



Rethinking organic efficiency: A dynamic analysis of resource trade-offs in Italian agriculture through the FWEE nexus

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ABSTRACT

This paper evaluates whether converting to organic farming delivers resource efficiency once cross-domain trade-offs are measured within the Food–Water–Energy–Environment (FWEE) nexus framework. Using 53,804 Italian crop-farm observations (2015–2022) from FADN, the analysis applies a dynamic difference-in-differences estimator for reversible conversion. Findings show that total energy intensity per euro of adjusted output rises overall, with pronounced and persistent penalties in permanent crops and volatile, only partly reversing spikes in annuals. Irrigation burdens per adjusted output increase during conversion, evidencing tighter water-energy coupling under yield dips. Environmental gains are non-automatic: biodiversity and nitrogen proxies show no consistent improvements, while crop-protection burdens per output often rise. Results imply nexus-aware, system-specific technical support, technology integration, conversion payment mechanisms, and moving beyond input reduction alone to address system heterogeneity, yield gaps, and momentary inefficiencies through coordinated soil-water-energy management strategies to convert temporary trade-offs into durable synergies for Farm-to-Fork implementation.

1. Introduction

The European Union (EU) has lately established specific policy targets to conversion its agricultural sector of about six million commercial farms toward a more sustainable system. Among other sustainability-enhancing sectorial policies, by 2030 one fourth of total EU land shall be organic, the use of chemical pesticides reduced by half and energy usage by more than one third (i.e., 32.5 %), stepping up as the worldwide leader for a more sustainable food systems: the agricultural sector uses 30 % of the total energy and 70 % of global freshwater resources (Münch et al., 2023). Whether the expected resource efficiency improvements will materialise or if they will result in expensive compromises between environmental goals and production capabilities.

Given the pivotal role assigned to organic agriculture, the empirical literature lacks consistent results concerning its efficiency in terms of the use of resources. Most studies focus on single crops or small-scale pilot farms at the detriment of the generalisation of results (Fess and Benedetto, 2018; Pimentel et al., 2005; Redlichová et al., 2021); for instance, vegetable farming received limited attention so far, with research attempts concentrated onto restricted crop types. Besides, when studying resource-use interactions between organic farming practices, theoretical

values are often used instead of empirical data-driven ones (Chmelíková et al., 2024; Gomiero et al., 2011). Current research efforts lack of a systemic approach, relying often on univariate indicator frameworks, which prevents assessing the interactions between different dimensions (Hoff, 2011; Möhring et al., 2024). Moreover, time-dependent effects of organic conversion has received insufficient attention despite their impact on both immediate and extended results (Burton et al., 2003; Läßle and Rensburg, 2011).

This article analyses how conversion to organic farming impacts resource efficiency by measuring trade-offs and synergies within the Food–Water–Energy–Environment (FWEE) nexus framework and how these effects vary across different agricultural systems. We provide three empirical contributions that advance our understanding of sustainable agriculture conversion. First, we improve internal validity by employing a dynamic difference-in-differences estimator (de Chaisemartin and D'Haultfoeuille, 2024) (hereafter dCDH24) specifically designed to handle the non-absorbing, reversible nature of organic conversion, addressing a critical limitation of previous studies that relied on static evaluation methods, inappropriate for organic farming contexts. Second, we enhance external validity through a comprehensive analysis of 53,804 Italian crop-farm observations (2015–2022) from the Farm

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Accountancy Data Network (FADN), representing one-fifth of the EU's organic agricultural area across diverse farming systems, moving beyond the single-crop or pilot-scale studies that dominate existing literature. Third, we provide the first systematic application of the FWEE nexus framework to organic farming evaluation, operationalising integrated indicators that capture cross-domain resource interactions rather than isolated sectoral effects, revealing trade-offs and synergies that single-indicator approaches cannot detect.

Our analysis reveals that organic conversion raises energy intensity per euro of output by an average of 1.229 percentage points, with pronounced system heterogeneity: permanent crops experience larger and more persistent energy penalties (2.118 percentage points) compared to field crops and horticulture (1.235 percentage points). Water burdens per adjusted output increase during conversion in annual systems but decrease in permanent crops, while environmental gains prove non-automatic, biodiversity proxies show no consistent improvements, and crop-protection burdens per output often rise. These findings challenge conventional assumptions about the automatic resource efficiency gains from organic farming gains and highlight the need for system-specific, nexus-aware policy interventions.

These findings are directly relevant to advancing the European Union's Vision for Sustainable and Competitive Agriculture, particularly regarding the integration of digital tools for resilience monitoring and adaptive farm management under climate change. Successful agro-ecological conversions require system-specific pathways that respect how annual and perennial crops couple production, energy, water, and environmental outcomes. Rather than relying solely on input reductions, the shift should be underpinned by targeted technologies: precision irrigation for annual systems to raise water productivity, renewable power where conversion creates persistent energy penalties, and micro-irrigation to ease water-energy constraints. Because penalties to energy use and water efficiency tend to peak early, concentrated technical and financial payment during the first three years is critical to sustain momentum and prevent abandonment. Ultimately, coordinated soil–water–energy management, tuned to local heterogeneity and yield dynamics, offers a more resilient route to closing temporary inefficiencies and achieving durable performance gains.

The remainder of this paper is organised as follows. [Section 2](#) presents the theoretical framework and literature foundations, establishing the FWEE nexus framework and reviewing existing evidence on organic farming resource efficiency. [Section 3](#) describes our data from the Italian FADN and the econometric strategy, detailing the dynamic difference-in-differences methodology and FWEE indicator construction. [Section 4](#) presents and discusses our empirical results across the five nexus dimensions, examining both system-level differences and temporal dynamics. [Section 5](#) concludes with policy recommendations for nexus-aware sustainable agriculture conversions and directions for future research.

2. Theoretical framework and literature foundations

2.1. Contextual background: organic farming in Italy and the EU

Italy represents a strategic case study within the European organic farming landscape. According to the Research Institute of Organic Agriculture (FiBL), the EU organic sector encompasses 16.9 million hectares (9.9 % of total agricultural land) as of 2022, with Italy leading this transformation. Italy hosts over 80,000 organic operators, representing approximately 20 % of all EU organic farmers. It manages 2.2 million hectares under organic certification, accounting for 17.4 % of the national agricultural area and 13 % of total EU organic land (Willer et al., 2024).

The Italian organic sector has experienced sustained growth throughout the study period (2015–2022), with both operator numbers and certified area increasing by approximately 28 % and 35 % respectively. This expansion occurred within the framework of significant

public investment: Italy allocated 62 % (€1.7 billion) of its Rural Development Programme budget to organic farming payment during 2015–2022, making it the second-largest EU investor after Germany (European Court of Auditors, 2024).

Comprehensive evaluation evidence from Member State assessments demonstrates that CAP payment for organic agriculture has contributed substantially to area expansion, with notable increases in both organically farmed land and participating farmers across European regions (European Commission, 2025).

The selected temporal scope (2015–2022) encompasses pivotal policy changes, notably the CAP 2014–2020 programming period, the transitional year of 2021, and the final year of transition (2022) before the implementation of the 2023–2027 CAP programming period. Before 2014, the FADN database did not distinguish organic farming payments from other agri-environmental climate measures, which constrained the analysis to subsequent years. Limiting the study to 2015–2022 ensures that farms can be accurately identified as switching into or out of organic farming, thereby aligning the research with meaningful policy shifts and reliable data availability.

Italy's organic development follows EU Regulation 2018/848 and national implementing legislation, ensuring standardised practices that enhance the external validity of results for broader European policy applications.

The study uses the FWEE nexus framework lens to evaluate the implications of organic farming conversion in Italy with the support of the dCDH24 estimator to understand the interdependencies between agricultural system conversions and resource utilisation patterns. The methodology addresses selection bias correction and dynamic treatment effect estimation.

2.2. FWEE nexus framework in agricultural systems

The theoretical foundation of this research rests on two interconnected frameworks: nexus theory and dynamic treatment effects theory. The FWEE nexus framework provides the conceptual lens for understanding and assessing resource interdependencies, while dynamic treatment effects theory guides our methodological approach for reaching an unbiased causal inference.

Nexus theory posits that resource systems exhibit complex interdependencies that cannot be understood through isolated sectoral analysis (Hoff, 2011): for our framework, conversion to organic generates cascading effects across water, energy, food, and environmental systems through three mechanisms: (i) direct substitution effects (e.g., synthetic inputs replaced by mechanical operations), (ii) indirect efficiency changes (e.g., yield impacts affecting per-unit resource intensity), and (iii) system adaptation dynamics (e.g., learning and optimisation over time).

[Fig. 1](#) illustrates the pairwise relationships among food, energy, water, and the environment, which operate through trade-offs, synergies and mixed effects (Hoff, 2011). *Trade-offs* define relationships where improving the performance in one dimension systematically worsens another's, generally in the absence of technological innovation that decouples input intensity from output growth (e.g. higher food output generally increases energy or water burdens per unit). *Synergy* refers to practices that improve performance in multiple dimensions simultaneously (e.g. reduced agrochemical use simultaneously improves water quality and environmental outcomes). However, in specific contexts, certain practices may result in *mixed relationship* (e.g. for instance, pushing for higher food production may force agricultural systems to operate at environmental limits through over-exploitation of natural resources, particularly when such output targets are imposed on areas ecologically unsuitable for that crop, thereby creating cascading negative effects on water availability, soil health, and biodiversity alongside any productivity gains), that is when context-dependent or non-systematic effects take place and neither a trade-off nor a synergy dominates the same relationship across studies.

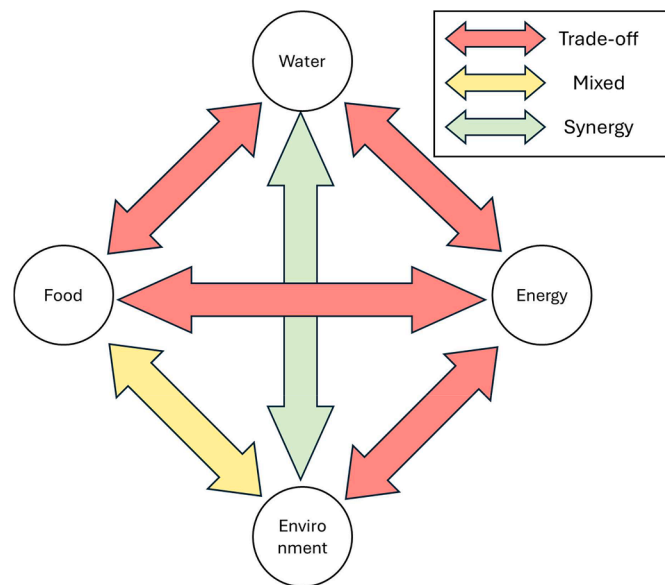


Fig. 1. Representation of the conceptual FWEE nexus framework and main results regarding the role of organic farming conversion based on the literature. Diagram adapted from Hoff (2011).

These three relationship types (i.e., trade-off, synergy, and mixed) are also adopted in Table 1, which systematically presents results from the literature on the FWEE. The literature shows that the conversion to organic farming generates trade-offs and synergies across the six pairwise combinations of food, water, energy, and environment. The colours in Fig. 1 summarise the main results of the literature review that are reported in detail in Table 1 and the following text.

Table 1¹ summarises the results of the literature review on organic conversion and the FWEE nexus framework trade-offs and synergies across different resource pairs.

Food-Energy Nexus: Trade-off relationship. The most commonly found is a trade-off relationship. This is because lower yields in organic systems increase energy consumption per unit of output. This occurs through two mechanisms: mechanical operations replace chemical inputs, raising direct energy requirements, and yield reductions mean the same energy investment produces less output, raising energy intensity per euro of production. Literature confirms that reduced productivity necessitates additional energy to match conventional farming output levels (Chmelíková et al., 2024; Paris et al., 2022; Smith et al., 2015).

Food-Water Nexus: Trade-off relationship. Also in this case the most commonly found is a trade-off relationship. Organic production maintains similar water consumption per hectare as conventional farming however, because of the lower amount of other inputs (e.g. fertilisers), yield declines. Furthermore, organic farmers may select more water-intensive crops to compensate for lower yields. This creates a paradox: while per-hectare water use does not necessarily increase, per-unit-output water requirements rise because yield gaps expand water burdens relative to production capacity (Dhanapala et al., 2023).

¹ In line with nexus theory (Hoff, 2011), a *trade-off* denotes a relationship where improving performance in one domain systematically worsens performance in another (e.g. higher food output increases energy or water burdens per unit). A *synergy* refers to changes that jointly improve performance in both domains (e.g. reduced agrochemical use simultaneously improves water quality and environmental outcomes). A *mixed relationship* is used where empirical evidence shows context-dependent or non-systematic effects, so that neither a clear trade-off nor a clear synergy dominates across studies. These three relationship types (i.e., trade-off, synergy, and mixed) are also adopted in Table 1, which systematically presents the literature evidence on the dynamics of the FWEE nexus framework across the six pairwise resource combinations..

Food-Environment Nexus: Mixed relationship. The literature reports mixed results. Organic conversion does not necessarily imply environmental improvements in all conditions. The agrochemical reductions that occur is expected to have a positive impact on the environment. However, empirical evidence shows heterogeneous outcomes: biodiversity changes are inconsistent across farms, nitrogen-fixing crop distribution remains limited, and crop-protection burdens often increase as mechanical and alternative control methods substitute for chemicals. Context-dependent factors (farm size, rotation design, regional conditions) drive whether synergies or trade-offs dominate (Castillo-Díaz et al., 2024; Gomiero et al., 2011).

Water-Energy Nexus: Trade-off relationship. The most encounter results point to a trade-off relationship. Organic farming improves soil organic matter and water retention, creating potential water conservation benefits. However, these gains are offset by higher irrigation needs during and after conversion when yields decrease. Moreover, the mechanical energy required for field operations during conversion periods increases per-unit-output energy requirements, tightening the water-energy coupling (Dhanapala et al., 2023; Holmatov et al., 2023).

Water-Environment Nexus: Synergy relationship. Synergy relationships are generally found in the literature. Exclusion of synthetic agrochemicals under organic standards directly reduces water contamination. This is the most consistent positive nexus relationship because it follows directly from certification requirements (Kragten et al., 2011; Winqvist et al., 2012).

Energy-Environment Nexus: Mixed relationship. The literature provides mixed results. Organic conversion eliminates chemical inputs but replaces them with mechanical operations, creating dual and conflicting outcomes. Reduced chemical environmental impacts are accompanied by increased machinery-based energy consumption. The net environmental effect depends on whether the gains from reduced chemicals exceed the costs of higher mechanical energy use, which varies by farm system and energy sources (Kragten et al., 2011; Winqvist et al., 2012).

2.3. Literature gaps in organic conversion evaluation

The debate surrounding energy efficiency in organic versus conventional agriculture remains contentious, with empirical evidence varying significantly in methodological approaches and measurement units, generating substantial knowledge gaps limiting the generalisation

Table 1

Synthesis of the results of the literature review on organic conversion and the FWEE nexus framework.

Nexus Pair	Relationship	Key Finding	Citation
Food-Energy	TRADE-OFF	Energy efficiency per unit of output decreases in organic systems	Chmelfiková et al., 2024; Smith et al., 2015; Paris et al., 2022
Food-Water	TRADE-OFF	Similar water use per hectare, but organic systems may use more water-intensive crops to compensate for lower yields.	Dhanapala et al., 2023
Food-Environment	MIXED	Improvements are not automatic: changes in crop diversity and nitrogen-fixing crops are often minimal or non-significant	Castillo-Díaz et al., 2024; Gomiero et al., 2011
Water-Energy	TRADE-OFF	Organic farming achieves water conservation through improved soil organic matter, but higher irrigation needs counterbalance the benefits.	Dhanapala et al., 2023; Holmatov et al., 2023
Water-Environment	SYNERGY	Organic practices lead to better water conditions through decreased water pollution threats and better groundwater recharge capabilities.	Kragten et al., 2011; Winqvist et al., 2012
Energy-Environment	TRADE-OFF	More mechanical operations for weed/pest control replace chemical use, creating dual impacts on environmental results and energy performance.	Paris et al., 2022; Holmatov et al., 2023

Source: authors' own elaboration.

of evidence-based agricultural policies.

First, the absence of farm-level analyses at broader geographical scopes and multi-crops undermines results' reliability; the majority of investigations restrict the analyses to single crop and/or for pilot farms. Extrapolating results from such fragmented evidence risks producing misleading interpretations of the broader input–output trade-offs associated with organic farming (Aragón et al., 2024; Fess and Benedito, 2018; Pimentel et al., 2005; Pimentel and Burgess, 2014; Redlichová et al., 2021).

A second limitation concerns the scarcity of reliable real data: a significant part of studies relies on theoretical values due to a lack of comprehensive data on the FWEE interactions across diverse organic farming practices, e.g. tillage (Chmelfiková et al., 2024; Gomiero et al., 2011).

Third, there is a pronounced lack of studies considering the different typology of farms. Most studies fail to provide a comprehensive analysis across agricultural categories, with certain crop systems underrepresented (e.g. vegetables, which comprise <5 % of observations in several studies).

The fourth limitation concerns the reliance on single-indicator approaches, neglecting the Food-Water-Energy-Environment (FWEE) nexus framework. This methodological limitation obscures the actual trade-offs and synergies inherent in Food-Water-Energy-Environment (FWEE) nexus interactions, producing interpretations that systematically misrepresent the interconnections between these core dimensions (Hoff, 2011; Möhring et al., 2024).

Finally, there is limited attention to the temporal dynamics of the conversion; studies rarely integrate the conversion phase (i.e. the period before becoming formally organic), overlooking the heterogeneity between early and late adopters. Yet the dynamics of conversion, including the initial adjustment period and subsequent adaptation processes, may substantially influence both short and long-term effects (Burton et al., 2003; De Souza Filho et al., 1999; Läßle and Rensburg, 2011; Möhring et al., 2024; Padel, 2001; Sunding and Zilberman, 2001).

However, empirical nexus research faces significant methodological limitations. The predominance of static cross-sectional analytical approaches fails to capture the dynamic adjustment processes predicted by nexus theory, creating a critical gap between theoretical expectations and empirical validation (Eriksson et al., 2025; Möhring et al., 2024).

Eriksson et al. (2025) surveyed 70 nexus research specialists and found that while nexus scholarship has conceptually evolved, expanding from resource-security concerns toward governance frameworks and ecosystem-service integration, empirical methodologies have stalled. Most nexus studies still rely on univariate indicators and cross-sectional designs, leaving the theoretically sophisticated governance-integration claims largely unvalidated through robust dynamic causal analysis.

Dynamic treatment effects theory addresses the temporal dimensions of policy interventions (Heckman et al., 2016), recognising that treatment effects evolve and may exhibit non-absorbing characteristics (i.e. farms may opt-in and out from the organic system) (de Chaisemartin and

D'Haultfœuille, 2024). This framework proves particularly relevant for organic conversion processes, where agricultural operations undergo multi-year conversion periods characterised by heterogeneous adaptation trajectories, allowing for testing empirically:

- Temporal variation: Treatment effects vary systematically over time as farming operations adapt to new production systems.
- Learning dynamics: Early treatment periods exhibit different effect magnitudes compared to later periods due to learning processes and system optimisation.
- Reversible treatment considerations: Non-absorbing treatment status requires specialised identification strategies to avoid contamination bias.

The integration of dynamic treatment effects theory necessitates econometric methodologies that accommodate three key characteristics: time-varying treatment intensity, non-absorbing treatment status, and heterogeneous treatment timing payments. Traditional difference-in-differences estimators violate these requirements, creating systematic bias in estimated treatment effects. Indeed, recent methodological advances demonstrate that the widely applied two-way fixed effects (TWFE) approaches produce contamination bias when multiple treatments interact over time; it includes "forbidden comparisons" between units that have both already received treatment, leading to potentially misleading coefficient interpretations (Goodman-Bacon, 2021).

The dynamic treatment effects framework, therefore, requires specialised estimators accommodating staggered conversion patterns and heterogeneous treatment effects while avoiding contamination bias (Callaway & Sant'Anna (2021); de Chaisemartin and D'Haultfœuille (2024) among others). This methodological foundation establishes the analytical framework for examining organic conversion as a dynamic, multi-dimensional intervention within interconnected resource systems, enabling robust causal inference regarding FWEE nexus framework outcomes over time.

2.4. Research objectives and contribution

This study addresses four critical gaps in the organic farming literature through targeted methodological innovations that directly tackle existing research limitations.

For the first two shortcomings in the literature, we utilise the Farm Accountancy Data Network (FADN). This representative farm dataset is uniformly adopted in the EU and can be easily generalised. This dataset is representative of the whole national farm population (in our case, using 53,804 Italian farms representing 20 % of the EU organic agricultural area), overcoming the issues of evaluating a narrow area, we rely on the whole national territory, using real accountancy data.

To consider the different types of farms and the heterogeneity effect of the organic conversion, we conduct our analysis considering only the crop farm and differentiate among the whole sample (Total), Field crop

and horticulture farms (or Annual crops - Type of farms 1 and 2) and Permanent Crops (Type of farms 3) different types of farms.²

The study operationalises the FWEE nexus framework to simultaneously measure trade-offs and synergies across energy, water, food, and environmental domains (Hoff, 2011; Möhring et al., 2024). This directly addresses the limitation of traditional single-indicator assessments by revealing previously hidden cross-domain interactions that cannot be captured through isolated sectoral analysis

To overcome the limitation of static evaluations, the research employs the DiD estimator as per de Chaisemartin & D'Haultfœuille (2024); its specific design allows for capturing the dynamic and reversible nature of organic conversion, assessing how impacts of converting evolve, which would violate the assumptions of the canonical DiD.

3. Data and methods

3.1. Data

This analysis utilises panel data from the Italian FADN³ from 2015 to 2022. FADN provides comprehensive longitudinal farm-level information on food, water, energy and environmental aspects expenses, also including farms and farmers' characteristics, which allows an in-depth assessment of organic conversion (Chmelíková et al., 2024). Annual data collection follows standardised EU procedures, ensuring consistency and comparability across periods and EU countries.

Treatment assignment is defined through the RDP_{ORG} variable, identifying farms receiving Rural Development Programme (RDP) payments for organic conversion or maintenance under Measure 11 of Regulation (EU) No 1305/2013. This treatment definition ensures policy relevance by capturing organic and in conversion farms, addressing limitations of standard organic classification variables that may misrepresent farm-level conversion status by including farms with partial organic certification or temporary participation patterns. RDP_{ORG} is however available only from 2015, forcing the period under study to be 2015–2022⁴; this ensures correct treatment timing, include farms in conversion, and allow switching-in and out paths. Homogeneity in organic practices and input uses, as requested by the literature, is obtained using crop farms and excluding livestock. This selection reduces heterogeneity that could confound treatment effect estimation.

To take into account the price premium received through organic products (and obtained a proxy for production), we have isolated and removed the price premium by utilising the Fisher index methodology.⁵ The resulting sample comprises 53'804 observations with 46'405 conventional farms and 7'339 organic farms, providing sufficient statistical power for robust effect estimation while maintaining representative coverage of Italian agriculture (Möhring et al., 2024).

To evaluate the heterogeneity effect in different types of farms, we select the farms that belong to field crops (Type of farming 1) and horticulture (Type of farming 2) (23'287 observations, of which 21'674 are conventional and 1'613 organic) and permanent crops (Type of

Table 2
Descriptive by farming system (2015–2022) statistics.

	TOTAL						Fieldcrops and Horticulture						Permanent Crops					
	Conventional Farms (n = 46'405)			Organic Farms (n = 7'339)			Conventional Farms (n = 21'674)			Organic Farms (n = 1'613)			Conventional Farms (n = 20'430)			Organic Farms (n = 5'083)		
	Mean	SD		Mean	SD		Mean	SD		Mean	SD		Mean	SD		Mean	SD	
TR	114,020.29	258,924.91		96,374.32	222,006.87		134,790.69	265,553.09		94,286.86	216,566.24		98,062.10	260,465.91		102,139.59	235,416.29	
TR Adj	117,133.64	316,414.92		128,184.32	462,488.80		137,039.23	286,581.66		119,183.10	281,815.75		102,638.98	362,098.18		139,010.92	530,808.24	
VA	72,506.99	165,882.75		67,215.78	153,561.17		79,063.13	165,540.75		61,011.83	155,731.92		69,092.39	173,508.58		72,610.98	160,733.93	
FNVA	69,653.77	164,944.55		72,278.11	160,638.44		76,866.43	167,157.73		69,283.74	168,937.88		65,556.95	170,369.57		77,096.64	166,291.88	
FNI	46,277.11	128,779.58		50,926.00	134,338.54		49,966.12	124,224.02		48,701.91	122,931.53		44,910.37	139,195.29		54,448.65	144,515.38	
UAA	26.94	48.52		25.42	43.21		40.15	62.44		48.57	73.44		13.56	22.66		18.15	25.62	
AWU	1.85	2.74		1.84	2.12		1.83	2.64		1.53	1.97		1.88	2.58		1.98	2.24	
FAWU	1.14	0.67		1.02	0.54		1.18	0.69		1.06	0.52		1.10	0.65		1.01	0.55	
Labour	3885.75	5120.27		3782.16	3954.88		3868.76	4925.74		3263.48	3677.16		3909.77	4855.75		4022.40	4169.77	
Total Capital	578,031.94	2243,387.18		507,926.55	990,495.42		663,386.16	3095,594.44		615,862.82	1345,028.84		513,697.53	1016,965.21		490,222.34	889,094.41	
Fixed Capital	462,874.64	2165,401.09		395,294.71	844,931.21		542,934.48	3034,211.84		536,332.28	1305,539.06		394,655.70	835,379.37		360,988.01	664,714.32	
AWU/UAA	0.20	0.38		0.15	0.16		0.18	0.50		0.09	0.21		0.22	0.20		0.17	0.14	
FAWU/UAA	0.15	0.20		0.10	0.11		0.12	0.22		0.07	0.11		0.17	0.15		0.12	0.11	
K/UAA	44,461.73	121,225.10		31,764.04	60,681.23		35,254.13	154,040.84		17,813.92	34,831.62		56,921.49	85,387.85		37,623.77	68,759.87	
Renewable Energy	447.28	14,167.33		1589.35	90,013.91		498.22	10,843.43		6051.75	191,580.75		166.24	4302.05		190.69	2566.28	
Shannon Index	0.86	0.53		0.73	0.54		1.00	0.49		1.08	0.53		0.63	0.50		0.57	0.48	

² FADN farm typology (TF8) classifies farms by economic size and specialisation. Type of Farms (TF) 1 and 2 encompass field crops and horticulture systems, characterised by annual production cycles. Type of Farms (TF) 3 includes permanent crops (vineyards, orchards, olive groves) with multi-year production cycles. This classification follows EU Regulation (EC) No 1242/2008 on farm classification based on standard output and principal agricultural activity. Our analysis excludes mixed farming systems (TF 5) and other non-crop categories to maintain homogeneity in production systems and treatment effect estimation

³ The code of the principal variables used is reported in Appendix A.1

⁴ Pre-2015 data do not provide a consistent, separate flag for Measure 11 in FADN (organic conversion/maintenance), as organic payments in 2007–2013 were embedded in Measure 214; including those years would misclassify treatment status.

⁵ This procedure is described in appendix A.3

farming 3) (25'513 observations, of which 20'430 are conventional and 5'083 organic). The remaining 5'004 observations have a mixed cultivation pattern that does not allow for isolating a heterogeneity effect.

Table 2 presents comprehensive descriptive statistics across principal farm characteristics.

The descriptive statistics show that conventional and organic farms maintained similar revenue and income levels throughout 2015–2022. However, organic farms generated slightly lower raw revenue. Still, they achieved comparable or superior results after adjusting for subsidies and price effects in Total Revenue Adjusted (TR Adj) and income metrics, Farm Net Value Added (FNVA) and Farm Net Income (FNI). The number of workers between conventional and organic farms remains similar, but organic permanent crop operations require more labour per hectare of land. The field-crop farms maintain a larger Utilised Agricultural Area (UAA), similar to EU structural patterns, than permanent-crop farms, while conventional permanent-crop farms use less Annual Work Unit (AWU). The capital stock of field-crop conventional farms exceeds that of organic permanent-crop farms. Still, organic permanent-crop farms demonstrate lower fixed capital per hectare and equivalent or superior Total Capital (K)/UAA ratios in specific segments. The adoption of on-farm renewable energy systems shows different patterns between field crops because organic field crops use more renewable energy than conventional field crops, but organic permanent crops use less renewable energy than conventional permanent crops. The Shannon index shows that field crops, particularly organic farms, exhibit higher diversification levels than permanent crops because the index measures both abundance and evenness of crop mixes, and research supports that arable systems maintain more land-cover diversity than specialised perennial systems.

3.2. Indicators for assessing the FWEE nexus framework

The FWEE nexus framework requires explicit consideration of cross-domain interactions rather than individual dimensional analysis.

This study operationalises nexus interactions through the following integrated approach⁶:

Food-Energy Nexus: Captured through energy costs per unit of food output, measured as total energy expenses relative to adjusted revenues, eliminating price differentials to isolate productivity effects (Chmelfiková et al., 2024; Smith et al., 2015). According to this literature, we break down the Total Energy Consumption (TEC) into Direct Energy Consumption (DEC), which encompasses Fuels, Lubricants, Electricity and Water Costs and Indirect Energy Consumption (IEC), which is Fertiliser and Crop Protection expenses.

Specifically to measure the Food-Energy nexus, we use $\frac{TR_{Adj}}{TEC} \cdot \frac{TR_{Adj}}{IEC}$, and $\frac{TR_{Adj}}{FEC}$. That represents the relation with production (using TR_{Adj} as a proxy for actual production capacity) and the amount of direct, indirect and total energy used (Abbas et al., 2022; Paris et al., 2022). An increase in these ratios represents a synergy (improved energy efficiency per unit output), whereas a decrease indicates trade-offs (higher energy intensity per unit output).

Food-Water Nexus: Assessed through irrigation requirements relative to food production capacity, specifically adjusted revenue per water volume ($\frac{TR_{Adj}}{Water}$) and water costs per ($\frac{TR_{Adj}}{Water Costs}$), revealing trade-offs between water consumption and food security objectives (Dhanapala et al., 2023; FAO, 2014). To evaluate this nexus, we use $\frac{TR_{Adj}}{Water}$, as a physical efficiency metric and adjusted revenue per water cost $\frac{TR_{Adj}}{Water Costs}$, as an economic efficiency metric. The latter reveals how water-cost coupling affects production capacity, directly reflecting nexus

interactions between resource use and output (Holmatov et al., 2023).

Food-Environments: The nexus is evaluated through three key indicators that proxy agricultural sustainability and environmental performance. TR_{Adj} per Nitrogen Application represents fertiliser intensity and associated production (Prudhomme et al., 2022). Additionally, $\frac{TR_{Adj}}{Fertilizer Costs}$ and $\frac{TR_{Adj}}{Crop Protection Costs}$ approximate the efficiency in the use of chemical inputs to produce the output, serving as proxies for environmental intensity relative to productive capacity (Hua et al., 2020).

Energy-Environment Nexus: The relationship between energy use and environmental outcomes is evaluated via fertiliser and crop protection energy costs relative to chemical application indicators. Fertiliser Costs and Crop Protection Costs relative to DEC, IEC, and TEC indicate the amount of energy that is strictly linked with environmental management approaches. The renewable energy share or autonomy indicator represents the conversion toward sustainable energy sources in agricultural operations (IRENA, 2015; Paris et al., 2022).

Energy-Water Nexus: Measured through the irrigation volume and energy costs, encompassing both direct water consumption and energy required for distribution systems, reflecting the interconnected nature of water and energy resource management (FAO, 2014; Shah, 2023). The *Microirrigated UAA/irrigated UAA* ratio and *microirrigated UAA/potential irrigated UAA* ratio indicate the adoption of more efficient irrigation methods (i.e., micro irrigation systems) relative to total and potential irrigation. An increase in these ratios indicates an improvement in energy efficiency (because micro-irrigation is more efficient) and reduced water consumption (Z. Chen et al., 2019; Rizwan et al., 2018). Finally, Water Cost/Water Volume is evaluated as the ratio between the amount of water and the cost of water for irrigation, indicating economic efficiency from the water-energy coupling perspective (González Perea et al., 2018).

Environment-Water Nexus: This nexus is evaluated through the relationship between agrochemical inputs and their water quality impacts. The ratio between Fertiliser Costs/Water Cost and Crop Protection Costs/Water Cost is related to pollution potential and water quality degradation (B. Chen et al., 2025; Prudhomme et al., 2022). These indicators capture how intensive chemical use affects water resources, with higher ratios indicating greater potential for water contamination from agricultural chemicals.

3.3. Econometric strategy⁷

To investigate the causal effects of organic conversion on the TWEE nexus, we use the dCDH24 estimator.⁸ Non-absorbing and dynamic treatment effects characterise the conversion of conventional to organic farming systems, and farms may enter and exit organic status multiple times during the observation period (de Chaisemartin and D'Haultfeuille, 2024). This estimator has been integrated with the Imbens and Xu (2024) checklist to overcome Lalonde's critique (Lalonde, 1986).⁹

ATT estimates using two-way fixed-effect estimators generate biased results when applied to observations with varying periods of treatment participation, requiring reweighting or relying on multiple 2×2 designs to account for treatment heterogeneity (Baker et al., 2025). Notably, such approaches generally presume absorbing treatment effects and uniform treatment timing. These assumptions are not in line with organic farming contexts, where conversions are often heterogeneous and reversible.

The dCDH24 estimator evaluates how switcher groups change their outcomes relative to their appropriate counterfactuals while accounting

⁶ The price adjustment methodology for all the monetary values is obtained with a specific price deflator as indicated in the appendix A.2 (EEA, 2022; GWP, 2021).

⁷ The code is available here https://osf.io/bj475/?view_587681dd92d9b4179897379535ac9bfa4

⁸ An in-depth explanation of the dCDH24 estimator is reported in Appendix A.4

⁹ The explanation of Lalonde's critique and the use of Imbens and Xu (2024) checklist is reported in Appendix A.5

for different treatment timing patterns and reversible treatment status. The method measures treatment effects through comparisons between farms that conversion to organic status at various times versus farms that stay conventional throughout the observation period. The research method prevents contamination effects that occur when using farms that received treatment as controls in traditional DiD studies. The estimator produces unbiased treatment effect estimates based on parallel trends assumptions (PTA), which are more realistic than the strict exogeneity requirements of other methods.

PTA requires outcome trajectories to be similar between treatment and control groups absent conversion, tested through placebo tests in pre-treatment periods. The tests assess whether there are differences in trends of dependent variables between the future treatment group and the control group before the actual start of treatment. The no-anticipation assumption (NAA) prevents current outcomes from being affected by future treatment expectations, which helps minimise bias from farmers who modify their behaviour in anticipation of organic conversion. The analysis relies on PTA and NAA assumptions, which can be tested according to dCDH24 and reported in the outcomes tables. The model tracks dynamic treatment effects through lagged treatment variables (evaluated by test of joint nullity of the effects (TJNE) to evaluate if treatment has a statistically meaningful impact and test of equality of the effects (TEE) to know if the treatment has an homogeneous effect the years after the conversion happens), which will enable researchers to study how conversion impacts change throughout time.

3.3.1. Treatment variable and model specification¹⁰

The basic dynamic DiD estimator specification is:

$$Y_{it} = \alpha_i + \mu_t + \sum_{l=1}^5 \delta_l D_{it-l+1} + \gamma' X_{it} + \varepsilon_{it}$$

where Y_{it} represents outcomes for the farm i in year t , α_i captures time-invariant farm effects, μ_t represents year fixed effects, X_{it} is a vector of time-varying control variables selected through adaptive LASSO (Appendix A.7) and weighted via entropy balancing, and D_{it-l+1} indicates treatment status ℓ periods after first treatment.

The treatment variable (D_i) is defined as receipt of RDP payments for organic farming under Measure 11 of Regulation (EU) No 1305/2013:

$$D_i = \{1 \text{ if } RDP_{ORG} > 0; 0 \text{ if } RDP_{ORG} = 0\}$$

Treatment is defined by receipt of Measure 11 organic payments under Article 29 of Regulation (EU) No 1305/2013 in a given year. This policy-linked definition captures both fully converted farms and those in the conversion window, reflecting contractual, time-bounded adoption rather than static certification labels that may cover only a subset of products or parcels. Because Measure 11 participation can start and end over time, treatment is non-absorbing and dynamically timed, matching the dCDH24 intertemporal DiD design used for estimation.¹¹ The approach ensures policy relevance by tracking actual subsidy recipients while accommodating the heterogeneous nature of conversion processes.

Within the (Italian) FADN survey, public aid granted by public entities must be recorded according to the accrual accounting principle (accrual basis). This means that aid is recorded in the accounting period to which it relates or accrues, regardless of when it is actually received by the farmer, ensuring each aid payment to be matched to the financial year to which it refers, delivering a more accurate representation of the farm's economic results.¹² This ensures no time misalignment can

happen between the farm officially entering the organic regime and the recording of Measure 11 (e.g., administrative delays in payments), hence the treatment variable accurately captures when the organic regime is triggered by each unit.

This, combined with the EU regulatory framework stating that Measure 11 payments are delivered to farms that initiated the conversion to organic (European Union, 2013, Article 29.1; Rete Rurale Nazionale, 2020), provides a robust institutional alignment between how the treatment is defined and the real conversion timing.

To address the residual cases of no economic rational behaviors, we corrected the dataset for farms whose treatment status followed the sequence treated – untreated – treated. Specifically, when a farm was classified as organic in a year it appeared as untreated, its treatment path was recoded as treated – treated – treated. Selection bias correction employs entropy balancing using variables identified through adaptive lasso machine learning techniques, which allow for to eliminated collinearity problem, combined with theoretical considerations. These variables¹³ satisfy the criterion for valid control variables by being predetermined and unaffected by treatment status (Angrist and Pischke, 2009). Invalid control variables (post-treatment covariates) potentially affected by treatment status are excluded. Consider that a fundamental assumption in DiD is the PTA. The estimation adopted is evaluated both the unconditional and conditional PTA are satisfied as a robustness check. The model adopted is selected according to consistency. Note that the errors are clustered at the farm level.

The estimator compares outcome evolution of switcher farms from the period immediately preceding the first treatment change ($t-1$) to ℓ periods after treatment, relative to farms maintaining status-quo treatment status. This approach addresses contamination effects common in two-way fixed-effects estimators and accommodates heterogeneous treatment timing.

The framework estimates separate effects for each post-treatment period ($\beta_1, \beta_2, \dots, \beta_5$), capturing how conversion impacts evolve as farms adapt to organic practices. The overall average treatment effect on the treated (ATT) represents the weighted average of all treatment changes throughout the panel period. This value is calculated as $Overall\ ATT = \sum w_\ell ATT_\ell$, where w_ℓ and ATT_ℓ represents respectively the weights based on the number of observations and ATT at each treatment lag (de Chaisemartin and D'Haultfoeulle, 2024). The estimator generates normalised treatment effects which combine current and lagged treatment impacts to evaluate time-dependent treatment effects.

3.3.2. Interpretation of dynamic treatment effect estimates

The results tables report three key diagnostic tests alongside treatment effect estimates:

- Parallel Trends Assumption (PTA) test examines whether treated and control groups exhibited parallel outcome trajectories before treatment implementation. Non-significant p-values (>0.05) support the validity of the parallel trends assumption, our fundamental identification requirement for causal interpretation. Significant pre-treatment differences would undermine the validity of our causal estimates.
- Test of Joint Nullity of the Effects (TJNE) jointly tests the null hypothesis that all treatment effects are equal to zero. Significant p-values (≤ 0.05) indicate that treatment has a statistically meaningful overall impact, rejecting the null hypothesis of no treatment effects across all post-treatment periods.

3.3.3. Test of equality of the effects (TEE) tests the null hypothesis that treatment effects are constant across all post-treatment periods. Significant p-values (≤ 0.05) indicate heterogeneous treatment effects

¹⁰ Step-by-step procedure is reported in Appendix A.6.

¹¹ "Public subsidies: Within the RICA survey, subsidies disbursed by public entities are recorded on an accrual basis" (RICA-FADN, 2024).

¹² "Public subsidies: Within the RICA survey, subsidies disbursed by public entities are recorded on an accrual basis" (RICA-FADN, 2024).

¹³ The lists of these variables are reported in Appendix A.7.

over time, suggesting that conversion impacts evolve as farms adapt to organic practices. Non-significant results support the assumption of constant treatment effects. Crop-type heterogeneity: field crops and horticulture vs permanent

To capture structural differences in agronomic practices, input bundles, seasonality, and irrigation/energy profiles, the analysis is stratified by crop system into Field crops (Type of Farming 1) and Horticulture (Type of Farming 2) with 23'169 observations and Permanent Crops (Type of Farming 3) with 25'368 observations, in addition to reporting pooled results (Total) that include all the observations (53'804). These two subgroups cover over than 90 % of the total sample.

This split aligns with FADN classification and with FWEE nexus framework that predicts distinct water–energy–food trade-offs across annual (Field crops and Horticulture) vs perennial (Permanent Crops) systems. Methodologically, heterogeneity is estimated using subgroup event-study models run separately on each crop-type subsample.

This integrated approach addresses the research question by providing unbiased estimates of how organic conversion affects energy costs while accounting for interconnected effects across water use, food production, and environmental outcomes (Möhring et al., 2024).

4. Results

The literature demonstrates that, before the advent of the FWEE nexus framework, policy evaluation predominantly relied on single indicators, thereby neglecting the interaction effects, such as synergies or trade-offs, between different resource domains.¹⁴ In contrast, FWEE and related nexus frameworks emerged to address these limitations, enabling the integrated assessment and management of interlinked resources for improved sustainability and policy coherence (Mirzaei et al., 2023; Segovia-Hernández et al., 2023).

In this study, a comprehensive set of indicators is employed to encompass the FWEE nexus framework, to reveal system-specific nexus pathways that challenge uniform or "fit-for-all" policy strategies. By capturing the dynamic and interdependent relationships among food, water, energy, and environmental factors, these indicators facilitate more nuanced and context-sensitive policy evaluation (Zahedi et al., 2024).

4.1. Food-Energy nexus

Organic conversion raises energy intensity per euro of output, with early spikes and incomplete normalisation, and this pattern is stronger in permanent crops than in field crops and horticulture (Table 3 and Figures A.9.1 in Appendix A).

In the total sample, energy per adjusted revenue increases: TEC/TR_{Adj} rises overall by 1.229 pp (SE 0.575, $p < 0.05$), driven by a significant early spike (ATT₂: +2.291 pp, $p < 0.01$) and persistent positive lags (ATT₄: +0.496 pp, $p < 0.05$; ATT₅: +1.160 pp, $p < 0.01$), while DEC/TR_{Adj} is also positive on average (+1.999 pp, n.s.) with a pronounced year-2 increase (+4.802 pp, $p < 0.05$). IEC/TR_{Adj} shows late pressure (ATT₅: +4.295 pp, $p < 0.01$), indicating that both mechanical operations and certified input costs raise per-output energy burdens despite learning effects.

Patterns in Field crops and horticulture are volatile but smaller in magnitude: TEC/TR_{Adj} rises on average by 1.235 pp (SE 0.583, $p < 0.05$), with an early level shift (ATT₁: +1.088 pp, n.s.) and a mid-conversion bump (ATT₂: +0.825 pp, $p < 0.05$), then flattens (ATT₃ ≈ 0). DEC/TR_{Adj} dips in later lags (ATT₄: −0.312 pp; ATT₅: −0.703 pp), suggesting partial operational efficiency gains, while IEC/TR_{Adj} shows modest, imprecise increases, consistent with short-cycle adjustment and learning.

For permanent crops, energy intensity penalties are larger and more

persistent: TEC/TR_{Adj} increases by 2.118 pp (SE 0.672, $p < 0.01$) overall, with sustained positives in later years (ATT₄: +1.033 pp, $p < 0.05$; ATT₅: +1.607 pp, $p < 0.01$). DEC/TR_{Adj} is positive on average (+2.994 pp, n.s.) with significant later intensity (ATT₄: +1.852 pp, $p < 0.05$), while IEC/TR_{Adj} shows early negative adjustments but turns positive by ATT₅ (+1.359 pp), indicating persistent energy needs for perennial management and pest control even after conversion.

The mechanical-for-chemical substitution in organic conversions produces early energy intensity spikes and incomplete normalisation, especially for perennials, due to higher organic input costs and yield shortfalls (Paris et al., 2022; Ponisio et al., 2015). Annual systems indicate volatile energy expenses but obtain partial relief in later conversion years, without complete stabilisation. Literature confirms that lower yields in organic systems increase energy use per product (Chmelíková et al., 2024; Paris et al., 2022; Smith et al., 2015). Permanent crops face the highest energy penalties linked to extended adjustment and demanding practices. The documented pattern of rapid initial increase, learning period, and technical adjustments aligns with recognised nexus conversion challenges (Holmatov et al., 2023).

4.2. Food-water nexus

Table 4 and Figures in Appendix A.9.2 show how irrigation burdens evolve when normalised by the adjusted revenue proxy (TR_{Adj}), which reflects the farm's production mix valued at conventional prices and thus isolates output quantity/composition from organic price premia.

For the total sample, production per volume of water used decreases only in the first year of conversion, indicating adaptation and short-term learning costs (Wheeler et al., 2015). The quantity of product in relation to the cost of irrigation tends to increase in the second year after conversion. Then it becomes negative by the fourth year, signalling a strong oscillation. Annual crops show an overall ATT increase in water efficiency, particularly evident in the third year; this suggests that declining yields during the conversion cause water use per unit of production to fall sharply, with a sharp swing between years due to swings in production yields (Gündoğmuş, 2010; Hoff, 2011; Raimondo et al., 2021). On the contrary, perennial systems experience an initial decline in water use efficiency, which, however, does not remain in subsequent years, a sign that the entrepreneur has a swift adaptation curve. This can also be seen in the fact that water use costs per unit of production remain at pre-conversion levels. (Dhanapala et al., 2023; Paris et al., 2022)

These results highlight that water–energy nexus coupling in agriculture strongly depends on output dynamics through the conversion period. Literature affirms that organic conversions rarely reduce irrigation needs per product unless paired with new technologies or management changes and often require context-specific efficiency adaptations (Chmelíková et al., 2024; Smith et al., 2015). The observed conversion peaks and delayed normalisation demonstrate the importance of tailored adaptation pathways for different crop systems and periods of adjustment.

4.3. Food-environment nexus

Table 5 and figures in the Appendix A.9.3, tracks environmental input burdens relative to the adjusted output mix (TR_{Adj}), isolating quantity/composition effects from organic price premia to reveal per-euro pressures along the conversion path.

The Food-Environment nexus assessment shows variable nitrogen application per unit of adjusted output after organic conversion, with no clear pattern (Paris et al., 2022; Smith et al., 2015). In contrast, the intensity of fertiliser and crop protection use per output generally declines, indicating improved efficiency over time. However, initial conversion costs suppress efficiency gains in the short term while longer-term adaptation supports sustainable input reduction. In annual crops, crop-protection use spikes mid-conversion, reflecting the

¹⁴ Classical single indicator results are reported in Appendix A.8

Table 3

Dynamic treatment effects on food-energy nexus indicators (ATT estimates).

Dependent	Overall ATT	ATT ₁	ATT ₂	ATT ₃	ATT ₄	ATT ₅	PTA Parallel Trend Assumption Placebo test	TJUE Test of joint nullity of the effects	TEE Test of equality of the effects
Total Sample									
TR Adj/	1.999	−1.843	4.802**	−0.785	0.364	1.437	0.696	0.014	0.007
DEC	(1.908)	(1.489)	(2.118)	(0.909)	(0.815)	(1.155)			
TR Adj/IEC	1.059	−3.720	0.905	−0.905	1.019	4.295***	0.052	0.037	0.111
	(4.234)	(6.711)	(1.717)	(5.350)	(0.628)	(1.321)			
TR Adj/	1.229**	−1.125**	2.291***	−0.447	0.496**	1.160***	0.059	0.001	0.000
TEC	(0.575)	(0.441)	(0.870)	(0.494)	(0.248)	(0.444)			
Fieldcrops and Horticulture Farms									
TR Adj/	−0.646	−4.940*	2.452	0.992	−0.312	−0.703	0.521	0.195	0.227
DEC	(2.166)	(2.794)	(2.968)	(1.105)	(0.617)	(0.447)			
TR Adj/IEC	4.022	2.242	4.357	1.047	−0.071	1.293	0.464	0.144	0.287
	(3.347)	(1.186)	(6.455)	(1.163)	(0.517)	(0.728)			
TR Adj/	1.235**	1.088	0.825**	0.196	0.560	0.051	0.666	0.154	0.150
TEC	(0.583)	(0.790)	(0.421)	(0.612)	(0.361)	(0.105)			
Permanent Crops Farms									
TR Adj/	2.994	−1.351	3.443	−0.577	1.852**	1.910	0.309	0.031	0.017
DEC	(1.951)	(1.287)	(2.642)	(0.685)	(0.842)	(1.185)			
TR Adj/IEC	4.759	−7.557	−3.206	−1.978	0.508	1.359	0.147	0.094	0.069
	(4.655)	(4.679)	(2.788)	(3.294)	(0.838)	(2.062)			
TR Adj/	2.118***	−0.301	1.355	0.197	1.033**	1.607***	0.112	0.008	0.013
TEC	(0.672)	(0.445)	(0.859)	(0.326)	(0.350)	(0.578)			

Note: ATT_ℓ represents the year-ℓ dynamic effect after the first treatment change; Overall ATT is the cumulated effect across all ℓ. PTA, TJUE, and TEE report p-values from placebo tests, joint significance tests, and homogeneity tests, respectively (see Methods section for detailed interpretation). Standard errors in parentheses. *, **, *** indicate significance at 10 %, 5 %, and 1 % levels respectively.

Table 4

Dynamic treatment effects on food-water nexus indicators (ATT estimates).

Dependent	Overall ATT	ATT ₁	ATT ₂	ATT ₃	ATT ₄	ATT ₅	PTA Parallel Trend Assumption Placebo test	TJUE Test of joint nullity of the effects	TEE Test of equality of the effects
Total Sample									
TR Adj/	29.465	−76.695**	51.178	21.776	29.901	17.304	0.180	0.030	0.015
Water	(87.682)	(37.614)	(61.947)	(33.357)	(41.626)	(75.427)			
TR Adj/	5.500	−4.245	31.469	3.911	−13.887**	−26.452	0.639	0.183	0.173
Water Cost	(16.852)	(8.115)	(20.608)	(6.289)	(6.391)	(19.540)			
Fieldcrops and Horticulture Farms									
TR Adj/	376.423**	−50.672	108.666	291.286**	86.020	373.891	0.380	0.268	0.337
Water	(178.355)	(63.613)	(66.538)	(132.631)	(53.564)	(253.559)			
TR Adj/	14.328	3.015	52.928	−8.887	−9.577	−8.653	0.342	0.478	0.810
Water Cost	(35.392)	(33.788)	(52.000)	(8.407)	(10.246)	(5.233)			
Permanent Crops Farms									
TR Adj/	−90.286	−114.128*	−15.430	−16.498	−4.627	−53.828	0.173	0.227	0.149
Water	(86.362)	(58.398)	(61.337)	(39.034)	(19.151)	(40.787)			
TR Adj/	−10.579	−5.608	26.831	0.258	−20.624	−21.488	0.454	0.387	0.263
Water Cost	(30.841)	(13.548)	(26.318)	(9.752)	(14.776)	(19.576)			

Note: See Table 3 notes for notation and test descriptions. Standard errors in parentheses. *, **, *** $p < 0.10, 0.05, 0.01$, respectively.

demands of pest management and rotational adjustments during organic conversion (Chmelíková et al., 2024).

Overall, conversion results in lower input-use intensity per output, based on reduced input costs and confirmed by recent studies examining energy and input dynamics during the conversion phase. These trade-offs highlight the need for system-integrated solutions early in conversion to prevent temporary spikes from undermining the process. Achieving environmental benefits depends on tailored practices and policies that address the specific costs, requirements, and adjustment periods for each crop type (Holmatov et al., 2023).

4.4. Energy-Environment nexus

The results for the Energy-Environment nexus indicators are reported in Table 6 with the relative figures in the Appendix A.9.4. The outcomes indicate how environmental input burdens map into energy intensity once normalised by the adjusted output mix (TR_{Adj}), thereby isolating quantity/composition effects from organic price premia and

highlighting per-euro pressures along the conversion path.

The share of renewables in total energy use remains unchanged after conversion, except for a temporary first-year rise in permanent crops (even if with a minimal effect). Fertiliser expenditure as a share of direct energy costs does not increase post-conversion, except for an apparent decrease in permanent crops, possibly reflecting substitution toward direct energy-based alternatives such as green manuring or residue mulching. Across all systems but especially in permanent crops, fertiliser costs relative to indirect energy costs show no significant difference from conventional farming, except for two temporary dips after conversion.

Fertiliser costs as a proportion of total energy consumed notably decline for total, field, and perennial crops, indicating reduced importance of fertiliser costs in overall energy spending. Crop protection costs relative to direct energy show no systematic substitution except for one year in field crops and horticulture, contradicting the literature's claim that herbicide use is commonly replaced with mechanical energy (Smith et al., 2015). However, the ratio of crop protection to indirect energy costs decreases sharply in most systems, reflecting reduced chemical

Table 5

Dynamic treatment effects on food-environment nexus indicators (ATT estimates).

Dependent	Overall ATT	ATT ₁	ATT ₂	ATT ₃	ATT ₄	ATT ₅	PTA Parallel Trend Assumption Placebo test	TJUE Test of joint nullity of the effects	TEE Test of equality of the effects
Total Sample									
TR Adj/N	1288.309 (780.124)	419.604 (320.737)	573.966 (743.095)	−142.620 (120.841)	372.903 (434.364)	1486.424 (1327.962)	0.303	0.303	0.202
TR Adj/ Fertilizer costs	136.320** (63.225)	75.623** (37.017)	39.753 (25.775)	23.116 (23.981)	113.987 (78.301)	16.700 (12.323)	0.258	0.230	0.253
TR Adj/Crop Protection	23.502 (16.843)	−31.550 (22.736)	10.048 (7.780)	41.208*** (15.202)	−2.712 (4.501)	26.179*** (8.882)	0.235	0.000	0.000
Fieldcrops and Horticulture Farms									
TR Adj/N	23.989 (17.495)	23.285 (25.373)	−2.118 (6.095)	0.336 (6.648)	5.199 (4.653)	30.809 (26.488)	0.168	0.397	0.272
TR Adj/ Fertilizer costs	125.761 (102.786)	46.259 (47.988)	111.812 (100.683)	110.035 (110.100)	3.150 (4.266)	−0.591 (3.362)	0.779	0.691	0.559
TR Adj/Crop Protection	19.354 (74.104)	−99.221 (114.284)	43.966 (28.904)	84.944 (54.542)	−5.957 (18.050)	−0.509 (27.226)	0.068	0.010	0.016
Permanent Crops Farms									
TR Adj/N	1971.321 (1183.098)	1095.469 (710.899)	838.018 (1081.937)	−145.510 (134.083)	604.880 (731.999)	1799.180 (1847.014)	0.543	0.284	0.210
TR Adj/ Fertilizer costs	155.186 (88.161)	43.654 (45.564)	28.596 (24.364)	11.069 (20.637)	198.771 (132.900)	27.985 (22.312)	0.433	0.591	0.572
TR Adj/Crop Protection	11.382 (9.497)	−7.981 (6.226)	−2.518 (3.559)	18.543 (16.226)	4.719** (2.087)	10.867** (4.742)	0.156	0.043	0.110

Note: See Table 3 notes for notation and test descriptions. Standard errors in parentheses. *, **, *** $p < 0.10, 0.05, 0.01$, respectively.

input under organic rules.

Interestingly, crop protection costs as a share of total energy spend spike in permanent crops in the third year only, while declining or proving negligible elsewhere, likely due to managerial adaptation challenges during early conversion years.

Overall, per-output energy–environment gains do not occur automatically with organic conversion: fertiliser–energy per euro may drop after adjustment (particularly in perennials), but crop-protection energy often remains high and annual crops show marked fluctuations. These outcomes are consistent with findings that organic systems lower inputs per hectare but may experience higher per-product energy intensity under yield gaps or mechanical substitution (Bellassen et al., 2021; Knapp and van der Heijden, 2018; O'Brien et al., 2015) and align with research emphasising the need for integrated, context-aware investments, like targeted renewables, instead of relying solely on input bans (Bellassen et al., 2021; Knapp and van der Heijden, 2018; O'Brien et al., 2015; Smith et al., 2015).

4.5. Energy-water nexus

The results (Table 7 and Figures in Appendix A.9.5) for the energy–water nexus practices highlight heterogeneous effects over time and across categories.

For the total sample, water-per-energy ratios (*Water /DEC, IEC, TEC*) generally increase, especially in the later post-conversion years, indicating persistent or rising water intensity per euro spent on energy, with significant short-term reductions only emerging for direct energy expenditures among field crops and horticulture ($ATT_5 = -0.103, p < 0.01$). Permanent crops exhibit positive effects over the conversion trajectory, corresponding to long-term investment horizons and delayed operational learning, as emphasised in nexus theory and recent literature (Hoff, 2011; Holmatov et al., 2023). The predominance of positive or non-significant trends in water intensity after organic conversion reinforces findings from studies showing organic systems often fail to deliver automatic per-product resource efficiencies and may even exacerbate input trade-offs when compared on output-normalised bases (Chmelfiková et al., 2024; Paris et al., 2022; Smith et al., 2015).

The micro-irrigation ratios indicate marginal or slightly negative

impacts, consistent with sectoral evaluations in the CAP context that find technological uptake is necessary but not sufficient to systematically reduce water intensity at the whole-farm output level (Holmatov et al., 2023; EC, 2025). The observed water cost relief in later periods ($ATT_5 = -1.692, p < 0.001$ for total; ATT_4, ATT_5 strongly negative for fieldcrops/horticulture), coupled with non-significant micro-irrigation impacts, matches international meta-analyses emphasising that management innovation and price system reforms—rather than practice conversion alone—are required to unlock meaningful energy–water synergies (Fleischmann et al., 2023; Liu et al., 2018).

Overall, these results reinforce the literature's shift toward understanding resource nexus effects as context-dependent, often governed by system boundaries, output mix adjustments, and learning curves that may delay or even inhibit the realisation of integrated resource gains (Chmelfiková et al., 2024; Hoff, 2011; Holmatov et al., 2023; Liu et al., 2018). Direct water cost savings are possible in the medium to long term (especially in annual crop systems), but overall energy–water coupling persists in the absence of coordinated investments.

4.6. Environment-water nexus

Table 8 and Figures in Appendix A.9.6 report the effect of organic conversion in the Environment-Water nexus Indicators. Organic conversion reshapes fertilisers and crop protection cost related with water used (m^3).

The fertilisers intensity associated with water in the entire sample shows a short term decline ($ATT_1 = -7.543, p < 0.10$) but no lasting effect, while crop-protection intensity rises sharply and persistently (Overall $ATT = +7.634, p < 0.001$; $ATT_3 = +2.982, p < 0.05$; $ATT_4 = +7.705, p < 0.001$; $ATT_5 = +5.931, p < 0.001$). This indicates that crop protection per water use increases as systems adjust and stabilise.

Annual systems amplify these pressures. In field crops and horticulture, water-fertiliser intensity is consistently higher (Overall $ATT = +33.607, p < 0.05$), with mid-conversion surges ($ATT_2 = +13.863, p < 0.10$; $ATT_3 = +16.745, p < 0.05$). Water-Crop-protection intensity also rises (Overall $ATT = +26.645, p < 0.10$; $ATT_2 = +6.048, p < 0.10$; $ATT_5 = +29.652, p < 0.10$). These models intuitively demonstrate that organic conversion increases the complexity of water management, due

Table 6

Dynamic treatment effects on energy-environment nexus indicators (ATT estimates).

Dependent	Overall ATT	ATT ₁	ATT ₂	ATT ₃	ATT ₄	ATT ₅	PTA Parallel Trend Assumption Placebo test	TJUE Test of joint nullity of the effects	TEE Test of equality of the effects
Total Sample									
Renewable	−0.009	0.014	−0.025	−0.003	−0.011	0.010	0.793	0.190	0.116
Energy/TEC	(0.0276)	(0.008)	(0.042)	(0.002)	(0.011)	(0.009)			
Fertilizer	−0.091	−0.139	−0.016	−0.040	−0.001	−0.022	0.109	0.196	0.140
costs/DEC	(0.067)	(0.098)	(0.038)	(0.031)	(0.021)	(0.018)			
Fertilizer	−0.006	−0.017	−0.013	0.005	0.004	0.004	0.851	0.114	0.064
costs/IEC	(0.010)	(0.011)	(0.007)*	(0.007)	(0.005)	(0.006)			
Fertilizer	−0.012	−0.019	−0.005	−0.002	0.002	−0.005	0.419	0.005	0.004
costs/TEC	(0.005)**	(0.006)***	(0.003)	(0.004)	(0.002)	(0.002)**			
Crop	−0.069	−0.093	−0.025	−0.032	0.001	−0.013	0.911	0.027	0.016
Protection/DEC	(0.043)	(0.034)***	(0.027)	(0.019)*	(0.019)	(0.015)			
Crop	−0.017	−0.009	−0.001	−0.011	−0.009	−0.005	0.189	0.010	0.079
Protection/IEC	(0.008)**	(0.007)	(0.004)	(0.004)***	(0.003)***	(0.003)			
Crop	0.043***	0.038***	0.023***	0.013***	0.011***	0.008***	0.571	0.000	0.001
Protection/TEC	(0.006)	(0.009)	(0.004)	(0.004)	(0.002)	(0.002)			
Fieldcrops and Horticulture Farms									
Renewable	−0.073	0.051	−0.112	−0.004	−0.059	0.001	0.678	0.425	0.439
Energy/TEC	(0.138)	(0.042)	(0.218)	(0.006)	(0.051)	(0.003)			
Fertilizer	0.198	−0.395	0.318	−0.094	0.293	0.142	0.289	0.008	0.010
costs/DEC	(0.210)	(0.321)	(0.186)	(0.113)	(0.197)	(0.221)			
Fertilizer	−0.024	−0.026	−0.012	−0.004	−0.007	−0.007	0.475	0.677	0.736
costs/IEC	(0.018)	(0.016)	(0.010)	(0.010)	(0.012)	(0.007)			
Fertilizer	−0.018	−0.030	0.014	−0.021	−0.002	−0.008	0.188	0.006	0.004
costs/TEC	(0.011)*	(0.014)**	(0.009)	(0.007)***	(0.005)	(0.005)			
Crop	0.177	0.113	0.000	0.021	0.133**	0.017	0.217	0.002	0.017
Protection/DEC	(0.136)	(0.102)	(0.056)	(0.064)	(0.052)	(0.026)			
Crop	0.000	−0.002	−0.001	0.001	0.002	−0.000	0.144	0.965	0.918
Protection/IEC	(0.008)	(0.007)	(0.005)	(0.006)	(0.004)	(0.003)			
Crop	−0.002	−0.003	−0.003	−0.002	0.002	0.002	0.203	0.511	0.455
Protection/TEC	(0.006)	(0.005)	(0.004)	(0.003)	(0.002)	(0.002)			
Permanent Crops Farms									
Renewable	0.009	0.005**	0.000	0.000	−0.001	0.013	0.917	0.165	0.131
Energy/TEC	(0.008)	(0.002)	(0.002)	(0.003)	(0.002)	(0.012)			
Fertilizer	−0.310***	−0.252	−0.110**	−0.149***	−0.073**	−0.073***	0.404	0.023	0.582
costs/DEC	(0.113)	(0.226)	(0.056)	(0.053)	(0.029)	(0.027)			
Fertilizer	0.020	−0.061	−0.019*	0.099***	−0.007	0.001	0.127	0.000	0.000
costs/IEC	(0.028)	(0.043)	(0.01)	(0.027)	(0.011)	(0.013)			
Fertilizer	0.037**	−0.034	−0.020***	−0.003	−0.012**	−0.012	0.35	0.005	0.474
costs/TEC	(0.017)	(0.031)	(0.006)	(0.013)	(0.005)	(0.007)			
Crop	−0.073	−0.197	−0.038	0.026	0.019	−0.005	0.54	0.630	0.491
Protection/DEC	(0.120)	(0.246)	(0.044)	(0.030)	(0.053)	(0.044)			
Crop	−0.022*	−0.009	−0.002	−0.016**	−0.017***	−0.001	0.378	0.027	0.113
Protection/IEC	(0.013)	(0.016)	(0.009)	(0.007)	(0.006)	(0.006)			
Crop	0.047***	−0.003	0.004	0.046***	−0.004*	−0.003	0.380	0.000	0.000
Protection/TEC	(0.004)	(0.005)	(0.003)	(0.002)	(0.002)	(0.002)			

Note: See Table 3 notes for notation and test descriptions. Standard errors in parentheses. *, **, *** $p < 0.10, 0.05, 0.01$, respectively.

both to higher plant protection expenditures and to the elevated unit costs of organic fertilisers. This reflects fundamental trade-offs in organic system conversions, where inputs become more expensive and water use requires adaptive strategies to maintain crop performance (Depo et al., 2020).

Perennial systems show the most substantial water-fertiliser intensification. Permanent crops face significant and durable increases (Overall ATT = +53.289, $p < 0.05$), with strong effects at ATT₂ (+33.932, $p < 0.001$), ATT₃ (+23.871, $p < 0.01$), ATT₄ (+47.525, $p < 0.001$), and ATT₅ (+18.914, $p < 0.01$). Crop-protection intensity remains flat on average, with only a modest early dip (ATT₁ = −1.271, $p < 0.10$) and no lasting reduction.

Efforts to reduce synthetic inputs per area in conversion in agricultural systems do not necessarily lower water burdens per unit of output; instead, water-use efficiency often declines due to yield gaps and increased volatility (Bellassen et al., 2021; Biernat et al., 2020; Cooper et al., 2011; Mondelaers et al., 2009; O'Brien et al., 2015). Trade-offs intensify as output contracts and new practices interact with adjustment dynamics, matching nexus theory expectations (Gardner and Drinkwater, 2009; Hoff, 2011). Permanent crops allow for longer planning horizons and more integrated conversion, while annuals face greater volatility and water burden spikes.

Rising fertilisers per water intensity (perennials) and crop protection (totals and annuals) show sustainability policies must move beyond

Table 7

Dynamic treatment effects on energy-water nexus indicators (ATT estimates).

Dependent	Overall ATT	ATT ₁	ATT ₂	ATT ₃	ATT ₄	ATT ₅	PTA Parallel Trend Assumption Placebo test	TJUE Test of joint nullity of the effects	TEE Test of equality of the effects
Total Sample									
Water/DEC	0.147* (0.081)	−0.082 (0.090)	−0.110** (0.054)	0.233*** (0.030)	0.178 (0.151)	−0.073*** (0.018)	0.588	0.000	0.000
Water/IEC	0.343 (0.254)	0.137 (0.196)	0.012 (0.139)	0.141 (0.106)	0.157* (0.091)	0.234 (0.173)	0.261	0.408	0.655
Water/TEC	0.111*** (0.039)	0.096*** (0.036)	−0.033* (0.019)	0.064*** (0.023)	0.082*** (0.025)	0.029* (0.018)	0.118	0.000	0.000
Microirr UAA/ Irrigated UAA	0.009 (0.007)	−0.002 (0.006)	−0.005 (0.004)	−0.003 (0.003)	−0.005 (0.003)	−0.002 (0.003)	0.593	0.519	0.555
Microirr UAA/ Pot Irr UAA	−0.012** (0.006)	−0.003 (0.004)	−0.004 (0.003)	−0.000015 (0.003)	−0.006** (0.003)	−0.005** (0.002)	0.137	0.292	0.943
Water/Water costs	−8.600 (6.363)	−15.587 (11.748)	−0.010 (0.516)	−0.350 (0.325)	0.661 (1.255)	−1.692*** (0.270)	0.505	0.000	0.000
Fieldcrops and Horticulture Farms									
Water/DEC	−0.097 (0.067)	−0.009 (0.093)	−0.038 (0.044)	−0.069 (0.037)	−0.015 (0.028)	−0.103*** (0.024)	0.193	0.001	0.050
Water/IEC	0.216 (0.540)	−0.320 (0.341)	0.954 (1.011)	−0.149** (0.072)	−0.060 (0.063)	−0.087** (0.034)	0.372	0.039	0.225
Water/TEC	−0.120 (0.106)	−0.083 (0.246)	−0.042** (0.021)	−0.082** (0.040)	−0.023 (0.028)	−0.039*** (0.012)	0.078	0.002	0.425
Microirr UAA/ Irrigated UAA	−0.026** (0.013)	−0.028 (0.021)	−0.015 (0.012)	−0.010 (0.013)	−0.003 (0.003)	−0.004 (0.004)	0.200	0.417	0.502
Microirr UAA/ Pot Irr UAA	−0.012 (0.016)	−0.003 (0.015)	−0.009 (0.009)	−0.001 (0.011)	−0.002 (0.006)	−0.011 (0.009)	0.701	0.813	0.772
Water/Water costs	1.307 (4.655)	9.058 (7.853)	2.180 (1.124)	−1.590*** (0.322)	−11.295*** (0.331)	0.130 (0.159)	0.102	0.000	0.000
Permanent Crops Farms									
Water/DEC	0.147 (0.081)	−0.082 (0.090)	−0.110** (0.054)	0.233*** (0.030)	0.178 (0.151)	−0.073*** (0.018)	0.588	0.000	0.000
Water/IEC	0.343 (0.254)	0.137 (0.196)	0.012 (0.138)	0.141 (0.106)	0.157 (0.091)	0.234 (0.173)	0.286	0.000	0.000
Water/TEC	0.030 (0.083)	0.089*** (0.027)	−0.046* (0.028)	0.059* (0.030)	0.004 (0.058)	−0.035 (0.066)	0.351	0.000	0.000
Microirr UAA/ Irrigated UAA	−0.010 (0.007)	−0.004 (0.008)	−0.003 (0.004)	−0.004 (0.004)	−0.000028 (0.003)	−0.003 (0.003)	0.831	0.565	0.671
Microirr UAA/ Pot Irr UAA	−0.012** (0.006)	−0.003 (0.004)	−0.004 (0.003)	−0.000015 (0.003)	−0.006** (0.003)	−0.005** (0.002)	0.137	0.292	0.943
Water/Water costs	−8.600 (6.363)	−15.587 (11.748)	−0.010 (0.516)	−0.350 (0.325)	0.661 (1.255)	−1.692*** (0.270)	0.505	0.000	0.000

Note: See Table 3 notes for notation and test descriptions. Standard errors in parentheses. *, **, *** $p < 0.10, 0.05, 0.01$, respectively.**Table 8**

Dynamic treatment effects on energy-water nexus indicators (ATT estimates).

Dependent	Overall ATT	ATT ₁	ATT ₂	ATT ₃	ATT ₄	ATT ₅	PTA Parallel Trend Assumption Placebo test	TJUE Test of joint nullity of the effects	TEE Test of equality of the effects
Total Sample									
Fertilizer costs/Water	−0.250 (9.306)	−7.543* (3.865)	0.421 (4.500)	−1.000 (3.345)	3.174 (4.371)	2.746 (8.081)	0.227	0.012	0.006
Crop Protection/Water	7.634*** (2.669)	−1.639 (1.756)	−1.105 (2.167)	2.982** (1.291)	7.705*** (1.375)	5.931*** (1.263)	0.631	0.000	0.000
Fieldcrops and Horticulture Farms									
Fertilizer costs/Water	33.607** (15.482)	−6.060 (10.278)	13.863* (7.286)	16.745** (7.486)	6.861 (5.200)	41.069 (24.861)	0.413	0.315	0.241
Crop Protection/Water	26.645* (15.275)	1.271 (3.704)	6.048* (3.187)	17.902 (12.333)	4.190 (3.234)	29.652* (18.938)	0.597	0.326	0.415
Permanent Crops Farms									
Fertilizer costs/Water	53.289** (14.609)	3.820 (2.504)	33.932*** (10.303)	23.871*** (7.886)	47.525*** (13.856)	18.914*** (5.780)	0.718	0.008	0.007
Crop Protection/Water	5.233 (4.683)	−1.271* (0.649)	1.173 (1.261)	1.803 (1.201)	3.047 (3.046)	5.303 (5.466)	0.326	0.139	0.098

Note: See Table 3 notes for notation and test descriptions. Standard errors in parentheses. *, **, *** $p < 0.10, 0.05, 0.01$, respectively.

input reductions alone to address system heterogeneity, yield gaps, and temporary inefficiencies (Gardner and Drinkwater, 2009; Hoff, 2011). Targeted interventions, such as precision irrigation, tailored to the crop system and conversion stage, can foster more efficient and synergistic outcomes (EC, 2025; Eriksson et al., 2025). Nexus-based policies are needed to reconcile these complexities, as recent evidence highlights misalignments and calls for governance-oriented approaches rather than isolated measures (EC, 2025; Eriksson et al., 2025).

5. Conclusions: all that glitters is green?

The FWEE nexus framework proves essential for sustainability research, causally uncovering cross-domain trade-offs during organic conversion, linking energy, water, food output, and environmental pressures. Our comprehensive analysis of a representative sample of Italian crop-farm for the period 2015–2022 using dynamic DiD estimation reveals that organic farming’s sustainability benefits are neither automatic nor uniform across agricultural systems.

5.1. The impact of organic conversion considering the FWEE nexus framework

Total energy costs per euro of adjusted output increase by 1.229 percentage points overall, with pronounced system heterogeneity. Permanent crops experience larger and more persistent energy penalties (2.118 percentage points) compared to field crops and horticulture (1.235 percentage points). This mechanical-for-chemical substitution produces early energy intensity spikes and incomplete normalisation, especially for perennials, due to higher organic input costs and yield shortfalls. Contrary to conventional wisdom, the conversion to organic farming increases rather than decreases energy burdens per unit of output, challenging fundamental assumptions about organic farming’s resource efficiency.

Water-energy nexus demonstrates significant complexity during conversion periods. For annual crops, irrigation burdens per adjusted output initially increase, then partially stabilise, while permanent crops show better adaptation trajectories. Production per volume of water used decreases in the first year of conversion, then re-establishes at pre-conversion levels, indicating short-term learning costs but eventual adaptation. However, water-per-energy ratios generally increase in later post-conversion years, suggesting persistent water intensity challenges that require coordinated technological and management interventions

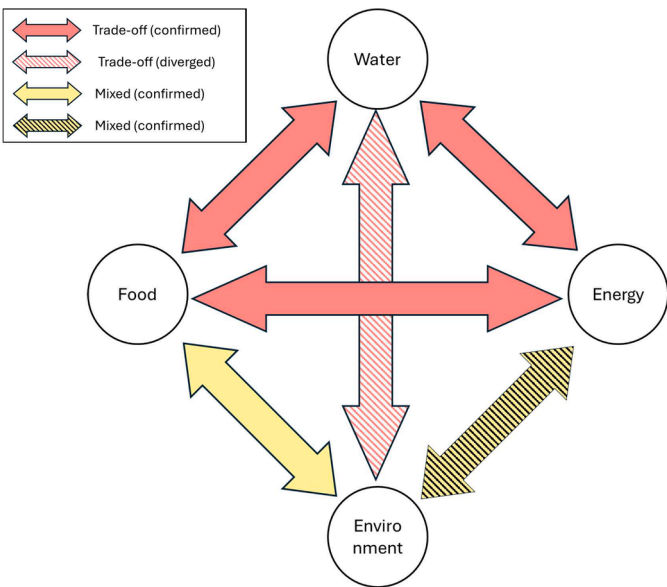


Fig. 2. FWEE nexus frameworkTrade-offs and synergies in organic farming conversion based on empirical results.

rather than organic conversion alone.

Perhaps most surprisingly, environmental benefits prove to be non-automatic across the FWEE nexus framework. Biodiversity and nitrogen proxies show no consistent improvements, while crop-protection burdens per output often rise. Fertiliser intensity associated with water shows short-term decline but no lasting effect, while crop-protection intensity rises sharply and persistently (Overall ATT = +7.634, $p < 0.001$). This contradicts the widespread assumption that organic certification automatically delivers environmental benefits and highlights the need for targeted interventions beyond input substitution.

The heterogeneous effects across farming systems demand differentiated policy approaches (See Table 9 and Fig. 2).

Annual crop systems (field crops and horticulture) exhibit volatile but energy penalties of minor magnitude with partial operational efficiency gains in later conversion years. Permanent crops face larger, more persistent energy penalties but show better water adaptation curves. These system-specific bottlenecks require targeted interventions: precision irrigation technology integration for annual systems, soil-

Table 9
FWEE nexus frameworkTrade-offs and synergies in organic farming conversion explained.

Pair	Relationship	Comparison with the literature	Key Finding
Food-Energy	TRADE-OFF	Confirmed expectations	Energy intensity per euro of adjusted output increases by 1.229 pp overall, with pronounced system heterogeneity: permanent crops face larger penalties (2.118 pp) vs. field crops/horticulture (1.235 pp). Mechanical-for-chemical substitution produces early spikes and incomplete normalisation.
Food-Water	TRADE-OFF	Confirmed expectations	Production per water volume decreases initially, then re-establishes at pre-conversion levels. Annual crops show overall water efficiency gains by the third year, while permanent crops demonstrate faster adaptation curves. Water-energy coupling depends critically on output dynamics during conversion.
Food-Environment	MIXED/NO CONSISTENT EFFECT	Confirmed expectations	Environmental gains prove non-automatic: biodiversity and nitrogen proxies show no consistent improvements. Crop-protection burdens per output rise significantly (Overall ATT = +23.502). Fertiliser intensity shows variable patterns with no apparent improvement trend.
Water-Energy	TRADE-OFF	Confirmed expectations	Water-per-energy ratios generally increase in later post-conversion years, indicating persistent water intensity per euro spent on energy. Micro-irrigation adoption shows marginal impacts. Direct water cost savings are possible long-term in annual systems, but coupling persists without coordinated investments.
Water-Environment	TRADE-OFF	Diverging from expectations	Fertiliser intensity per water shows a short-term decline but no lasting effect. Crop-protection intensity rises sharply and persistently (Overall ATT = +7.634, $p < 0.001$). Permanent crops face the most substantial water-fertiliser intensification (ATT = +53.289, $p < 0.05$).
Energy-Environment	MIXED	Diverging from expectations	Renewable energy share unchanged post-conversion, except temporary rise in permanent crops. Fertiliser costs as a proportion of total energy decline, but crop-protection energy costs spike in permanent crops (third year). Per-output energy-environment gains do not occur automatically

Source: authors’ own elaboration.

water-energy management for perennial systems, and integrated crop protection energy management.

5.2. Policy recommendations for EU farm-to-fork implementation

The persistent resource intensity penalties suggest that achieving the EU's ambitious targets for organic expansion while maintaining resource efficiency will require coordinated policy interventions. Our findings indicate that organic certification alone does not deliver integrated sustainability benefits. Instead, nexus-aware policies must address:

- **System-Specific Technical Payments:** Different conversion pathways for annual versus perennial systems, recognising their distinct energy-water-environment coupling patterns.
- **Technology Integration:** Precision irrigation systems for annual crops, renewable energy integration for persistent energy penalties, and micro-irrigation adoption to address water-energy coupling challenges.
- **Transition Payment Mechanisms:** Enhanced payment during the critical first three years when energy penalties peak and water efficiency declines, preventing farmers from abandoning conversion efforts.
- **Integrated Management Approaches:** Moving beyond input reduction alone to address system heterogeneity, yield gaps, and temporary inefficiencies through coordinated soil-water-energy management strategies.

5.3. Research limitations and future directions

While our analysis provides a comprehensive assessment of organic conversion impacts within the FWEE nexus framework, limitations persist. Firstly, the study focuses exclusively on Italian crop farms, limiting generalizability to other EU contexts and livestock systems. Likewise, the 2015–2022 timeframe, while capturing pivotal policy changes, may not reveal longer-term adaptation effects beyond five years post-conversion. Secondly, FADN data does not directly capture environmental quality outcomes such as air quality, groundwater contamination, pesticide residues, or soil biological activity. Our indicators serve as proxies for environmental performance (e.g., fertiliser and crop-protection costs as proxies for chemical intensity), but they cannot directly measure actual environmental improvements in water or soil quality. Consequently, the environmental dimensions of our nexus assessment remain partially indirect, and claims about environmental synergies should be interpreted as potential pathways rather than validated environmental outcomes.

Future research should extend this nexus approach to other EU member states and incorporate climate adaptation scenarios. The dynamic methodology employed here could be applied to evaluate other agricultural conversion, such as precision agriculture adoption or agroecological intensification programs. Additionally, research investigating the governance mechanisms needed to implement the system-specific interventions identified here would support more effective policy design.

5.4. Final implications: rethinking organic efficiency

"All that is green glitters?" finds a nuanced answer in empirical evidence. While organic farming can contribute to sustainability objectives, the path is neither straightforward nor universally beneficial across resource domains. The FWEE nexus framework reveals that organic conversion involves complex trade-offs that vary significantly by farming system and temporal dynamics.

The findings pose a challenge to policymakers to move beyond basic assumptions about the automatic benefits of organic farming and adopt evidence-based, system-specific strategies. Success in achieving the EU's Green Deal objectives will require recognising these empirical

realities and designing interventions that address the specific bottlenecks revealed in our analysis. Only through such nexus-aware, differentiated policies can the EU transform organic farming from a certification label into a genuine driver of integrated sustainability outcomes.

This research demonstrates that effective sustainability conversion require understanding and managing complex resource interdependencies rather than pursuing isolated sectoral improvements. The FWEE nexus framework provides the analytical foundation for such integrated approaches, revealing both the challenges and opportunities inherent in Europe's sustainable agriculture transformation.

Italian organic crop conversion exhibits system-specific dynamics that overturn assumptions of uniform sustainability gains, with per-output indicators revealing cross-domain trade-offs rather than automatic efficiency improvements across FWEE nexus framework. Permanent crops follow a U-shaped adjustment with early losses and later partial recovery but carry larger, persistent energy-intensity penalties per adjusted output. In contrast, annual systems face acute mid-conversion volatility with only partial late relief in select components and no full normalisation of total energy intensity per euro of adjusted revenue.

CRedit authorship contribution statement

Luigi Biagini: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Severini:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis. **Federico Antonioli:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2026.108853](https://doi.org/10.1016/j.resconrec.2026.108853).

Data availability

The authors do not have permission to share data.

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