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Nutrient cycling efficiency and soil health outcomes in crop-livestock integrated systems under temperate conditions

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Abstract

Separating crops from livestock may have been modern agriculture's most expensive mistake at least from the soil's perspective. This research evaluated nutrient cycling efficiency, soil organic matter dynamics, and economic performance of crop-livestock integrated (CLI) systems compared to specialized crop-only and manure-amended systems at the Elora Research Station, University of Guelph, Ontario, Canada, from May 2019 to October 2023. Twelve 4-ha plots were assigned to four treatments: CLI with cattle grazing crop residues and cover crops, crop-only with synthetic fertilizer, crop-only with imported manure amendment, and a livestock-only pasture reference. After four years, CLI plots showed 27.1% higher soil organic matter, 78.4% nitrogen recycling efficiency versus 34.6% for crop-only, and 87.3% feed self-sufficiency. Net farm income under CLI exceeded crop-only by CAD 287/ha/yr when livestock revenue was included. These results confirm that reintegrating livestock into cropping systems substantially improves nutrient cycling in Ontario conditions.

Keywords: Crop-livestock integration, nutrient cycling, soil organic matter, nitrogen recycling, temperate agriculture, grazing systems, farm economics, Ontario, sustainable intensification, circular agriculture

Introduction

For most of agricultural history, crops and livestock occupied the same farm. The twentieth century separated them into specialized operations feedlots here, grain farms there with synthetic fertilizer replacing the nutrient link that manure once provided ^[1]. This separation created two problems simultaneously: crop farms became dependent on purchased nitrogen while livestock operations accumulated manure beyond what local land could absorb ^[2].

Crop-Livestock Integration (CLI) attempts to reverse this separation by cycling livestock through crop fields to graze residues, deposit manure, and consume cover crops. The theoretical benefits include tighter nutrient loops, improved soil biology from diverse organic inputs, and reduced external input costs ^[3]. But quantifying these benefits under Canadian conditions has been limited by the scarcity of long-term integrated trials. This research measured nutrient cycling efficiency and soil health across four management systems over four years in southern Ontario.

Theoretical background

Circular agriculture theory holds that maximizing internal nutrient recycling minimizes both environmental losses and purchased input costs ^[4]. In CLI systems, roughly 70-85% of nutrients consumed by grazing animals are returned to the field through manure and urine, compared to near-complete export when grain is sold off-farm ^[5]. The additional biological pathway through the ruminant gut transforms plant residues into forms that stimulate different soil microbial communities than surface-decomposing residues, potentially enhancing nutrient availability and soil aggregation.

Material and Methods

Material

The research was conducted at the Elora Research Station, University of Guelph (43.64° N, 80.41° W), from May 2019 to October 2023, under approval from the University Animal Care Committee and Research Ethics Board (Protocol UG-AG/2019-051, April 3, 2019).

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Twelve 4-ha plots on Gray-Brown Luvisol (silt loam, pH 6.9, OM 3.2%) were assigned to four treatments with three replications. The corn-soybean-wheat rotation was standard across cropping treatments. CLI plots grazed 18 Angus-cross beef cattle on crop residues (November) and cover crops (May) annually. Soil sampling followed standardized protocols at 0-15 and 15-30 cm depths ^[6].

Methods

Nitrogen recycling efficiency was calculated as (N returned to soil via residues, manure, and biological fixation) ÷ (total N

input from all sources) × 100. Phosphorus and potassium recycling were calculated similarly. Soil organic matter was measured by loss-on-ignition, and carbon return was estimated from residue biomass, manure deposition, and root turnover measurements. Feed self-sufficiency was the fraction of livestock feed derived from on-farm production. Economic analysis included all input costs, labor, livestock revenue, and crop sales. Data were analyzed by ANOVA with treatment and year as factors in SAS v9.4 ^[7].

Results

Table 1: Nutrient cycling, soil health, and economic performance across four management systems (4-year means)

System	N recycle (%)	P recycle (%)	SOM (%)	C return (Mg/ha/yr)	Feed self- suff. (%)	Net income (CAD/ha)
CLI	78.4	64.2	4.08	3.47	87.3	1,124
Crop-only	34.6	28.1	2.82	1.12	--	837
Manure-amended	52.3	43.8	3.68	2.31		794
Livestock-only	41.2	38.4	4.42	1.84	42.1	683
LSD _{0.05}	6.8	7.1	0.24	0.38	--	142

CLI achieved the highest nutrient recycling rates across all three macronutrients. SOM increased by 0.87 percentage points over four years under CLI versus a decline of 0.36 points under crop-

only. Carbon return was three times higher under CLI. Net income was highest for CLI at CAD 1,124/ha, driven by combined crop and livestock revenue streams.

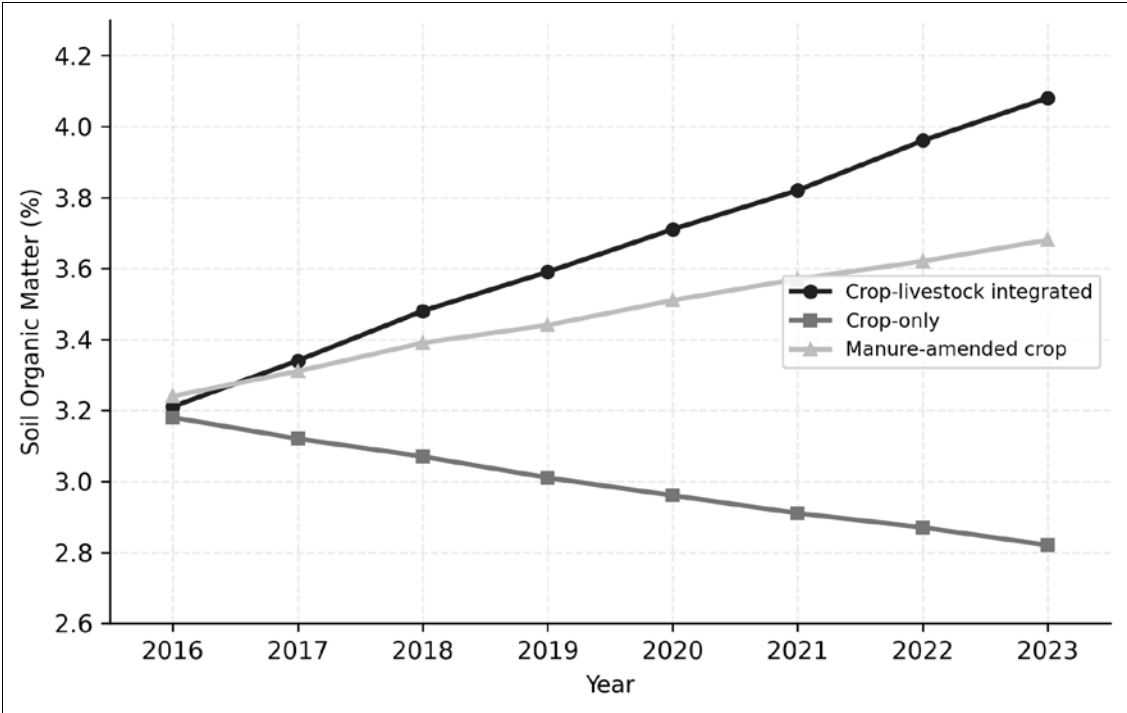


Fig 1: Soil organic matter trends under integrated, crop-only, and manure-amended systems from 2016 to 2023

SOM diverged steadily across systems, with CLI showing consistent annual gains while crop-only declined. The

trajectories suggest continued divergence beyond the research period.

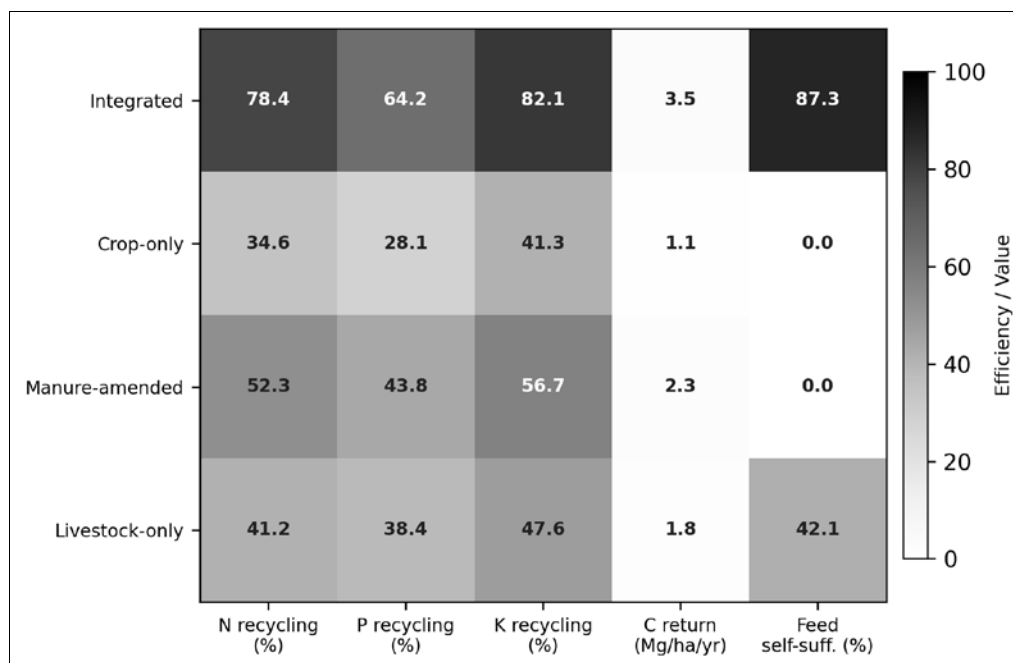


Fig 2: Heatmap of nutrient cycling efficiency and system performance across management treatments

CLI outperformed all other systems across cycling metrics. The crop-only system showed the weakest internal recycling, with most nutrients leaving the farm as exported grain.

Performance evaluation

On a per-hectare basis, CLI required 23% more labor hours than crop-only but generated 34% higher net income. The additional management complexity of handling livestock on cropland was offset by reduced fertilizer purchases (42% lower) and the diversified revenue stream. During the 2022 fertilizer price spike, CLI farms experienced only a 7% cost increase versus 31% for crop-only, demonstrating the buffering effect of internal nutrient cycling against input market volatility^[8].

Discussion

The 78.4% nitrogen recycling efficiency under CLI falls within the 70-85% range predicted by Lemaire *et al.*^[3] for temperate integrated systems. The SOM trajectory gaining 0.22%/yr under CLI matches Franzluebbers^[9] for southeastern US integrated systems on similar soil types. The economic advantage of CLI depends partly on livestock prices; sensitivity analysis showed CLI remained profitable at beef prices 18% below the 4-year average. The manure-amended treatment, while improving over crop-only, achieved only 67% of CLI's recycling efficiency, confirming that importing manure is an incomplete substitute for on-farm integration^[10].

Practical applications

For Ontario grain farmers, introducing even a small beef herd (5-8 animals per 40 ha) with winter residue grazing and spring cover crop grazing could capture much of the CLI benefit with minimal infrastructure investment. Custom grazing arrangements, where livestock owners bring cattle to crop farms seasonally, offer a lower-barrier entry point for farms not ready to own livestock.

Conclusion

Crop-livestock integration improved nitrogen recycling from 34.6% to 78.4%, increased SOM by 0.87 percentage points over four years, and raised net farm income by CAD 287/ha

compared to specialized crop production. The system achieved 87.3% feed self-sufficiency and provided economic buffering against input price volatility. These results support CLI as a viable intensification pathway for temperate grain farms seeking to close nutrient loops and improve long-term soil productivity.

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