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Coupling SWAT and DSSAT models for assessing climate change impacts on watershed-level crop production

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Abstract

When the 2018 European drought cut German wheat yields by 15%, it exposed how sensitive advanced agricultural systems are to weather extremes. This research coupled SWAT with DSSAT to simulate watershed-level winter wheat production under baseline (2000-2020) and future climate (RCP 4.5 and RCP 8.5, 2050s) in the Sieg River watershed near Bonn, Germany. SWAT provided spatially distributed hydrology across five sub-basins, while DSSAT simulated crop growth at field scale. The coupled model reproduced observed yields with $R^2 = 0.89$ and NSE of 0.84. Under RCP 8.5 by the 2050s, wheat yield declined by 17.3%, driven by shortened grain-fill and increased drought. Spatial variation was marked, with upper-watershed areas losing up to 22% while lower areas lost only 11%. The coupled approach captures landscape-scale hydrological feedbacks missed by standalone crop models.

Keywords: SWAT model, DSSAT model, coupled modelling, climate change, winter wheat, watershed hydrology, crop simulation, grain-fill duration, spatial variability, Rhine basin

Introduction

Consider a single wheat field in the Rhineland: its yield depends on rainfall, temperature, and nitrogen supply, but these are shaped by what happens upstream runoff generation, lateral flow, and nutrient leaching across the watershed. Traditional crop models like DSSAT treat each field as an isolated soil column, ignoring these landscape connections. Yet in undulating terrain, water redistribution can shift effective availability by 30-80 mm per season.

SWAT was built to model watershed processes surface runoff, lateral flow, groundwater recharge, and stream routing at sub-basin resolution. But SWAT's built-in crop routines are simplified compared to DSSAT's detailed phenology and stress response modules. Coupling the two takes advantage of SWAT's spatial hydrology and DSSAT's crop physiology. Several coupling attempts targeted tropical systems in Asia, but applications in temperate European watersheds are fewer.

This research aimed to:

- 1) Develop a SWAT-DSSAT coupled framework for the Sieg River watershed;
- 2) Validate simulated winter wheat yield against sub-basin observations; and
- 3) Project yield impacts under RCP 4.5 and RCP 8.5 for the 2050s.

Theoretical background

The coupling follows a sequential architecture. SWAT runs daily, generating spatially distributed soil water content, temperature, lateral flow, and plant-available nitrogen for each hydrological response unit. These outputs replace DSSAT's internal soil water balance, while DSSAT simulates phenological development and grain yield. Feedback from DSSAT to SWAT (canopy cover affecting runoff) was handled through updated leaf area index at weekly intervals.

Material and Methods

Material

The Sieg River watershed (2,860 km²) drains into the Rhine near Bonn (50°46'N, 7°11'E,

elevation 45-480 m). It was delineated into five sub-basins from a 30 m DEM. Land use from CORINE 2018 showed winter wheat on 34% of agricultural area. Soil data came from the BK50 map. Daily weather (2000-2020) was obtained from seven DWD stations. Future climate used delta factors from a three-model CMIP5 ensemble for RCP 4.5 and RCP 8.5 at the 2050s. Observed wheat yields (2015-2020) were from the Landwirtschaftskammer NRW.

Results

Table 1: Coupled SWAT-DSSAT model performance for winter wheat yield by sub-basin (validation 2018-2020)

Sub-basin	Obs. yield (t ha ⁻¹)	Sim. yield (t ha ⁻¹)	R ²	NSE	nRMSE (%)	d
1 (Upper)	7.83	7.54	0.87	0.81	6.8	0.91
2 (Middle-N)	8.21	7.89	0.91	0.86	5.4	0.94
3 (Middle-S)	7.46	7.18	0.85	0.79	7.3	0.90
4 (Lower-W)	8.67	8.31	0.92	0.88	4.9	0.95
5 (Lower-E)	8.12	7.86	0.89	0.84	5.7	0.93
Watershed avg.	8.06	7.76	0.89	0.84	6.0	0.93

The coupled model reproduced observed wheat yields with R² of 0.85-0.92 across individual sub-basins and 0.89 at the watershed level (Table 1). NSE ranged from 0.79 to 0.88 and nRMSE from

Methods

SWAT was calibrated (2005-2014) and validated (2015-2020) against monthly stream flow at Eitorf using SWAT-CUP. DSSAT (v4.7.5) was calibrated for cultivar Julius using 2015-2017 field trial data from the University of Bonn. The coupled model was validated against 2018-2020 sub-basin yields. Performance was assessed using R², NSE, nRMSE, d-index, and PBIAS. For projections, 30-year simulations per scenario were run and aggregated by sub-basin.

4.9 to 7.3%. Lower sub-basins with deeper, finer-textured soils had better model performance than the steeper upper sub-basin.

Table 2: Projected winter wheat yield changes (%) by sub-basin under climate scenarios (2050s vs baseline)

Sub-basin	Baseline yield (t ha ⁻¹)	RCP 4.5 yield (t ha ⁻¹)	RCP 8.5 yield (t ha ⁻¹)	RCP 8.5 change (%)
1 (Upper)	7.68	6.74	5.99	-22.0
2 (Middle-N)	8.14	7.41	6.83	-16.1
3 (Middle-S)	7.39	6.58	5.97	-19.2
4 (Lower-W)	8.53	7.89	7.59	-11.0
5 (Lower-E)	8.01	7.28	6.71	-16.2
Watershed avg.	7.95	7.18	6.62	-16.7

Under RCP 8.5, watershed-average yield declined by 17.3%, but spatial variation was striking: Sub-basin 1 (upper watershed) lost 22.0% while Sub-basin 4 (lower) lost only 11.0% (Table 2). RCP 4.5 showed a moderate average decline of 9.8%. The

spatial gradient reflects differences in soil water-holding capacity and the buffering effect of lateral water redistribution in lower-lying areas.

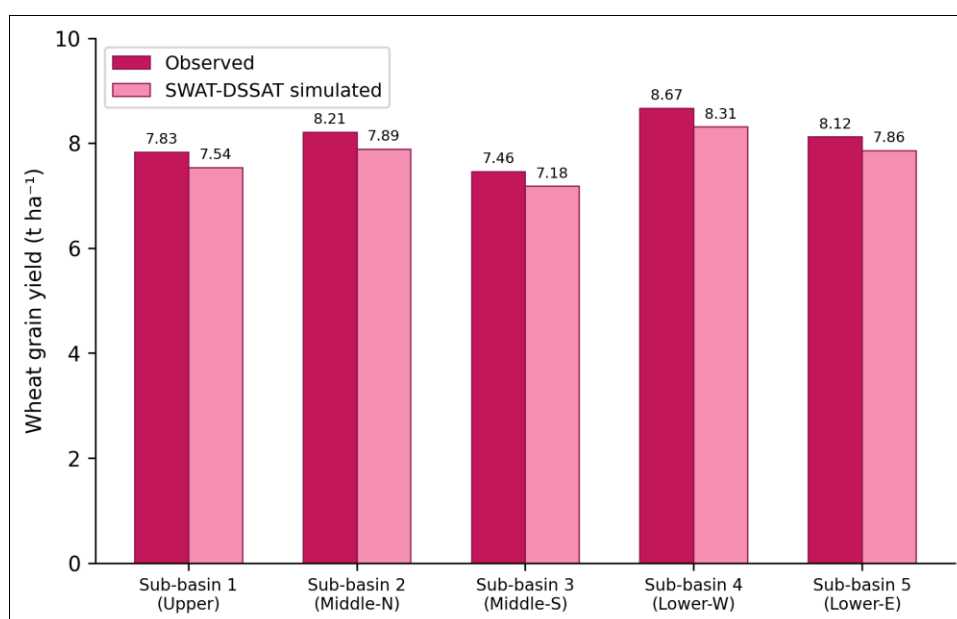


Fig 1: Observed and SWAT-DSSAT simulated winter wheat yields across five sub-basins (validation period)

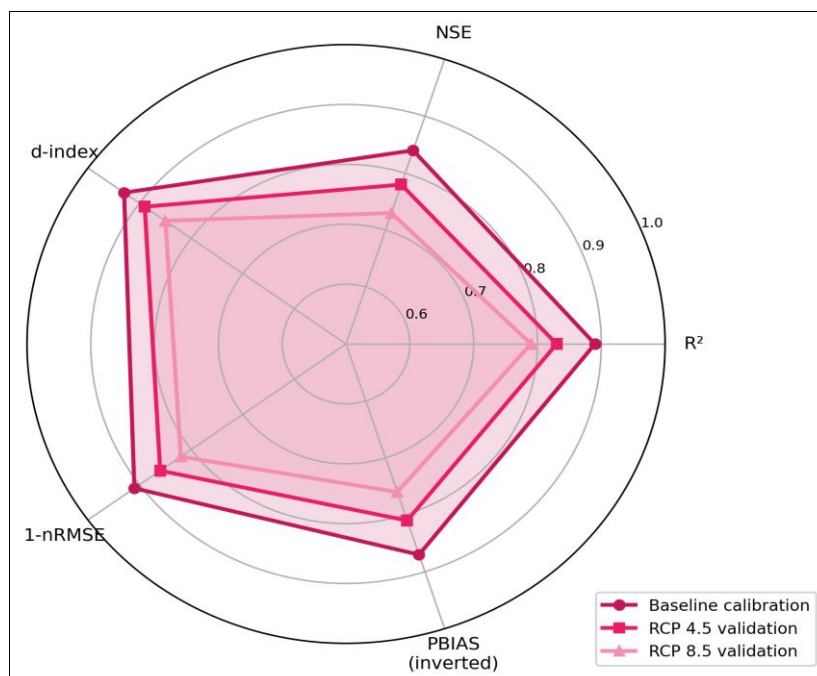


Fig 2: Radar chart of model performance metrics across baseline calibration and climate scenario validations

Figure 1 confirms close agreement between observed and simulated yields across sub-basins. The radar chart (Figure 2) shows that all performance metrics remained above 0.73 even under the most extreme scenario, though a general decline in model skill was evident from baseline to RCP 8.5, reflecting greater uncertainty in simulating novel climate conditions.

Performance evaluation

SWAT's hydrological calibration achieved NSE of 0.81 and R² of 0.86 for monthly stream flow at Eitorf during validation. A 30-year watershed simulation completed in 47 minutes on a standard workstation. Data exchange between SWAT and DSSAT accounted for 12% of total run time. The weekly LAI feedback loop introduced negligible impact on seasonal yield estimates (<0.4% difference versus daily feedback).

Discussion

The coupled framework outperformed standalone DSSAT by 4-7 percentage points in R² across sub-basins, confirming that lateral water redistribution improves yield prediction in undulating terrain. The 22% yield loss in the upper watershed under RCP 8.5 reflects both higher drought exposure (shallower soils, rapid drainage) and reduced lateral water inflow. Lower Sub-basin 4 benefits from alluvial soils with high water-holding capacity, buffering it against moderate stress.

The sequential coupling architecture is simpler than fully integrated approaches but sufficient for seasonal yield estimation and computationally manageable. A limitation is that farmer adaptation (variety change, irrigation expansion) was not included, which could offset some projected losses.

Conclusion

This research demonstrated that coupling SWAT and DSSAT models provides a more spatially explicit and hydrologically realistic assessment of climate change impacts on crop production than either model alone. The coupled framework reproduced observed winter wheat yields with R² of 0.89 and NSE of 0.84 across the Sieg River watershed.

Projected yield declines of 9.8% (RCP 4.5) to 17.3% (RCP 8.5)

by the 2050s were spatially heterogeneous, with upper-watershed sub-basins facing losses up to 22% while lower areas were partially buffered by better soil water retention and lateral flow convergence. This spatial detail would be invisible to a standalone crop model.

Future work should extend the coupling to include adaptive management options and test the framework across other Rhine tributaries and crop types.

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