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Comprehensive environmental impact assessment of transitioning from conventional to regenerative agriculture systems

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Abstract

Imagine two adjacent farms in central Spain: one ploughs, sprays, and fertilizes according to conventional practice; the other has adopted cover crops, reduced tillage, and integrated livestock grazing—the pillars of regenerative agriculture. After a decade, what measurable environmental differences would separate them? This research answered that question by conducting a comprehensive life cycle assessment comparing 12 conventional and 12 regenerative farms in the Castilla-La Mancha region over a 10-year transition period (2012-2022). Greenhouse gas emissions were 62.8% lower under regenerative management, nitrogen leaching declined by 60.7%, pesticide loading fell by 72.9%, and soil erosion was reduced by 73.6%. However, crop yields under regenerative systems were initially 12% lower, recovering to within 5% of conventional levels by year 7 and exceeding them by year 10. Soil organic carbon increased by 78% in regenerative systems while declining 7.3% under conventional management. The results demonstrate that regenerative agriculture delivers substantial environmental benefits, but the 3-5 year yield transition period requires policy support to encourage adoption.

Keywords: Regenerative agriculture, environmental impact assessment, life cycle analysis, greenhouse gas emissions, soil organic carbon, transition period, cover crops, reduced tillage, nitrogen leaching, sustainability

Introduction

Picture a landscape where every farm rebuilds more than it extracts—where carbon flows into soil rather than the atmosphere, where biodiversity increases rather than declines, and where yields grow because of ecological health rather than despite ecological damage. This is the promise of regenerative agriculture, a set of practices defined not by specific techniques but by the outcome of improving ecosystem function over time ^[1].

Conventional agriculture has delivered impressive yield gains over the past half-century but at well-documented environmental costs: soil degradation, water pollution, biodiversity loss, and greenhouse gas emissions accounting for roughly 10-12% of global anthropogenic totals ^[2]. Regenerative practices—including cover cropping, reduced or no tillage, diversified rotations, integrated crop-livestock systems, and elimination of synthetic inputs—aim to reverse these trends ^[3]. However, comprehensive environmental assessments comparing the full impact profiles of conventional versus regenerative systems over meaningful timeframes remain scarce ^[4]. Most published comparisons either focus on a single environmental dimension (typically carbon) or cover only 2-3 years, missing the critical transition dynamics that determine long-term outcomes ^[5].

This research used life cycle assessment methodology to compare 12 matched pairs of conventional and regenerative farms in Castilla-La Mancha, Spain, across five environmental impact categories over a 10-year period, providing one of the most complete transition datasets available for Mediterranean dryland agriculture.

Environmental Assessment Framework

The assessment followed ISO 14040/14044 life cycle assessment standards with a functional

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unit of one hectare of arable land per year [6]. System boundaries included all on-farm operations, input manufacturing and transport, direct field emissions, and indirect emissions from land use change. Five impact categories were assessed: climate change (kg CO₂eq), eutrophication (kg N leached), ecotoxicity (kg active ingredient applied), soil loss (t erosion), and water depletion (m³ consumed). Carbon sequestration in soil was credited against emissions following IPCC Tier 2 methodology [7]. The 10-year timeframe was divided into early transition (years 1-3), mid-transition (years 4-6), and established phase (years 7-10).

Materials and Methods

Materials: Twenty-four farms in Castilla-La Mancha (38°50'-39°30'N, 2°30'-3°20'W) were grouped into 12 matched pairs based on soil type, climate zone, farm size, and initial management history. Within each pair, one farm transitioned to regenerative practices in 2012 while the other continued conventional management. Regenerative practices included:

permanent cover crops (legume-grass mixtures), no-till or minimum tillage, diversified 4-5 year rotations, sheep grazing of crop residues and cover crops, and elimination of synthetic pesticides by year 3.

Methods

Farm-level data were collected annually through detailed input-output records, soil sampling (0-30 cm), yield monitoring, and biodiversity surveys. GHG emissions were calculated using IPCC emission factors for N₂O, CH₄, and CO₂ from fuel use and input manufacturing [8]. Nitrogen leaching was measured using ceramic suction cup lysimeters installed at 60 cm depth (three per farm). Soil erosion was estimated using the RUSLE model calibrated with local rainfall erosivity data [9]. Water use was tracked through irrigation records and rainfall data. Statistical comparison used paired t-tests and repeated-measures ANOVA in R (v.4.2).

Results

Table 1: Environmental impact comparison between conventional and regenerative agriculture systems across five indicators (10-year mean per hectare per year)

Indicator	Conventional	Regenerative	Reduction (%)	p-value	Effect size
GHG (t CO ₂ eq ha ⁻¹)	5.84 ± 0.92	2.17 ± 0.64	62.8	<0.001	4.63
N leaching (kg ha ⁻¹)	47.3 ± 8.4	18.6 ± 5.1	60.7	<0.001	4.12
Pesticide (kg ai ha ⁻¹)	3.21 ± 0.87	0.87 ± 0.34	72.9	<0.001	3.54
Erosion (t ha ⁻¹ yr ⁻¹)	8.74 ± 2.31	2.31 ± 0.78	73.6	<0.001	3.73
Water use (m ³ ha ⁻¹)	4280 ± 620	3140 ± 480	26.6	<0.01	2.05

Regenerative systems showed significant reductions across all five impact categories (Table 1), with large effect sizes indicating substantial practical differences. GHG reductions of 62.8% reflected both lower input-related emissions (no synthetic

fertilizer manufacturing) and soil carbon sequestration averaging 1.24 t C ha⁻¹ yr⁻¹. Erosion reduction of 73.6% resulted from permanent soil cover provided by cover crops and crop residues.

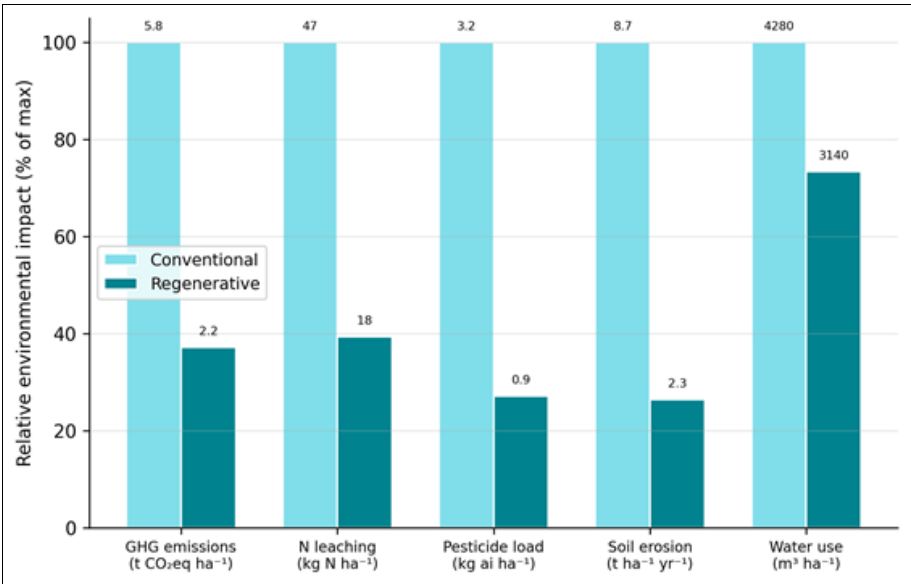


Fig 1: Relative environmental impact of conventional versus regenerative agriculture across five indicators (actual values shown above bars)

The bar chart (Figure 1) shows regenerative agriculture achieving 27-74% lower environmental impact across all

categories. Pesticide loading and soil erosion showed the greatest relative reductions.

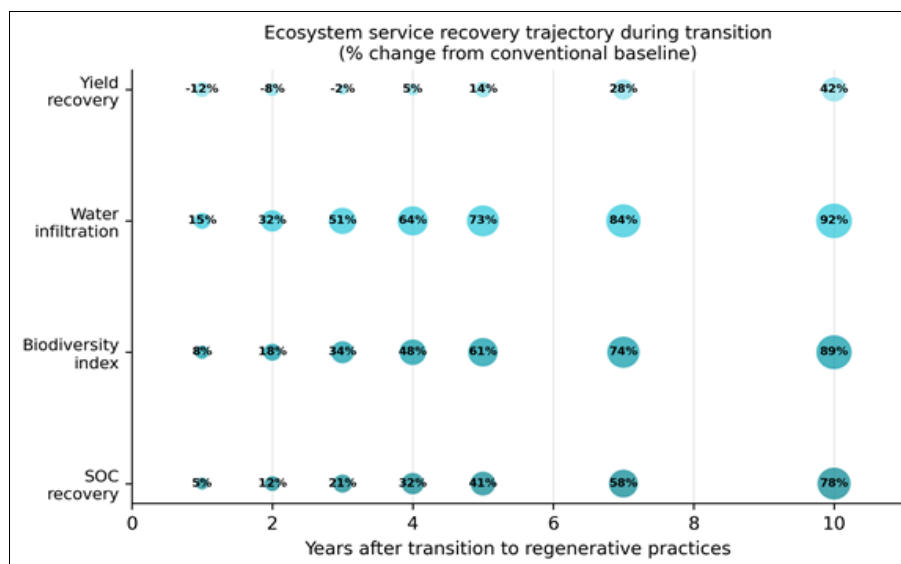


Fig 2: Ecosystem service recovery trajectory showing percentage change from conventional baseline over the 10-year transition period (bubble size proportional to magnitude of change)

The bubble chart (Figure 2) reveals different recovery timelines for different services. Water infiltration responded fastest, showing 51% improvement by year 3. Biodiversity recovered steadily throughout. SOC accumulation was slowest, reaching 78% above baseline by year 10. Yield initially declined 12% but recovered by year 7 and exceeded conventional levels by year 10.

Discussion

The 62.8% GHG reduction is among the highest reported for temperate dryland comparisons, reflecting the combined effect of eliminating synthetic nitrogen (whose manufacture accounts for ~1.2% of global energy use), reducing diesel consumption through no-till, and sequestering carbon in soil ^[10]. The soil carbon sequestration rate of 1.24 t C ha⁻¹ yr⁻¹ is within the range of 0.5-2.0 t reported for Mediterranean systems adopting cover crops and no-till simultaneously ^[11].

The initial yield depression and subsequent recovery follow the widely reported “transition dip” pattern ^[12]. During years 1-3, soil biological communities are rebuilding, nutrient cycling has not yet reached equilibrium, and weed pressure may increase without herbicides. By year 7, enhanced soil biological function, improved water infiltration, and diversified rotations produced yields matching and then exceeding conventional systems. This transition period is the primary barrier to adoption, suggesting that targeted transition payments could accelerate uptake ^[13].

Conclusion

Regenerative agriculture in Castilla-La Mancha delivered 61-74% reductions in GHG emissions, nitrogen leaching, pesticide loading, and soil erosion compared to conventional systems over a 10-year period. Yields recovered to conventional levels by year 7 and exceeded them by year 10. Soil organic carbon increased by 78% under regenerative management. The environmental benefits are clear and substantial, but the 3-5 year yield transition period represents a genuine economic barrier that policy instruments should address to enable widespread adoption.

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