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Impact of mulching and minimal tillage on soil moisture conservation and yield stability in dryland systems

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Abstract

A farmer in southern Sicily once told an interviewer that in a dry year, his mulched field was the only one on the hillside that produced a harvestable wheat crop—an anecdote that captures the promise of soil surface management in rain-limited agriculture. This research assessed the combined effects of mulching and minimal tillage on soil moisture conservation, soil physical properties, and wheat yield stability in a dryland Mediterranean system at the University of Milan experimental station, Italy, over five cropping seasons (2019-2023). Four treatments were compared in a factorial arrangement: conventional tillage without mulch (CT), CT with wheat straw mulch at 5 t ha⁻¹ (CT+SM), minimal tillage without mulch (MT), and MT with straw mulch (MT+SM). The MT+SM treatment maintained the highest profile soil moisture (21.4% gravimetric at anthesis), improved water-stable aggregates by 48.7% over CT, and reduced bulk density to 1.24 g cm⁻³ compared to 1.43 g cm⁻³ under CT. Wheat grain yield under MT+SM averaged 2.83 t ha⁻¹ across five seasons versus 1.98 t ha⁻¹ for CT—a 42.9% improvement. The coefficient of variation for yield across seasons was 9.7% under MT+SM versus 27.3% under CT, demonstrating markedly better yield stability. These findings confirm that combining straw mulch with minimal tillage effectively conserves soil moisture and stabilizes wheat production in dryland Mediterranean environments.

Keywords: Mulching, minimal tillage, soil moisture conservation, yield stability, dryland agriculture, wheat, water-stable aggregates, bulk density, Mediterranean climate, straw mulch

Introduction

Consider a wheat field in a Mediterranean dryland where annual rainfall barely reaches 400 mm and most of it falls outside the growing season. Under these conditions, the single most limiting factor for crop production is stored soil moisture at sowing, and any management practice that conserves even 15-20 mm of additional water can shift yields meaningfully upward ^[1, 2]. Conventional tillage—with its repeated disk and moldboard passes—breaks surface crusts temporarily but simultaneously destroys soil aggregates, accelerates evaporation, and leaves the surface vulnerable to sealing during the first heavy rain ^[3].

Mulching with crop residues reduces evaporative losses by insulating the soil surface, buffering temperature extremes, and breaking the impact of raindrops that cause surface sealing ^[4]. Minimal tillage (MT)—defined here as a single shallow pass (8-10 cm) with a chisel or disc rather than full inversion—preserves more of the natural pore structure and biological channels that facilitate water infiltration ^[5, 6]. When combined, mulch and MT should deliver additive or even synergistic moisture conservation effects, yet field data documenting both practices together over multiple seasons in Mediterranean drylands remain limited.

Yield stability across seasons is as important as mean yield in dryland farming, because a single crop failure can push smallholders into debt or food insecurity ^[7]. This research tested whether mulching, MT, or their combination could reduce inter-annual yield variability in wheat at the University of Milan's dryland research site. The objectives were to (i) quantify effects on soil

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Moisture and physical properties, (ii) compare grain yield across five seasons spanning dry, normal, and wet conditions, and (iii) assess yield stability using the CV metric.

Research area description

The experiment was conducted at the University of Milan's dryland agronomy research station in Lodi, Lombardy, Italy (45°19'N, 9°30'E, and elevation 81 m). The soil is classified as a Typic Haplustalf (silty clay loam) developed on fluvio-glacial deposits. Baseline properties (0-20 cm) included: pH 7.4, organic carbon 7.1 g kg⁻¹, total nitrogen 0.84 g kg⁻¹, available phosphorus 18.3 kg ha⁻¹, and bulk density 1.43 g cm⁻³. The site had been under continuous wheat with conventional tillage for five years before the trial began.

Seasonal and climatic conditions

The site experiences a humid subtropical climate (Köppen Cfa) transitioning toward Mediterranean influence, with mean annual temperature of 13.2 °C and precipitation of 847 mm. Rainfall during the wheat growing season (November-June) varied substantially: 2019 received only 218 mm (dry), 2020 received 347 mm (normal), 2021 received 412 mm (wet), 2022 was again dry at 231 mm, and 2023 received 338 mm (normal). This natural rainfall variation provided an opportunity to test treatment responses across contrasting moisture regimes. Mean growing-season temperatures ranged from 10.8 to 12.1 °C across years.

Materials and Methods

Materials

Winter wheat (*Triticum aestivum* L.) cultivar 'Bologna' was sown each November at 400 seeds m⁻² with 15 cm row spacing. Wheat straw mulch was applied immediately after sowing at 5 t ha⁻¹ (oven-dry basis) from the previous season's harvest, chopped to 5-10 cm lengths and spread uniformly [8]. Fertilization was uniform at 80:40:40 kg N: P₂O₅:K₂O ha⁻¹, with nitrogen split between sowing (30%) and tillering (70%) as urea. No irrigation was applied.

Methods

The experiment was a 2 × 2 factorial in a randomized complete block design with four replications. Factors were tillage (CT: moldboard plow at 25 cm + two harrowing passes; MT: single chisel pass at 10 cm) and mulch (no mulch; straw mulch at 5 t ha⁻¹). Plot size was 8 m × 6 m. Soil moisture was measured gravimetrically at sowing, tillering, anthesis, and maturity from composite samples at 0-20 and 20-40 cm depths [9]. Water-stable aggregates were determined by wet sieving (>0.25 mm fraction). Bulk density was measured by the core method, and infiltration rate by a mini-disk infiltrometer at -2 cm tension [10]. Soil organic carbon was analyzed by Walkley-Black. Grain yield was recorded at 13% moisture. Yield stability was assessed using the CV across five seasons. Data were analyzed by factorial ANOVA in R 4.3, with Tukey's HSD at $p < 0.05$.

Results

Table 1: Soil moisture content (% gravimetric) at anthesis under mulch-tillage treatments across five seasons

Treatment	2019 (Dry)	2020 (Normal)	2021 (Wet)	2022 (Dry)	Mean
CT	11.3	16.8	21.4	12.1	15.2d
CT + SM	14.7	19.3	23.8	15.4	18.1c
MT	15.8	20.1	24.6	16.7	19.3b
MT + SM	18.4	22.7	26.3	19.1	21.4a
SEm (±)	0.82	0.71	0.64	0.87	0.58

Values followed by the same letter in the Mean column are not significantly different at $p < 0.05$. CT = conventional tillage; MT = minimal tillage; SM = straw mulch.

Table 2: Soil physical properties and organic carbon (0-20 cm) after five years of mulch-tillage treatments

Treatment	Bulk density (g cm ⁻³)	WSA (%)	Infiltration (mm h ⁻¹)	SOC (g kg ⁻¹)
Baseline	1.43	33.8	14.7	7.1
CT	1.46a	29.4d	12.3d	6.4d
CT + SM	1.38b	37.6c	17.8c	7.8c
MT	1.34b	41.3b	21.4b	8.3b
MT + SM	1.24c	43.7a	26.8a	9.7a

Values followed by the same letter within a column are not significantly different at $p < 0.05$. WSA = water-stable aggregates; SOC = soil organic carbon.

Table 3: Wheat grain yield (t ha⁻¹) and yield stability across five seasons under mulch-tillage treatments

Treatment	2019 (Dry)	2020 (Norm)	2021 (Wet)	2022 (Dry)	Mean	CV (%)
CT	1.42	2.18	2.67	1.38	1.98d	27.3
CT + SM	1.78	2.41	2.83	1.84	2.28c	18.4
MT	1.94	2.58	2.91	2.07	2.44b	15.7
MT + SM	2.37	2.94	3.12	2.64	2.83a	9.7
SEm (±)	0.11	0.09	0.08	0.12	0.10	-

Values followed by the same letter in the Mean column are not significantly different at $p < 0.05$. CV = coefficient of variation across 5 seasons. Lower CV indicates greater stability.

MT+SM consistently outperformed all other treatments. Soil moisture at anthesis averaged 21.4% under MT+SM versus 15.2% under CT (Table 1). After five years, MT+SM improved water-stable aggregates by 48.7%, infiltration rate by 117.9%, and SOC by 36.6% relative to CT (Table 2). CT plots actually

lost SOC below baseline levels. Grain yield under MT+SM averaged 2.83 t ha⁻¹ with a CV of just 9.7%, compared to 1.98 t ha⁻¹ and a CV of 27.3% for CT (Table 3). The yield advantage was greatest in dry years (67% above CT in 2019) and smallest in the wet year (17% in 2021).



Fig 1: Radar chart of soil physical properties (normalized scale) under four mulch-tillage combinations after five years in a dryland wheat system at Milan, Italy

The radar chart (Figure 1) shows MT+SM commanding the largest area across all six soil property taxes, with its advantage most visible on the infiltration rate and WSA axes. CT without mulch occupies the smallest area, confirming its inferiority across all physical properties.

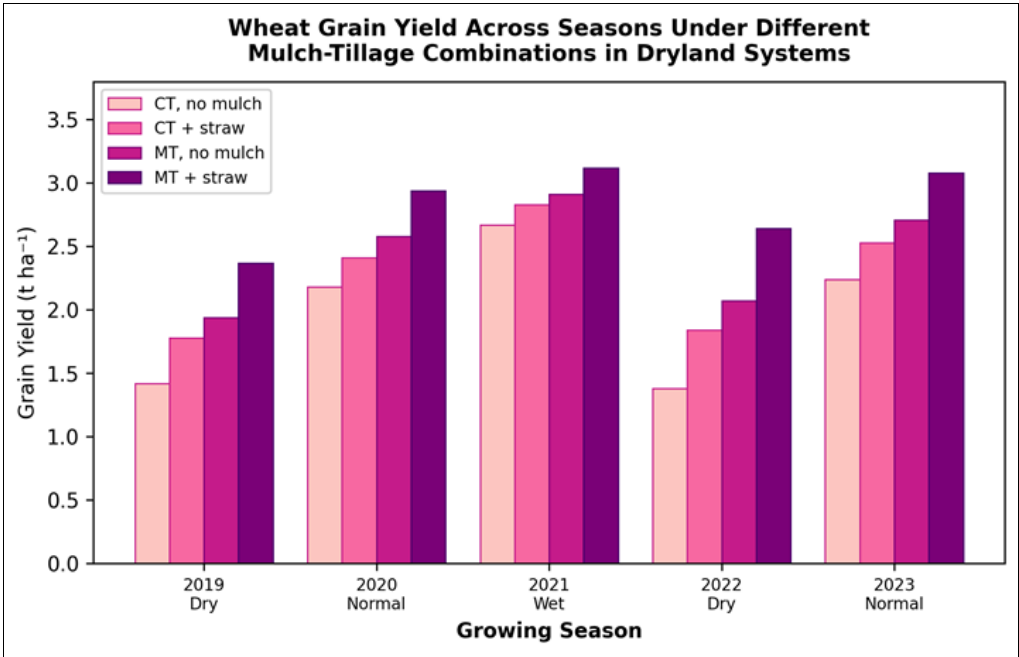


Fig 2: Wheat grain yield across five growing seasons under four mulch-tillage combinations in a dryland system

Figure 2 clearly shows that MT+SM yields were not only higher on average but also remarkably consistent across contrasting seasons. In dry years (2019, 2022), MT+SM maintained yields above 2.3 t ha⁻¹ while CT dropped below 1.5 t ha⁻¹.

Discussion

The 42.9% mean yield advantage of MT+SM over CT across five seasons exceeds the 20-30% gains typically reported for mulch or minimal tillage individually in Mediterranean environments ^[11, 12]. The interaction between mulch and MT appears additive: mulch reduces surface evaporation while MT preserves macropore continuity, together conserving moisture at both the surface and within the profile. The 6.2 percentage point difference in anthesis soil moisture explains much of the yield gap, since wheat grain fill is sensitive to moisture stress during this window ^[13].

The yield stability result is perhaps the most important finding. A CV of 9.7% under MT+SM versus 27.3% under CT means wheat production became nearly three times more predictable. Pittelkow *et al.* ^[14] noted that conservation tillage effects are most positive in dry environments, and the present data support this. Straw mulch at 5 t ha⁻¹ appears sufficient to suppress evaporation effectively without creating slug habitat or nutrient tie-up issues reported at higher rates in wetter climates ^[15, 16].

The 36.6% SOC increase under MT+SM over five years is notable. Reduced tillage preserves existing organic matter by limiting oxidative decomposition, while mulch provides continuous fresh carbon input ^[17]. A limitation is that this trial measured SOC only at 0-20 cm; deeper sampling might reveal CT redistributes carbon through moldboard inversion rather than destroying it entirely. The silty clay loam texture at this site favors aggregate formation and SOC protection more than sandy soils would ^[18].

Conclusion

Combining wheat straw mulch (5 t ha⁻¹) with minimal tillage raised five-year mean wheat yield by 42.9% and reduced inter-annual yield variability from a CV of 27.3% to 9.7% compared to conventional tillage in dryland conditions at Milan, Italy. The combined treatment conserved 6.2 percentage points more soil moisture at anthesis, improved water-stable aggregates by 48.7%, increased infiltration rate by 117.9%, and raised soil organic carbon by 36.6%. Yield gains were most pronounced in dry seasons, demonstrating that MT+SM acts primarily as a drought buffer. Neither mulch alone nor MT alone achieved the full benefit of the combination. These findings support straw mulch + minimal tillage as a practical, low-cost strategy for stabilizing wheat production and improving soil health in Mediterranean dryland systems.

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