

Supplementary Information for

“Modeling Land Use and Management Practices Impacts on Soil Organic Carbon Loss in an Agricultural Watershed in the Mid-Atlantic Region”

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1. Percentage area of each land-use type in the Upper Maurice River Watershed in southern New Jersey

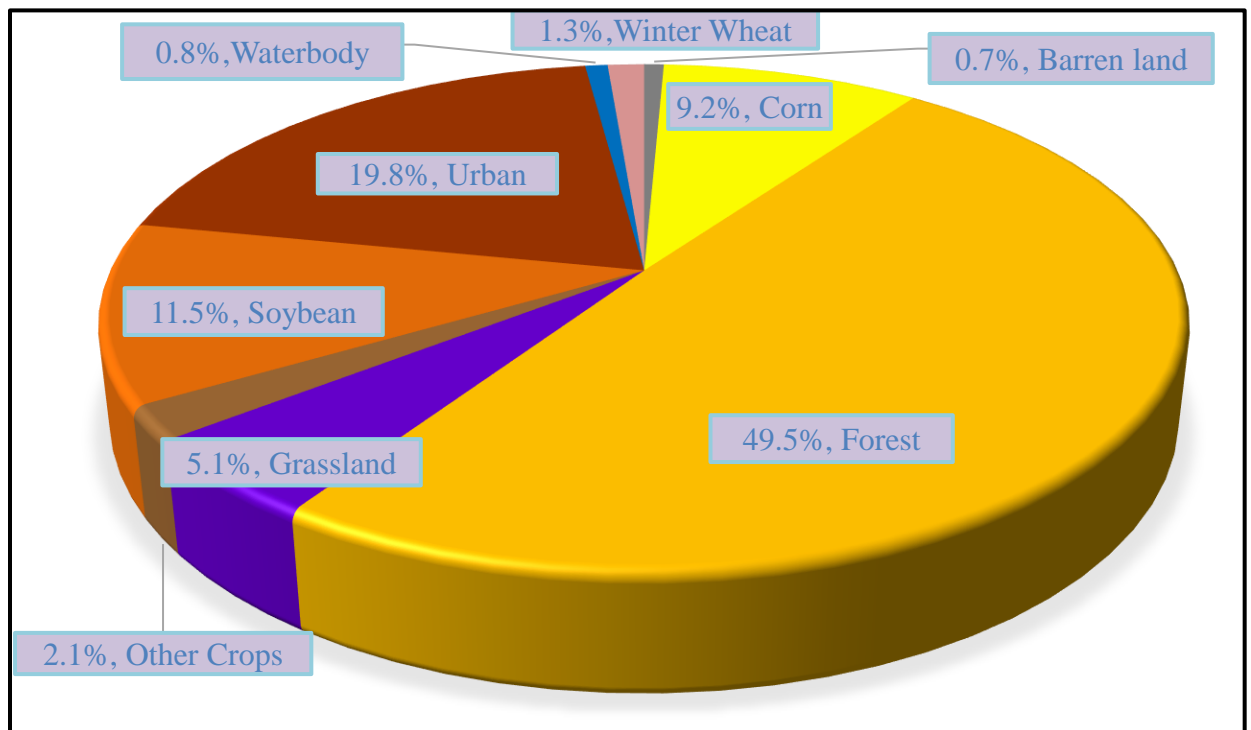


Figure S1. Percentage area of each land-use type in the Upper Maurice River Watershed (UMRW) in southern New Jersey.

Table S1 Detailed land use types in the study area (excluding urban and water areas).

Land use types		Land uses in the watershed
Forest		Wetland-forested
		Peppers
		Forest-evergreen
		Forest-deciduous
		Forest-mixed
		Orchard
Grass		Slender wheatgrass
		Hay
		Pasture
		Range-brush
Barren land		---
Agriculture	CS	Corn-Soybean
	CSS	Corn-soybean-soybean
	CSW	Corn-soybean-winter wheat
	Other Crops	Sweet potato
		Barley
		Peas
		Grain sorghum
		Potato
		Strawberry
		Pinto bean
		Alfalfa

2. Climatic Conditions

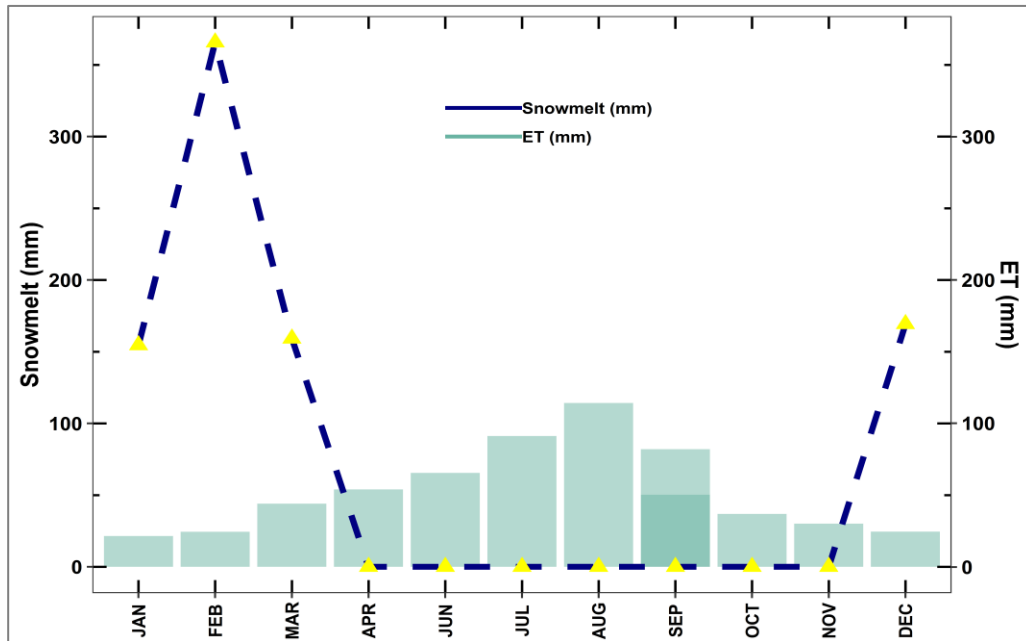


Figure S2. Monthly average evapotranspiration and snowmelt from 2000-2020 in the UMRW.

3. SWAT-C Model

Within the SWAT-C model, SOM turnover rates are influenced by nonlinear processes governed by environmental and management factors. SOM in the soil is divided into five primary pools: slow humus, passive humus, metabolic litter, structural litter, and microbial biomass. Carbon (C) and nitrogen (N) flow among these pools through various pathways, affected by both biotic and abiotic factors (Fig. 2 in the main text). The turnover time for different pools can range from days for metabolic litter to thousands of years for passive humus. The decomposition and transformation rates of C and N among slow humus, passive humus, metabolic litter, structural litter, and microbial biomass pools are influenced by factors such as soil temperature, soil water content, soil texture, land management, soil aeration, and soil conditions like the soil C/N ratio [46]. Carbon movement within the soil profile is also connected to hydrological processes, including percolation, surface runoff, lateral flow, and erosion. Tillage and percolation can cause a vertical redistribution of SOM, while surface runoff, lateral flow, and erosion contribute to the lateral redistribution of SOM.

The quantity of SOC in the soil profile can be lost through soil erosion, leaching, and surface runoff. The amount of dissolved organic carbon (DOC) is calculated as the product of an allocation coefficient of microbial biomass into the soil solution (ABL; fraction) and the stock of microbial biomass in a soil layer. (SOL_{BMC} ; kgC/ha). ABL is calculated as [46]:

$$ABL = 1 - \exp \left[-\frac{V}{SW + Kd \times DB \times THICK} \right] \quad S1$$

$$V = \text{surf}q + \text{sol_prk} + \text{flat} \quad S2$$

$$Kd = K_{OC} \times SOC_con \quad S3$$

where SW is soil water content (mm); K_d is solid-liquid partition coefficient; K_{OC} is organic carbon-water partition coefficient for microbial biomass (m³/Mg); SOC_{con} is the concentration of SOC (not including litter; Mg/Mg); DB is soil bulk density (Mg/m³); THICK is the thickness of a soil layer (mm); and surfq, sol_prk, and flat are surface runoff, percolation, and lateral flow (mm), respectively, from a soil layer. SWAT models soil water by simulating all relevant terrestrial hydrological processes, such as snowfall and melt, vadose zone processes (including infiltration, evaporation, plant uptake, lateral flows, and percolation), and groundwater flow. The United States Department of Agriculture (USDA) Soil Conservation Service (SCS) Curve Number (CN) method is employed to partition surface runoff and infiltrated water. A kinematic storage model is utilized to estimate lateral flow, while return flow is simulated by creating a shallow aquifer [32]. Evapotranspiration is calculated with the widely applied Penman-Monteith method [32]. Considering the amount of DOC in the soil solution (ABL×SOL_BMC) and the simulated volume of runoff, lateral flow, and percolation, it is easy to determine the transfer and loss of DOC through the water cycle. The percolated DOC (the product of percolated water volume and DOC concentration) is either added to the lower soil layer or leached out from the soil bottom. Alongside runoff and lateral flow, DOC exits the soil column and enters rivers.

Water erosion in SWAT is computed with MUSLE as a function of surface residue amount, soil erodibility, total runoff volume and peak runoff rate, conservation practices, and slope length and steepness.

$$sed = 11.8 * (Q_{surf} * q_{peak} * Area_{hru})^{0.56} \quad S4$$

$$K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG$$

S4

where sed is the sediment yield on a given day (Mg), Q_{surf} is the surface runoff volume (mm H_2O ha^{-1}), q_{peak} is the peak runoff rate ($m^3 s^{-1}$), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor that is determined by sand, clay, silt, and organic C content, C_{USLE} is the USLE cover and management factor (dimensionless), P_{USLE} is the USLE support practice factor (dimensionless), LS_{USLE} is the USLE topographic factor (dimensionless), $CFRG$ is the coarse fragment factor (dimensionless). C_{USLE} is land cover specific, with grassland having smaller values than row crops. Residue collection influences this factor by reducing surface cover, leading to more erosion.

The concentration of SOC in eroded soils is higher than that in surface soils due to enrichment, as SOC particles are primarily associated with clay. The concentration of SOC in eroded mineral soils is the result of the concentration of SOC in topsoil multiplied by an enrichment ratio. To calculate the amount of eroded SOC, we employ the following equation:

$$sedC = sed * conc_{SOC,soil} * ER \quad S5$$

where $sedC$ is the eroded C yield on a given day (Mg), $conc_{SOC,soil}$ is the fraction of SOC in the topsoil layer where eroded sediment comes from, ER is the ratio of the concentration of organic C transported with the sediment to the concentration in the soil surface layer.

A combined factor (CMF), which is modified based on Izaurre et al. [46], is calculated to represent the integrated effect of all factors on SOM decomposition. In the SWAT-C model, CMF is calculated as:

$$CMF = \begin{cases} \sqrt{TMPF * WATF * OXGF * TILLF}; & CMF \leq 10 \\ 10; & CMF > 10 \end{cases} \quad S6$$

where TMPF, WATF, OXGF, and TILLF represent the soil temperature factor, soil water factor, oxygen factor, and tillage factor, respectively. A non-linear oxygen factor calculation method that associates oxygen availability with soil depth was applied [46].

The TMPF method (Eq. S7) used here is the following Kemanian et al. [44]. When the soil temperature is at or below 35°C, there is a positive correlation between TMPF and soil temperature, indicating that the SOC decomposition rate increases with temperature. However, when the temperature exceeds 35°C, soil temperature becomes a limiting factor for SOC decomposition.

$$TMPF = \frac{(sol_{tmp}-\alpha)^{\varepsilon}*(\gamma-sol_{tmp})}{(\beta-\alpha)^{\varepsilon}*(\gamma-\beta)}; \quad S7a$$

where sol_{tmp} is soil temperature in Celsius (°C), α, β, γ are temperature parameters, and the values of α, β, γ are defined as -5, 35, and 50 °C, respectively. ε is expressed as

$$\varepsilon = \frac{\alpha-\beta}{\beta-\gamma} \quad S7b$$

Eq. S8 outlines the calculation method for WATF as a function of soil water content, field capacity, permanent wilting point, soil porosity, and soil voids [44].

$$WATF = W_1 * W_2 \quad S8a$$

$$W_1 = (1 + 4 * (1 - X_1)) * X_1^4 \quad S8b$$

$$W_2 = 0.5 + 0.5 * \frac{X_2}{X_2 + \exp(-20 * X_2)} \quad S8c$$

where X_1 and X_1 are calculated as

$$X_1 = \begin{cases} 0.4 * \frac{sol_{st}}{sol_{wpmm}}; & sol_{st} \leq sol_{wpmm} \\ 0.4 + 0.6 * \frac{sol_{st} - sol_{wpmm}}{sol_{fc} - sol_{wpmm}}; & sol_{wpmm} < sol_{st} \leq FC \\ 1; & sol_{st} > FC \end{cases} \quad S8d$$

$$X_2 = \begin{cases} 0.2 + 0.8 * \frac{sol_{void} - 0.1}{sol_{por} - 0.1}; & sol_{void} \geq 0.1 \\ 0.2 * \frac{sol_{void}}{0.1}; & 0 \leq sol_{void} < 0.1 \end{cases} \quad S8e$$

where $sol_{void} = sol_{por} * \left(1 - \frac{sol_{st}}{sol_{sat}}\right)$; sol_{sat} is the amount of soil water held in the soil layer at saturation. sol_{por} represents soil porosity.

Tillage practices influence the distribution of SOC in the topsoil layers and promote the decomposition of soil organic matter (SOM). In the SWAT model, when tillage occurs, SOC is mixed to the depth of tillage according to the tillage mixing efficiency. Here, the method from the DeNitrification-DeComposition (DNDC) model as used to simulate tillage effects (TILLF) on decomposition rate as shown in Eq. S9,

$$TILLF = \begin{cases} till_{fact}; & top\ 10\ mm \\ till_{fact}; & sol_{z_i} \leq tillage_{depth} \\ 1 + (till_{fact} - 1) * \frac{(tillage_{depth} - sol_{z_{i-1}})}{sol_{z_i} - sol_{z_{i-1}}}; & sol_{z_{i-1}} < tillage_{depth} \text{ and } sol_{z_i} > tillage_{depth} \end{cases} \quad S9a$$

where $tillage_{depth}$ is the depth of tillage, $till_{fact}$ is the tillage factor that varies with tillage depth (mm). The $till_{fact}$ is defined as

$$till_{fact} = \begin{cases} 1.0; & tillage_{depth} \leq 50 \text{ mm} \\ 3.0; & 50 \text{ mm} < tillage_{depth} \leq 100 \text{ mm} \\ 4.0; & 100 \text{ mm} < tillage_{depth} \leq 200 \text{ mm} \\ 5.0; & 200 \text{ mm} < tillage_{depth} \leq 300 \text{ mm} \\ 6.0; & tillage_{depth} > 300 \text{ mm} \end{cases} \quad \text{S9b}$$

4. Datasets Used for Model Setup

Table S2. Management practices are concomitant with irrigation scheduling operations for corn and soybean in the SWAT model.

Crop type	Management operation	Parameters and quantity
Corn	Tillage Operation (April 10)	Chisel Plow Gt15ft
	Fertilizer application (April 15)	AnhydrousAmmonia(145.71 kg/ha)
	Pesticide Application (April 15)	Atrazine (1.68 kg/ha)
	Tillage Operation (April 17)	Disk Plow Ge 23ft
	Planting: (planting on May 10)	Corn
	Fertilizer application (May 10)	Elemental Phosphorus(35.31 kg/ha)
	Fertilizer application (May 10)	Elemental Nitrogen(11.77 kg/ha)
	Irrigation (automatic irrigation)	Start date: May 11
	Pesticide Application (June 1)	Metolachlor(1 kg/ha)
	Irrigation (automatic irrigation)	End date: October 15
	Harvesting: (harvest and kill)	October 15
Soybean	Tillage operation 1(May 1)	Chisel Plow Gt21ft
	Tillage operation 2(May 15)	Disk Plow Ge23ft
	Planting: (planting on May 27)	Soybean
	Fertilizer application (May 27)	Elemental Phosphorus: 28 kg/ha
	Irrigation (automatic irrigation)	Start date: May 28
	Irrigation (automatic irrigation)	End date: October 15
	Harvesting: (harvest and kill)	October 15
Winter Wheat	Tillage operation (October 16)	
	Planting: (planting on October 17)	
	Fertilizer application (October 17)	Elemental Phosphorus: 56 kg/ha
	Irrigation (automatic irrigation)	Elemental Nitrogen: 44.83 kg/ha
	Harvesting: (harvest and kill)	July1 st

5. Model Calibration, Sensitivity, and Uncertainty Analyses

$$NS = 1 - \frac{\sum_{i=1}^m (O_i - S_{mean})^2}{\sum_{i=1}^m (O_i - O_{mean})^2} \quad (S10)$$

$$R^2 = \left(\frac{\sum_{i=1}^m (O_i - O_{mean}) * (S_i - S_{mean})}{(\sum_{i=1}^m (O_i - O_{mean})^2 * \sum_{i=1}^m (S_i - S_{mean})^2)^{0.5}} \right) \quad (S11)$$

$$P_{BIAS} = \frac{(O_{mean} - S_{mean})}{O_{mean}} * 100 \quad (S12)$$

$$P = \frac{n_{in}}{m} * 100 \quad (S13)$$

$$R = \frac{\frac{1}{m} \sum_{i=1}^m (O_U - O_L)_i}{\partial_O} \quad (S14)$$

$$g = \alpha + \sum_{i=1}^m \beta_n * c_n \quad (S15)$$

where m represents the total number of observation-simulation pairs, O_{mean} is the observed mean, S_{mean} is the simulated mean, O_i is observed data, S_i is simulated data, g is the objective function, α and β_n are the variables and c_n is a parameter, n_{in} is the number of observations bracketed by the 95PPU, O_U is the 97.5th percentile of the cumulative distribution of every simulated point, and O_L is the 2.5th percentile of the same cumulative distribution.

5.1 Model performance evaluation

Table S3. Calibrated model parameter values for the study watershed's streamflow, sediment, POC, and DOC loads.

Variable	Parameter	Explanation	Range	Calibrated Value	Unit
Streamflow	RCHRG_DP	Deep aquifer percolation fraction	[0.821, 1]	0.82	day
	CH_K2	Eff. hydraulic cond. for the main channel	[-0.01, 500]	18.04	mm hr ⁻¹
	GW_DELAY	Groundwater delay	[0, 500]	7.18	day
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	[0, 5000]	685	mm
	SLSUBBSN	Average slope length	[-0.5, 0.5]	-0.24	m
	ALPHA_BF	Baseflow alpha factor	[0, 1]	0.65	day
	EPCO	Plant uptake compensation factor	[0, 1]	0.79	-
	SMFMN	Melt factor for snow on December 21	[0, 10]	18.62	mm
Sediment/POC	USLE_K	USLE K factor	[0, 0.65]	0.11	-
	USLE_P	USLE P factor		0.38	-
	CH_COV1	Channel erodibility factor	[0, 1]	0.497	-
	CH_COV2	Channel cover factor	[0, 1]	0.093	-
	V _{lpoc}	LPOC settling velocity	[0, 5]	2.38	m day ⁻¹
	V _{rpoc}	RPOC settling velocity	[0, 5]	2.22	m day ⁻¹
	ER _{POC}	POC enrichment ratio	[0, 5]	2.16	-
DOC	β _{DOC}	DOC percolation coefficient	[0, 1]	0.36	-
	k _{OC}	Organic C partition coefficient	[0, 4000]	3035	day ⁻¹

Table S4 presents the performance of the hydrological model in simulating daily streamflow, sediment, POC, and DOC loads during calibration and validation periods, as evaluated by R^2 , NS, and P_{BIAS} . We followed the model performance evaluation criteria outlined by Moriasi et al. [60], where a model simulation is deemed acceptable if NSE is greater than 0.50 and P_{BIAS} falls within $\pm 25\%$ for streamflow, $\pm 55\%$ for sediment, and $\pm 70\%$ for N and P. As there are no established criteria for evaluating carbon fluxes, we assumed that the criteria used for N and P were also applicable to POC and DOC. Furthermore, we considered R^2 to be a relevant statistical measure since it is based on the squared difference between observations and predictions.

Table S4. Model performance on daily streamflow, sediment, POC, and DOC loads during calibration (2001–2010) and validation (2011–2020) periods at USGS gauging station 01411500, Maurice River at Norma.

Variable	Calibration			Validation		
	R^2	NS	P_{BIAS} (%)	R^2	NS	P_{BIAS} (%)
Flow Rate	0.67	0.67	1	0.70	0.67	1
Sediment	0.70	0.70	1	0.70	0.66	2
POC	0.74	0.64	27	0.76	0.62	26
DOC	0.89	0.55	-26	0.55	0.56	23

R^2 = coefficient of determination; NS = Nash-Sutcliffe efficiency coefficient; P_{BIAS} = relative error

The calibration/validation results demonstrate satisfactory model performance for the four-water quantity and quality variables. Model performance on simulating streamflow and sediment load was particularly good. For example, the SWAT model only slightly underestimated streamflow by $\sim 1\%$ in the calibration and validation periods (indicated by positive P_{BIAS} values in Table S4), and the sediment load was slightly underestimated by $\sim 1\%$ (calibration) and 2%

(validation). Model performance on POC and DOC simulations was satisfactory overall, given that $NS > 0.50$. The POC load was underestimated by 27% and 26% in the calibration and validation periods, respectively, and the DOC load was overestimated during calibration ($P_{BIAS} = -26\%$) and underestimated during validation ($P_{BIAS} = 23\%$).

Figure S3 shows simulated versus observed daily streamflow, sediment, DOC, and POC loads. POC and sediment are calibrated together due to the close relationship in their fluxes. This happens when C particles adsorb themselves to sediment particles. In general, simulated streamflow, sediment, POC, and DOC load hydrographs matched observations well. However, the model underestimated peak flows dominated by storm events (Figure S3a). The inability of the SWAT model to predict peak flows has been documented in several studies (e.g., [33]). In addition to the SWAT model underestimating the peak flows, the variation between simulated and observed DOC and POC can also be attributed to their low temporal resolution sampling (e.g., weekly to monthly compared to daily streamflow monitoring). Low sampling resolution can introduce model simulation uncertainty. Overall, simulated flow, sediment, POC, and DOC loads followed observed data patterns and seasonal variations.

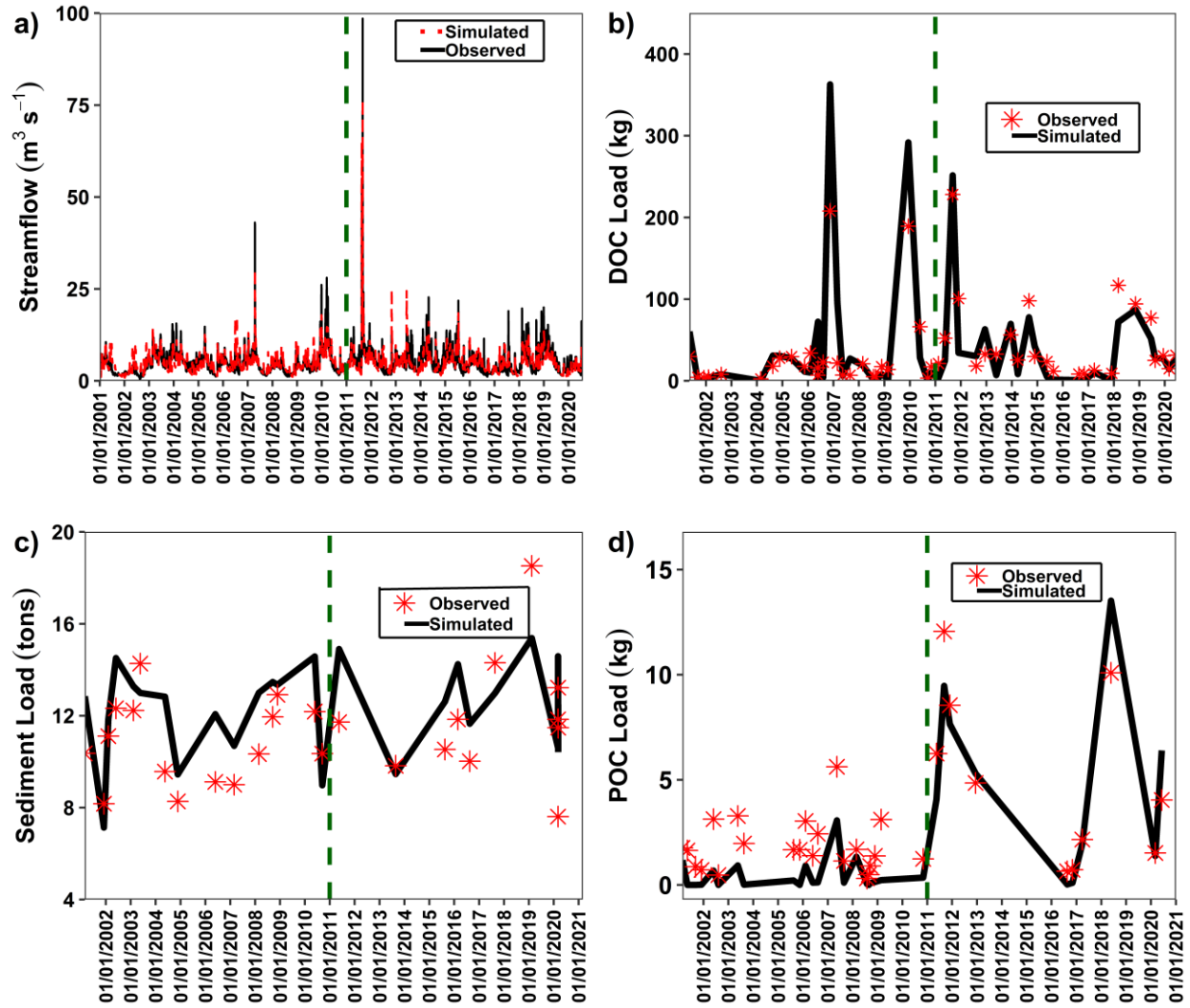


Figure S3. Simulated versus observed daily (a) streamflow (b) sediment, (c) POC, and (d) DOC loads during the calibration (2001–2010) and validation (2011–2020) periods.

5.2 Model uncertainty analysis

Table S5 lists p- and r-factor values for estimated 95PPU bands for streamflow, sediment, POC, and DOC loads. The p-factor values indicate that the 95PPU bands included 89–90% of observed daily streamflow, 63–68% of observed sediment loads, 60–62% of observed POC loads, and 75–77% of observed DOC loads during the study period. The decrease in p-values from calibration to validation for DOC/POC and sediment loads indicates the large uncertainty in modeling due to the complexity of parameterizing these loads compared to parameterizing streamflow. The r-factor values for streamflow during calibration and validation were greater than 1, as was the r-factor during sediment calibration (Table S5). The r-factor values for POC and DOC calibration and validation were less than or around 1, indicating an acceptable uncertainty in the model simulation. The r-factor for sediment validation indicates the same (Table S4).

Table S5. Model parameter uncertainty analysis results indicated by the p-factor and the r-factor for streamflow, sediment, POC, and DOC load simulations during calibration (2001–2010) and validation (2011–2020) at USGS gauging station 01411500, Maurice River at Norma.

Variable	Calibration		Validation	
	p-factor	r-factor	p-factor	r-factor
Streamflow	0.89	1.55	0.90	1.44
DOC	0.77	0.52	0.75	1.11
POC	0.50	0.59	0.56	0.90
Sediment	0.68	2.62	0.63	0.17

5.3 Model parameter sensitivity analysis

Table S6 lists the p-value and sensitivity ranking of different parameters for simulating various water quantity and quality variables. The most sensitive parameters for daily streamflow are divided into three categories. The first category includes RCHRG_DP, GWQMN, GW_DELAY, and ALPHA_BF, all related to baseflow and groundwater recharge and distribution. This is not surprising considering groundwater's contribution to surface water flow during dry periods. The second category includes SLSUBBSN and EPCO controlling soil water flow. The third category is SMFMN related to snowmelt, as the region receives winter snow, indicating the snowmelt's contribution to hydrological resources. Parameters sensitive to sediment load are categorized into upland and channel sediment transport and deposition processes. Upland factors such as USLE_P and USLE_K are associated with land management practices like tillage in agricultural lands. Channel sediment transport factors include CH_COV1, which indicates erosion from the channel sides and/or bottom, and CH_COV2, which indicates erosion due to inadequate vegetation cover, slowing down sediment transport from the channel sides. Parameters sensitive to POC calibration include the POC enrichment ratio (ER_{POC}), which is defined as the ratio of the concentration of POC in eroded soils to the concentration of SOC in the soil surface layer; the RPOC (V_{rpoc}) and LPOC (V_{lpoc}) controls the deposition of POC ($m\ d^{-1}$) in streams. Parameters sensitive to DOC calibration include the liquid-solid partition coefficient (k_{OC}), which determines the production of DOC in soil solution, and the DOC percolation coefficient (β_{DOC}), which specifies the concentration of DOC in surface runoff as a fraction of the concentration in percolation.

Table S6. Model parameter sensitivity analysis results for streamflow, sediment, POC, and DOC load simulations in the Upper Maurice River watershed.

Variable	Parameter	P-value	Ranking
Streamflow	RCHRG_DP	0.00	1
	GWQMN	0.00	2
	CH_K2	0.00	3
	GW_DELAY	0.00	4
	ALPHA_BF	0.00	5
	SLSUBBSN	0.01	6
	EPCO	0.03	7
	SMFMN	0.04	8
	CN2	0.20	9
	SFTMP	0.20	10
	REVAPMN	0.47	11
	SOL_AWC	0.62	12
	OV_N	0.81	13
POC/ Sediment	USLE_P	0.00	1
	USLE_K	0.00	2
	ER _{POC}	0.00	3
	V _{rpoc}	0.00	4
	V _{lpoc}	0.02	5
	CH_COV1	0.04	7
	CH_COV2	0.08	9
	SPEXP	0.19	10
	SPCON	0.27	11
DOC	β_{DOC}	0.00	1
	k _{OC}	0.01	2

6. Annual Water Yield, Sediment, POC, and DOC Loads

The high coefficient of variation (CV) values of annual POC and DOC load (Table S7) than water yield indicates that the two variables are correlated not only with precipitation/runoff intensity but also with temperature, farm management, etc.

Table S7. Annual water yield, sediment, POC, and DOC loads over Upper Maurice River Watershed in New Jersey.

Year	Water Yield (mm)	POC (kg ha⁻¹)	DOC (kg ha⁻¹)	Sediment (ton/ha)
2001	437	4.4	20.7	0.45
2002	372	3.7	18.5	0.67
2003	681	3.1	17.8	0.76
2004	520	3.1	16.6	0.51
2005	507	3.6	22.0	0.66
2006	577	6.3	31.8	1.76
2007	530	10.1	38.4	1.34
2008	464	2.1	16.4	0.48
2009	588	3.2	22.6	0.80
2010	667	3.3	16.2	0.58
2011	822	15.1	64.8	5.93
2012	577	6.4	36.2	1.75
2013	612	8.8	36.1	1.37
2014	540	4.4	28.9	1.49
2015	702	5.4	39.2	1.49
2016	509	1.5	14.1	0.46
2017	431	4.0	21.9	0.87
2018	670	5.1	39.5	1.34
2019	550	1.3	13.8	0.41
2020	575	3.2	28.7	1.16
Mean	565.0	4.9	27.2	1.21
Max.	817.1	15.1	64.8	5.93
Min.	367.2	1.3	13.8	0.41
CV (%)	0.2	0.7	0.5	0.99

Note: CV stands for coefficient of variation

7. Tukey Analysis

Table S8. POC Tukey.

\$LULC	diff	lwr	upr	p adj
CS-Barren Land	0.6899	0.4023	0.9776	0.0000
CSW-Barren Land	0.5006	0.2186	0.7826	0.0000
Forest-Barren Land	0.0276	-0.0288	0.0839	0.7782
Grassland-Barren Land	0.0443	-0.0134	0.1019	0.2615
Other Crops-Barren Land	0.9967	0.9333	1.0602	0.0000
SSC-Barren Land	0.7396	0.4531	1.0261	0.0000
CSW-CS	-0.1893	-0.5845	0.2059	0.7955
Forest-CS	-0.6623	-0.9449	-0.3798	0.0000
Grassland-CS	-0.6456	-0.9285	-0.3628	0.0000
Other Crops-CS	0.3068	0.0228	0.5909	0.0245
SSC-CS	0.0497	-0.3487	0.4481	0.9998
Forest-CSW	-0.4730	-0.7498	-0.1962	0.0000
Grassland-CSW	-0.4563	-0.7334	-0.1793	0.0000
Other Crops-CSW	0.4961	0.2178	0.7745	0.0000
SSC-CSW	0.2390	-0.1554	0.6334	0.5571
Grassland-Forest	0.0167	-0.0037	0.0371	0.1947
Other Crops-Forest	0.9692	0.9356	1.0027	0.0000
SSC-Forest	0.7120	0.4306	0.9934	0.0000
Other Crops-Grassland	0.9525	0.9168	0.9881	0.0000
SSC-Grassland	0.6953	0.4137	0.9770	0.0000
SSC-Other Crops	-0.2571	-0.5400	0.0258	0.1033

Table S9. DOC Tukey.

\$LULC	diff	lwr	upr	p adj
CS-Barren Land	3.3295	2.2565	4.4025	0.0000
CSW-Barren Land	1.6184	0.5664	2.6703	0.0001
Forest-Barren Land	2.0212	1.8111	2.2314	0.0000
Grassland-Barren Land	2.2233	2.0083	2.4383	0.0000
Other Crops-Barren Land	3.8711	3.6344	4.1078	0.0000
SSC-Barren Land	4.3322	3.2635	5.4008	0.0000
CSW-CS	-1.7112	-3.1854	-0.2370	0.0111
Forest-CS	-1.3083	-2.3623	-0.2543	0.0047
Grassland-CS	-1.1062	-2.1612	-0.0513	0.0327
Other Crops-CS	0.5416	-0.5180	1.6012	0.7408
SSC-CS	1.0026	-0.4835	2.4888	0.4216
Forest-CSW	0.4029	-0.6297	1.4354	0.9123
Grassland-CSW	0.6050	-0.4286	1.6385	0.5986
Other Crops-CSW	2.2527	1.2145	3.2910	0.0000
SSC-CSW	2.7138	1.2428	4.1849	0.0000
Grassland-Forest	0.2021	0.1259	0.2783	0.0000
Other Crops-Forest	1.8499	1.7249	1.9748	0.0000
SSC-Forest	2.3109	1.2614	3.3605	0.0000
Other Crops-Grassland	1.6478	1.5148	1.7807	0.0000
SSC-Grassland	2.1089	1.0583	3.1594	0.0000
SSC-Other Crops	0.4611	-0.5941	1.5163	0.8576

8. Temporal and Spatial Analysis

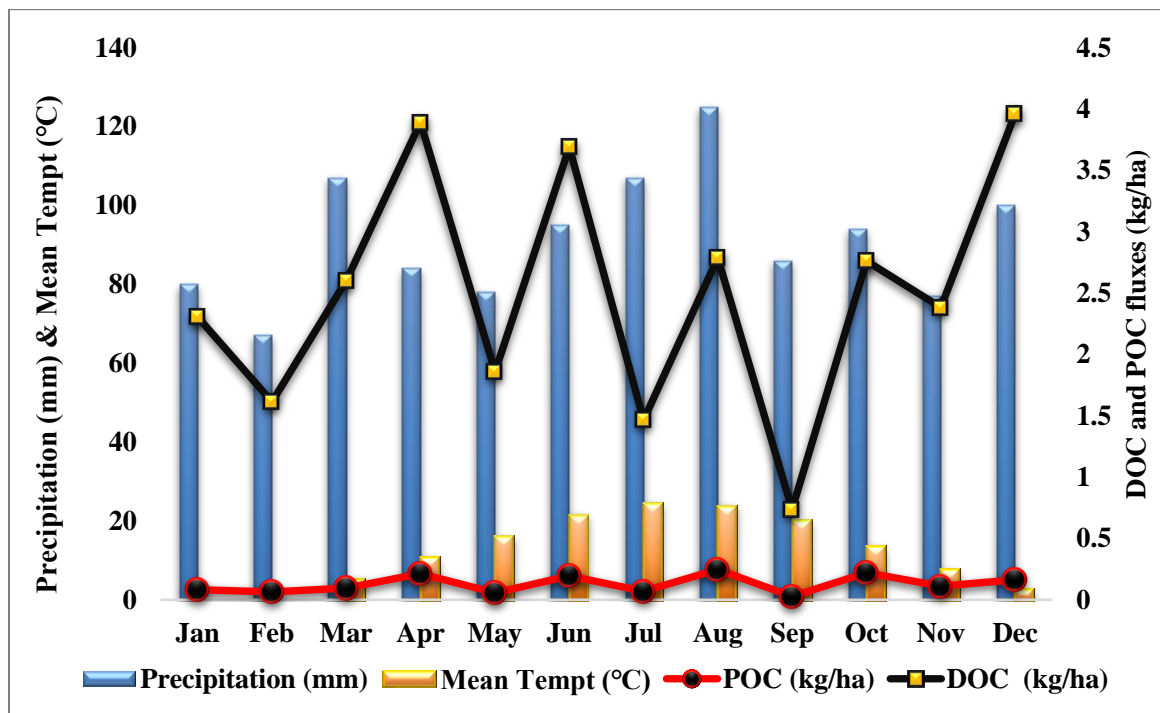


Figure S4. Average monthly precipitation and temperature vs. DOC and POC load from 2001 to 2020.

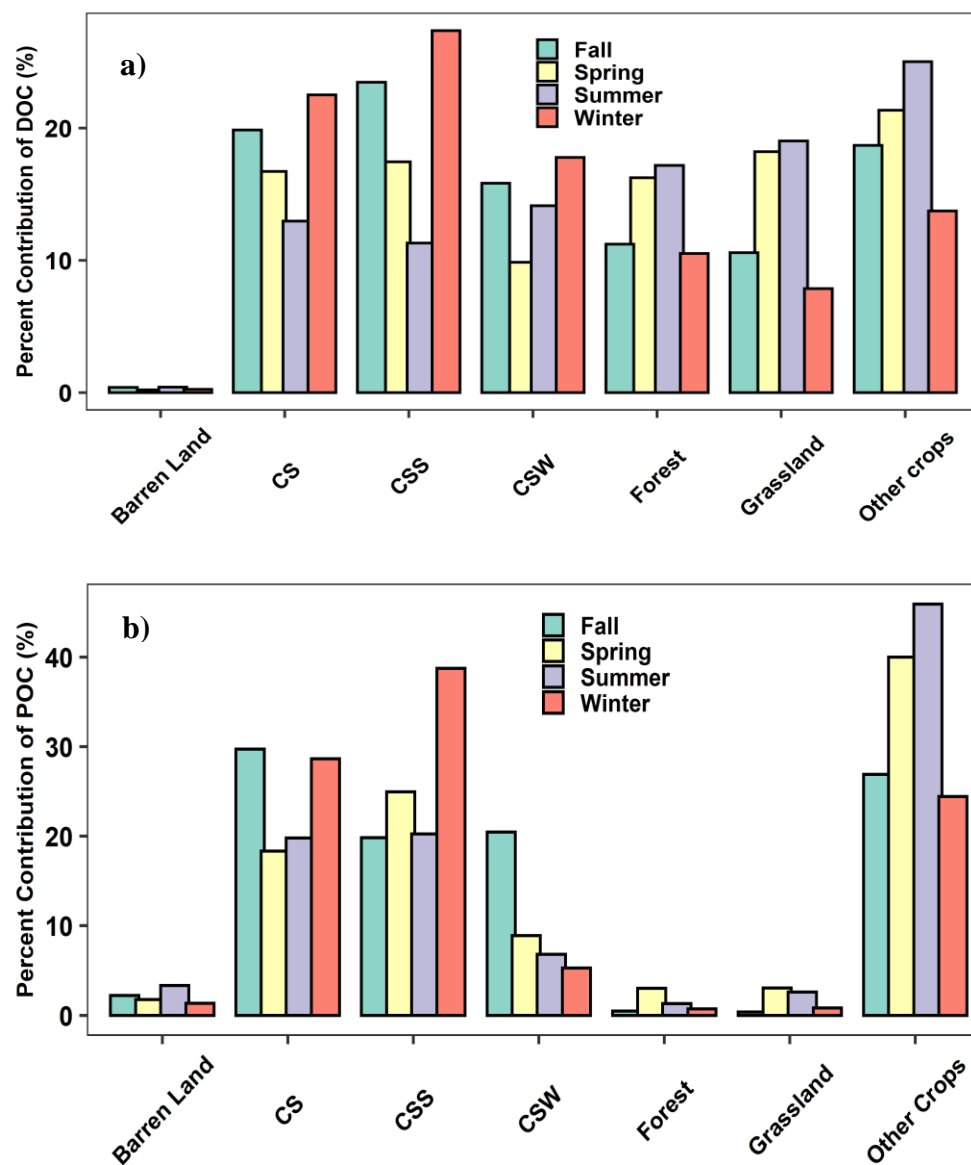


Figure S5. (a) Percentage contributions to DOC and (b) POC load during the fall, spring, winter, and summer seasons in the UMRW.

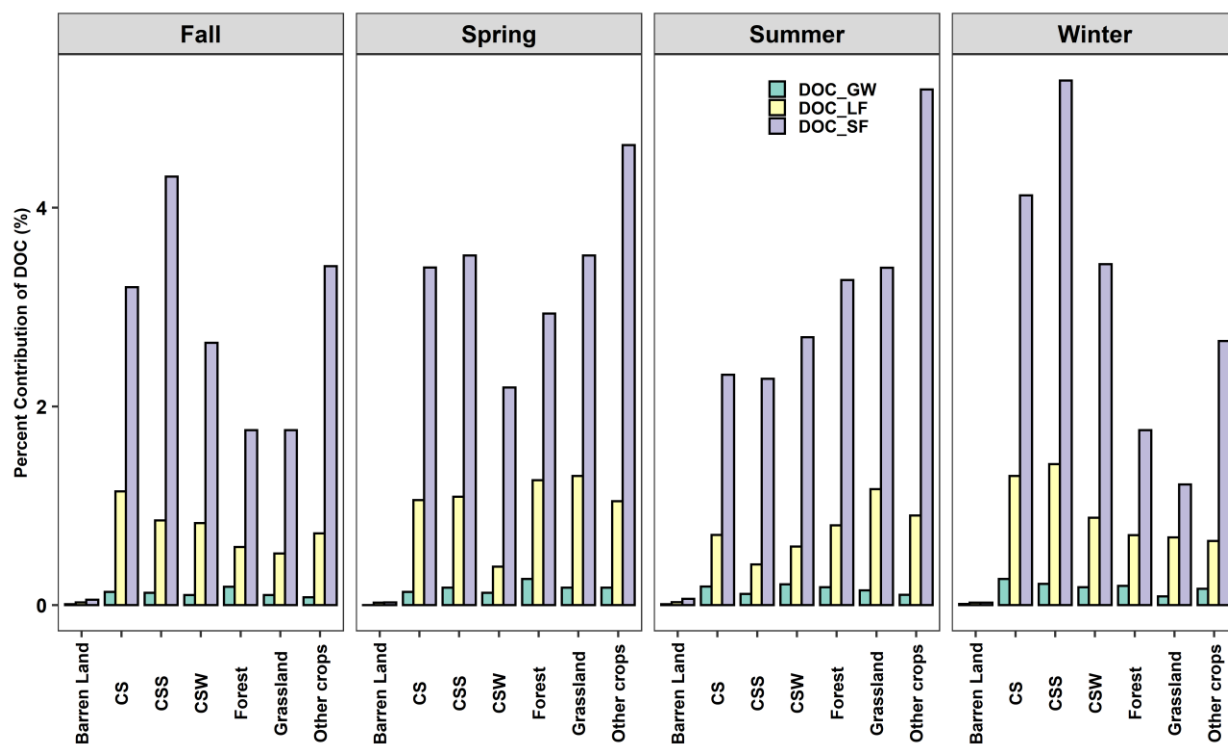


Figure S6. Percentage contributions of surface runoff, lateral flow, and groundwater DOC load during the fall, spring, winter, and summer seasons in the UMRW.

9. Management Practice Scenarios

We extracted the five variables: CO₂ (kg/ha), SOC (tons/ha), biomass (kg/ha), POC (kg/ha), and DOC (kg/ha) from SWAT-C output files at the end of each simulation. We did not calibrate SOC as a recent study by Liang et al. [50] showed that SWAT-C could predict SOC dynamics from different soil profiles with 90% accuracy without calibration. In addition, we calibrated crop yield in this study.

9.1. Corn, Soybean, and Winter wheat calibration for the UMRW

To understand how management practices such as irrigation affect DOC, POC, SOC, and biomass accumulation, we adapted a previously calibrated annual irrigation from Tijjani et al. [33] for the UMRW. Corn and soybean yields were calibrated using annual, county-level data. An area-weighted crop yield was calculated for the UMRW based on each county's proportion within the watershed area. Crop yield units from USDA-NASS (bu/ac) were converted into metric tons/ha. P_{BIAS} was used as an evaluation criterion. Comparison between NASS observed, and SWAT simulated annual corn and soybean yields for the UMRW are presented in Fig. S2. The area-weighted average P_{BIAS} values for corn, soybean, and winter wheat at the watershed level were -25%, 12%, and 19%, respectively, which is acceptable. The negative P_{BIAS} value of corn indicates that the SWAT model overestimated corn yield. In contrast, the positive value of P_{BIAS} for soybean and winter wheat depicts underestimated soybean and winter wheat yield in the UMRW (Details of the calibration setup in SWAT can be found in Tijjani et al. [33]).

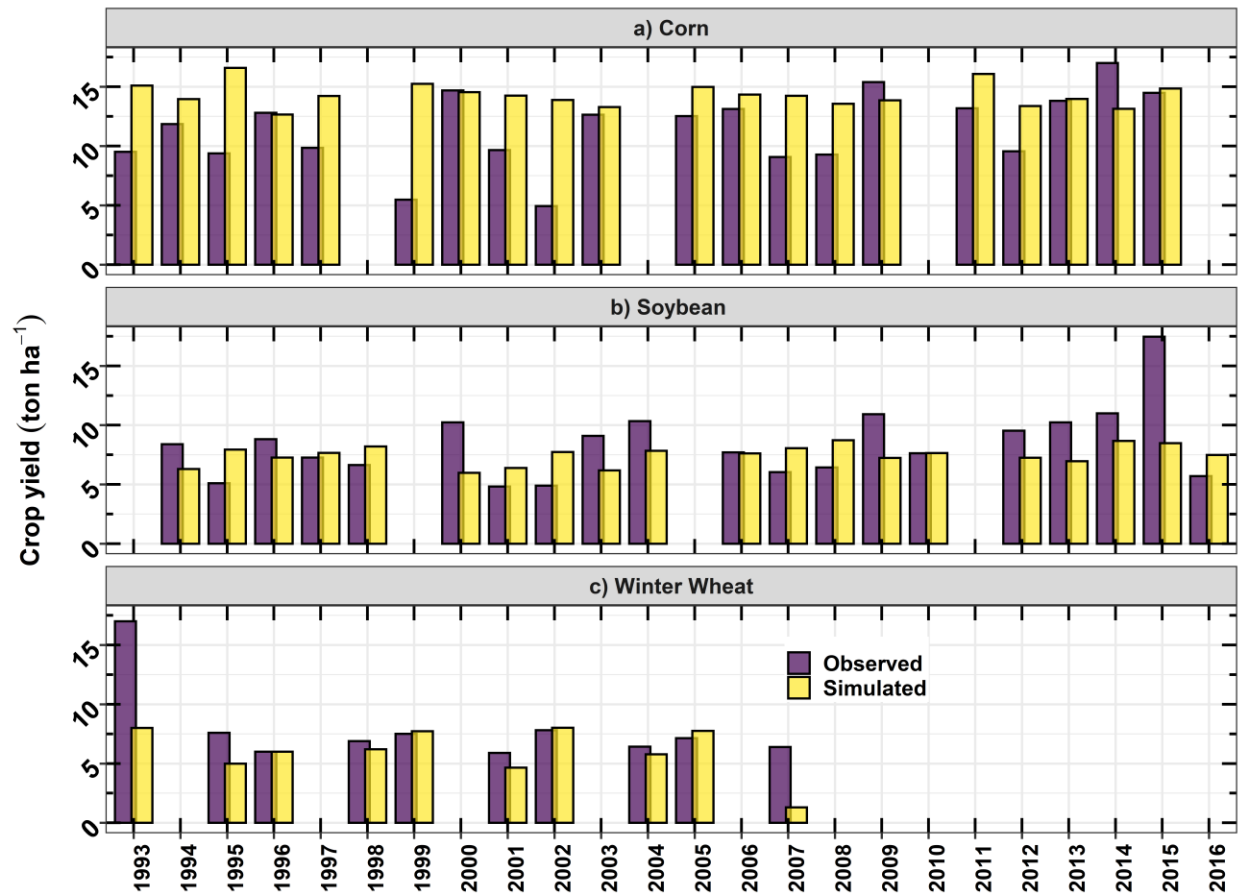


Figure S7. (a) Corn, (b) soybean, and (c) winter wheat calibrations. Observed values are obtained from USDA-NASS, while simulated values are obtained from SWAT's output file.

9.2. Modification of fertilizer application timings

To test whether fertilizer management can reduce N load, we developed a dynamic N fertilizer use scheme for treatment 9. Considering that corn is included in each of the rotations (CSS, CS, CWS) and is associated with the largest consumption of N fertilizer throughout the entire river basin (Table S3), we used the growth phases of corn as a proxy for all the crops to examine the impact of fertilizer application timing. The total N fertilizer amount remains the same as the traditional N application practice for all the other treatments. Specifically, we input N fertilizer twice per year, referring to V1 (the plant phase for which the first leaf has fully emerged)

and V5 (the phase at which the collar of the fifth leaf is visible) growth phases of corn. We shifted the peak fertilizer application date from April. Each fertilizer application stage receives half (i.e., 50% each) of the total annual amount. The growth phases of corn are determined by the growing degree unit or heat unit, whose values range from 232 to 282 and from 496 to 546 when corn reaches V1 and V5 phases, respectively.

Table S10. 20-year annual average SOC (ton/ha) and POC load (kg/ha), along with percentage change (i.e., values in bracket) compared with the pre-treatment level under baseline 1 for three rotations and various treatments.

	SOC			POC		
	CSS	CSW	CS	CSS	CSW	CS
Pre-treatment	98.73	97.47	102.86	2.60	2.33	2.60
Treatment 1	98.7(0%)	98.3(0.8%)	102.9(0.05)	2.6(1.6%)	2.1(-18.5%)	2.6(0%)
Treatment 2	101(2.6%)	99.5(2.1%)	106(2.6%)	5.6(115%)	3.2(37%)	5.3(103%)
Treatment 3	96.7(-2.1)	95.5(-2%)	102.8(-0.11%)	2.7(2.9%)	2.1(-9.7%)	2.6(1.7%)
Treatment 4	97.7(-1.1%)	96.7(-0.8%)	102.8(-0.08%)	2.6(-2%)	2.3(-1.9%)	2.6(0.6%)
Treatment 5	99.6(0.9%)	98.2(0.7%)	103.7(0.08%)	2.6(0.4%)	2.3(-2.2%)	2.5(-2.3%)
Treatment 6	98.7(0%)	97.6(0.17%)	102.9(0.01%)	2.6(0%)	2.2(-5.9%)	2.6(-1.6%)
Treatment 7	101(2.4%)	97(-0.5%)	102.6(-0.24%)	5.3(102.6%)	3.1(34%)	5.3(104.3%)
Treatment 8	101.3(2.6%)	99.5(2%)	105.6(2.6%)	5.6(115.5%)	3.1(34%)	5.3(103%)
Treatment 9	99(0.23%)	99.7(2.3%)	104.3(1.4%)	2.8(9%)	1.9(-19%)	2.7(4.2%)
Treatment 10	97.4(-1.33%)	97.5(0.04%)	102.4(-0.5%)	3.4(30%)	1.9(-20%)	2.8(5.8%)
Treatment 11	98.7(0%)	97.6(0.17%)	102.9(0.01%)	2.6(0%)	2.2(-5.9%)	2.6(1.6%)

Table S11. 20-year annual average DOC load (kg/ha) and soil respiration CO₂ (kg/ha), along with percentage change (i.e., values in bracket) compared with the pre-treatment level under baseline 1 for three rotations and various treatments.

	DOC			CO ₂		
	CSS	CSW	CS	CSS	CSW	CS
Pre-treatment	21.00	17.00	20.00	4,153.86	4,136.35	4,571.94
Treatment 1	21.3(1.6%)	14.1(-19%)	20(0%)	4,164(0.23%)	3,744(-9.4%)	4,571(0%)
Treatment 2	27.5(31%)	20.2(17%)	31(53%)	3,936(-5.2%)	3,744(-9.4)	4,571(0%)
Treatment3	21.2(0.79%)	15(-13.3%)	17.2(-14%)	4,116(-0.9%)	3,624(12%)	3,864(-16%)
Treatment 4	21.4(1.9%)	16.2(-6.5%)	18.4(-7.8%)	4,140(-0.3%)	3,936(-5%)	4,212(-8%)
Treatment 5	22(4%)	17.6(1.9%)	20.4(2.1%)	4,446(2%)	4,290(3.7%)	4,608(0.8%)
Treatment 6	21(0%)	17.2(0.8%)	20.3(1.6%)	4,154(0%)	4,188(0.12%)	4,584(0.23%)
Treatment 7	24.2(16%)	33.4(93%)	23.2(16%)	3,204(-22.7%)	3,192(-22.8%)	4,039(-12%)
Treatment 8	28.4(35%)	26.6(54%)	23.4(17%)	3,936(-5.2%)	3,600(-13%)	4,097(-10)
Treatment 9	23.3(10.8%)	14(-20%)	20.4(1.9%)	4,404(6%)	3792(-8%)	4,656(1.9%)
Treatment 10	23.1(10%)	9.3(-45.3%)	19.3(-3.3%)	4,044(-2.8%)	18,792(28%)	3,756(18%)
Treatment 11	21(0%)	17(-0.6%)	20.3(1.6%)	4,154(0%)	4,188(1.12%)	4,584(0.23%)

Table 12. 20-year annual average biomass (kg/ha) along with percentage change (i.e., values in bracket) compared with the pre-treatment level under baseline 1 for three rotations and various treatments.

	BIOMASS		
	CSS	CSW	CS
Pre-treatment	25,178	12,651.65	14,865.05
Treatment 1	25,128(-0.23%)	18,218(44%)	14,865(0%)
Treatment 2	25,260(0.35%)	17,208(36%)	14,088(-5.2%)
Treatment3	17,880(-29%)	9,612(-24%)	14,448(-2.8%)
Treatment 4	24,792(-0.3%)	11,580(-8.5%)	12,780(14.3%)
Treatment 5	28,356(12.6%)	13,284(5%)	15,060(1.4%)
Treatment 6	25,178(0%)	13,068(3.3%)	14,832(-0.2%)
Treatment 7	25,614(-8.8%)	8,472(-33%)	13,560(-9%)
Treatment 8	25,260(0.4%)	17,580(39%)	15,636(5.2%)
Treatment 9	26,136(3.8%)	18,792(48%)	19,104(29%)
Treatment 10	16,152(-36%)	11,412(-9.8%)	13,380(-10%)
Treatment 11	25,178(0%)	13,068(3.3%)	14,832(-0.21%)

Table S13. 20-year annual average SOC (tons/ha) and POC load (kg/ha), along with percentage change (i.e., values in bracket) compared with the post-treatment level under baseline 2 for three rotations and various treatments.

	SOC			POC		
	CSS	CSW	CS	CSS	CSW	CS
Post-treatment	97.95	97.53	102.79	2.60	2.30	2.60
Treatment 1	96.28(-1.71%)	98.46(0.62%)	100.8(-1.96%)	3(15.2%)	1.27(-44.7%)	3.5(-33.9%)
Treatment 2	99(0.86%)	98(0.51%)	103(0.1%)	2.61(0.39%)	2.4(3.9%)	2.62(0.7%)
Treatment3	95.9(-2.1%)	95.4(-2.5%)	102.7(-0.12%)	2.68(2.9%)	2.2(-4.1%)	2.6(0%)
Treatment 4	96.9(-1.1%)	96.6(-0.97%)	102.7(-0.1%)	2.61(0.5%)	2.4(4.17%)	2.61(0.4%)
Treatment 5	98.8(0.86%)	98(0.5%)	102.9(0.1%)	2.59(-0.39)	2.39(3.94%)	2.62(0.7%)
Treatment 6	97.2(-0.78%)	97.6(0.1%)	102.7(-0.1%)	2.61(0.25%)	2.22(-3.7%)	2.58(-0.66)
Treatment 7	100.3(2.43%)	97(-0.5%)	102(-1.02%)	5.3(103%)	3.2(37.6%)	5.2(99.7%)
Treatment 8	100.5(2.57%)	99.5(2.05%)	105.5(2.62%)	5(90.5%)	2.82(22.7%)	3.8(45.7%)
Treatment 9	98.9(0.93%)	99.3(1.8%)	104.1(1.29%)	2.8(8.5%)	1.82(-21%)	2.68(1.8%)
Treatment 10	96(-2.1%)	95(-2.6%)	102(-0.58%)	3.41(31%)	1.9(-17.9%)	2.7(3.4%)

Table S14. 20-year annual average DOC load (kg/ha) and soil respiration CO₂ (kg/ha), along with percentage change (i.e., values in bracket) compared with the post-treatment level under baseline 2 for three rotations and various treatments.

	DOC			CO ₂		
	CSS	CSW	CS	CSS	CSW	CS
Post-treatment	21.00	17.00	20.00	4,421	4,104	4,597
Treatment 1	32.3(54%)	15.4(-9.2%)	22(10%)	5,568(26%)	4,104(0.14%)	5,256(14.4%)
Treatment 2	22.5(7.4%)	17.4(2.5%)	20.1(0.4%)	4,728(7%)	4,212(2.6%)	4,620(0.6%)
Treatment3	18(-14.3%)	14.1(-17.2%)	19.8(-0.82%)	2,964(-15.5%)	3,420(-16.7%)	4,476(-1.1%)
Treatment 4	20.9(-0.4%)	15.7(-7.8%)	18.8(-5.9%)	4,068(-8%)	3,660(-6%)	4,572(-0.5%)
Treatment 5	22.5(7.4%)	17.4(2.5%)	20.1(0.43%)	4,728(7%)	4,212(2.6%)	4,620(0.6%)
Treatment 6	20.9(-0.43%)	17.2(1.1%)	18.7(-6.3%)	4,152(-6.1%)	4,284(4.3%)	4,524(-1.5%)
Treatment 7	25.2(20%)	18.5(8.7%)	22.6(13.2%)	384(-12.3%)	3,156(-23%)	3,348(-27.3%)
Treatment 8	26.3(25.4%)	18.7(-10%)	23(15%)	4,192(-5.2%)	3,528(-13.9%)	4,116(-10.6%)
Treatment 9	20.9(4.7%)	15.4(-9.4%)	18.42(-7.9%)	4,615(4.4%)	3,720(-9.4%)	4,152(-9.6%)
Treatment 10	21.6(2.9%)	9.5(-44.3%)	18.9(-5.3%)	3,404(-23%)	2,940(-3.5%)	4,440(-3.5%)

Table S15. 20-year annual average biomass (kg/ha), along with percentage change (i.e., values in bracket) compared with the post-treatment level under baseline 2 for three rotations and various treatments.

	BIOMASS		
	CSS	CSW	CS
Post	28,085	12,127	15,097
-treatment			
Treatment 1	40,164(43%)	16,848(39%)	17,064(13.4%)
Treatment 2	31,632(12.6%)	12,336(1.7%)	15,336(1.6%)
Treatment3	20,052(-28.6%)	11,808(-2.6%)	11,172(-26%)
Treatment 4	27,720(-13%)	10,752(-11.4%)	12,936(-14.3%)
Treatment 5	31,632(12.6%)	12,336(1.7%)	15,288(1.6%)
Treatment 6	25,176(-10.4%)	12,648(4.3%)	14,808(-1.5%)
Treatment 7	25,620(-8.8%)	8,160(-32.7%)	10,020(-33.6%)
Treatment 8	30,708(9.4%)	15,156(25%)	15,852(5%)
Treatment 9	30,024(6.9%)	17,700(46%)	19,176(27%)
Treatment 10	16,152(-43%)	11,088(-9%)	13,416(-11%)

References

Please refer to the reference list in the main manuscript.

