Causal Effects of Winter Wheat on Soil Organic Carbon Under Climate Variability

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NEURAL INFORMATION PROCESSING SYSTEMS

Motivation

SOC is key to climate mitigation and soil health.
We need to understand how it responds to crop choice/rotation.
But effects of crops vary with local climate.

We ask: What is the effect of wheat-based rotations on SOC and how is this effect moderated by soil and environmental conditions?

We aim to: Understand the heterogeneous effect of practices to prioritize them where they are most effective

Data

Variable	Description	Units	Role
winter_wheat	Winter wheat-based rotations for ≥3 years	binary	Treatment
SOC	Soil Organic Carbon content	g C/kg	Outcome
clay	Three-year average clay content	%	Heterogeneity (X)
eco	Organic or conventional farming	binary	Heterogeneity (X)
t2m	Air temperature at 2 meters	K	Heterogeneity (X)
tp	Total precipitation	m	Heterogeneity (X)
rotation_diversity	Number of distinct crop types within 5 years	1–5	Control (W)
geo	Latitude and longitude of field centroid	degrees	Control (W)
u10	10 m wind speed	m/s	Control (W)
snowc	Snow cover	%	Control (W)
stl	Soil temperature	K	Control (W)
swvl	Volumetric soil water	m^3/m^3	Control (W)
ssro	Subsurface runoff	m	Control (W)

Conditional average treatment effect (CATE) (1)

Double Machine Learning (DML)

$$Y = \theta(X)\cdot T + g(X,W) + \varepsilon$$
$$\rightarrow \textit{Structural model (treatment effect + nuisance function)}$$

$$T = f(X,W) + \eta$$
$$\rightarrow \textit{Treatment assignment model}$$

$$\hat{m}(X,W) = E[Y \mid X,W], \quad \hat{e}(X,W) = E[T \mid X,W]$$
$$\rightarrow \textit{Estimate nuisance functions with ML models}$$

Conditional average treatment effect (2)

$$\tilde{Y} = Y - \hat{m}(X,W), \quad T = T - \hat{e}(X,W)$$
$$\rightarrow \textit{Compute residuals (remove confounding effects)}$$

$$\tilde{Y} = \theta(X)\cdot T + \varepsilon$$
$$\rightarrow \textit{Final stage regression for heterogeneous treatment effect (CATE)}$$

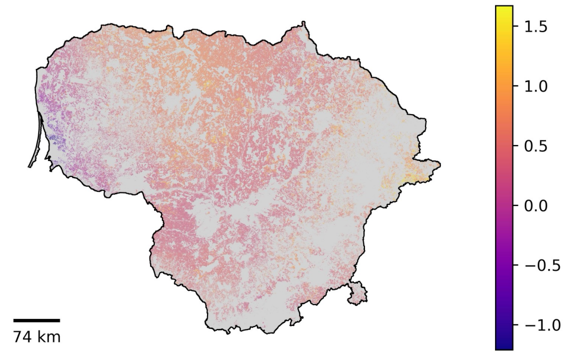
$$\theta = arg\,min_{\theta}\, E_n[(\tilde{Y} - \theta(X)\cdot T)^2]$$
$$\rightarrow \textit{DML estimator minimizing residual prediction error}$$

Heterogeneity of effects

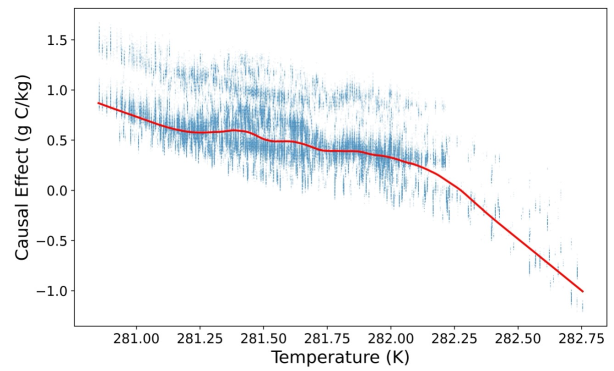
Average Treatment Effect (ATE) = +0.44 g/kg

Heterogeneity:

Variable	Estimate	Std. Error	Z-score	P-value
clay	0.033	0.060	0.545	0.586
eco	0.535	0.654	0.819	0.413
t2m	−0.192	0.086	−2.217	**0.027**
tp	−0.159	0.094	−1.683	0.092
ATE	**0.439**	0.089	**4.914**	**0.000**

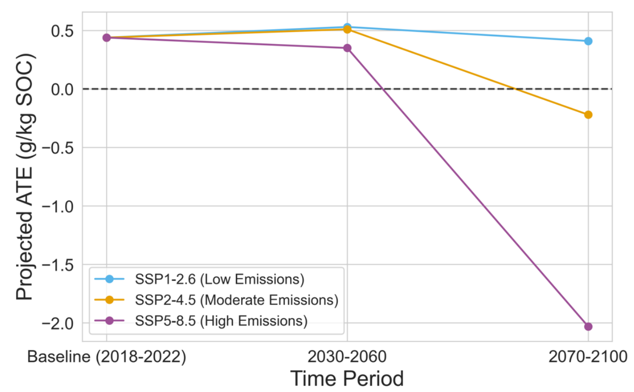


Map of the effects (in g/kg) of winter wheat rotations on SOC at the field-level in Lithuania



Causal effects as a function of temperature

Climatic scenarios



Projected ATEs of winter wheat rotations on SOC under different climate scenarios.

Conclusions

Winter wheat rotations increase SOC (+0.44 g/kg) but effects vary

Cooler, drier regions gain the most

CATE insights guide **region-specific management**:

- Promote winter wheat in the east
- Use cover crops or erosion control in the west

Policy impact: CATE maps support **targeted incentives** and **climate-smart programs** that align local conditions with sustainability goals.

Climate sensitivity: under **low emissions (SSP1-2.6)** benefits persist; under **high emissions (SSP5-8.5)** they may vanish or reverse.

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