

RESEARCH ARTICLE OPEN ACCESS

Trade-Off Analysis Between Environmental Effects and Profitability in Agriculture: A Finnish Case-Study

Roberta Calone¹  | Domna Tzemi²  | Elena Valkama³  | Marco Acutis⁴  | Alessia Perego⁴  | Marco Botta⁴  | Simone Bregaglio¹ 

¹Council for Agricultural Research and Economics (CREA), Research Centre for Agriculture and Environment, GeoModelLab, Bologna, Italy | ²Natural Resources Institute Finland (Luke), Unit of Bioeconomy and Environment, Bioeconomy Policies and Markets, Helsinki, Finland | ³Natural Resources Institute Finland (Luke), Unit of Bioeconomy and Environment, Sustainability Food Systems and Society, Turku, Finland | ⁴Department of Agricultural and Environmental Sciences, University of Milan, Milan, Italy

Correspondence: Roberta Calone (roberta.calone@crea.gov.it)

Received: 9 September 2025 | **Revised:** 5 February 2026 | **Accepted:** 10 February 2026

Keywords: boreal climate | climate change | fuzzy logic | nitrate leaching | nitrous oxide emissions | process-based model | profitability | soil organic carbon

ABSTRACT

Finding equilibrium between profitability and environmental impacts poses a fundamental challenge in cropping systems management. Identifying trade-offs requires robust tools to reconcile diverse and frequently conflicting objectives, especially in low data availability scenarios. This study presents a novel methodological framework combining the outputs of a process-based crop model with a fuzzy-expert trade-off analysis system in order to perform a structured comparison of alternative cropping systems. Model outputs on soil organic carbon, nitrous oxide emissions, nitrate leaching, and economic return expressed as Net Present Value were aggregated using fuzzy logic to inform a composite index (Σi) ranking trade-off performance on a scale from 0 (worst) to 1 (best). The framework was applied in a case study in Finland, evaluating nine cropping systems under current and future climate conditions. The systems included both crop-based (annual cereals and oilseeds) and livestock-based (with temporary grass) rotations, managed conventionally or organically, and varying in fertilization strategy, residue management, and tillage depth. The analysis was applied using a balanced weighting scheme and three alternative schemes reflecting the priorities of distinct stakeholder categories (young farmers, an agrochemical company, and a Common Agricultural Policy paying agency), allowing assessment of how changes in analytical context affect the resulting index. Under current climate conditions, the conventional livestock-based system with mixed fertilization and residue retention performed best ($\Sigma i = 0.69$) while the conventional crop-based system relying exclusively on mineral fertilization and residue removal underperformed ($\Sigma i = 0.30$). This latter system experienced the sharpest Σi decline under future climate conditions ($\Sigma i = 0.10$), while organic livestock-based systems exhibited stable outcomes ($\Sigma i \sim 0.50$). When evaluation criteria were adjusted to reflect stakeholder priorities, the framework consistently captured shifts in system rankings. This application illustrates the capacity of the framework to differentiate contrasting systems under harmonized assumptions, supporting its potential transferability particularly where long-term site-specific empirical datasets are limited.

1 | Introduction

Decision-making in agriculture requires balancing input costs and resource availability with diverse and often competing stakeholders' priorities (Klapwijk et al. 2014; Kanter et al. 2018).

Reconciling these conflicting objectives is widely recognized as a core challenge in the management of agricultural systems (Yang et al. 2023; Shi and Umair 2024). Climate change further exacerbates these pressures, intensifying trade-offs between short-term productivity and long-term sustainability goals.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial](https://creativecommons.org/licenses/by-nc/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2026 The Author(s). *European Journal of Soil Science* published by John Wiley & Sons Ltd on behalf of British Society of Soil Science.

Highlights

- A trade-off framework links process-based simulations with fuzzy logic aggregation.
- The framework consistently differentiates farming systems across contrasting climate periods.
- Temporary grass and organic inputs enhance trade-off performance under future conditions.
- Stakeholder-defined weighting schemes drive context-adaptive shifts in the trade-off index.

Organic farming exemplifies these tensions. While organic farming plays a pivotal role in EU strategies within the Green Deal, such as the Farm to Fork and Biodiversity initiatives, which aim to increase the share of organic farmland to 25% by 2030 (Billen et al. 2024), its economic viability remains debated due to lower and less stable yields and higher labor requirements compared to conventional systems (Boix-Fayos and de Vente 2023; Knapp and van der Heijden 2018; Smith et al. 2019). These challenges underscore the need for robust analytical frameworks to assess trade-offs between environmental and economic outcomes under changing climatic conditions, beyond the spatial and temporal constraints of field trials, while accounting for the inherent complexity of agricultural systems and the uncertainty of climate projections. Process-based crop models partly address this need by dynamically simulating cropping system performance under contrasting pedo-climatic and management conditions (Timlin et al. 2024). Their outputs are commonly combined with econometric assessments (Antle and Valdivia 2021; Armatas et al. 2018; Stoorvogel et al. 2004), cost-benefit analyses, optimization approaches (Lautenbach et al. 2013), and multi-criteria decision analysis (Radmehr et al. 2022; Deng et al. 2016), often complemented by participatory processes to incorporate stakeholder perspectives and contextual knowledge (Breure et al. 2024; Klapwijk et al. 2014; van Wijk et al. 2016). Integrative approaches based on composite indicators, typology-based clustering, and fuzzy logic have been proposed to synthesize multidimensional outcomes, manage uncertainty, and translate expert knowledge into operational decision-support tools (Carozzi et al. 2013; Bellocchi et al. 2015; Li et al. 2020). However, although these approaches are often used together, combining complex, interdependent model outputs and evaluative criteria in a transparent, coherent, and reproducible way remains methodologically challenging.

To address these limitations, we propose a methodological framework that combines a process-based crop model with a fuzzy logic-based trade-off analysis system. Specifically, outputs from the ARMOSA crop model (Perego et al. 2013), which simulates the effects of alternative management practices and climate periods on soil organic carbon dynamics, nitrogen fluxes, greenhouse gas emissions, and crop yields (Bancheri et al. 2024), are integrated into the Σ ommit trade-off analysis system (Calone et al. 2024, 2025). Within this framework, stakeholder-informed weighting schemes are explicitly defined, and fuzzy inference (Zadeh 1965; Bellocchi et al. 2002; Bosma et al. 2011; Schiavon et al. 2021) is used to aggregate multiple indicators into a transparent and internally consistent comparative assessment. This approach enables the evaluation of environmental and

economic trade-offs across contrasting systems and scenarios that would be difficult to investigate through experimental approaches alone. As a proof of concept, we applied the framework to nine organic and conventional cropping systems representative of boreal conditions in Finland, a region characterized by a sustained decline in soil organic carbon stocks (Heikkinen et al. 2013, 2022) and considered critical for climate adaptation (Wiréhn 2018; Wiréhn et al. 2020). The application illustrates how the framework can differentiate system performance across climate periods and management strategies, providing a structured basis for comparative trade-off analyses in contexts where detailed site-specific empirical data are limited.

2 | Methods

The methodological workflow developed in this study comprised three main phases (Figure 1). First (Section 2.1), nine representative Finnish cropping systems were designed, including five crop-based and four livestock-based systems, each implemented either under organic farming or conventional management. Second (Section 2.2), the ARMOSA model was calibrated and used to simulate cropping systems performance under current (1999–2022) and future climate periods (2040–2069 and 2070–2099). Third (Section 2.3), a trade-off analysis was conducted using the Σ ommit index, integrating four components: changes in soil organic carbon (SOC), nitrous oxide (N_2O -N) emissions, nitrate (NO_3 -N) leaching, and farm profitability expressed as Net Present Value (NPV). The analysis was performed using a balanced weighting scheme and three expert-informed narratives: young farmers, agrochemical company, and CAP paying agency to reflect contrasting stakeholder perspectives by incorporating diverse priorities into the decision-support process.

2.1 | Study Site and Cropping System Management

The South Savo region of Finland was selected as the test area to demonstrate the functioning of the framework. The region has been promoting organic farming for over 40 years, with a network of local organizations fostering organic practices both regionally and globally. This region has been recognized for its excellence in organic farming, including being a finalist in the 2024 EU Organic Awards. The local climate is classified as sub-arctic (Dfc, Köppen-Geiger) and boreal (Metzger et al. 2005), with annual averages of 4.3°C of temperature and 617 mm of cumulated precipitation, peaking in July (73 mm). According to Soil Taxonomy, the soil is a sandy Aquic Haplocryod (Yli-Halla and Mokma 1999). Texture is loamy sand (76% sand, 20% silt, 4% clay) in the Finnish classification system (Yli-Halla et al. 2000), with 3.8% organic carbon in the top 0.3 m, declining to 0.8% in the subsoil (0.3–1.0 m), a soil C/N ratio of 17, and pH 6.2.

Nine five-year cropping systems were designed to represent typical management practices in conventional and organic farms in the study area, distinguishing between crop-based (C) and livestock-based (L) systems (Table 1). Crop-based systems included cereals (spring barley, oat, rye, wheat), oilseed rape, and meadow hay, with organic systems intercropped with fodder pea and ryegrass, the last incorporated as green manure. Livestock-based systems consisted of arable cropping

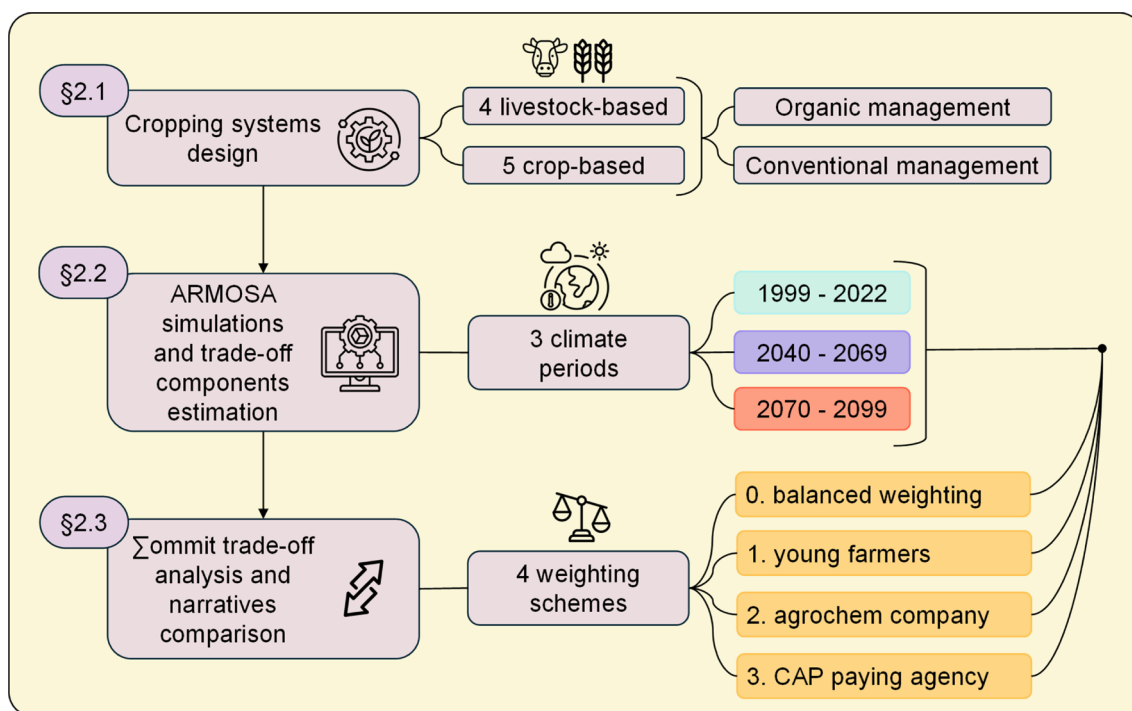


FIGURE 1 | Methodological workflow developed in this study. Boxes provide references to the corresponding subsections in Section 2.

systems alternating cereal crops (barley and oat) with a three-year phase of forage crops (fescue and timothy meadow hay), with clover incorporation as green manure under organic management.

Fertilizer amounts were defined based on regional nitrogen fertilizer sales data (Luke Statistics Database 2025) and applied in a single pre-sowing operation in annual crops. In meadow grass, fertilization was repeated annually during the active growing phase of the meadow. Residue management was varied by either retaining (+) into the soil or removing (–) crop residues from the fields. Tillage depth was set to 20 cm in conventional systems and reduced to 15 cm in organic systems, reflecting common practices in the study area. In conventional crop-based systems (CC, Table 1), ammonium nitrate was applied either alone (CC_M) or in combination with slurry (CC_{MIX}, hereafter mixed fertilization). Organic crop-based systems (CO) included applications of green manure and a meat-bone commercial fertilizer (Ecolan Agra, containing 75% of organic matter, N, 8%; P, 4%; K, 8%; S, 4%) applied either only to oilseed rape (CO_R, hereafter reduced fertilization) or to all the crops in the system (CO_F, hereafter full fertilization). In livestock-based systems, conventional systems combined mineral fertilizer and slurry applications (LC_{MIX}), while organic systems relied solely on slurry (LO_C).

2.2 | Model Simulations

Simulations were conducted with the ARMOSA process-based model (Perego et al. 2013), which has been widely applied in previous studies (Gabbrielli et al. 2025; Garofalo et al. 2024; Schillaci et al. 2023; Tadiello et al. 2023) and was already calibrated for Finnish cropping systems (Valkama et al. 2020). ARMOSA reproduces crop development and growth at a daily time step with a SUCROS-type light interception and gross

photosynthesis approach. Soil water dynamics, changes of bulk density and hydrological characteristics in response to the tillage operations, and changes in the soil organic matter are simulated. Carbon and nitrogen cycles (including mineralization, immobilization, nitrification, denitrification, and leaching) are simulated with an approach that distinguishes among different typologies of crop residues incorporated in the soil and organic fertilizers (Perego et al. 2013).

The model was calibrated and validated using official regional yield statistics for conventionally managed crops (barley, oat, wheat, rye, and grass) from at least 23 years, and for organic production (barley, oats, grass, and oilseed rape) from 3 to 9 years (Luke Statistics database 2023). The calibration was informed by previous studies conducted in Jokioinen (270 km southwest from the test area; Valkama et al. 2020). Key parameters calibrated included the maximum carbon dioxide assimilation rate under light saturation, the N dilution curve, and the water stress sensitivity coefficient, selected based on a previous sensitivity analysis of ARMOSA outputs (Colombi et al. 2024). To assess the consistency of simulated yield distributions, boxplots were compared with statistical yield data in terms of range, central tendency, and variability. As in Schillaci et al. (2023), differences in central tendency between observed and simulated values for each crop were assessed using the non-parametric Mann–Whitney U test, while differences in dispersion were evaluated using Levene's test on the median.

Simulations were performed for the current climate (1999–2022) and for two future periods (2040–2069 and 2070–2099), hereafter referred to as the baseline, 2050 and 2080 periods, respectively, for simplicity. Daily maximum and minimum temperature (°C), precipitation (mm), and global solar radiation (MJ m⁻² day⁻¹) data were collected from a weather station in Mikkeli, South Savo (61°41' N, 027°16' E, 85 m asl), while future climate periods were

TABLE 1 | Management scheme of simulated 5-year crop-based (C) and livestock-based (L) systems under conventional (C) and organic (O) management, with details on residue management and the amount of inorganic and organic fertilization applied.

Farm type	Acronym	Residues	N fertilization (kg ha ⁻¹ year ⁻¹)	Year 1	Year 2	Year 3	Year 4	Year 5	
Crop based (C)	Conventional management (C)								
	CC _M ⁺	Retained	Crop:	Barley	Oilseed	Oat	Meadow	Wheat	
	CC _M ⁻	Removed	80 mineral		rape		hay		
			Hay:						
			120 mineral						
	CC _{MIX} ⁺	Retained	Crop:						
		40 slurry+							
		40 mineral							
		Hay:							
		80 slurry+							
		40 mineral							
Organic management (O)									
CO _R ⁺	Retained	Oilseed rape:	Barley +	Oat	Ryegrass	Rye	Ryegrass as		
		40 Ecolan ^a	Pea	+ Pea	+ clover as		green manure		
		Other crops:			green manure				
		No fert.							
CO _F ⁺	Retained	Oilseed rape:					Oilseed rape		
		40 Ecolan							
		Rye:							
		40 Ecolan							
		Barley/oat – pea:							
		30 Ecolan							
Livestock based (L)	Conventional management (C)								
	LC _{MIX} ⁺	Retained	Crop:	Oat	Timothy–fescue hay			Barley	
	LC _{MIX} ⁻	Removed	40 mineral+						
			40 slurry						
			Hay:						
			80 mineral+						
		75 slurry							
Organic management (O)									
LO _S ⁺	Retained	Crop:	Oat	Timothy–fescue hay + clover			Barley		
LO _S ⁻	Removed	80 slurry							
		Hay:							
		155 slurry							

^aEcolan Agra, a meat-bone commercial fertilizer.

based on the Representative Concentration Pathway 4.5 obtained from the HadGEM2 global climate model (Collins et al. 2011) accessed via the BonaRes repository (Fronzek et al. 2024). Compared to the baseline period (Figure 2), the mean annual temperature and precipitation are expected to increase by 2.9°C and 40 mm in 2050, and by 3.3°C and 67 mm in 2080. Temperature increases are observed across all months, with relatively higher values in March, April, August, and October. Precipitation changes exhibit a seasonal pattern, with increases concentrated in winter months (September–January and March–April), while late spring and summer show declines (May–August under the 2050 scenario and May–July under the 2080 scenario).

ARMOSA outputs were used to calculate the four components used as input to the trade-off analysis systems,

hereafter referred to as trade-off components: SOC changes (kg ha⁻¹ year⁻¹), N₂O-N emissions (kg ha⁻¹ year⁻¹), NO₃-N leaching (kg ha⁻¹ year⁻¹), and the NPV (€ ha⁻¹ year⁻¹; Arshad 2012). The annual SOC changes were calculated as the difference between final and initial soil total stable carbon (0.3 m depth) divided by the number of simulated years. N₂O-N emissions were expressed as average annual fluxes, calculated as the cumulative N₂O-N emissions from nitrification and denitrification processes (0.3 m depth) over the simulation period divided by the number of simulated years. The mean annual NO₃-N leaching was quantified at the soil bottom profile (1 m depth) as the cumulative leached NO₃-N divided by the number of simulated years. According to Arshad (2012), the NPV represents the sum of all future cash flows discounted to their present value. The NPV of each of the nine management schemes was estimated as

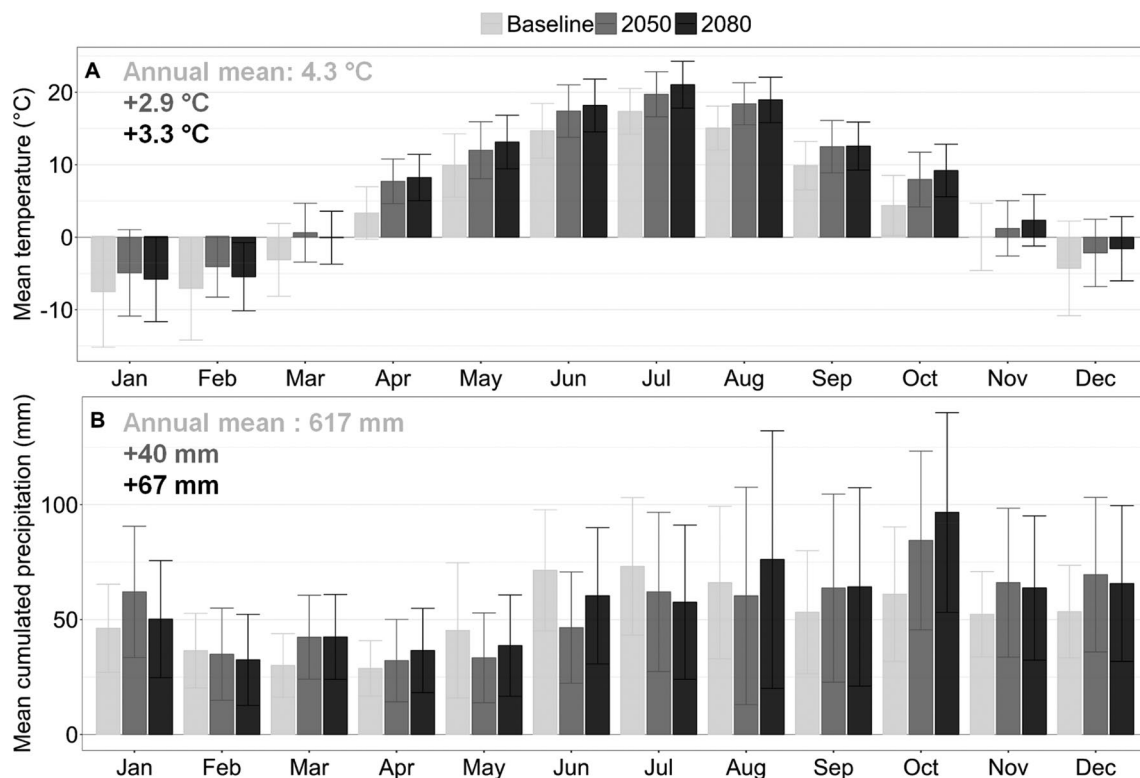


FIGURE 2 | Monthly mean (A) temperature (°C) and (B) cumulated precipitation (mm) under the baseline period (1999–2022, light-gray) and future periods (2050, gray; 2080, black) for Mikkeli, South Savo region of Finland. Error bars represent the standard deviation across years ($n = 24$ for baseline, $n = 31$ for future periods) for temperature and precipitation, respectively.

the sum of the annual gross margins over the simulation period, discounted at a fixed annual discount rate (Equation 1):

$$NPV = \frac{\sum_c^n GM_{c,t}}{(1+i)^t} \quad (1)$$

where $GM_{c,t}$ is the gross margin of each crop c at time t , n is the number of crops in each cropping system, and i is the discount rate. The discount rate was set to 6%, reflecting the average annual return of the Helsinki stock exchange from 1921 to 2020, adjusted for typical transaction costs faced by small-scale investors such as farmers (Pörssisäätiö 2023). The gross margin for each crop was estimated as the sum of crop production and subsidies minus the crop-specific variable costs (Equation 2).

$$GM_{c,t} = \text{yield}_{c,t} \times \text{price}_{c,t} + \text{subsidies}_{c,t} - \text{variable costs}_{c,t} \quad (2)$$

The production inputs per hectare used to calculate gross margins were provided by ProAgria, a Finnish rural consultancy organization (ProAgria 2021). Subsidies were calculated under the assumption that farmers receive all basic subsidies. Crop prices were obtained from ProAgria (ProAgria 2021) and VYR, the Finnish Cereal Committee, which publishes national statistics on cereal prices (VYR 2025). In the case of livestock-based systems, only crop production was considered, assuming that dairy farms derive monetary value from the amount of grass grown for cattle feeding. A market price for baled grass silage

was assumed based on Doyle et al. (2024). The NPV under future climate periods was estimated using yield projections generated by the ARMOSA model, while keeping input data constant, as no reliable estimates for future prices or interest rates were available. Yields, prices, costs, subsidies and production inputs per each cropping system are provided in Tables S1–S7.

2.3 | Trade-Off Analysis

The trade-off components were analyzed using the fuzzy logic-based framework developed by Calone et al. (2024) within the EJP-Soil ΣOMMIT project (Sustainable management of soil organic matter to mitigate trade-offs between C sequestration and nitrous oxide, methane, and nitrate losses). This system integrates the four trade-off components into a composite metric, the Σommit index (Σi), ranging from 0 (worst trade-off) to 1 (best trade-off).

The analysis was applied separately under current and future climate periods. Four weighting schemes were considered to assess the sensitivity of the index to contrasting priority settings. These included a balanced scheme with equal weights attributed to the four trade-off components (narrative 0) and three alternative narratives representing hypothetical stakeholder profiles: young innovative farmers (narrative 1), a multinational agrochemical company (narrative 2), and a national Common Agricultural Policy paying agency (narrative 3). These stakeholder narratives were implemented through a role-based expert elicitation process described in Calone et al. (2024, 2025), involving 60 soil

TABLE 2 | Mean, 10th, and 90th percentiles of the weights assigned by 60 experts to the four trade-off components under three stakeholder narratives, from Calone et al. (2024, 2025).

Stakeholder narratives	Trade-off components	Narrative 0 (balanced)	Mean weight ^a	10 th percentile	90 th percentile
1. Young farmers	SOC	25	23	10	30
	N ₂ O-N	25	16	10	25
	NO ₃ -N	25	17	10	20
	NPV	25	44	27	60
2. Agrochemical company	SOC	25	18	10	30
	N ₂ O-N	25	22	10	30
	NO ₃ -N	25	25	11	30
	NPV	25	35	10	64
3. CAP paying agency	SOC	25	32	25	40
	N ₂ O-N	25	24	17	30
	NO ₃ -N	25	23	20	30
	NPV	25	21	10	30

^aGreen, weight is higher than narrative 0; red, weight is lower than narrative 0.

science experts who assigned weights to each trade-off component by adopting the perspective of each stakeholder profile.

To evaluate how variability in expert-derived weights within each narrative propagates to the Σi , the 10th and 90th percentiles of the distribution of weights assigned to each trade-off component were extracted (Table 2), rescaled (0–100) and cross-combined, resulting in 16 distinct weighting schemes per narrative. Two additional schemes based on the mean and mode of the weight distributions were included, yielding a total of 18 different weighting schemes per narrative. The Σi was then computed across all schemes, and its sensitivity to variations in weight distributions was described using the median and interquartile range of the resulting Σi values.

The detailed description of the fuzzy logic aggregation methodology, including the design of the membership functions, rule base, stakeholder narratives, and corresponding weighting schemes, is provided in Calone et al. (2024, 2025). All analyses were conducted using the RStudio environment, using the *sets* R package (Meyer and Hornik 2023).

3 | Results

Figure 3 shows the distribution of simulated yields for each crop alongside the corresponding observed statistical values used for model calibration. Despite some discrepancies, particularly in the distribution tails, the simulated values reproduced the observed central tendencies and ranges with reasonable agreement across most crop types. Statistical tests indicated no significant differences in central tendency (Mann–Whitney *U* test, $p > 0.05$) for any crop. In contrast, variance differences (Levene's test on the median, $p < 0.05$) were detected for conventional barley, oat, and wheat, where simulated yields displayed greater dispersion than observed yields.

3.1 | Impact of Management Strategies and Climate Periods on the Trade-Off Components

Figure 4 presents the simulated trade-off components for the nine cropping systems under the baseline climate conditions, with projected changes in 2050 and 2080.

3.1.1 | SOC Change

Under baseline climate conditions, livestock-based systems (L) generally exhibited more favorable SOC dynamics than crop-based systems (C, Figure 4A), with LO_S⁺, LO_S⁻, and LC_{MIX}⁺ gaining 0.15%, 0.07%, and 0.03% year⁻¹, respectively, corresponding to increments of 164, 78, and 31 kg ha⁻¹ year⁻¹, while LC_{MIX}⁻ exhibited a slight SOC decline (−0.08% year⁻¹). Among crop-based systems, the greatest SOC depletion was observed in CC_M⁻, with a 0.30% decline (−311 kg ha⁻¹ year⁻¹), while CC_{MIX}⁺ yielded a small positive increase (+ 33 kg ha⁻¹ year⁻¹). Organic cropping systems showed less pronounced SOC reductions than their conventional counterparts (CO_R⁺ = −0.08%; CO_F⁺ = −0.04%).

Under future climate conditions, livestock-based (L) systems experienced lower SOC losses than crop-based (C) systems. LO_S[±] maintained a positive Δ SOC by 2080, LC_{MIX}⁺ shifted from positive to slightly negative values, while LC_{MIX}⁻ continued to decline. In crop-based systems, CC_M⁻ showed the largest decline (−0.41%) by 2080, followed by CC_{MIX}⁺ (−0.33%) and CC_M⁺ (−0.28%). Organic systems (CO_R⁺, CO_F⁺) also became increasingly negative, reaching Δ SOC values below −0.20%.

3.1.2 | N₂O-N Emissions

Under baseline climate conditions, livestock-based systems (L) exhibited higher N₂O-N emissions than crop-based

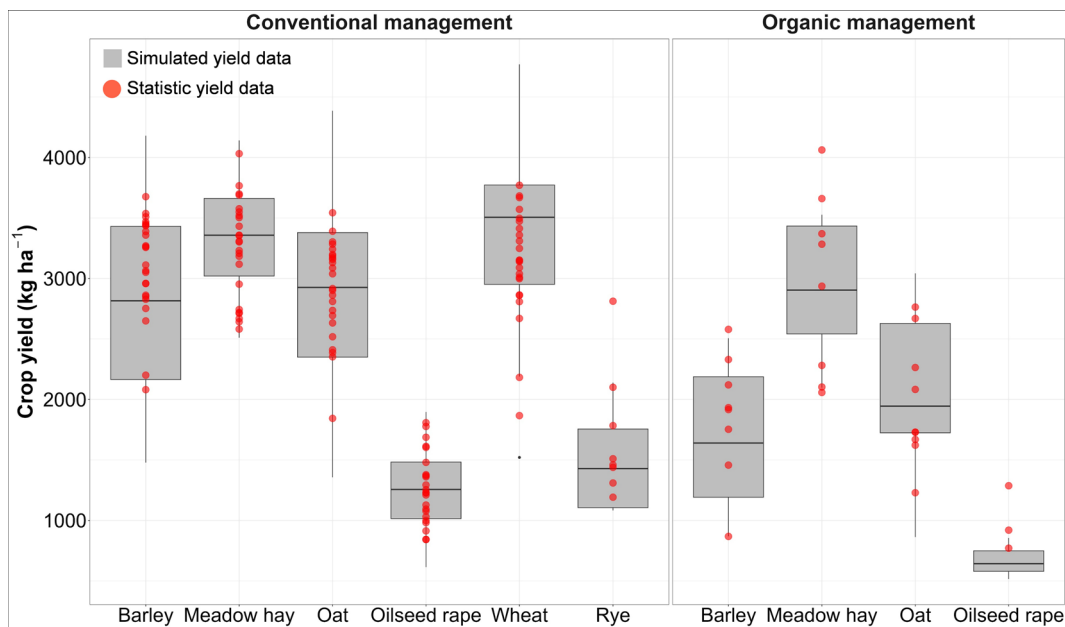


FIGURE 3 | Simulated yield distributions (gray boxplots) and observed statistical yields for the years 1999–2022 (red dots) for each crop under conventional and organic management.

systems (C, Figure 4B), with LO_{S-} and LO_{S+} reaching 1.66 and 1.52 $kg\ ha^{-1}\ year^{-1}$, respectively. The lowest emissions occurred in organic crop-based systems (CO), particularly in CO_{R+} (0.41 $kg\ ha^{-1}\ year^{-1}$), followed by CO_{F+} , while conventional crop-based systems (CC) showed intermediate emission levels ($CC_{MIX+} = 0.79\ kg\ ha^{-1}\ year^{-1}$; $CC_{M-} = 1.21\ kg\ ha^{-1}\ year^{-1}$).

Future climate projections indicated increasing N_2O-N emissions across most systems. The largest increase was simulated for CO_{R+} (+86% by 2080). Conventional crop-based systems (CC) with exclusive mineral fertilization also showed substantial increases, with peaks of +31% by 2080 in CC_{M+} . In contrast, organic livestock-based systems remained more stable with LO_{S-} even showing a 15% decrease by 2050.

3.1.3 | NO_3-N Leaching

Under baseline climate conditions, NO_3-N leaching was the lowest in the organic crop-based system with reduced fertilization (CO_{R+} , 3.7 $kg\ ha^{-1}\ year^{-1}$, Figure 4C), whereas highest leaching was associated with conventional crop-based systems ($CC_{M\pm}$, ~15 $kg\ ha^{-1}\ year^{-1}$). Organic livestock-based systems (LO) showed intermediate values ($LO_{S\pm}$, ~11 $kg\ ha^{-1}\ year^{-1}$), higher than those of their counterpart under conventional management ($LC_{MIX\pm}$, ~7 $kg\ ha^{-1}\ year^{-1}$).

Future climate conditions led to a consistent increase in NO_3-N leaching across all systems, with the largest increase occurring in crop-based systems (C). CO_{R+} and CO_{F+} increased by 223% and 107% by 2080, respectively, while CC_{M-} and CC_{M+} raised by 103% and 125%, respectively. The conventional crop-based system with mixed fertilization (CC_{MIX+}) showed moderate increases (51%). Organic livestock-based systems ($LO_{S\pm}$) were less variable, remaining stable by 2050 and increasing by ~14% by 2080, whereas $LC_{MIX\pm}$ showed a ~59% increase by 2080.

3.1.4 | Net Present Value

Under baseline climate conditions, conventional livestock-based systems achieved the highest NPV (Figure 4D), reaching 425 and 400 $\text{€}\ ha^{-1}\ year^{-1}$ in LC_{MIX-} and LC_{MIX+} , respectively. Organic livestock-based systems ($LO_{S\pm}$) showed lower but comparable values (~298 $\text{€}\ ha^{-1}\ year^{-1}$). Among crop-based systems (C), the highest NPVs were obtained in organic systems with reduced fertilization (CO_{R+}) and in conventional systems with mixed fertilization (CC_{MIX+}), both exceeding 300 $\text{€}\ ha^{-1}\ year^{-1}$. These were followed by $CC_{M\pm}$, while CO_{F+} showed the lowest value (263 $\text{€}\ ha^{-1}\ year^{-1}$).

Under future climate conditions, NPV declined across all crop-based systems (C), with the strongest reductions in CO_{F+} (-52%), CO_{R+} (-43%), and CC_{MIX+} (-39%) by 2080. In contrast, organic livestock-based systems ($LO_{S\pm}$) exhibited moderate NPV increases (~3% by 2050 and ~19% by 2080), while conventional livestock-based systems ($LC_{MIX\pm}$) showed even stronger gains by 2080 (~27%).

3.2 | Trade-Off Analysis Under the Balanced Weighting Scheme

According to the balanced weighting scheme (narrative 0), the overall Σ index (Σi) values for the nine cropping systems under current and future climate conditions ranged between 0.10 and 0.69, with no system achieving either completely adverse ($\Sigma i = 0$) or excellent ($\Sigma i = 1$) performance (Figure 5). Highest Σi values were observed in LC_{MIX+} (livestock-based conventional with mixed fertilization and residue retention), CC_{MIX+} (crop-based conventional with mixed fertilization and residue retention), and CO_{F+} (crop-based organic with full fertilization and residue retention), all exceeding 0.58. Intermediate Σi values were observed in CO_{R+} , LC_{MIX-} , CC_{M+} , and LO_{S+} (ranging

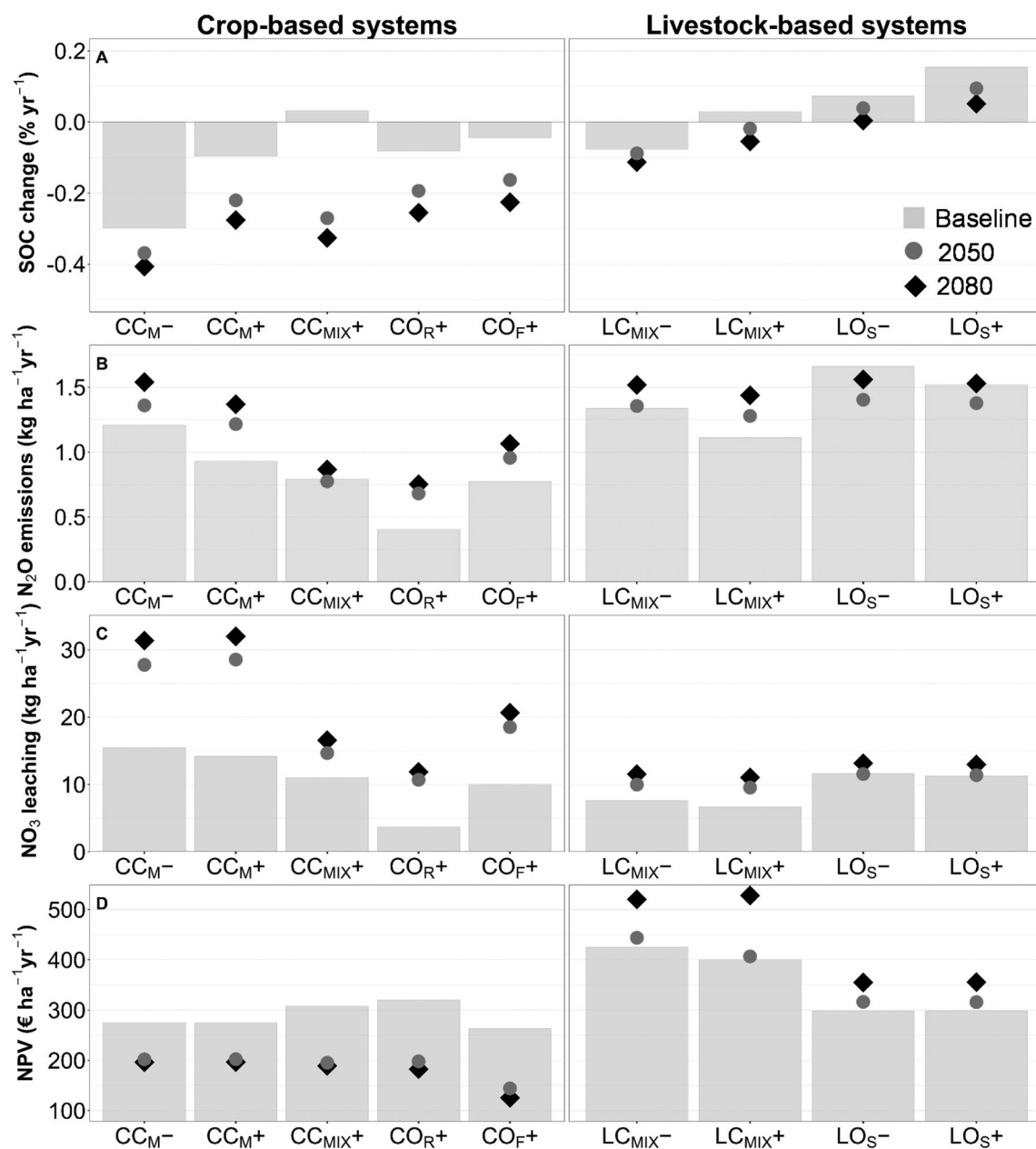


FIGURE 4 | (A) mean rate of SOC change (% year⁻¹), (B) mean N₂O-N emissions (kg ha⁻¹ year⁻¹), (C) mean NO₃-N leaching (kg ha⁻¹ year⁻¹), and (D) Net Present Value (€ ha⁻¹ year⁻¹) for the nine cropping systems, averaged across simulated years within each climate period (baseline: light-gray bars; 2050: gray circles; 2080: black diamonds). Numbers below the x-axis correspond to bare-soil days per year. Cropping systems are grouped into crop-based (C) and livestock-based (L) systems, under conventional (C) or organic (O) management, with residue retention (+) or removal (-). Detailed definitions are provided in Table 1.

from 0.57 to 0.51), while CC_M⁻ (crop-based conventional with residue removal) reached the lowest score.

Under future climate conditions, a general Σi decline is projected across all systems. The steepest reductions occurred in the conventional crop-based systems (CC_M[±]), with average Σi decreases of 49% and 69% by 2050 and 2080, respectively. CC_{MIX}⁺, CO_F⁺, and CO_R⁺ also showed marked reductions, with Σi values falling below 0.45 by 2080. In contrast, organic livestock-based systems (LO_S[±]) showed small Σi gains (~4%) by 2050, followed by moderate declines by 2080 (~8%). The LC_{MIX}⁻ system showed negligible changes, maintaining a Σi value of approximately 0.52 across both future periods,

whereas LC_{MIX}⁺ exhibited a moderate decline, reaching a Σi value of 0.56 by 2080.

3.3 | Trade-Off Analysis Under the Stakeholder-Informed Weighting Schemes

Figure 6 compares Σi values computed under the balanced weighting scheme (narrative 0) and the three stakeholder narratives across baseline and future climate conditions.

Conventional livestock-based systems (LC_{MIX}[±]) were the only systems that consistently obtained higher Σi values across all

climate periods and stakeholder narratives relative to the balanced scheme. In addition, narrative 3 (CAP paying agency) systematically increased Σi values for all cropping systems across all climate periods. By contrast, under current climate

conditions, slight decreases in Σi values were observed across almost all crop-based systems (C) under narrative 1 (young farmers) and 2 (agrochemical company), except for the organic cropping system with reduced fertilization (CO_{R+}). Similar

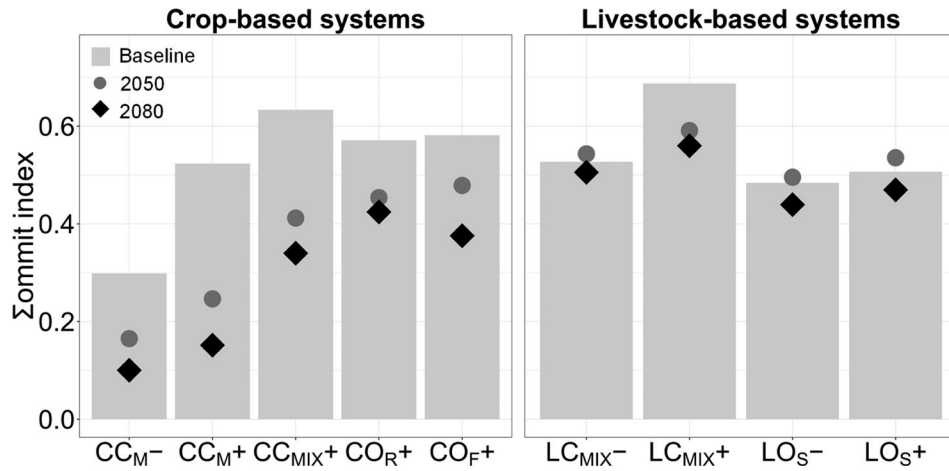


FIGURE 5 | Σ omit index values (Σi) for the nine cropping systems under the baseline period (light-gray bars) and future periods (2050, gray circles and 2080, black diamonds) computed under the balanced weighting scheme (narrative 0). Cropping systems are grouped into crop-based (C) and livestock-based (L) systems, under conventional (C) or organic (O) management, with residue retention (+) or removal (-). Detailed definitions are provided in Table 1.

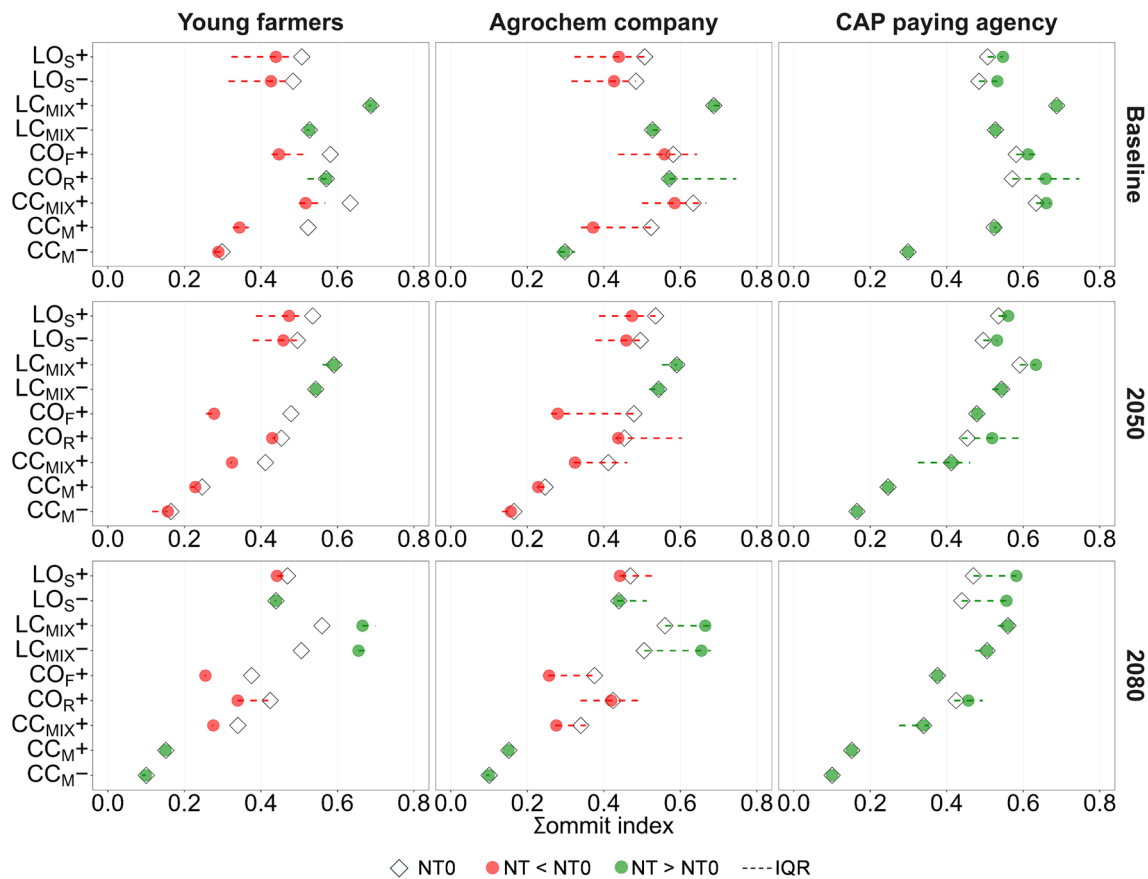


FIGURE 6 | Median (points) and interquartile range (IQR, dashed lines) of Σ omit index values (Σi) under stakeholder narratives (NT: young farmers, agrochemical company, CAP paying agency) compared to values under narrative 0 (NT0, diamonds), across climate periods (baseline, 2050, 2080). Red points indicate Σi medians lower than narrative 0; green points Σi medians higher than narrative 0. Cropping systems are grouped into crop-based (C) and livestock-based (L) systems, under conventional (C) or organic (O) management, with residue retention (+) or removal (-). Detailed definitions are provided in Table 1.

decreases were also observed in organic livestock systems ($LO_S \pm$).

In the 2050 period, the decreasing Σi trend under narrative 1 and 2 extended to CO_R+ and CC_{M-} , which obtained lower values than in current climate conditions.

In the 2080 period, responses under the same narratives were intermediate, with Σi increases maintained for $LC_{MIX \pm}$ and additionally observed for LO_S- and $CC_{M \pm}$.

4 | Discussion

4.1 | Methodological Framework: Rationale, Added Value, and Scope for Improvement

Process-based models provide a detailed representation of agroecosystem dynamics, yet their outputs are often challenging to interpret collectively, particularly when trade-offs between multiple, and sometimes conflicting, environmental and economic objectives must be assessed. This study introduces a novel framework that integrates the outputs of the ARMOSA crop model with the Σ commit trade-off analysis system to address this limitation. The Σ commit trade-off analysis system functions as a post-processing layer, aggregating model results into a single composite indicator, the Σ commit index, through fuzzy logic and expert-informed weightings. This integration facilitates a structured assessment of trade-offs across contrasting management strategies and climate periods, thereby translating complex simulation outputs into more accessible decision-support information.

This work extends previous applications of the Σi framework, which relied either on static Tier 1 methodology to estimate the trade-off components (Calone et al. 2024) or site-specific orchard data (Bregaglio et al. 2024), by coupling the index with Tier 2, process-based model outputs that explicitly simulate climate–management interactions. ARMOSA was calibrated using long-term regional yield statistics, consistent with other crop modeling studies (Bregaglio et al. 2023; Ferrara et al. 2010; Lawes et al. 2022; Schillaci et al. 2023; Therond et al. 2011), while outputs related to SOC dynamics, N_2O -N emissions, and NO_3 -N leaching were cross-validated against literature data from Nordic environments to ensure plausibility. This approach provides a scenario-oriented tool that can operate under data-scarce conditions while maintaining robustness.

The framework does not aim to provide predictive precision at the site level but rather supports structured comparative analyses of system-level trade-offs under harmonized assumptions (Gabbrielli et al. 2025). While regional calibration limits the resolution of local dynamics, it ensures internal consistency across scenarios. Consequently, the reported values for SOC, N_2O -N emissions, NO_3 -N leaching, and profitability should not be interpreted as site-specific predictions but as illustrative outcomes that demonstrate the framework's capacity to discriminate between contrasting systems and to capture stakeholder-informed priorities.

The economic evaluation followed the same rationale. Gross margin estimates were derived from current regional data on

crop prices, inputs, and subsidies and applied as static values across scenarios, without accounting for interannual variability, potential reforms in subsidy schemes, or market fluctuations, nor including revenues from animal-derived products such as milk. While these simplifications may lead to underestimation of absolute profitability, particularly in livestock-based systems, they do not affect the relative comparisons underpinning the trade-off analysis.

Finally, the study employed a single climate model and emission pathway. While this constraint reduces predictive robustness and excludes the variability that could arise from multi-model ensembles, it does not compromise the primary objective of demonstrating the framework's capacity to integrate process-based model outputs into a transparent and transferable system for trade-off analysis.

Within this scope, the framework is intended for researchers, policy analysts, and technical advisors interested in comparative and scenario-based evaluations of agricultural systems, rather than for operational field-level decision-making by individual farmers. Transferability to other European contexts requires a defined minimum set of input data sufficient to ensure internal consistency of simulations. This includes: (i) continuous daily climate forcing from ground-based meteorological observations or harmonized gridded datasets (e.g., E-OBS, ERA5), adequate to represent long-term temperature and precipitation regimes; (ii) basic soil physical and chemical properties at representative spatial scales (e.g., texture class, soil organic carbon content, C/N ratio, pH), derived from regional soil surveys or European-scale databases such as ESDAC or LUCAS; and (iii) long-term regional yield statistics for the main crops, used, when site-specific experimental data are unavailable, to constrain average system behavior during model calibration. This information is sufficient to support realistic simulations of crop productivity and soil carbon and nitrogen dynamics and to enable robust relative comparisons of trade-off components across management scenarios and climate periods.

4.2 | Impact of Management Strategies and Climate Periods on the Trade-Off Components

The application of the framework to the Finnish case study highlights distinct patterns across systems, differentiating their performance under current and future climate conditions. The simulated SOC changes under baseline climate conditions ranged from +0.15% to −0.30% year^{−1}, with net carbon gains in organic livestock-based systems, whereas losses were associated with crop-based systems. These data are consistent with long-term data from Finnish mineral agricultural soils, which indicate average SOC declines of −0.35% year^{−1} (1974–2009) and −0.40% year^{−1} (2009–2018) (Heikkinen et al. 2013, 2022), with slower depletion observed in cropping systems based on temporary grass crops rather than annual crops. The SOC increase in organic and mixed fertilization systems with temporary grass likely reflects the cumulative benefits of continuous soil cover, prolonged root persistence, reduced tillage intensity, and larger organic matter inputs from livestock manure and green manure (Lessmann et al. 2022; Shang et al. 2024). Additionally, crop residues retention is known to

further reinforce these positive effects leading to the maintenance of high soil organic matter levels (Liu et al. 2023; Lu 2020; Piccoli et al. 2020).

N_2O -N emissions in this study ranged from 0.41 to $1.66 \text{ kg ha}^{-1} \text{ year}^{-1}$, corresponding to an emission factor close to 1% of nitrogen inputs. Nitrous oxide emission factors are strongly controlled by climate and water regime, soil properties, and the form and timing of nitrogen inputs (Cayuela et al. 2017). Under cold boreal conditions, this sensitivity is further amplified by pronounced seasonality, freeze–thaw cycles (Olesen et al. 2023), and early spring rewetting often leading to emission factors that diverge substantially from the generic reference values of 1% (IPCC 2019). In this study, the relatively narrow range of simulated N_2O -N emissions may be attributed to the site's coarse sandy texture and modest annual precipitation, both of which constrain denitrification by limiting water-filled pore space (Pihlatie et al. 2004). Lowest simulated emissions were observed in the organic crop-based system with reduced fertilization, while highest emissions were associated with organic livestock-based system with temporary grass, due to the higher fertilization inputs. The simulated levels of N_2O -N emissions align with field measurements in Finland for organic (1.4 kg N ha^{-1} , $\sim 1.1\%$ of N input) and conventional (1.2 kg N ha^{-1} , 0.7% of N input) forage systems reported by Syväsalo et al. (2006), and for cereal-based conventional systems ($0.74\text{--}1.2 \text{ kg N ha}^{-1}$, $\sim 0.7\%\text{--}1.2\%$ of N input) reported by Regina et al. (2021). Our simulations highlighted larger emission rates from organic livestock-based systems ($1.5\text{--}1.7 \text{ kg N ha}^{-1}$), despite shorter bare soil periods (Figure 4), compared to organic crop-based systems ($0.4\text{--}0.8 \text{ kg ha}^{-1} \text{ year}^{-1}$). This divergence may reflect distinct biogeochemical processes associated with forage leys, which have been shown to emit comparable or higher N_2O -N than cereals or legumes, particularly when manure is the dominant nitrogen source (Petersen et al. 2006). In this context, the larger manure inputs in organic livestock-based systems relative to their conventional counterparts likely contributed to higher emissions. Unlike mineral fertilizers, manure contains a large proportion of organic nitrogen that mineralizes gradually under cool conditions before becoming available for crop uptake (Kasimir and Klemedtsson 2002; Lægred and Aastveit 2002). This prolonged nitrogen availability, coupled with transient increases in soil moisture, such as in freeze–thaw cycles or early spring rewetting, can trigger short but intense denitrification pulses, contributing to cumulative emissions even in well-drained sandy soils (Tesfai 2016).

Simulated NO_3 -N leaching ranged from 4 to $15 \text{ kg ha}^{-1} \text{ year}^{-1}$ under current climate conditions. The lowest nitrate leaching occurred in the organic crop-based system with reduced fertilization, while the highest rates were simulated in the conventional crop-based systems. These values align with those for grass ley measured or predicted by the COUP model, which varied from 2 to $10\text{--}15 \text{ kg ha}^{-1} \text{ year}^{-1}$ in Finland (Salo and Turtola 2006; Valkama et al. 2016). Additionally, they correspond with the average NO_3 -N leaching losses for cereal-based rotations under conventional management ($10.7 \text{ kg ha}^{-1} \text{ year}^{-1}$) and under organic management ($8.5 \text{ kg ha}^{-1} \text{ year}^{-1}$) reported for Finnish conditions (Kostensalo, Lemola, et al. 2024).

As observed for N_2O -N emissions, organic management reduced NO_3 -N leaching in crop-based systems but increased it in livestock-based systems. At comparable fertilization rates, conventional livestock-based systems achieved higher yields and nitrogen uptake than their organic counterparts, likely reducing nitrate leaching. In contrast, lower yields in organic livestock-based systems, combined with reduced nitrogen uptake and an exclusive reliance on organic fertilizers, likely enhanced off-season nitrogen mineralization under cold and wet conditions (Hansen et al. 2019; Pandey et al. 2018), contributing to greater NO_3 -N leaching. In crop-based systems, conventional management involved higher nitrogen fertilization rates than in organic crop-based systems (Table 1), which enhanced crop productivity (Table S6) but also increased nitrogen surpluses, thereby contributing to higher simulated NO_3 -N leaching. Additionally, extended periods of bare soil and reliance on annual crops can potentially increase drainage (Simmelsgaard 1998), thereby amplifying the effects of nitrogen surpluses on nitrate leaching.

Profitability was highest in livestock-based systems, consistent with broader trends in Finland (Luke Statistics Database 2024) where dairy production benefits from stable milk prices, long-term contracts, and substantial EU subsidies. In these systems, manure recycling also contributes to nutrient self-sufficiency, reducing reliance on external fertilizer inputs. The higher profitability of conventional livestock-based systems compared with their organic counterparts is mainly explained by higher grass yields, which translate into lower variable costs through reduced need for purchased feed (Tables S3–S5). By contrast, organic livestock-based systems showed lower yields and higher production costs, which constrained profitability despite higher subsidy levels ($\sim +25\%$ than conventional systems; Tables S4 and S5). This pattern is consistent with the literature reporting lower profitability of organic systems under boreal conditions, largely driven by yield penalties of $\sim 35\%$ compared with conventional systems (Poutala et al. 1994; Korsæth 2012). In crop-based systems, yield reductions under organic management were partly offset by higher subsidy amounts (approximately $+30\%$ relative to conventional systems; Tables S1 and S2), resulting in more comparable profitability levels between conventional and organic systems. This gap may further narrow with the adoption of better-adapted or higher-yielding varieties in organic systems, as suggested by recent evidence (Grovermann et al. 2022).

Under future climate conditions, all systems showed declining SOC balance and increasing N_2O -N emissions and NO_3 -N leaching. These trends are primarily driven by rising temperatures and increased precipitation, which stimulate microbial activity and accelerate SOC mineralization (Qi et al. 2016), especially in Nordic soils where SOC stocks are high (Heikkinen et al. 2022; Tao et al. 2023). Concurrently, warming and increased precipitation associated with climate change intensify nitrogen cycling, increasing soil nitrogen availability and stimulating nitrification–denitrification processes, thereby promoting both N_2O -N emissions and NO_3 -N leaching (Butterbach-Bahl et al. 2013; Hui et al. 2024). Conventional crop-based systems emerged as the most vulnerable under future climate periods due to their reliance on annual crops, mineral fertilization, deeper tillage, and prolonged periods of bare soil. Collectively, these management

practices are likely to result in reduced organic matter inputs, impair soil structure and its capacity to retain water and nutrients, and increase susceptibility to nitrogen losses, ultimately compromising soil productivity and crop yields (Olesen et al. 2011). The observed reduction in the profitability of these systems is consistent with projected declines for cereal yields, primarily driven by shorter growing periods and reduced biomass accumulation (Olesen et al. 2011; Poggi et al. 2022). In contrast, livestock-based systems relying on temporary grass showed greater stability, as temporary grass may benefit from future warming through longer harvest windows and increased forage biomass production. These effects can partly offset declining cereal yields, thereby contributing to yield stability and improved economic performance (Khanal 2023; Thivierge et al. 2023).

4.3 | Trade-Off Analysis Under the Balanced Weighting Scheme

The analysis of the Σ ommit index under the baseline climate conditions revealed that the conventional livestock-based system with residue retention achieved the highest Σi score ($LC_{MIX+}=0.69$), followed by the conventional crop-based system with mixed fertilization and residue retention ($CC_{MIX+}=0.63$) and the organic crop-based systems with residue retention ($CO_F+=0.58$, $CO_R+=0.57$). In LC_{MIX+} , the high Σi reflects a combination of strong economic performance, limited NO_3 -N leaching, and modest SOC gains. Although N_2O emissions were intermediate, the overall balance highlights the potential of livestock-based systems with temporary meadow hay within the rotation, livestock manure application and residue retention to sustain production while promoting carbon conservation (Jensen et al. 2022; Bolinder et al. 2020). In CC_{MIX+} , the relatively high Σi indicates a favorable compromise between agronomic and environmental outcomes. The combined use of mineral fertilizers and slurry, together with residue retention, resulted in moderate SOC losses, intermediate N_2O -N emissions, and comparatively low NO_3 -N leaching with respect to other conventional crop-based systems. While profitability was not the highest, it remained competitive, suggesting that incorporating organic amendments into conventional systems can reduce environmental impacts (Körschens et al. 2013) without compromising economic performance. The CO_F+ system presented a particularly balanced profile, with limited SOC losses, low N_2O -N emissions, and moderate NO_3 -N leaching. Although associated with lower economic returns, its strong environmental performance contributed to reach a favorable trade-off value. Close behind, the CO_R+ system exhibited the lowest N-related impacts and limited SOC losses, with intermediate profitability. This performance reflects the joint effect of residue retention and green manure application, which supported soil organic carbon stocks, and low nitrogen inputs, which constrained both gaseous emissions and nitrate leaching, while economic returns were partly sustained by reduced fertilization costs and subsidy support (Table S2).

At the opposite end of the spectrum, the lowest Σi score was recorded by the conventional crop-based system with residue removal ($CC_M-=0.30$). In CC_M- , exclusive reliance on mineral fertilization combined with residue removal and the absence of perennial crops resulted in minimal organic carbon inputs and extended periods of bare soil, driving pronounced SOC losses

and increased NO_3 -N leaching that could not be compensated by the moderate economic returns.

Across future climate conditions, a general decline in Σi values was observed, particularly in conventional crop-based systems without organic inputs ($CC_{M\pm}$), where yield reductions were pronounced. Remarkably, CC_{MIX+} (conventional with mixed fertilization), despite being the second-best performing system under current climate conditions, showed a pronounced decline in Σi values under future periods, primarily due to a marked shift in SOC dynamics, from modest gains to substantial losses. These results suggest that, while mixed fertilization can generate favorable trade-off configurations under current conditions, it may be insufficient to offset the absence of perennial phases and their associated benefits for SOC in conventional annual cropping systems under future climate conditions (Crews et al. 2018). A particularly noteworthy case is LO_S+ , which, despite not ranking among the top-performing systems under baseline climate conditions due to intermediate profitability and elevated N_2O -N emissions, is the only system that consistently achieved SOC gains across all climate periods and maintained nearly stable trade-off values over time. These patterns reflect the role of perennial phases in increasing carbon inputs, reducing bare-soil periods, and dampening climate-driven variability in soil C and N dynamics (Kostensalo, Hyväluoma, et al. 2024; Shang et al. 2024).

Consistent patterns have emerged across previous applications of the Σ ommit trade-off analysis system that employed the same narrative schemes and trade-off components adopted in this study, and were based either on a synthetic dataset derived using Tier 1 based methodologies (Calone et al. 2024) or on empirical measurements (Bregaglio et al. 2024). In the large-scale assessment by Calone et al. (2024), based on ~1.8 million synthetic agronomic case-scenarios with annual field crops, Σi values ranged from 0.13 to 0.82; systems integrating organic fertilization, green manure, vegetated fallows, and reduced tillage consistently achieved the highest scores, whereas scenarios relying on mineral inputs, bare fallows, and conventional tillage performed poorly. Similarly, in a Mediterranean organic apricot orchard case study (Bregaglio et al. 2024), where the Σi framework was applied to empirical field data from three agrobiodiversity-oriented management strategies, Σi values ranged from 0.35 to 0.70. Here, strategies involving compost application and vegetative cover outperformed others by mitigating nitrogen losses and preserving SOC levels, despite reduced productivity.

The convergence of findings across contrasting climates, crop types, and management strategies underscores the Σi framework's robustness in capturing trade-off gradients and its reliability as a comparative tool.

4.4 | Trade-Off Analysis Under the Stakeholder-Informed Weighting Schemes

The behavior of the Σ ommit index under the three different narrative schemes, each reflecting distinct stakeholder priorities, highlights how shifts in trade-off components weighting affect trade-off assessment. In narrative 1 (young farmers), the highest weight is assigned to economic return, reflecting

a decision-making orientation in which economic viability is a precondition for acceptability (Dessart et al. 2019), while lower importance is given to soil health and nitrogen-related losses. Consequently, systems with strong profitability, despite moderate environmental trade-offs, such as the conventional livestock-based LC_{MIX-} , are perceived as more favorable, resulting in an increased Σi value. This pattern becomes even more pronounced under future climate conditions, as the profitability of LC_{MIX-} and LC_{MIX+} improves, leading to an upward shift in their relative rankings. Conversely, systems with strong environmental performance but lower economic returns, such as the crop-based CC_{MIX+} and CO_{F+} , tend to be penalized across all time horizons. By 2080, however, even CC_{M+} and CC_{M-} experience a slight increase in their Σi values, as their nitrogen-related impacts become relatively less influential within the narrative 1 weighting structure.

Narrative 2 (agrochemical company) adopts a more balanced perspective, assigning relatively high weight to both economic return and NO_3-N leaching, while giving lower priority to SOC and N_2O emissions. This reflects a focus on maintaining productivity while addressing off-site nitrogen losses, consistent with regulatory and reputational concerns surrounding fertilizer management (Dobermann et al. 2022). Under narrative 2, the ranking of systems largely mirrors the trends observed in narrative 1; however, the interquartile ranges are notably wider, indicating greater variability in the expert-assigned weights within this stakeholder group and a broader distribution of trade-off analysis outcomes.

Narrative 3 (CAP paying agency) reflects a distinct policy-oriented narrative explicitly aligned with long-term environmental objectives, such as soil health and climate mitigation (Panagos et al. 2022). In this configuration, the highest weights are assigned to SOC and N_2O emissions, while economic return is comparatively downweighted. This narrative prioritization favors systems that deliver environmental co-benefits, even at the expense of short-term profitability. Accordingly, systems such as LO_{S+} and LO_{S-} , which offer consistent SOC gains despite modest economic returns, see marked improvements in their Σi values and perform well across all climate periods. Similarly, CO_{R+} , which was penalized under narrative 0 in 2050 and 2080 periods due to its limited profitability, achieves higher scores owing to its ability to limit nitrogen losses and maintain SOC levels, aligning closely with narrative 3's environmental focus.

Different results across narrative schemes confirm the Σi framework's responsiveness to variations in stakeholder priorities, supporting its applicability in participatory decision processes where evaluation criteria may differ across institutional, economic, or policy domains.

5 | Conclusions

This study presents a methodological framework that integrates a process-based crop model with a fuzzy logic-based trade-off analysis system for the comparative assessment of agricultural systems. The framework is not intended to provide site-specific

predictive precision, but to ensure internal consistency and comparability across scenarios, supporting scenario-based assessments by researchers and policy analysts.

Results indicated that no single system consistently ranked highest; instead, outcomes varied depending on the relative importance assigned to the economic and environmental components and on changes in climate conditions. In this context, systems integrating perennial phases and organic inputs emerged as more resilient under future climate conditions, particularly with respect to soil carbon dynamics and productivity.

Future developments, including the use of multi-model climate ensembles, spatially explicit datasets, and dynamic economic assumptions, could further improve robustness and broaden the range of European regions and farming contexts in which the framework can be applied.

Author Contributions

Roberta Calone: conceptualization, data curation, formal analysis, methodology, writing – original draft, writing – review and editing, visualization, software, investigation. **Domna Tzemi:** conceptualization, data curation, formal analysis, software, writing – review and editing, investigation. **Elena Valkama:** investigation, conceptualization, methodology, writing – review and editing, validation. **Marco Acutis:** investigation, conceptualization, methodology, writing – review and editing, validation. **Alessia Perego:** software, validation, writing – review and editing. **Marco Botta:** validation, formal analysis, software, data curation. **Simone Bregaglio:** funding acquisition, methodology, project administration, resources, writing – review and editing, supervision, conceptualization, validation.

Acknowledgements

This research was developed in the framework of the project ARTEMIS – Agro-ecological strategies for promoting climate change Mitigation and Adaptation by enhancing soil ecosystem services and sustainable crop production – funded by the European Union's Horizon 2020 research and innovation program under grant agreement no. 862695 EJP SOIL. The project QuantiSOIL– Quantifying the impact of farming practices on soil health in arable lands – received funding from the Natural Resources Institute Finland (Luke). During the preparation of this work, the authors used ChatGPT to revise the structure of some sentences and improve the English. Having used this tool, the authors reviewed and edited the content as required, taking full responsibility for the publication's content.

Funding

This work was supported by HORIZON EUROPE Framework Programme, Grant/Award Number: P101095835 AGRARSENSE (Smart, digitalized components and system for data-based Agriculture and Forestry); Horizon 2020 Framework Programme, Grant/Award Number: 862695 EJP SOIL; Natural Resources Institute Finland (Luke).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

- Antle, J. M., and R. O. Valdivia. 2021. "Trade-Off Analysis of Agri-Food Systems for Sustainable Research and Development." *Q Open* 1: 1–34. <https://doi.org/10.1093/qopen/qoaa005>.
- Armatas, C. A., R. M. Campbell, A. E. Watson, W. T. Borrie, N. Christensen, and T. J. Venn. 2018. "An Integrated Approach to Valuation and Tradeoff Analysis of Ecosystem Services for National Forest Decision-Making." *Ecosystem Services* 33: 1–18. <https://doi.org/10.1016/j.ecoser.2018.07.007>.
- Arshad, A. 2012. "Net Present Value Is Better Than Internal Rate of Return." *Interdisciplinary Journal of Contemporary Research in Business* 4: 211–219.
- Bancheri, M., A. Basile, F. Terribile, et al. 2024. "A Web-Based Operational Tool for the Identification of Best Practices in European Agricultural Systems." *Land Degradation & Development* 35, no. 13: 3965–3980. <https://doi.org/10.1002/ldr.5114>.
- Bellocchi, G., M. Acutis, G. Fila, and M. Donatelli. 2002. "An Indicator of Solar Radiation Model Performance Based on a Fuzzy Expert System." *Agronomy Journal* 94: 1222–1233. <https://doi.org/10.2134/agronj2002.1222>.
- Bellocchi, G., M. Rivington, K. Matthews, and M. Acutis. 2015. "Deliberative Processes for Comprehensive Evaluation of Agroecological Models. A Review." *Agronomy for Sustainable Development* 35: 589–605. <https://doi.org/10.1007/s13593-014-0271-0>.
- Billen, G., E. Aguilera, R. Einarsson, et al. 2024. "Beyond the Farm to Fork Strategy: Methodology for Designing a European Agro-Ecological Future." *Science of the Total Environment* 908: 168160. <https://doi.org/10.1016/j.scitotenv.2023.168160>.
- Boix-Fayos, C., and J. de Vente. 2023. "Challenges and Potential Pathways Towards Sustainable Agriculture Within the European Green Deal." *Agricultural Systems* 207: 103634. <https://doi.org/10.1016/j.agsy.2023.103634>.
- Bolinder, M. A., F. Crotty, A. Elsen, et al. 2020. "The Effect of Crop Residues, Cover Crops, Manures and Nitrogen Fertilization on Soil Organic Carbon Changes in Agroecosystems: A Synthesis of Reviews." *Mitigation and Adaptation Strategies for Global Change* 25: 929–952. <https://doi.org/10.1007/s11027-020-09916-3>.
- Bosma, R., U. Kaymak, J. van den Berg, H. Udo, and J. Verreth. 2011. "Using Fuzzy Logic Modelling to Simulate Farmers' Decision-Making on Diversification and Integration in the Mekong Delta, Vietnam." *Soft Computing* 15: 295–310. <https://doi.org/10.1007/s00500-010-0618-7>.
- Bregaglio, S., A. Fiore, R. Calone, et al. 2024. "Application of the Σommit Index to Fruit Orchards: Background, Methods and Results of the Application of the Σommit Index on Fruit Tree Orchards." <https://doi.org/10.5281/zenodo.14055580>.
- Bregaglio, S., F. Ginaldi, E. Raparelli, G. Fila, and S. Bajocco. 2023. "Improving Crop Yield Prediction Accuracy by Embedding Phenological Heterogeneity Into Model Parameter Sets." *Agricultural Systems* 209: 103666. <https://doi.org/10.1016/j.agsy.2023.103666>.
- Breure, T., N. Estrada-Carmona, A. Petsakos, E. Gotor, B. Jansen, and J. Groot. 2024. "A Systematic Review of the Methodology of Trade-Off Analysis in Agriculture." *Nature Food* 5: 211–220. <https://doi.org/10.1038/s43016-024-00926-x>.
- Butterbach-Bahl, K., E. M. Baggs, M. Dannenmann, R. Kiese, and S. Zechmeister-Boltenstern. 2013. "Nitrous Oxide Emissions From Soils: How Well Do We Understand the Processes and Their Controls?" *Philosophical Transactions of the Royal Society, B: Biological Sciences* 368: 20130122. <https://doi.org/10.1098/rstb.2013.0122>.
- Calone, R., A. Fiore, G. Pellis, et al. 2024. "A Fuzzy Logic Evaluation of Synergies and Trade-Offs Between Agricultural Production and Climate Change Mitigation." *Journal of Cleaner Production* 442: 140878. <https://doi.org/10.1016/j.jclepro.2024.140878>.
- Calone, R., A. Fiore, G. Pellis, et al. 2025. "A Harmonized Dataset Relating Alternative Farmer Management Practices to Crop Yield, Soil Organic Carbon Stock, Nitrous Oxide Emissions, and Nitrate Leaching Generated Using IPCC Methodologies and Meta-Analyses." *Data in Brief* 58: 111226. <https://doi.org/10.1016/j.dib.2024.111226>.
- Carozzi, M., S. Bregaglio, B. Scaglia, E. Bernardoni, M. Acutis, and R. Confalonieri. 2013. "The Development of a Methodology Using Fuzzy Logic to Assess the Performance of Cropping Systems Based on a Case Study of Maize in the Po Valley." *Soil Use and Management* 29: 576–585. <https://doi.org/10.1111/sum.12066>.
- Cayuela, M. L., E. Aguilera, A. Sanz-Cobena, et al. 2017. "Direct Nitrous Oxide Emissions in Mediterranean Climate Cropping Systems: Emission Factors Based on a Meta-Analysis of Available Measurement Data." *Agriculture, Ecosystems & Environment* 238: 25–35. <https://doi.org/10.1016/j.agee.2016.10.006>.
- Collins, W. J., N. Bellouin, M. Doutriaux-Boucher, et al. 2011. "Development and Evaluation of an Earth-System Model - HadGEM2." *Geoscientific Model Development* 4: 1051–1075. <https://doi.org/10.5194/gmd-4-1051-2011>.
- Colombi, A., M. Bancheri, M. Acutis, A. Basile, M. Botta, and A. Perego. 2024. "A Sound Understanding of a Cropping System Model With the Global Sensitivity Analysis." *Environmental Modelling & Software* 173: 105932. <https://doi.org/10.1016/j.envsoft.2023.105932>.
- Crews, T. E., W. Carton, and L. Olsson. 2018. "Is the Future of Agriculture Perennial? Imperatives and Opportunities to Reinvent Agriculture by Shifting From Annual Monocultures to Perennial Polycultures." *Global Sustainability* 1: e11. <https://doi.org/10.1017/sus.2018.11>.
- Deng, X., Z. Li, and J. Gibson. 2016. "A Review on Trade-Off Analysis of Ecosystem Services for Sustainable Land-Use Management." *Journal of Geographical Sciences* 26: 953–968. <https://doi.org/10.1007/s11442-016-1309-9>.
- Dessart, F. J., J. Barreiro-Hurle, and R. van Bavel. 2019. "Behavioural Factors Affecting the Adoption of Sustainable Farming Practices: A Policy-Oriented Review." *European Review of Agricultural Economics* 46, no. 3: 417–471. <https://doi.org/10.1093/erae/jbz019>.
- Dobermann, A., T. Bruulsema, I. Cakmak, et al. 2022. "Responsible Plant Nutrition: A New Paradigm to Support Food System Transformation." *Global Food Security* 33: 100636. <https://doi.org/10.1016/j.gfs.2022.100636>.
- Doyle, P., M. O'Donovan, P. Crosson, and T. Tubritt. 2024. "Feed Costs – Current Situation and Future Scenario Analysis." In *Climate Adaption Conference*, edited by B. Mc Carthy and M. Dineen, 12–15. Teagasc, Animal & Grassland Research and Innovation Centre.
- Ferrara, R. M., P. Trevisiol, M. Acutis, G. Rana, G. M. Richter, and N. Baggaley. 2010. "Topographic Impacts on Wheat Yields Under Climate Change: Two Contrasted Case Studies in Europe." *Theoretical and Applied Climatology* 99: 53–65. <https://doi.org/10.1007/s00704-009-0126-9>.
- Fronzek, S., H. Webber, R. Rötter, A. C. Ruane, and F. Ewert. 2024. "A Daily Time-Step Observed and Scenario Climate Dataset on a European Grid for Crop Modelling Applications." *Open Data Journal for Agricultural Research* 10: 28–34. <https://doi.org/10.4228/ZALF.DK.59>.
- Gabrielli, M., M. Peretto, M. Botta, et al. 2025. "Optimization of Agronomic Management Positively Affects Soil GHG Emission: Viable Solutions of Mitigation in Moist and Dry Mediterranean Climate Zones." *European Journal of Agronomy* 168: 127668. <https://doi.org/10.1016/j.eja.2025.127668>.
- Garofalo, P., M. Parlavacchia, L. Giglio, et al. 2024. "ARMOSA Model Parametrization for Winter Durum Wheat Cultivation Under Diverse

- Cropping Management Practices in a Mediterranean Environment.” *Agronomy* 14, no. 1: 164. <https://doi.org/10.3390/agronomy14010164>.
- Grovermann, C., M. Weiner, L. Levy, M. Locher, J. Manuel Herrera, and E. Winter. 2022. “Three Decades of Organic Wheat Improvement: Assessing the Impact and Returns on Investment.” *Q Open* 2: 1–14. <https://doi.org/10.1093/qopen/qaoc005>.
- Hansen, S., R. B. Frøseth, M. Stenberg, et al. 2019. “Reviews and Syntheses: Review of Causes and Sources of N₂O Emissions and NO₃ Leaching From Organic Arable Crop Rotations.” *Biogeosciences* 16, no. 14: 2795–2819. <https://doi.org/10.5194/bg-16-2795-2019>.
- Heikkinen, J., R. Keskinen, J. Kostensalo, and V. Nuutinen. 2022. “Climate Change Induces Carbon Loss of Arable Mineral Soils in Boreal Conditions.” *Global Change Biology* 28: 3960–3973. <https://doi.org/10.1111/gcb.16164>.
- Heikkinen, J., E. Ketoja, V. Nuutinen, and K. Regina. 2013. “Declining Trend of Carbon in Finnish Cropland Soils in 1974–2009.” *Global Change Biology* 19: 1456–1469. <https://doi.org/10.1111/gcb.12137>.
- Hui, D., A. Ray, L. Kasrija, and J. Christian. 2024. “Impacts of Climate Change and Agricultural Practices on Nitrogen Processes, Genes, and Soil Nitrous Oxide Emissions: A Quantitative Review of Meta-Analyses.” *Agriculture* 14, no. 2: 240. <https://doi.org/10.3390/agriculture14020240>.
- IPCC. 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.
- Jensen, J. L., A. M. Beucher, and J. Eriksen. 2022. “Soil Organic C and N Stock Changes in Grass–Clover Leys: Effect of Grassland Proportion and Organic Fertilizer.” *Geoderma* 424: 116022. <https://doi.org/10.1016/j.geoderma.2022.116022>.
- Kanter, D. R., M. Musumba, S. L. R. Wood, et al. 2018. “Evaluating Agricultural Trade-Offs in the Age of Sustainable Development.” *Agricultural Systems* 163: 73–88. <https://doi.org/10.1016/J.AGSY.2016.09.010>.
- Kasimir, K., and L. Klemmedtsson. 2002. “A Critical Analysis of Nitrous Oxide Emissions From Animal Manure.” In *Greenhouse Gas Inventories for Agriculture in the Nordic Countries. Proceedings of the International Workshop in Helsingør, 24–25. DIAS Report No. 81*, edited by S. O. Petersen and J. E. Olesen, 107–121. Danish Institute of Agricultural Sciences.
- Khanal, N. 2023. “Integration of Perennial Forage Seed Crops for Cropping Systems Resiliency in the Peace River Region of Western Canada.” *Canadian Journal of Plant Science* 103: 1–12. <https://doi.org/10.1139/cjps-2022-0125>.
- Klapwijk, C. J., M. T. van Wijk, T. S. Rosenstock, P. J. A. van Asten, P. K. Thornton, and K. E. Giller. 2014. “Analysis of Trade-Offs in Agricultural Systems: Current Status and Way Forward.” *Current Opinion in Environmental Sustainability* 6: 110–115. <https://doi.org/10.1016/J.COSUST.2013.11.012>.
- Knapp, S., and M. G. A. van der Heijden. 2018. “A Global Meta-Analysis of Yield Stability in Organic and Conservation Agriculture.” *Nature Communications* 9: 3632. <https://doi.org/10.1038/s41467-018-05956-1>.
- Korsaeth, A. 2012. “N, P, and K Budgets and Changes in Selected Topsoil Nutrients Over 10 Years in a Long-Term Experiment With Conventional and Organic Crop Rotations.” *Applied and Environmental Soil Science* 2012, no. 1: 539582. <https://doi.org/10.1155/2012/539582>.
- Körschens, M., E. Albert, M. Armbruster, et al. 2013. “Effect of Mineral and Organic Fertilization on Crop Yield, Nitrogen Uptake, Carbon and Nitrogen Balances, as Well as Soil Organic Carbon Content and Dynamics: Results From 20 European Long-Term Field Experiments of the Twenty-First Century.” *Archives of Agronomy and Soil Science* 59, no. 8: 1017–1040. <https://doi.org/10.1080/03650340.2012.704548>.
- Kostensalo, J., J. Hyväluoma, L. Jauhiainen, et al. 2024. “Diversification of Crop Rotations and Soil Carbon Balance: Impact Assessment Based on National-Scale Monitoring Data.” *Carbon Management* 15, no. 1: 2298373. <https://doi.org/10.1080/17583004.2023.2298373>.
- Kostensalo, J., R. Lemola, T. Salo, L. Ukonmaanaho, E. Turtola, and M. Saarinen. 2024. “A Site-Specific Prediction Model for Nitrogen Leaching in Conventional and Organic Farming.” *Journal of Environmental Management* 349: 119388. <https://doi.org/10.1016/j.jenvman.2023.119388>.
- Lægread, M., and A. H. Aastveit. 2002. “Nitrous Oxide Emissions from Field-Applied Fertilizers.” In *Greenhouse Gas Inventories for Agriculture in the Nordic Countries: Proceedings of an International Workshop, Helsingør, Denmark, 24–25 January 2002, Funded by the Nordic Council of Ministers*, edited by S. O. Petersen and J. E. Olesen, 122–134. DIAS Report No. 81. Danish Institute of Agricultural Sciences.
- Lautenbach, S., M. Volk, M. Strauch, G. Whittaker, and R. Seppelt. 2013. “Optimization-Based Trade-Off Analysis of Biodiesel Crop Production for Managing an Agricultural Catchment.” *Environmental Modelling and Software* 48: 98–112. <https://doi.org/10.1016/j.envsoft.2013.06.006>.
- Lawes, R., G. Mata, J. Richetti, A. Fletcher, and C. Herrmann. 2022. “Using Remote Sensing, Process-Based Crop Models, and Machine Learning to Evaluate Crop Rotations Across 20 Million Hectares in Western Australia.” *Agronomy for Sustainable Development* 42: 120. <https://doi.org/10.1007/s13593-022-00851-y>.
- Lessmann, M., G. H. Ros, M. D. Young, and W. de Vries. 2022. “Global Variation in Soil Carbon Sequestration Potential Through Improved Cropland Management.” *Global Change Biology* 28: 1162–1177. <https://doi.org/10.1111/gcb.15954>.
- Li, M., Q. Fu, V. P. Singh, D. Liu, T. Li, and Y. Zhou. 2020. “Managing Agricultural Water and Land Resources With Tradeoff Between Economic, Environmental, and Social Considerations: A Multi-Objective Non-Linear Optimization Model Under Uncertainty.” *Agricultural Systems* 178: 102685. <https://doi.org/10.1016/j.agsy.2019.102685>.
- Liu, J., L. Fang, T. Qiu, et al. 2023. “Crop Residue Return Achieves Environmental Mitigation and Enhances Grain Yield: A Global Meta-Analysis.” *Agronomy for Sustainable Development* 43: 78. <https://doi.org/10.1007/s13593-023-00928-2>.
- Lu, X. 2020. “A Meta-Analysis of the Effects of Crop Residue Return on Crop Yields and Water Use Efficiency.” *PLoS One* 15, no. 4: e0231740. <https://doi.org/10.1371/journal.pone.0231740>.
- Luke Statistics Database. 2023. “Yield of the Main Crops by ELY Centre 1999–2022.” https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__02%20Maatalous__04%20Tuotanto__14%20Satotilasto__90%20Arkisto/01_Viljelykasvien_sato.px/table/tableViewLayout2/.
- Luke Statistics Database. 2024. “Profitability Factor of Organic and Regular Production.” https://www.luke.fi/en/statistics/indicators/cap-indicators/profitability-factor-organicregular-production?utm_source=chatgpt.com.
- Luke Statistics Database. 2025. “Sales of Fertilizers to Farms.” https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__08%20Indikaatorit__06%20Ymp%C3%A4rist%C3%B6__12%20Typpi-%20ja%20fosforitase/02_Kasviravinteiden_myynti.px.
- Metzger, M. J., R. G. H. Bunce, R. H. G. Jongman, C. A. Múcher, and J. W. Watkins. 2005. “A Climatic Stratification of the Environment of Europe.” *Global Ecology and Biogeography* 14: 549–563. <https://doi.org/10.1111/j.1466-822X.2005.00190.x>.
- Meyer, D., and K. Hornik. 2023. “sets: Sets, Generalized Sets, Customizable Sets and Intervals.”
- Olesen, J. E., R. M. Rees, S. Recous, et al. 2023. “Challenges of Accounting Nitrous Oxide Emissions From Agricultural Crop Residues.” *Global Change Biology* 29: e16962. <https://doi.org/10.1111/gcb.16962>.
- Olesen, J. E., M. Trnka, K. C. Kersebaum, et al. 2011. “Impacts and Adaptation of European Crop Production Systems to Climate Change.” *European Journal of Agronomy* 34, no. 2: 96–112. <https://doi.org/10.1016/j.eja.2010.11.003>.

- Panagos, P., L. Montanarella, M. Barbero, A. Schneegans, L. Aguglia, and A. Jones. 2022. "Soil Priorities in the European Union." *Geoderma Regional* 29: e00510. <https://doi.org/10.1016/j.geodrs.2022.e00510>.
- Pandey, A., F. Li, M. Askegaard, I. A. Rasmussen, and J. E. Olesen. 2018. "Nitrogen Balances in Organic and Conventional Arable Crop Rotations and Their Relations to Nitrogen Yield and Nitrate Leaching Losses." *Agriculture, Ecosystems and Environment* 265: 350–362. <https://doi.org/10.1016/j.agee.2018.05.032>.
- Perego, A., A. Giussani, M. Sanna, et al. 2013. "The ARMOSA Simulation Crop Model: Overall Features, Calibration and Validation Results." *Italian Journal of Agrometeorology* 18: 23–38.
- Petersen, S. O., K. Regina, A. Pöllinger, et al. 2006. "Nitrous Oxide Emissions From Organic and Conventional Crop Rotations in Five European Countries." *Agriculture, Ecosystems and Environment* 112: 200–206. <https://doi.org/10.1016/j.agee.2005.08.021>.
- Piccoli, I., F. Sartori, R. Polese, and A. Berti. 2020. "Crop Yield After 5 Decades of Contrasting Residue Management." *Nutrient Cycling in Agroecosystems* 117: 231–241. <https://doi.org/10.1007/s10705-020-10067-9>.
- Pihlatie, M., E. Syväsalö, A. Simojoki, M. Esala, and K. Regina. 2004. "Contribution of Nitrification and Denitrification to N₂O Production in Peat, Clay and Loamy Sand Soils Under Different Soil Moisture Conditions." *Nutrient Cycling in Agroecosystems* 70: 135–141. <https://doi.org/10.1023/B:FRES.0000048475.81211.3c>.
- Poggi, G. M., I. Aloisi, S. Corneti, et al. 2022. "Climate Change Effects on Bread Wheat Phenology and Grain Quality: A Case Study in the North of Italy." *Frontiers in Plant Science* 13: 936991. <https://doi.org/10.3389/fpls.2022.936991>.
- Pörrsisäätiö. 2023. "Sijoituskohteet ja niiden valinta." *Pörrsisäätiö*. <https://www.porrsisaatio.fi/opi-sijoittamaan/sijoituskoulu/sijoituskohteet-ja-niiden-valinta/>.
- Poutala, R. T., O. Kuoppamäki, J. Korva, and E. Varis. 1994. "The Performance of Ecological, Integrated and Conventional Nutrient Management Systems in Cereal Cropping in Finland." *Field Crops Research* 37: 3–10. [https://doi.org/10.1016/0378-4290\(94\)90076-0](https://doi.org/10.1016/0378-4290(94)90076-0).
- ProAgria. 2021. "Tuottopuntari." <https://www.proagria.fi/>.
- Qi, R., J. Li, Z. Lin, et al. 2016. "Temperature Effects on Soil Organic Carbon, Soil Labile Organic Carbon Fractions, and Soil Enzyme Activities Under Long-Term Fertilization Regimes." *Applied Soil Ecology* 102: 36–45. <https://doi.org/10.1016/j.apsoil.2016.02.004>.
- Radmehr, A., O. Bozorg-Haddad, and H. A. Loáiciga. 2022. "Integrated Strategic Planning and Multi-Criteria Decision-Making Framework With Its Application to Agricultural Water Management." *Scientific Reports* 12: 8406. <https://doi.org/10.1038/s41598-022-12194-5>.
- Regina, K., H. Känkänen, and P. Singh. 2021. "Impacts of Green Manure on Crop Yield, Nitrogen Leaching and Nitrous Oxide Emissions in Sandy and Clay Soil Lysimeters." *Agricultural and Food Science* 30: 53–62. <https://doi.org/10.23986/afsci.99202>.
- Salo, T., and E. Turtola. 2006. "Nitrogen Balance as an Indicator of Nitrogen Leaching in Finland." *Agriculture, Ecosystems and Environment* 113: 98–107. <https://doi.org/10.1016/j.agee.2005.09.002>.
- Schiavon, E., A. Taramelli, and A. Tornato. 2021. "Modelling Stakeholder Perceptions to Assess Green Infrastructures Potential in Agriculture Through Fuzzy Logic: A Tool for Participatory Governance." *Environment and Development* 40: 100671. <https://doi.org/10.1016/j.envdev.2021.100671>.
- Schillaci, C., A. Perego, M. Acutis, et al. 2023. "Assessing Marginality of Camelina (*C. sativa* L. Crantz) in Rotation With Barley Production in Southern Europe: A Modelling Approach." *Agriculture, Ecosystems & Environment* 357: 108677. <https://doi.org/10.1016/j.agee.2023.108677>.
- Shang, Y., J. E. Olesen, P. E. Lærke, K. Manevski, and J. Chen. 2024. "Perennial Cropping Systems Increased Topsoil Carbon and Nitrogen Stocks Over Annual Systems—A Nine-Year Field Study." *Agriculture, Ecosystems and Environment* 365: 108925. <https://doi.org/10.1016/j.agee.2024.108925>.
- Shi, H., and M. Umair. 2024. "Balancing Agricultural Production and Environmental Sustainability: Based on Economic Analysis From North China Plain." *Environmental Research* 252: 118784. <https://doi.org/10.1016/j.envres.2024.118784>.
- Simmelsgaard, S. E. 1998. "The Effect of Crop, N-Level, Soil Type and Drainage on Nitrate Leaching From Danish Soil." *Soil Use and Management* 14: 30–36. <https://doi.org/10.1111/j.1475-2743.1998.tb00607.x>.
- Smith, O. M., A. L. Cohen, C. J. Rieser, et al. 2019. "Organic Farming Provides Reliable Environmental Benefits but Increases Variability in Crop Yields: A Global Meta-Analysis." *Frontiers in Sustainable Food Systems* 3: 82. <https://doi.org/10.3389/fsufs.2019.00082>.
- Stoorvogel, J. J., J. M. Antle, C. C. Crissman, and W. Bowen. 2004. "The Tradeoff Analysis Model: Integrated Bio-Physical and Economic Modeling of Agricultural Production Systems." *Agricultural Systems* 80: 43–66. <https://doi.org/10.1016/j.agry.2003.06.002>.
- Syväsalö, E., K. Regina, E. Turtola, R. Lemola, and M. Esala. 2006. "Fluxes of Nitrous Oxide and Methane, and Nitrogen Leaching From Organically and Conventionally Cultivated Sandy Soil in Western Finland." *Agriculture, Ecosystems and Environment* 113: 342–348. <https://doi.org/10.1016/j.agee.2005.10.013>.
- Tadiello, T., M. Gabbrielli, M. Botta, et al. 2023. "A New Module to Simulate Surface Crop Residue Decomposition: Description and Sensitivity Analysis." *Ecological Modelling* 480: 110327. <https://doi.org/10.1016/j.ecolmodel.2023.110327>.
- Tao, F., T. Palosuo, A. Lehtonen, J. Heikkinen, and R. Mäkipää. 2023. "Soil Organic Carbon Sequestration Potential for Croplands in Finland Over 2021–2040 Under the Interactive Impacts of Climate Change and Agricultural Management." *Agricultural Systems* 209: 103671. <https://doi.org/10.1016/j.agry.2023.103671>.
- Tesfai, M. 2016. "Emissions of N₂O From Agricultural Soils and Mitigation Options: A Review With Special Reference to Norwegian Agriculture." *Nibio Rapport Vol 2, NR 25*.
- Therond, O., H. Hengsdijk, E. Casellas, et al. 2011. "Using a Cropping System Model at Regional Scale: Low-Data Approaches for Crop Management Information and Model Calibration." *Agriculture, Ecosystems and Environment* 142: 85–94. <https://doi.org/10.1016/j.agee.2010.05.007>.
- Thivierge, M. N., G. Bélanger, G. Jégo, S. Delmotte, C. A. Rotz, and É. Charbonneau. 2023. "Perennial Forages in Cold-Humid Areas: Adaptation and Resilience-Building Strategies Toward Climate Change." *Agronomy Journal* 115: 1519–1542. <https://doi.org/10.1002/agg2.21354>.
- Timlin, D., K. Paff, and E. Han. 2024. "The Role of Crop Simulation Modeling in Assessing Potential Climate Change Impacts." *Agrosystems, Geosciences & Environment* 7, no. 1: e20453. <https://doi.org/10.1002/agg2.20453>.
- Valkama, E., G. Kunyapiyeva, R. Zhapayev, et al. 2020. "Can Conservation Agriculture Increase Soil Carbon Sequestration? A Modelling Approach." *Geoderma* 369: 114298. <https://doi.org/10.1016/j.geoderma.2020.114298>.
- Valkama, E., K. Rankinen, P. Virkajärvi, T. Salo, P. Kapuinen, and E. Turtola. 2016. "Nitrogen Fertilization of Grass Leys: Yield Production and Risk of N Leaching." *Agriculture, Ecosystems and Environment* 230: 341–352. <https://doi.org/10.1016/j.agee.2016.05.022>.
- van Wijk, M. T., C. J. Klapwijk, T. S. Rosenstock, P. J. A. van Asten, P. K. Thornton, and K. E. Giller. 2016. "Methods for Environment: Productivity Trade-Off Analysis in Agricultural Systems." In *Methods*

for Measuring Greenhouse Gas Balances and Evaluating Mitigation Options in Smallholder Agriculture, edited by T. S. Rosenstock, M. C. Rufino, K. Butterbach-Bahl, E. Wollenberg, and M. Richards, 189–198. Springer Cham. <https://doi.org/10.1007/978-3-319-29794-1>.

VYR. 2025. “Kotimaan hinnat.” <https://vyr.fi/markkinatieto/kotimaan-hinnat/>.

Wiréhn, L. 2018. “Nordic Agriculture Under Climate Change: A Systematic Review of Challenges, Opportunities and Adaptation Strategies.” *Land Use Policy* 77: 63–74. <https://doi.org/10.1016/j.landusepol.2018.04.059>.

Wiréhn, L., J. Käyhkö, T.-S. Neset, and S. Juhola. 2020. “Analysing Trade-Offs in Adaptation Decision-Making—Agricultural Management Under Climate Change in Finland and Sweden.” *Regional Environmental Change* 20: 18. <https://doi.org/10.1007/s10113-020-01585-x>.

Yang, X., M. Delgado-Baquerizo, Y. Niu, et al. 2023. “Optimizing Cropping Systems to Close the Gap Between Economic Profitability and Environmental Health.” *New Phytologist* 240: 2498–2512. <https://doi.org/10.1111/nph.19310>.

Yli-Halla, M., and D. L. Mokma. 1999. “Classification of Soils of Finland According to Soil Taxonomy.” *Soil Survey Horizons* 40: 59–69. <https://doi.org/10.2136/sh1999.2.0059>.

Yli-Halla, M., D. L. Mokma, T. Peltovuori, J. Sippola, and S. Maaprofileja. 2000. “Suomalaisia Maaprofileja. Agricultural Soil Profiles in Finland and Their Classification.” *Publications of the Finnish Agricultural Research Centre. Series A*: 1238–9935.

Zadeh, L. A. 1965. “Fuzzy Sets.” *Information and Control* 8: 338–353. [https://doi.org/10.1016/S0019-9958\(65\)90241-X](https://doi.org/10.1016/S0019-9958(65)90241-X).

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Input data for gross margin (GM) estimation of conventional crop-based systems under mineral fertilization and residue retention/removal ($CC_{M\pm}$) or under slurry-mineral fertilization and residue retention (CC_{MIX+}). **Table S2:** Input data for gross margin (GM) estimation of organic crop-based systems under full (CO_{F+}) or reduced (CO_{R+}) fertilization and residue retention. **Table S3:** Input data for gross margin (GM) estimation of conventional livestock-based systems under slurry-mineral fertilization and residue retention or removal ($LC_{MIX\pm}$). **Table S4:** Input data for gross margin (GM) estimation of organic livestock-based systems under slurry application and residue retention/removal ($LO_{S\pm}$). **Table S5:** Simulated average yields ($kg\ ha^{-1}$) in livestock-based (L) systems under conventional (C) or organic (O) management, with slurry (S) or slurry-mineral (MIX) fertilization, and residue retention (+) or removal (–). **Table S6:** Simulated average yields ($kg\ ha^{-1}$) in crop-based (C) conventional (C) systems with mineral (M) or slurry-mineral (MIX) fertilization and with residue retention (+) or removal (–). **Table S7:** Simulated average yields ($kg\ ha^{-1}$) in crop-based (C) organic (O) systems with full (F) or reduced (R) fertilization and with residue retention (+).