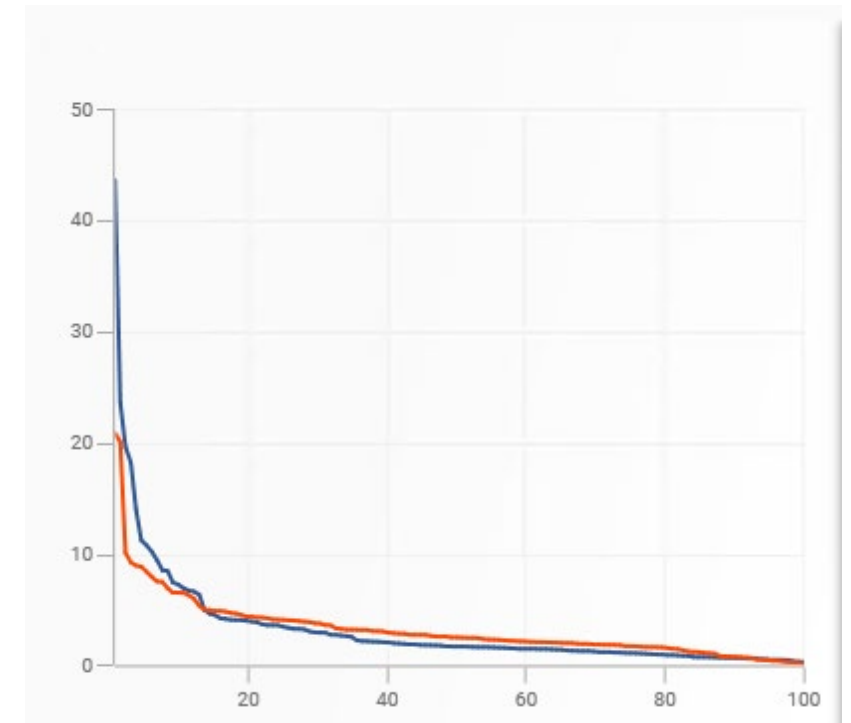
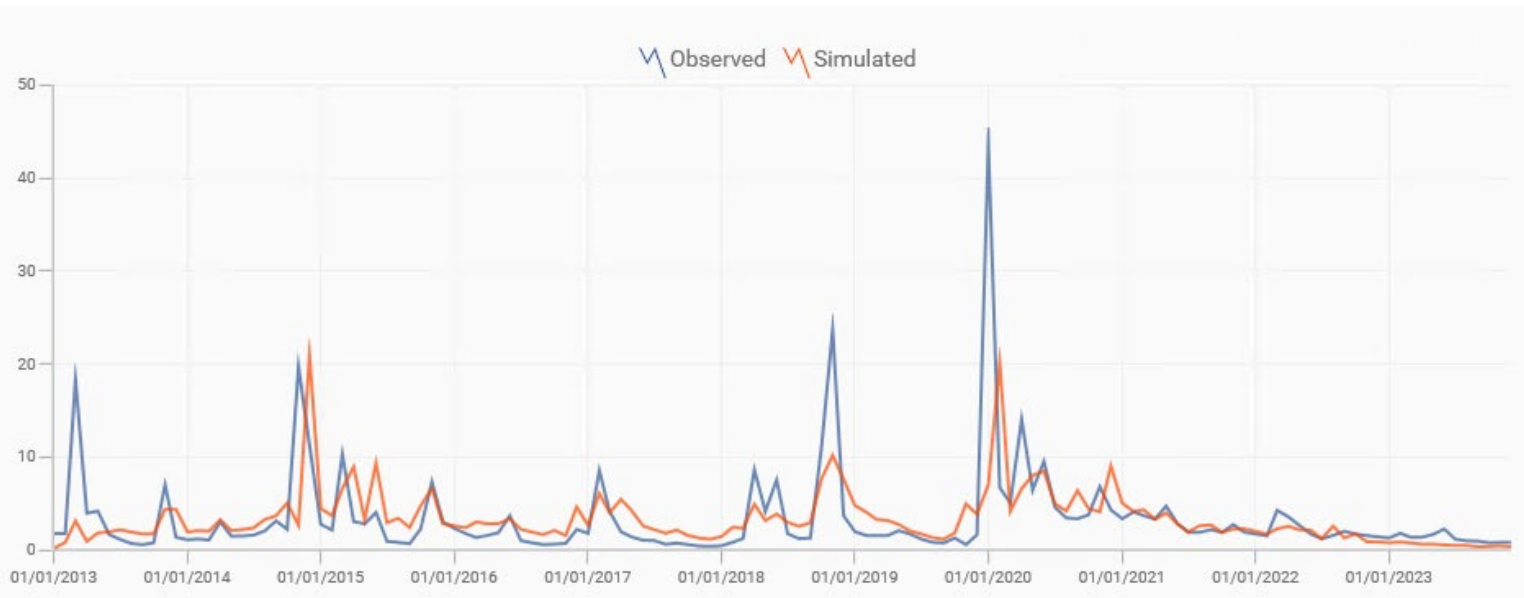


Calibrated parameters

Name	Change Type	Min	Max	Group	Curr. Best	Value	
cn2	Percent	-10.00000	-10.00000	hru	-10.000	-10.000	
esco	Replace	0.50000	0.50000	hru	0.500	0.500	
epco	Percent	0.73400	0.73400	hru	0.734	0.734	
canmx	Replace	38.40600	38.40600	hru	38.406	38.406	mm/H2O
perco	Replace	0.30000	0.30000	hru	0.300	0.300	fraction
lat_ttime	Percent	-2.24300	-2.24300	hru	-2.243	-2.243	days
cn3_swf	Replace	0.56900	0.56900	hru	0.569	0.569	
awc	Percent	2.35300	2.35300	sol	2.353	2.353	mm_H2O/mm
k	Percent	-15.00000	-15.00000	sol	-15.000	-15.000	mm/hr
revap_co	Replace	0.16700	0.16700	aqu	0.167	0.167	
flo_min	Percent	19.34700	19.34700	aqu	19.347	19.347	m
z	Percent	15.97000	15.97000	sol	15.970	15.970	mm
latq_co	Replace	0.05000	0.05000	hru	0.050	0.050	
bd	Percent	-29.74900	-29.74900	sol	-29.749	-29.749	mg/m**3
surlag	Replace	1.69800	1.69800	bsn	1.698	1.698	days
revap_min	Replace	45.32900	45.32900	aqu	45.329	45.329	m
petco	Replace	1.10000	1.10000	hru	1.100	1.100	fraction

Calibration outputs for discharge

PBIAS: 0.042
NSE: 0.18



Relative error for calibrated
average annual crop yields: 0.03 %

Comparison of observed and simulated yields

crop type	Observed yields [t/ha]	Simulated yields [t/ha]	Relative error
wwht	3.67	3.05293	-0.20127
barl	3.53	4.592562	0.232215
cana	2.55	2.305529	-0.10803
rye	3.80	2.324879	-0.63522
almd	0.55	0.591229	0.064543
alfa	7.99	7.519384	-0.06305
csil	12.01	9.876615	-0.21616
oats	2.32	2.548039	0.089309
oliv	0.43	0.535464	0.205541
sunf	1.76	2.839274	0.379066
appl	7.20	6.397826	-0.1251
agrl	1.34	2.161055	0.381452
			0.000274

Yields data are obtained from the Spanish Government
(Ministerio de Agricultura, Pesca y Alimentación)

<https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica#ancla2>

SWAT+ carbon modeling output

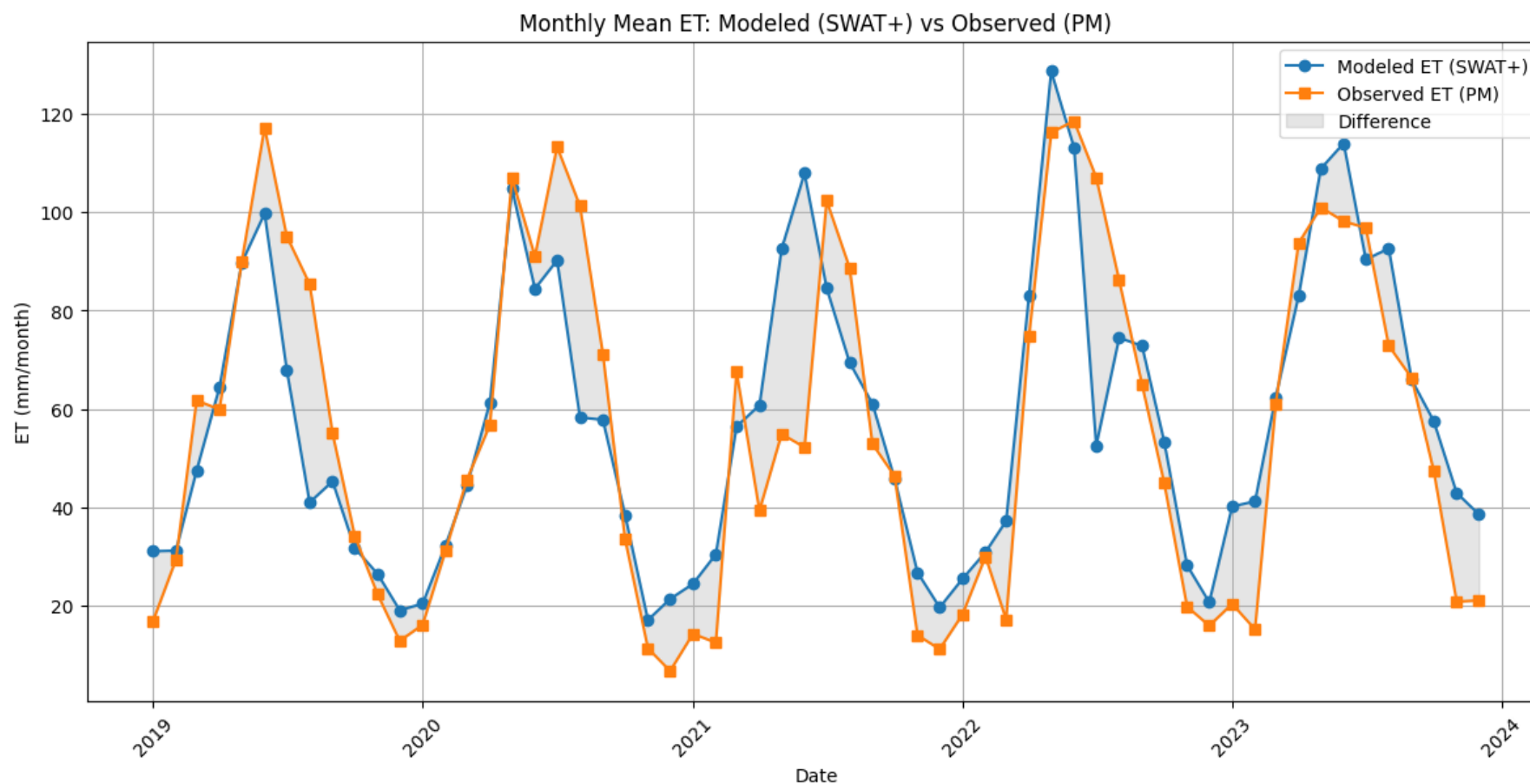
7	n	y	n			
8	crop_yld	mgtout	hydcon	fdcout		
9	b	y	n	n		
10	objects		daily	monthly	yearly	avann
11	basin_wb		n	y	y	y
12	basin_nb		n	n	y	y
13	basin_ls		n	n	y	y
14	basin_pw		n	y	y	y
15	basin_aqu		n	y	y	y
16	basin_res		n	n	y	y
17	basin_cha		n	y	y	y
18	basin_sd_cha		n	n	y	y
19	basin_psc		n	n	y	y
20	region_wb		n	n	y	y
21	region_nb		n	n	y	y
22	region_ls		n	n	y	y
23	region_pw		n	n	y	y
24	region_aqu		n	n	y	y
25	region_res		n	n	y	y
26	region_sd_cha		n	n	y	y
27	region_psc		n	n	y	y
28	water_allo		n	n	y	y
29	lsunit_wb		n	n	y	y
30	lsunit_nb		n	n	y	y
31	lsunit_ls		n	n	y	y
32	lsunit_pw		n	n	y	y
33	hru_wb		n	y	y	y
34	hru_nb		n	n	y	y
35	hru_ls		n	n	y	y
36	hru_pw		n	y	y	y
37	hru_cb		n	n	y	y
38	hru-lte_wb		n	n	y	y
39	hru-lte_nb		n	n	y	y
40	hru-lte_ls		n	n	y	y

codes.bsn

codes.bsn: written by SWAT+ Toolbox 3.0.7 - 2025/5/13 20:35:41

1	pet_file	wq_file	pet	event	crack	rtu_wq	sed_det	rte_cha	deg_cha	wq_cha	rte_pest	cn	c_fact	carbon	baseflo
2			1	0	0	0	0	1	0	1	0	0	0	1	0
3	null	null													
4															

Results of modeled (SWAT+) vs observed ETa data

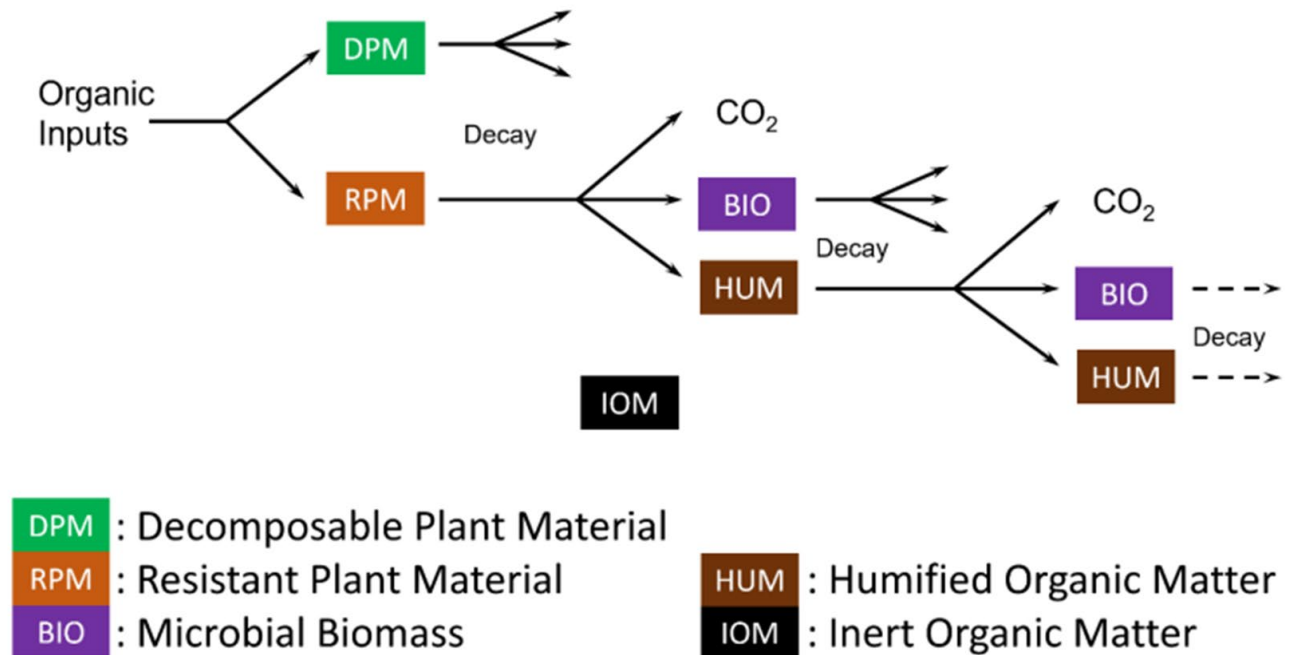


PBIAS: -3.30%
R²: 0.72

Roth-C for SOC modeling

The first version of RothC created by David Jenkinson and James Rayner in 1977 (Jenkinson and Rayner, 1977).

Estimating SOC based on RothC version by Mondini et al. (2017).



Selected HRUs based on crops and irrigation type

SWAT+					
site	crop type	area	lat	lon	elev
					m
hru0397	wwht	1.10467	42.24337	2.69182	386.294
hru0705	wwht_irr	6.05254	42.27135	2.53187	401.512
hru0013	barl	0.19389	42.33638	2.45607	945.667
hru0706	barl_irr	1.5162	42.27031	2.52848	412.522
hru0845	cana	0.13209	42.23972	2.59821	237.5
hru1171	cana_irr	0.06379	42.2165	2.61773	229
hru0715	rye_irr	0.48954	42.27091	2.52093	418.571
hru1919	rye_irr	0.52597	42.21291	2.62018	206.875

Roth C model Set up

- Input data: Soil Data (DSOLMap)
- Climate Data over 10 years: 2013-2022
- Crop yields from SWAT+ over the period 2013-2022.
- Depth selected was 30 cm.
- RothC DPM-RPM ratio was assumed as 1.44.
- Initial SOC per site estimated based on soil organic carbon content, bulk density, soil depth and corrected by coarse fraction.

Roth C model set up and assumptions

Fractions of SOC pools estimated based on the pretransfer function by Weihermüller et al. (2013) and inert pool based on Falloon et al. (1998).

- Resource-to-product ratios per crop type for West Europe from Ronzon et al. (2015)
- Root-to-shoot ratios per crop type from IPCC (2006), Chap. 11, Table 11.2.
- Total carbon inputs to soil consisted of crop residues and root fraction.
- Carbon content in the aboveground residues and roots assumed to be 50%.
- Harvest month was June except for site hru0845 and hru1171 which was May.

Carbon modeling

DPM : Decomposable Plant Material
RPM : Resistant Plant Material
BIO : Microbial Biomass

HUM : Humified Organic Matter
IOM : Inert Organic Matter

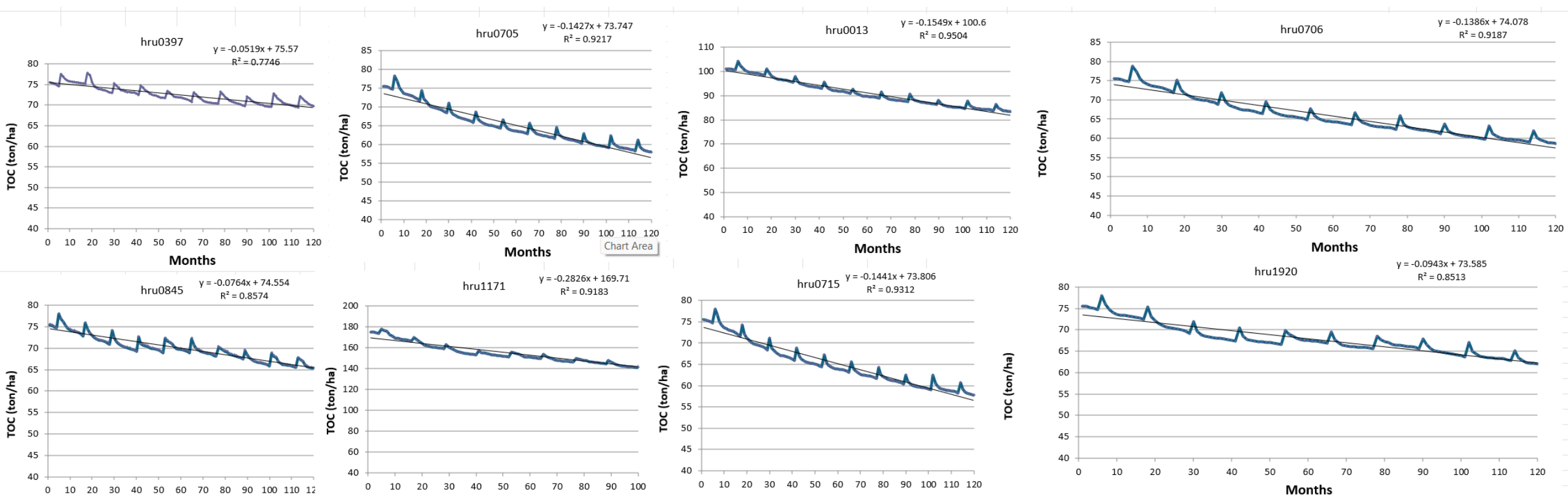
DPM	RPM	Bio	Hum	IOM	TOC initial
rate constant	rate constant	rate constant	rate constant		
10	0.30	0.66	0.02		
Initial Soil Pool values					
Initial	Initial	Initial	Initial	Initial	Initial
t C/ha	t C/ha	t C/ha	t C/ha	t C/ha	t C/ha
0.01	9.51	1.31	58.06	6.76	75.66
0.01	9.51	1.31	58.06	6.76	75.66
- 0.15	12.44	1.76	77.71	9.42	101.17
0.01	9.51	1.31	58.06	6.76	75.66
0.01	9.51	1.31	58.06	6.76	75.66
- 1.01	22.85	2.97	132.59	17.58	174.97
0.01	9.51	1.31	58.06	6.76	75.66
0.01	9.51	1.31	58.06	6.76	75.66

Roth C outputs

Initial SOC per site estimated based on soil organic carbon content, bulk density, soil depth and corrected by coarse fraction.

Input RothC					Outputs RothC		
Initial	Depth	Clay	DPM/RPM ratio	Initial SOC	Average Annual SOC Change	Delta SOC (2013-2022) (Ton C/ha)	Final SOC (2022)
t C/ha	cm	%		t C/ha	t C/ha	t C/ha	t C/ha
75.66	30.00	28.34	1.44	75.66	- 0.05	- 5.72	69.78
75.66	30.00	28.34	1.44	75.66	- 0.15	- 17.52	58.02
101.17	30.00	33.66	1.44	101.17	- 0.15	- 17.68	83.44
75.66	30.00	28.34	1.44	75.66	- 0.14	- 16.88	58.66
75.66	30.00	28.34	1.44	75.66	- 0.09	- 10.15	65.31
174.97	30.00	18.84	1.44	174.97	- 0.31	- 37.40	137.64
75.66	30.00	28.34	1.44	75.66	- 0.15	- 17.75	57.79
75.66	30.00	28.34	1.44	75.66	- 0.11	- 13.45	62.08

Roth C outputs (Not calibrated yet)



Future works

Calibration and validation of carbon in SWAT+ and Roth C

Comparison of carbon outputs in SWAT+ and ROTH C

Integration of Roth C and SWAT+

Working on other components of LCA

Thank you! Any Questions?

