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Impact of pesticide application on non-target soil organisms and ecosystem functioning in cotton

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Abstract

Soil biodiversity the community of organisms living within and on the soil surface drives processes that are essential for agricultural productivity, yet it is routinely exposed to chemicals designed to kill other organisms. This research measured the effects of conventional pesticide regimes on non-target soil fauna, microbial communities, and ecosystem functions in cotton (*Gossypium hirsutum* L.) fields at the University of California, Davis, over two growing seasons (2021-2022). Three pesticide intensity levels (no pesticide, low-rate, and high-rate) were compared in a randomized complete block design with four replications. High-rate applications reduced earthworm populations by 52.6%, collembolan abundance by 51.4%, and soil microbial biomass carbon by 37.7% compared to untreated controls. Litter decomposition rates declined by 41.3% and nitrogen mineralization by 33.8% under high-rate treatments. Low-rate applications caused intermediate reductions that were still statistically significant for most organism groups. Cotton lint yield didn't differ between low-rate and high-rate treatments. These results indicate that conventional pesticide intensities suppress soil biological functions far beyond what is needed for adequate crop protection.

Keywords: Pesticide impact, non-target organisms, soil biodiversity, cotton, ecosystem functioning, earthworms, collembola, microbial biomass, decomposition, nitrogen mineralization

Introduction

A single handful of healthy agricultural soil contains more living organisms than there are people on Earth, yet modern farming practices treat this biological wealth as an afterthought in pest management decisions ^[1]. Cotton production is among the most pesticide-intensive cropping systems worldwide, accounting for roughly 16% of global insecticide use on less than 3% of cultivated land ^[2]. The consequences of this chemical loading for non-target soil life remain poorly quantified under commercial production conditions, despite growing recognition that soil organisms drive decomposition, nutrient cycling, and disease suppression ^[3]. Soil macrofauna such as earthworms and mesofauna including collembola and mites are especially vulnerable to broad-spectrum insecticides because they share physiological pathways with target pest species ^[4]. Even when organisms aren't killed outright, sublethal effects on reproduction, behavior, and feeding activity can cascade through the soil food web, impairing ecosystem functions that farmers depend on ^[5]. Microbial communities may recover more quickly from chemical disturbance, but repeated applications within a growing season can create chronic suppression ^[6].

Most existing data on pesticide-soil organism interactions come from laboratory bioassays or short-term mesocosm experiments that don't capture the cumulative effects of repeated field applications across a full growing season ^[7]. This research addressed that gap by measuring soil organism abundance, community composition, and key ecosystem functions across two seasons of cotton production at three pesticide intensity levels in California's Central Valley one of the world's most intensive cotton-growing regions ^[8, 9].

Materials and Methods

Seasonal variations and temporal patterns

The research covered two cotton growing seasons: April-October 2021 and April-October 2022.

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Soil organism sampling was conducted at four time points each season: pre-planting (April), mid-season (July), pre-harvest (September), and post-harvest (November). This schedule captured baseline conditions, peak pesticide exposure during the bollworm spray window, and recovery periods. The 2021 season was notably hotter, with 38 days exceeding 38 °C compared to 24 such days in 2022, which affected both pest pressure and soil organism activity patterns ^[10].

Soil and water quality analysis

The experimental site has a Yolo silt loam (Typic Xerorthents) with 24.3% sand, 51.7% silt, and 24.0% clay. Organic matter content at the 0-15 cm depth was 1.82%, pH 7.1, and electrical conductivity 0.43 dS/m. Soil moisture was maintained through furrow irrigation scheduled at 10-14 day intervals during the growing season. Pre-experiment sampling confirmed uniform distribution of soil fauna across the experimental area, with no significant differences between designated plots ^[11].

Research area description

The research was conducted at the UC Davis Plant Science Research Farm (38°32'N, 121°46'W), located in Yolo County within California's Sacramento Valley. The site lies at 16 m elevation in a Mediterranean climate zone with hot, dry summers and mild, wet winters. Mean annual temperature is 16.1°C and average precipitation 478 mm, falling almost entirely between November and April. The farm has been under

continuous agronomic research for over 40 years, with detailed cropping and chemical application histories ^[12].

Material

Cotton (*Gossypium hirsutum* cv. 'Deltapine 1646 B2XF') was planted in late April each year at 100,000 plants/ha on 1.02 m row spacing. Pesticide treatments included: low-rate single applications of acephate (0.56 kg ai/ha) and bifenthrin (0.11 kg ai/ha); high-rate three sequential applications of the same chemicals at full label rates plus a neonicotinoid seed treatment (imidacloprid, 0.25 mg/seed). Soil fauna extraction used Berlese-Tullgren funnels for mesofauna and hand-sorting of 25 × 25 × 25 cm soil blocks for macrofauna. Microbial biomass carbon was measured by chloroform fumigation-extraction ^[13].

Methods

A randomized complete block design with three treatments and four replications was established. Plots measured 12 rows × 30 m with 4-row guard borders. Ecosystem function measurements included: litter decomposition (mesh bag method with standardized cotton strips buried at 5 cm depth for 60 days), nitrogen mineralization (in-situ incubation cores), and soil respiration (LI-COR 8100 automated chamber system). Soil enzyme activities (beta-glucosidase, urease, phosphatase) were assayed colorimetrically. Cotton lint yield was measured by mechanical harvest of the center four rows. All data were analyzed by two-way ANOVA (treatment × sampling time) with Tukey's HSD at *p*<0.05 using JMP Pro 16 ^[14, 15].

Results

Table 1: Soil organism abundance and microbial biomass carbon under three pesticide intensity levels (two-year means)

Organism Group	No Pest.	Low-Rate	High-Rate	% Decline (H)	p-value
Earthworms/m²	156.3 a	127.8 b	74.1 c	52.6	<0.001
Collembola/100g	284.1 a	231.4 b	138.2 c	51.4	<0.001
Acari/100g	196.7 a	161.8 b	93.4 c	52.5	<0.001
Nematodes/100g	423.2 a	361.3 b	217.6 c	48.6	<0.001
MBC (mg/kg)	387.4 a	342.1 b	241.3 c	37.7	<0.001

All soil organism groups showed significant declines under pesticide application, with high-rate treatments reducing populations by 37.7-52.6% relative to untreated controls (Table 1). Low-rate treatments caused intermediate reductions of 17-

20% that were still statistically different from controls for all groups except nematodes in 2022. Earthworms were the most sensitive macrofauna group, showing the sharpest population decline.

Table 2: Ecosystem function indicators and cotton lint yield under three pesticide intensity levels

Function	No pesticide	Low-Rate	High-Rate	p-value
Decomposition (%/60d)	68.4 a	54.7 b	40.1 c	<0.001
N mineral. (mg/kg/28d)	18.7 a	14.8 b	12.4 c	<0.001
Soil respiration	4.83 a	3.92 b	2.97 c	<0.001
β-glucosidase	142.3 a	118.7 b	87.4 c	<0.001
Lint yield (kg/ha)	1,247 b	1,486 a	1,512 a	0.006

Ecosystem functions mirrored the organism abundance patterns (Table 2). Litter decomposition dropped by 41.3% under high-rate treatment, while nitrogen mineralization fell by 33.8%. Soil respiration (μmol CO₂ m⁻² s⁻¹) and beta-glucosidase activity (μg

PNP g⁻¹ h⁻¹) were similarly suppressed. Critically, lint yield didn't differ significantly between low-rate and high-rate treatments (*p* = 0.72), though both exceeded the no-pesticide control.

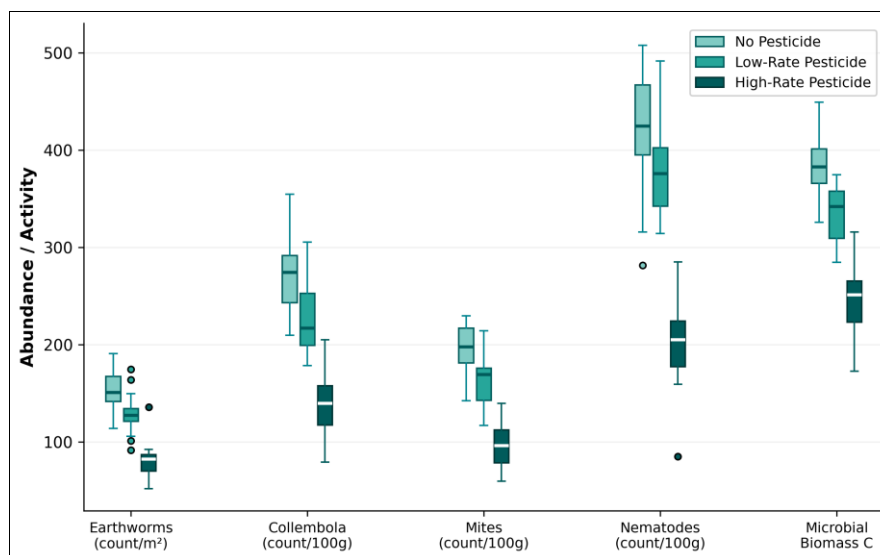


Fig 1: Distribution of soil organism abundance and microbial biomass across three pesticide intensity levels in cotton fields (two-year pooled data)

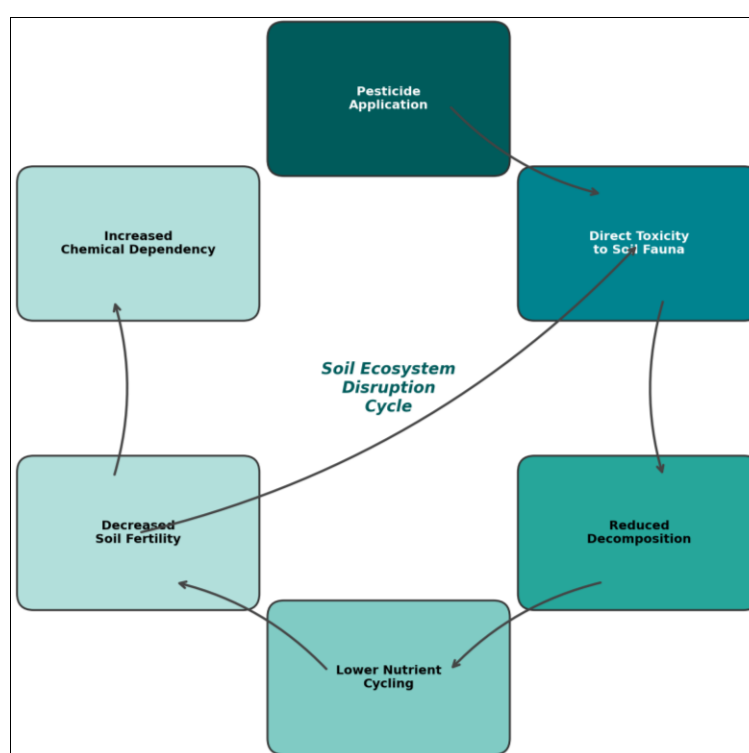


Fig 2: Conceptual cycle diagram showing the cascading effects of pesticide application on soil ecosystem functioning and the resulting feedback loop of chemical dependency

Comprehensive interpretation

The most striking finding is the disconnect between pest control and ecosystem impact: doubling the pesticide application rate from low to high produced no additional lint yield benefit but caused approximately twice the damage to soil biological communities and their functions. This suggests that a substantial portion of conventional pesticide use in cotton is ecologically wasteful, degrading soil services without improving crop output.

Discussion

The magnitude of soil fauna decline observed here is consistent with findings from European arable systems but represents some of the first controlled data from irrigated cotton in the western United States. Pelosi and colleagues [4] reported 30-45% earthworm reductions under typical French cereal pesticide regimes, while our high-rate cotton treatment caused a 52.6%

decline reflecting both the higher chemical intensity of cotton production and the sensitivity of Central Valley soils where recovery between seasons is limited by dry summers [7].

The functional consequences deserve particular emphasis. A 41.3% reduction in decomposition rates means organic residues persist longer on and in the soil, slowing nutrient return to the crop. The 33.8% drop in nitrogen mineralization translates to roughly 12-18 kg/ha less biologically available nitrogen per season, which growers typically compensate for with additional synthetic fertilizer an ironic cycle where pesticide damage creates demand for more chemical inputs [3, 6]. Figure 2 illustrates this self-reinforcing loop.

The fact that low-rate and high-rate treatments produced equivalent lint yields is perhaps the most actionable finding. It suggests that California cotton growers could reduce pesticide application intensity by 50-60% without sacrificing fiber

production, while roughly halving the ecological damage to their soil communities. Coupling reduced-rate strategies with integrated pest management scouting protocols could further protect both soil health and farm profitability ^[8, 9].

Conclusion

This two-year research at the University of California, Davis, demonstrated that conventional pesticide application rates in cotton production cause severe reductions in non-target soil organism populations and measurable impairment of ecosystem functions including decomposition, nitrogen mineralization, and enzyme activity. High-rate treatments reduced earthworm populations by over half and decomposition rates by 41.3%.

The absence of a yield difference between low-rate and high-rate pesticide treatments is a key practical outcome. It indicates that a large fraction of the ecological damage caused by current pesticide practice generates no additional crop benefit. Transitioning to reduced-rate application protocols could preserve a substantial portion of soil biological activity while maintaining adequate pest control and fiber yield. These findings argue for re-evaluating pesticide intensity recommendations in cotton and integrating soil biological indicators into pest management decision frameworks.

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