Management legacy effects drive soil food web resistance and resilience to climatic stress

Paula Lillo[1,2*], Tiaré Contreras Hernández[1], María del Mar Delgado[1], Miguel Talavera[3], Sara Sánchez-Moreno[1,4]

[1]Dpt. of Environment and Agronomy, National Institute of Agriculture and Food Research and Technology (INIA-CSIC), 28040 Madrid, Spain

[2]International Doctoral School, Rey Juan Carlos University, Móstoles, 28008 Madrid, Spain

[3]Dpt. Sustainable Plant Protection, IFAPA Alameda del Obispo, 14004 Córdoba, Spain

[4]Current address: Dpt. of Biodiversity and Evolutionary Biology, National Museum of Natural Sciences, 28006 Madrid, Spain

*Corresponding author: paula.lillo@inia.csic.es

The following Supporting Information is available for this article:

Figure S1: Mean hourly air temperature (°C) throughout the day for each of the three stress cycles: (1) March 13–23, (2) March 31–April 10, and (3) April 24–May 4, 2023.

Figure S2: Air temperature (°C) measurements recorded every 15 minutes during the three stress cycles. Each point represents a single observation under ambient (aT, green) or increased temperature (iT, red) conditions. Smoothed lines indicate general trends over time for each treatment.

Figure S3: Soil microbial responses under climate treatments across two management systems: conventional tillage (left panels) and no-tillage (right panels), and two crop systems: rotation (solid lines) and monoculture (dashed lines).

Figure S4: Soil nematode responses under climate treatments across two management systems: conventional tillage (left panels) and no-tillage (right panels), and two crop systems: rotation (solid lines) and monoculture (dashed lines). Measurements were taken during the stress and recovery phases.

Table S1: Initial soil chemical properties and enzyme activities under different tillage and cropping system treatments.

Table S2: Mean control temperature and temperature increase (ΔT) during each experimental cycle. Values are presented as mean ± standard error.

Table S3: Results of the glmmTMB models (χ^2 values) for the effects of tillage system, rotation system, drought, warming, and their interactions on soil electrical conductivity (Elect. Conduc.), nitrate (NO_3^-), ammonium (NH_4^+), soil organic carbon (SOC), available phosphorus (P olsen), and pH during recovery period.

Table S4: Results of the glmmTMB models (χ^2 values) for the effects of tillage system, crop system, drought, warming, and their interactions on microbial biomass carbon (MBC), CO_2 emission, dissolved organic carbon (DOC), and enzyme activities (β-glucosidase, phosphatase, urease) during the stress and recovery periods.

Table S5: Results of the glmmTMB models (χ^2 values) for nematode functional groups under climate treatments during stress and recovery phases.

Table S6: Results of the glmmTMB models (χ^2 values) for the effects of tillage system, crop rotation, climate factors (drought and warming combined), and their interactions on resistance (RS) and resilience (RL) indices of MBC, CO_2 emission, DOC, and enzyme activities (β-glucosidase, phosphatase, urease).

Table S7: Results of the glmmTMB models (χ^2 values) for the effects of tillage system, crop rotation, climate factors (drought and warming combined), and their interactions on resistance (RS) and resilience (RL) indices of nematode trophic groups.

Figure S1: Mean hourly air temperature (°C) throughout the day for each of the three stress cycles: (1) March 13–23, (2) March 31–April 10, and (3) April 24–May 4, 2023. The green line (aT) represents ambient temperature conditions, while the red line (iT) represents increased temperature conditions. Shaded areas indicate the standard error of the mean.

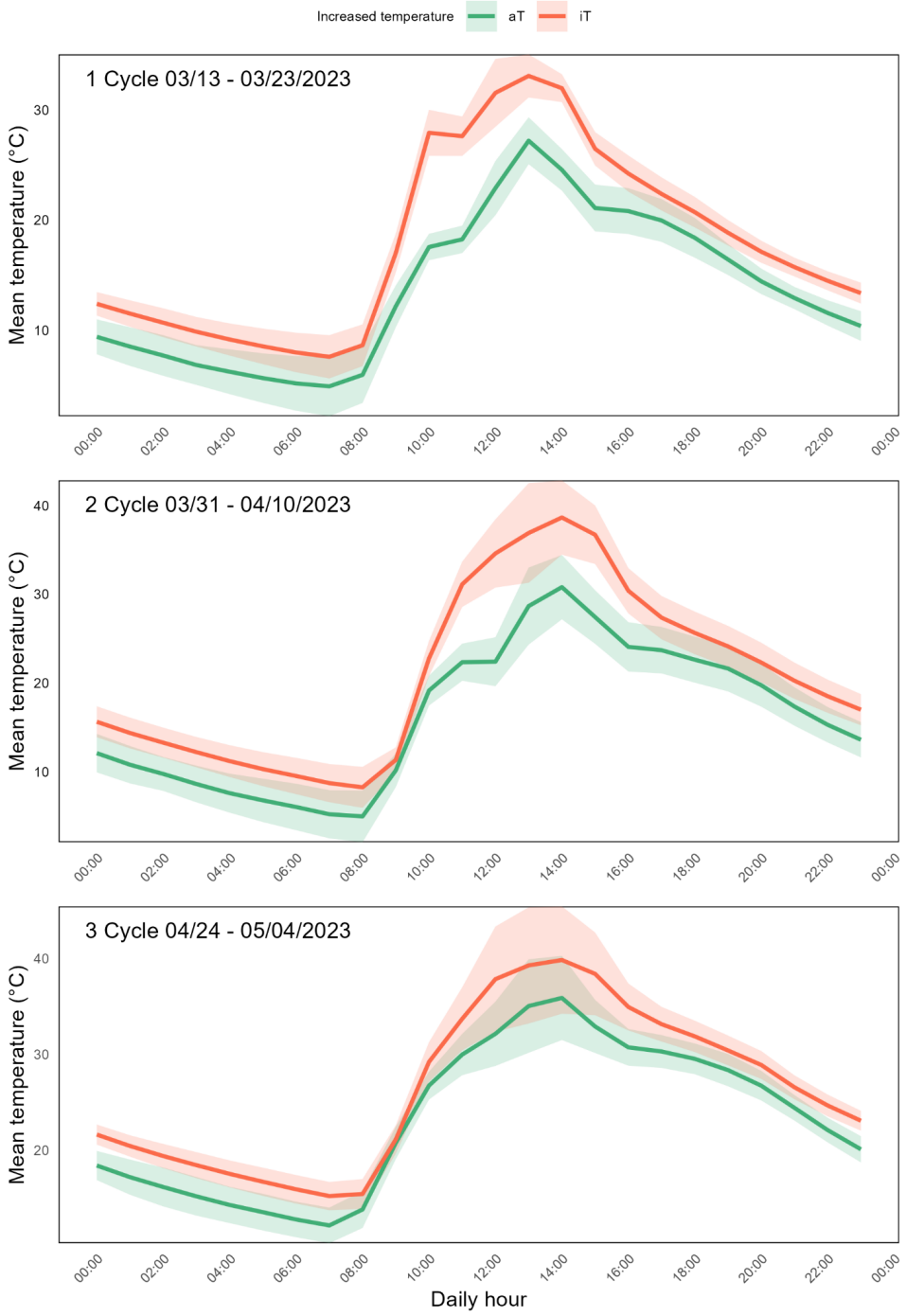

Figure S2: Air temperature (°C) measurements recorded every 15 minutes during the three stress cycles. Each point represents a single observation under ambient (aT, green) or increased temperature (iT, red) conditions. Smoothed lines indicate general trends over time for each treatment.

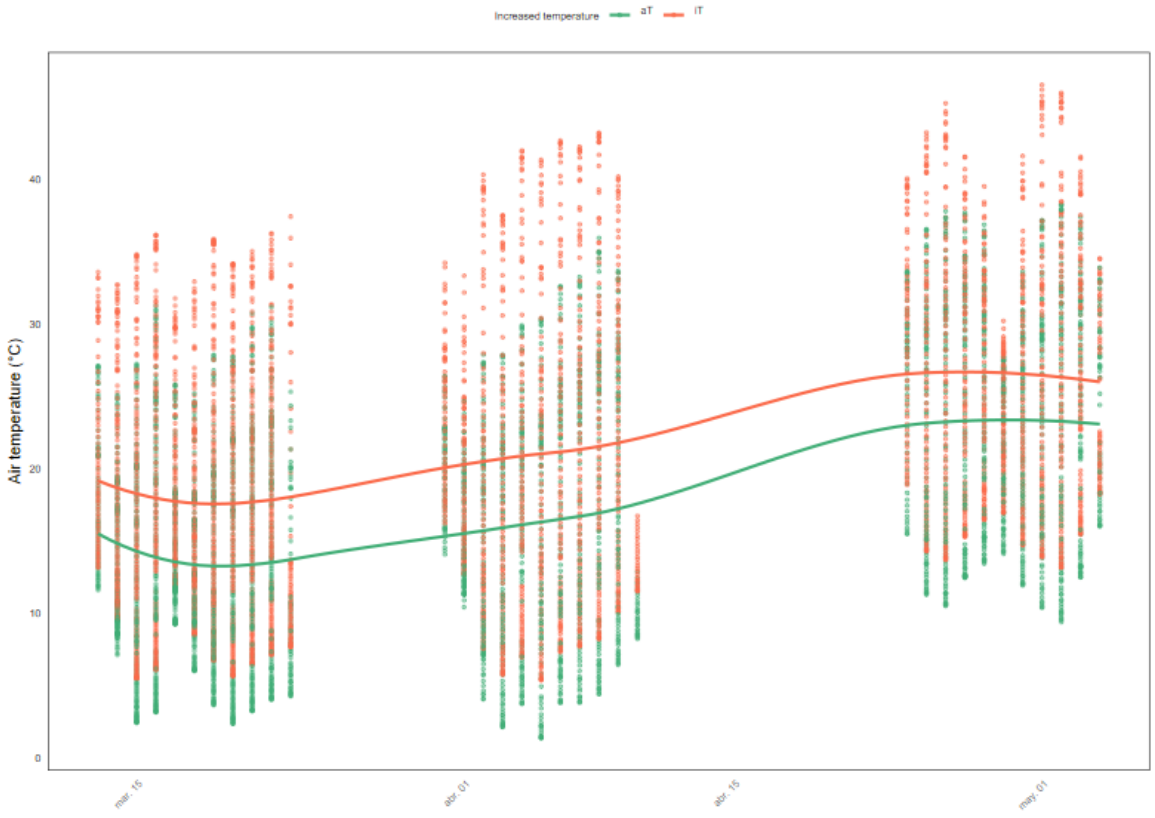

Figure S3: Soil microbial responses under climate treatments across two management systems: conventional tillage (left panels) and no-tillage (right panels), and two crop systems: rotation (solid lines) and monoculture (dashed lines). Variables measured include (A) dissolved organic carbon (DOC), (B) microbial biomass carbon (MBC), (C) soil respiration (CO_2), and the enzymatic activities of (D) urease, (E)β-glucosidase and (F) phosphatase. Measurements were taken during the stress and recovery phases. Different black uppercase letters indicate significant differences among treatments within each tillage system ($P < 0.05$); different colored uppercase letters indicate significant differences between climate treatments under monoculture systems, and lowercase letters under rotation systems.

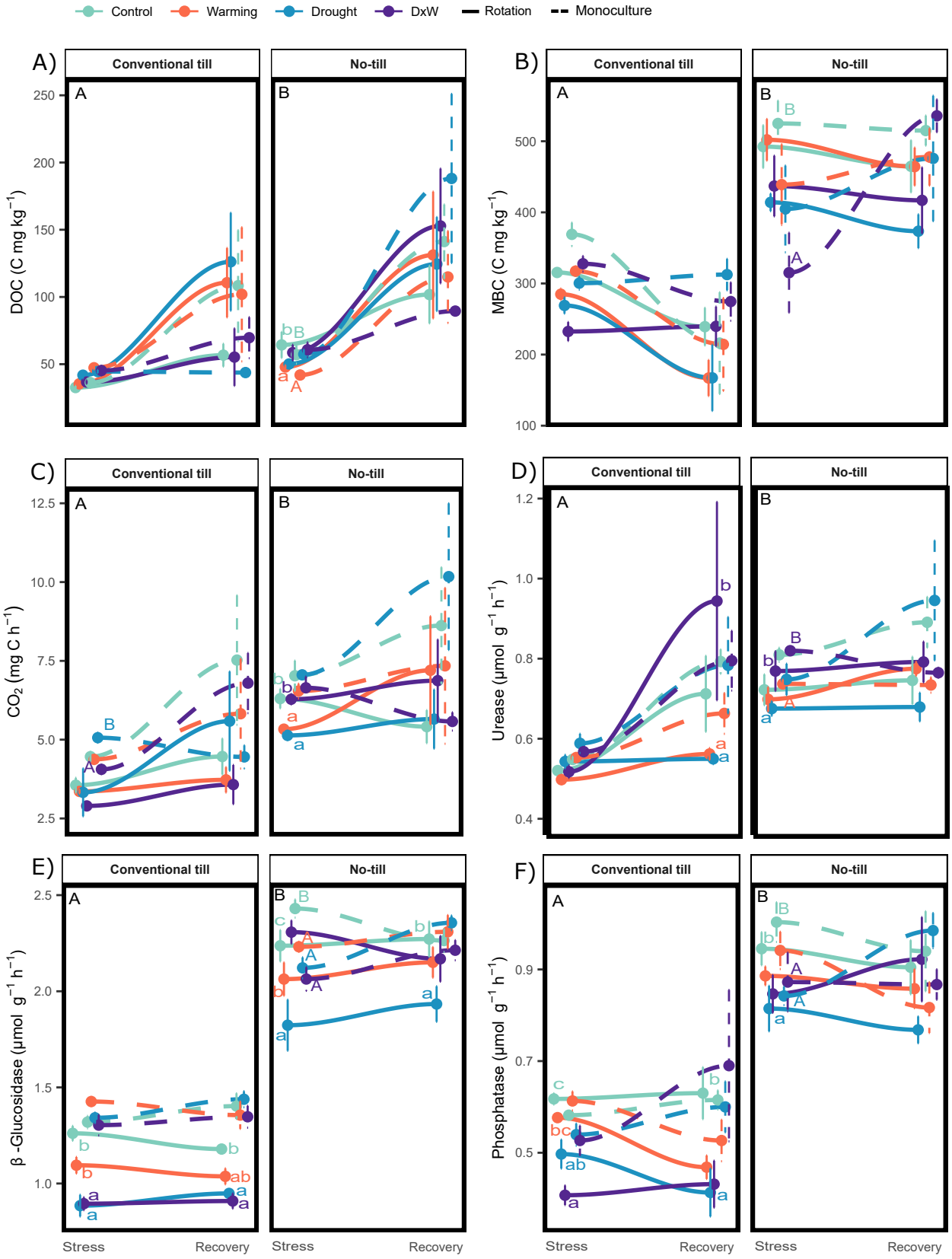

Figure S4: Soil nematode responses under climate treatments across two management systems: conventional tillage (left panels) and no-tillage (right panels), and two crop systems: rotation (solid lines) and monoculture (dashed lines). Measurements were taken during the stress and recovery phases. Different black uppercase letters indicate significant differences among treatments within each tillage system ($P < 0.05$); different colored uppercase letters indicate significant differences between climate treatments under monoculture systems, and lowercase letters under rotation systems.

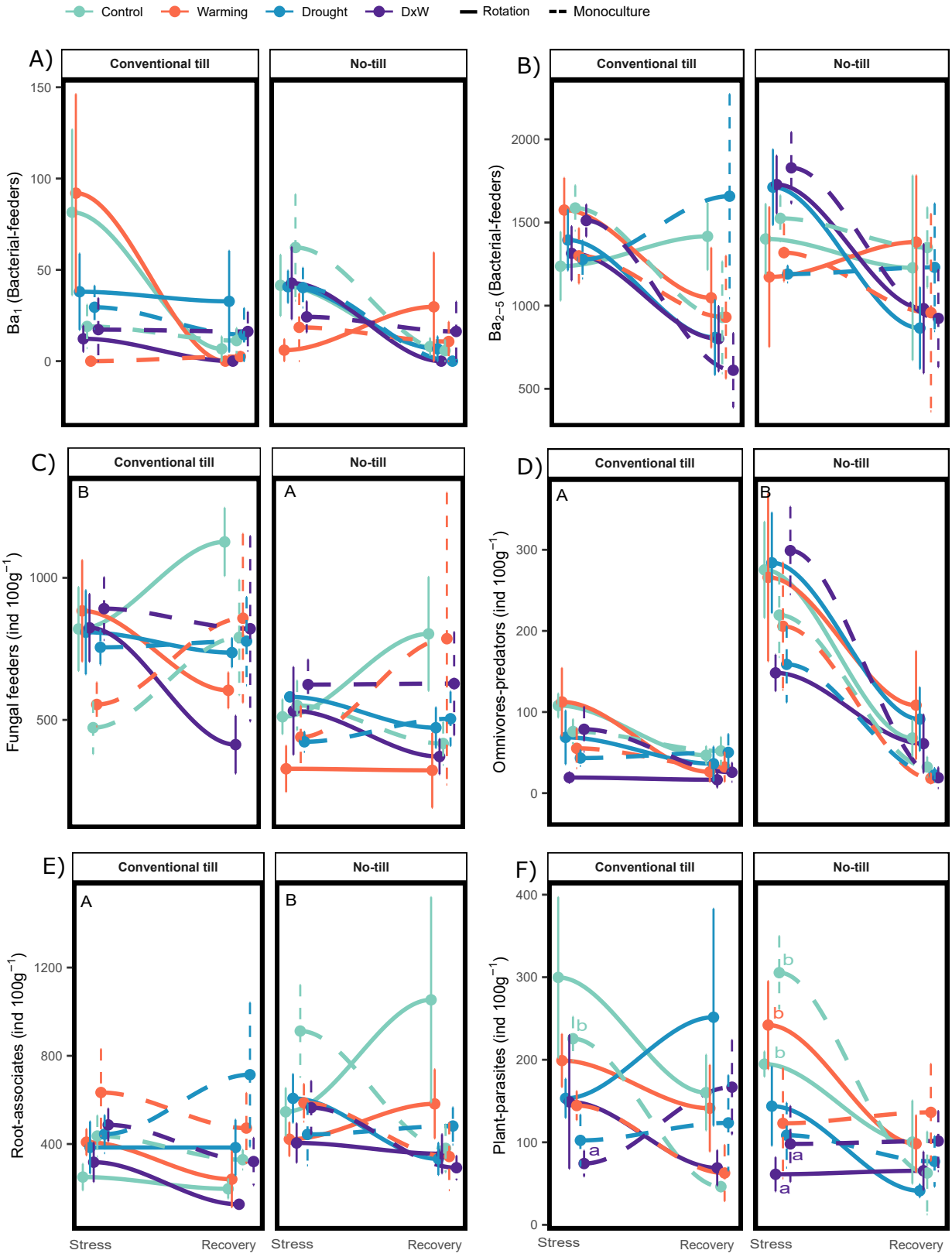

Table S1: Initial soil chemical properties and enzyme activities under different tillage and cropping system treatments.

	Conventional till		**No-till**	
	rotation	***monoculture***	***rotation***	***monoculture***
NO_3 (mg kg^{-1})	24.6	19.94	32.27	36.35
NH_4 (mg kg^{-1})	1.94	2.05	3.01	3.19
Available P (mg kg^{-1})	11.6	15	22.4	21.2
DOC (mg kg^{-1})	31.3	33.7	49.8	58.7
MBC (mg kg^{-1})	233.0	295.0	525.7	569.5
Phosphatase (μmol g^{-1} h^{-1})	0.535	0.573	1.000	0.889
β-Glucosidase (μmol g^{-1} h^{-1})	1.275	1.724	2.683	2.590
Urease (μmol g^{-1} h^{-1})	0.0046	0.0055	0.0087	0.0092

Table S2: Mean control temperature and temperature increase (ΔT) during each experimental cycle. Values are presented as mean ± standard error.

Cycle	**Mean control temperature (°C)**	**Temperature increased (ΔT, °C)**
1 – 03/14 – 03/23/2023	13.79 ± 0.679	4.16 ± 0.07
2 – 03/31 – 04/10/2023	16.43 ± 1.02	4.63 ± 0.11
2 – 04/24 – 05/04/2023	23.01 ± 0.82	3.25 ± 0.11

Table S3. Results of the glmmTMB models (χ^2 values) for the effects of tillage system, rotation system, drought, warming, and their interactions on soil electrical conductivity (Elect. Conduc.), nitrate (NO_3^-), ammonium (NH_4^+), soil organic carbon (SOC), available phosphorus (P olsen), and pH during recovery period. Significance levels: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, † $P < 0.1$.

	Elect. Conduc.	**NO_3^-**	**NH_4^+**	**SOC**	**Available P**	**pH**
R^2	0.637	0.68	0.256	0.637	0.943	0.387
Tillage (Till)	5.21*	7.11**		174.66***		4.382*
Rotation (Rot)			3.38†	32.58***		
Drought (D)		14.24***		7.96**		
Warming (W)			5.005*			
Till × Rotation		10.98***		23.21***		6.524*
Till × D		3.02†			10.94***	
Rot × D		4.93*		13.63***		
Till × W			3.76†	3.40†		
Rot × W				6.04*		
D × W				7.18**		
Till × Rot × D	2.81†			5.71*		9.60**
Till × Rot × W			4.41*	11.4***		
Till × Rot × D × W				3.99*		3.96*

Table S4. Results of the glmmTMB models (χ^2 values) for the effects of tillage system, crop system, drought, warming, and their interactions on microbial biomass carbon (MBC), CO_2 emission, dissolved organic carbon (DOC), and enzyme activities (β-glucosidase, phosphatase, urease) during the stress and recovery periods. Significance levels: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, † $P < 0.1$.

	MBC		**CO_2**		**DOC**		**β-glu**		**Phos**		**Urease**	
	Stress	Recov	Stress	Recov	Stress	Recov	Stress	Recov	Stress	Recov	Stress	Recov
R^2	0.72	0.74	0.887		0.729		0.96		0.91	0.72	0.88	0.33
Tillage (Till)	21.1***	18.***	61.5***		56.39***		175.4***	179.8***	64.6***	11.5***	49.6***	
Rotation (Rot)	0.7		4.2*	2.88†			6.8*				8.12**	
Drought (D)	4.15*	2.95†	11.1***		6.56*		5.5*	17.2***	10.26**	2.8†		
Warming (W)	0.06		7.6**		9.565**		31.4***					
Till× Rotation	0.15							4*				
Till× D			3.6†		14.4***						2.9†	
Rot× D			5.8*		3.87*			13.9***				
Till × W					8.0*							
Rot × W	3.08†										3.98*	8.04*
D× W			18.2***		11.25***		39.8***	9.5**		3.07†		
Till× Rot× D						3.8†	4.1*					
Till× Rot× W							3.9*					
Till× Rot× D× W						5.3*						

Table S5. Results of the glmmTMB models (χ^2 values) for nematode functional groups under climate treatments during stress and recovery phases. Significance levels: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, † $P < 0.1$.

	Opportunistic Bact-feeders		**Generalist Bact-feeders**		**Fungal-feeders**		**Root-associates**		**Plant-parasites**		**Omnivores-predators**	
	Stress	Recov	Stress	Recov	Stress	Recov	Stress	Recov	Stress	Recov	Stress	Recov
R^2	0.363	0.15	0.25	0.15	0.47	0.27	0.36	0.43	0.39	0.28	0.642	0.227
Tillage (Till)			5.5*		4.4*		15.7***				4.4*	
Rotation (Rot)					3.68†	6.75**	5.83*					
Drought (D)							7.4**					
Warming (W)	3.9*											
Till × Rotation			2.8†	4.3*			6.57*					
Till × D							9.2**					
Rot × D			3.6*		7.06**	5.4*						
Till × W	3.8*		2.8†									
Rot × W					8.4**				3.0†			
D × W										3.08†		
Till× Rot× D							5.4*					
Till × Rot × W												
Till × Rot × D × W											3.0†	

Table S6: Results of the glmmTMB models (χ^2 values) for the effects of tillage system, crop rotation, climate factors (drought and warming combined), and their interactions on resistance (RS) and resilience (RL) indices of MBC, CO_2 emission, dissolved organic carbon (DOC), and enzyme activities (β-glucosidase, phosphatase, urease). Significance levels: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, † $P < 0.1$.

	MBC		**CO_2**		**DOC**		**β-glu**		**Phosphatase**		**Urease**	
	RS	RL	RS	RL	RS	RL	RS	RL	RS	RL	RS	RL
Tillage (Till)			0.65	5.83*		5.557*	5.82*					8.14*
Rotation (Rot)			14.4***	15.9***	3.97*	9.9**				2.7†		3.1†
Climate	7.02*		12.6**	6.54*		13.3**	16.3***				5.8†	
Till × Rotation			3.07†	4.6*		4.71*	14.7***	5.27*	3.6†			2.76†
Till × Climate			18.8***	7.8*	7.078*	12.4**	8.7*		8.6*			
Rot × Climate			12.04**	4.83†			9.4*				18.1***	
Till × Rot × Climate	7.32*	6.18*	8.8*				8.4*				8.64*	

Table S7: Results of the glmmTMB models (χ^2 values) for the effects of tillage system, crop rotation, climate factors (drought and warming combined), and their interactions on resistance (RS) and resilience (RL) indices of nematode trophic groups. Significance levels: *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, † $P < 0.1$.

	Opportunistic Bact-feeders		**Generalist Bact-feeders**		**Fungal-feeders**		**Root-associates**		**Plant-parasites**		**Omnivores predators**	
	RS	RL	RS	RL	RS	RL	RS	RL	RS	RL	RS	RL
R^2	0.37	0.34	0.21	0.22	0.42	0.26	0.10	0.38	0.20	0.26	0.18	0.32
Tillage (Till)												
Rotation (Rot)						6.46*		11.7**		6.9**		3.52†
Climate	6.88*			5.12†	5.00†					5.92†		
Till × Rotation		3.3†					4.6*	8.938**		4.15*		4.59*
Till × Climate												
Rot × Climate												
Till × Rot × Climate					8.09*							