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Restoring Soil and Ecosystem Functions in Hilly Olive Orchards in Northwestern Syria by Adopting Contour Tillage and Vegetation Strips in a Mediterranean Environment

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Abstract

Steep olive orchards in northwest Syria are experiencing severe land degradation as a result of unsustainable uphill–downhill tillage, which accelerates erosion and reduces productivity. To address this problem, three tillage systems, no-till natural vegetation strips (NVSs), contour tillage, and uphill–downhill tillage, were evaluated at two research sites, Yakhour and Tel-Hadya, NW Syria. The adoption of no-till NVSs significantly increased soil organic matter (SOM) at both sites, outperforming uphill–downhill tillage. While contour tillage resulted in lower SOM levels than NVSs, it still performed better than the conventional uphill–downhill practice. Contour soil flux (CSF) was lower in Yakhour, where mule-drawn tillage on steep slopes (31–35%) was practiced, compared to higher CSF values in Tel-Hadya, where tractor tillage was applied on gentler slopes (11–13%), which highlights the influence of slope steepness on soil fluxes. Over four years, net soil flux (NSF) indicated greater soil loss under tractor tillage, confirming that mule-drawn tillage is less disruptive. Olive trees with no-till NVSs benefited from protected root systems, improved soil structure through SOM accumulation, reduced erosion risk, and improved surface runoff buffering, which resulted in increased water infiltration and soil water retention. This study was carried out using a participatory technology development (PTD) framework, which guided the entire research process, from diagnosing problems to co-designing, field testing, and refining soil conservation practices. In Yakhour, farmers actively identified the challenges of degradation. They collaboratively chose no-till natural vegetation strips (NVSs) and contour tillage as key interventions, valuing NVSs for their ability to conserve moisture, suppress weeds and pests, and increase olive productivity. The farmer–scientist co-learning network positioned PTD not only as an outreach tool but also as a core research method, enabling locally relevant and scalable strategies to restore soil functions and combat land degradation in northwest Syria's hilly olive orchards.

Keywords: Syria; olives (*Olea europaea*); soil erosion; tillage erosion; natural vegetation strips (NVSs); tractor-mounted tillage; mule-drawn tillage; PTD (participatory technology development)

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1. Introduction

Olive trees (*Olea europaea* L.) are predominantly cultivated in the Mediterranean basin, which accounts for 93.44% of the approximately 11 million hectares of global olive-growing land [1].

With roots tracing back to antiquity, olive cultivation remains the most economically and culturally significant perennial tree crop in the region, not only as a source of income and rural employment but also as a keystone component of Mediterranean agroecosystems and environmental significance [2]. However, the expansion of olive farming has increasingly encroached upon marginal lands. Only 15% of Mediterranean olive orchards are established on gentle slopes (<5% gradient), while the vast majority occupy steeper, erosion-prone terrain characterized by shallow soils, low organic matter content, and limited water retention capacity [3]. These inherent biophysical constraints are compounded by a climate typified by prolonged summer droughts and short, high-intensity winter rainfall events [4], which together create ideal conditions for accelerated soil erosion [5], compromising human-managed ecosystems and agricultural sustainability [1].

On such vulnerable landscapes, where soils are often shallow, highly erodible, and sparsely vegetated [6], soil degradation has become a pervasive threat to agricultural sustainability across the Mediterranean [7]. Olive groves, despite their deep cultural and ecological embeddedness, have increasingly emerged as hotspots of land degradation due to prevailing management practices that prioritize short-term agronomic convenience over long-term soil health [8,9]. This is especially evident in northwest Syria's Afrin district, where olive orchards cover nearly 84% of the hilly landscape [10]. Olive cultivation sustains economically marginal rural communities in an environment where few alternative crops can survive, functioning as both a socio-economic lifeline and a resilient agro-ecological adaptation to harsh conditions [5].

Historically, olive oil has served as the primary dietary fat for Mediterranean populations [9], and its production remains central to local livelihoods in Afrin [11]. Yet, mounting economic pressures, labor shortages, and the pursuit of higher yields have driven a shift toward "clean tillage" systems, frequent mechanical plowing aimed at weed suppression, fertilizer incorporation, and improved water infiltration [2]. Unintentionally, this intensification has undermined the very resource base it seeks to optimize. Reconnaissance surveys indicate that two-thirds of local farmers directly link declining yields to soil erosion resulting from repeated uphill–downhill tractor passes [12]. This trend accelerated with the mechanization of agriculture from the 1970s onward, which displaced traditional animal-drawn implements and coincided with the decline in rotational fodder crops (e.g., barley, lentils, vetch) that once supported draft-animal husbandry [13]. On steep slopes, tractors, less stable than mules, were often operated downhill for safety, inadvertently promoting severe downslope soil translocation and detachment [14].

The consequences are devastating. Field evidence includes the abandonment of six "ghost villages" and over 1000 ephemeral gully systems affecting 10% of olive orchards in northwest Syria [10,15]. Quantitative studies report annual soil losses as high as 80 Mg ha^{-1} on 25% slopes subjected to five annual tillage passes [16], with one long-term comparison revealing a 31% reduction in soil depth (equivalent to 7 mm yr^{-1}) in tilled olive orchards relative to adjacent undisturbed forest soils [17]. During the 2003–2004 rainy season alone, control plots in Afrin recorded sediment yields of 58.3 t ha^{-1} and volumetric losses of 2.9 m^3 ha^{-1} [2]; rainfall simulation experiments further confirmed the area's high soil erodibility [18,19]. Notably, just two intense rainfall events accounted for nearly two-thirds of the total seasonal sediment export in 2009–2010 [20], which underscores the episodic yet catastrophic nature of erosion in this system.

While water erosion is often emphasized, tillage erosion, the net downslope displacement of soil by mechanical implements, plays an equally critical, though less visible, role in landscape degradation on sloping olive farms [9,20]. Preliminary tracer studies using aluminum cubes have quantified soil displacement under different tillage regimes in the region [14,16], confirming the severity of downslope movement under conventional systems. Unlike water erosion, which removes fine particles, tillage erosion redistributes entire soil profiles, depleting upslope areas of fertile topsoil while burying downslope zones under less productive subsoil [21,22]. This process is exacerbated by conventional uphill–downhill tillage patterns, which systematically transport soil toward valley bottoms, accelerating gully formation and reducing on-site productivity [23]. Compounding the problem, the near-total removal of inter-row vegetation, a practice long used to minimize water and nutrient competition, eliminates natural barriers to both runoff and tillage-induced soil movement [24].

In response to these challenges, conservation-oriented approaches such as natural vegetation strips (NVSs), which consist of spontaneous or managed herbaceous cover established along contours, are increasingly being adopted due to their demonstrated efficacy in reducing both water and tillage erosion by intercepting runoff, enhancing infiltration, and stabilizing soil aggregates [25]. Widely implemented by smallholders on sloping lands across parts of Asia, NVS-based contour farming has proven adaptable to diverse agro-ecological contexts [26,27].

In Afrin, a revival of traditional mule-drawn contour plowing using the 'Faddan' implement seeks to counteract the recent legacy of mechanized downhill tillage. Operating along elevation contours rather than up and down slopes, this practice not only minimizes soil translocation but also encourages the establishment of NVSs in untilled inter-row zones, which function as biophysical buffers against erosion.

Therefore, our objective-driven research was based on participatory technology development (PTD), a collaborative approach that co-creates knowledge and conservation technologies among farmers, researchers, extension agents, and local institutions. It recognizes that land degradation in northwest Syria results not only from biophysical stressors but also from socio-economic constraints, such as limited financial resources, weak institutional support, and fragmented policies.

The PTD process started with a participatory diagnosis, carried out through community mapping, focus group discussions, and seasonal field walks. These activities identified specific drivers of degradation at each site and locally prioritized restoration goals, ensuring that interventions matched existing farming routines, cultural values, and indigenous ecological knowledge.

Based on this diagnosis, a set of low-cost, nature-based practices was co-designed and field-tested between 1996 and 2004, including stripped contour tillage and no-till natural vegetation strips (NVSs) established between olive tree rows. NVSs serve as integrated physical and biological barriers, reducing soil erosion and surface runoff while encouraging the buildup of organic matter, thus strengthening essential soil functions. To evaluate the impact of these practices on soil system resilience, SWC researchers defined a core set of long-term, measurable parameters: 1—soil flux and displacement, measured with aluminum tracer cubes; 2—erosion rates, monitored through permanent metal pins installed across topographic segments (upper, middle, lower); 3—soil organic carbon dynamics, tracked through annual composite sampling across treatments; and 4—soil structure, evaluated through measurements of water-stable aggregates (%), bulk density, and other quantitative indices, including mean weight diameter (MWD) and the standard deviation (STDEV) of cumulative aggregate size distribution curves. These parameters

were integrated to objectively assess improvements in soil structural stability following the improvement in SOM.

These biophysical indicators were integrated into a participatory monitoring framework to systematically evaluate the integrity and responsiveness of soil systems to research-informed management interventions.

Locally adapted, farmer-viable strategies present a promising yet underexplored pathway to reconcile agricultural productivity with ecological sustainability in landscapes severely affected by human-induced land degradation. This study investigates the potential of integrated natural vegetation strips (NVSs) combined with contour tillage to restore soil systems—defined as the complex interaction of physical, biological, and chemical processes that sustain soil function and resilience—in degraded olive agroecosystems in northwest Syria. By assessing whether these practices can simultaneously improve soil conservation, support farmers' livelihoods, and serve as a scalable model for landscape restoration, this research addresses a critical gap in Mediterranean soil conservation science (Figure 1).



Figure 1. Panoramic view of human-induced degraded hilly olive orchards in Afrin, NW Syria (36°30′45″ N 36°44′15″ E).

2. Materials and Methods

2.1. PTD Research Approach

The methodological approach is grounded in a participatory technology development (PTD) framework that highlights co-creation of knowledge and technologies among farmers, researchers, extension agents, and local institutions [28]. This approach recognizes that land degradation is not just a biophysical issue but is also closely linked to socio-economic challenges, such as limited financial resources, weak institutional support, and poor policy integration, which disproportionately impact resource-poor smallholders. Field activities were carried out through repeated cycles of participatory diagnosis, on-farm experimentation, and adaptive learning. Initial assessments included community mapping and focus group discussions with indigenous practices and local communities to identify site-specific causes of degradation and locally perceived restoration priorities. These conversations showed that effective interventions must fit with existing farming practices, cultural values, and ecological knowledge systems [29].

Based on this diagnostic phase, a series of nature-based, low-cost restoration practices was co-developed and field-tested. These included stripped contour tillage suited for steep terrain between olive tree rows, creating no-till natural vegetation strips (NVSs) that serve as physical and biological barriers against soil erosion and improve soil system restoration, increase soil water retention, suppress weed and pest infestations, and ultimately preserve land productivity.

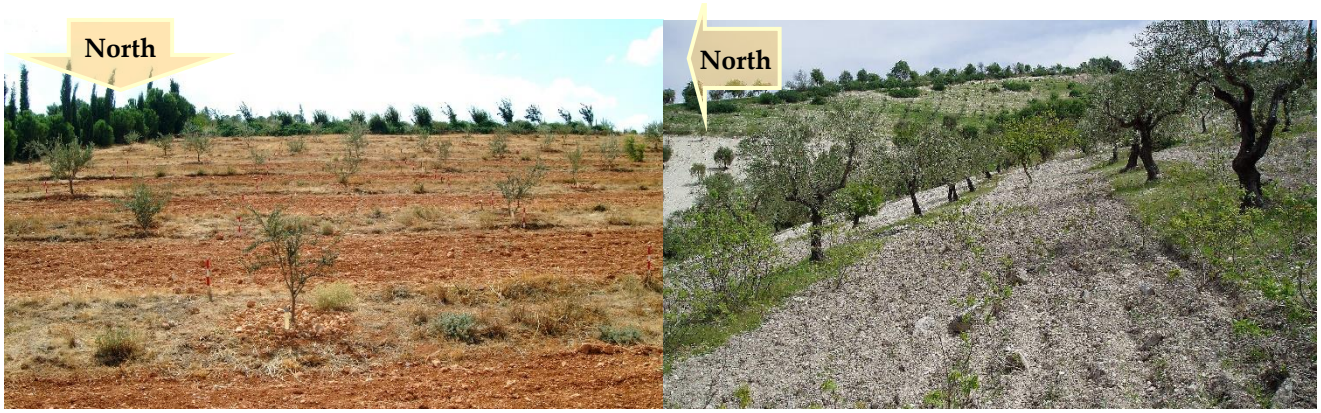
While ICARDA SWC's researchers identified key long-term soil parameters to study and support the resilience of soil systems in degraded areas and track indicators like soil flux and displacement, soil organic matter dynamics and enrichment, and soil moisture retention around olive trees, they also organized "field technologies market" and demonstration plots to effectively communicate with farmers and promote experiential learning and peer-to-peer knowledge exchange. These participatory platforms enabled farmers to observe, compare, and discuss how conservation practices such as contour tillage, no-till natural vegetation strips, and reduced tillage perform under real-world conditions. This approach connects scientific insights with local ecological knowledge. Over time, this ongoing dialogue builds trust, encourages adaptive management, and helps develop soil and water conservation strategies that are both technically effective and socially acceptable.

Data collection employed a combination of qualitative and quantitative methods, including semi-structured interviews, participatory rural appraisal (PRA) tools, and soil health indicators (such as organic carbon, bulk density, and soil structure) across multiple growing seasons. Other biophysical analyses were also performed by joint-graduating students to evaluate governance structures, policy coherence, and enabling conditions for scaling community-driven restoration.

2.2. Research Sites and Treatments Design

Two research sites were established in northwest Syria. The first was a PTD-led site in Yakhour, Afrin, where mule-drawn tillage was the dominant method. The second site was located at the main farm of ICARDA in Tal-Hadya, where tractor-mounted tillage practices were common.

At each research site, an adjacent field was subjected to uphill–downhill tillage passes to replicate the tillage operation—using mule-drawn equipment in Yakhour and tractor-mounted tillage in Tal-Hadya (Figure 2).



(**a**) ICARDA research site (**b**) Yakhour research site

Figure 2. Pictures of the NVSs—contour tillage research sites: (**a**) at the Tal-Hadya site with tractor-mounted tillage, and (**b**) at the Yakhour site with mule-drawn tillage.

Each site was divided, based on slope aspect, into upper, middle, and lower slope segments (or slope position) to merely reduce spatial variability, and 3 statistically based

replicates were presented. In each segment, 3 bands of soil erosion pins were permanently installed. Also, in each segment, 3 aluminum cube lines were deployed at appropriate locations, one line in each segment, preceding and following tillage operations and where composite soil samples were taken at 3 locations for each segment. The contour tillage at Yakhour and Tal-Hadya resulted in 10 and 8 parallel no-till NVSs, respectively, where soil and plant cover remained non-tilled within the rows of olive trees.

Subsequently, three treatments of no-till NVSs, contour tillage, and uphill–downhill tillage were implemented at each research site, spanning 3 segments and with 3 aluminum cube locations, resulting in 3 × 3 × 3 = 27 measurements. The same procedure was followed for the permanent 3 bands of soil erosion pins and the 3 locations of composite soil sampling procedure.

2.2.1. Yakhour Research Site

The research field (90 m length × 70 m width) has been cultivated with olives for at least 100 years. Yakhour research site (36°42′42″ N, 36°30′55″ E) is located in Afrin district, 95 km northwest of Aleppo city in NW Syria. The site was delineated in the fall of 2004, with a steep 31–35% slope and a north-facing aspect. The slope is relatively linear and uniform and tends to level off at the foot slope due to the continuous soil and water erosion and accumulation of sediments. Soil profile truncation is very clear in the upper parts of the hillslope due to the continuous improper tractor tillage and soil and water erosion.

The soil is "white type" formed on clayey limestones and classified as Lithic xerorthents and xeric xerochrept within an *Entisols* soilscape or *Cambisols* [30] in an area of sub-recent alluvial plains and valleys where steep slopes are dominant and active soil erosion occurs.

The research field has a Mediterranean climate and receives an annual rainfall of 400–650 mm distributed between September and June. The altitude ranges between 590 and 625 m ASL, and the mean annual temperature is 17 °C with an average of 7–27 °C. The soil temperature regime is thermic, and the moisture regime is xeric. The yearly evaporation is approximately 1200–1600 mm [30,31].

At the highest top, Tal-Hadya research site was bordered by stone terraces, and a neighboring road bordered the Yakhour site. Consequently, both sites had no external adverse effects of surface runoff or soil sediments.

2.2.2. Tal-Hadya Research Site

A controlled research field (75 m length × 55 m width) was set up in the summer of 2003 at Tal-Hadya (36°01′10″ N, 36°56′27″ E), 25 km south of Aleppo city, NW Syria. The site is relatively uniform, with an 11–13% slope and a north-facing aspect.

The farm is located in a region of a Mediterranean semi-arid climate associated with cold winters and hot summers. It receives 330–400 mm of annual rainfall, which falls mainly in the cold winter months, with significant variations in time, distribution, and precipitation intensity.

The altitude ranges between 350 and 360 m ASL. The mean annual temperature is 17 °C with an average of 7–27 °C. The soil temperature regime is thermic, and the moisture regime is xeric. Yearly evaporation is approximately 1200–1600 mm [29]. Exposed soil profiles indicate considerable variation in soil depth and truncation within the site, ranging from 23 to 60 cm at the upper reach, with increasing depth toward the toe slope. The soil is classified as very fine (clayey), monthmorillonitic, thermic, Chromic Calcixerert merging into a Calcixerollic xerochrept within an *Inceptisols* soilscape [30,31]. The soil is red (2.5 YR 4/6) when dry and dark red (2.5 YR 3/6) when wet, with fine to medium granular

structure and having about 150 to 200 g kg^{-1} (15–20%) calcium carbonate ($CaCO_3$) in the top 60–80 cm, and calcareous concretions are visible below that depth.

Due to clay texture class, available water was moderate, with field capacity (−33 kPa) at 360 g kg^{-1} (36%) water content and permanent wilting point (−1500 kPa) at 230 g kg^{-1} (23%).

2.3. Tillage Implements and Operations

Mule-drawn tillage: A mule-drawn tillage is based on a locally named and made "Faddan, an ancient Assyrian name for traction animal" of a single-furrow wood–metal cultivator pulled by a mule, with a plowshare connected to a shaft and a beam for maneuvering. The Faddan has a working depth ranging from 12 to 20 cm and a travel speed between 3 and 6 km h^{-1}, depending on the slope's steepness and the working direction. The plow features a 50 cm long, symmetrical wedge-shaped plowshare that cuts a 25 cm wide furrow and tosses soil to both sides [16]. As locally accepted, the mule tillage can operate on all slopes of different steepness.

Tractor-mounted tillage: A tractor Rabewerk tillage (Figure 3b) was completed with a locally made metal-tyned moldboard cultivator used at speeds ranging from 7 to 11 km h^{-1}, depending on the contour, uphill–downhill direction, and slope gradient [13]. The desired working depth ranged from 15 to 25 cm. Furrow plows, or cultivators, are mounted behind the tractor in two sets: three to four or four to five with 35–50 cm spacing and fixed together.



(**a**) (**b**)

Figure 3. Picture (**a**) shows a mule-drawn Faddan tillage system in white calcic soils in Yakhour, and picture (**b**) shows a tractor moldboard tilling downhill in red-brown soils, as used in Tal-Hadya.

At the same time, tractors cannot follow the contour lines on steeper slopes because of the risk of turning over, maneuverability, and the high fuel costs caused by uphill plowing. Farmers usually operate tractor tillage in a downhill direction, opposing soil conservation principles.

Contour tillage was operated bidirectionally forward and backward between no-till NVSs for 5.0 m, with a margin of error of ±0.1 m. The slopes' spacing averaged (90 m length × 70 m width) in Yakhour and (70 and 55 m) in Tal-Hadya. Thus, 10 and 8 parallel no-till NVSs were created in Yakhour and Tal-Hadya, respectively. Accordingly, the uphill–downhill average distances were measured at 90 and 70 m at Yakhour and Tal-Hadya, respectively (Table 1).

Table 1. Tillage types and frequencies, treatments, slope steepness, and aspect trend of Tal-Hadya and Yakhour research sites.

Research Site	Yakhour	Tal-Hadya
Tillage type	Mule-drawn	Tractor-mounted
Aspect	North	North
Slope steepness	31–35%	11–13%
Treatments	90 m length × 70 m width	75 m length × 55 m width
Natural vegetation strips	No-till	
Contour tillage	Bidirectional contour tillage	
Uphill tillage	Up–north	
Downhill tillage	Down–south	
Tillage frequency and time of operation	One tillage pass in late spring	Three tillage passes: Early and late spring and post-harvest.
NVS counts	10 parallel strips	8 parallel strips

2.3.1. Aluminum Cube Alignment and Detection

We used a basic approach of soil aggregate-sized aluminum cubes as tracers inserted in soil to measure their redistribution and displacement after tillage operations for erosion assessment [16,32].

This method is most widely applied in field studies. Each spring and only for a one-time tillage operation at each site, preceding tillage operation, one set of strip plot tracers was buried in each topographic segment—upper, middle, and lower segments—for the contour and uphill–downhill treatments. Each set contained twenty-one tracers (aluminum cubes) numbered 1 to 21 with paint. Tracers' burial was set in the soil at 12 cm depth using 0–100 cm spacing with 5 cm incremental spacing and positioned perpendicular to the tillage direction (Figure 4a).



(**a**) (**b**)

Figure 4. Picture (**a**) shows the burial and placement of aluminum tracers in the soil at 12 cm depth, spaced at 0–100 cm intervals with 5 cm increments, positioned perpendicular to the contour direction. Picture (**b**) demonstrates the process of detecting the aluminum tracer cubes.

Each set was demarcated with referenced wooden sticks at 0 cm and 100 cm points to determine the tracers' exact X, Y, and D displacement after retrieval and to calculate the actual soil flux. Tracers' retrieval (Figure 4b) was carried out after tillage passes using a Fisher M-Scope Model-96 metal detector (Fisher Research Laboratory, El Paso, TX, USA), to detect the translocated and hidden aluminum cubes.

Direct measurements of aluminum cube tracers' displacement were made to quantify the soil fluxes resulting from tillage in the contour and uphill–downhill directions in the Tal-Hadya and Yakhour sites.

2.3.2. Metal Erosion Pins

At both research sites, we installed metal erosion pins to monitor changes in soil level caused by soil tillage erosion over time. Each pin was marked with a metric measuring tape, driven flush with the ground surface (so its top was exactly at the initial soil level), and left in place permanently. The pins were placed every 5 m with high precision (±0.1 m) along the boundaries between the tilled areas and the no-till natural vegetation strips (NVSs), in three distinct upper, middle, and lower segments of each field (Figure 5).

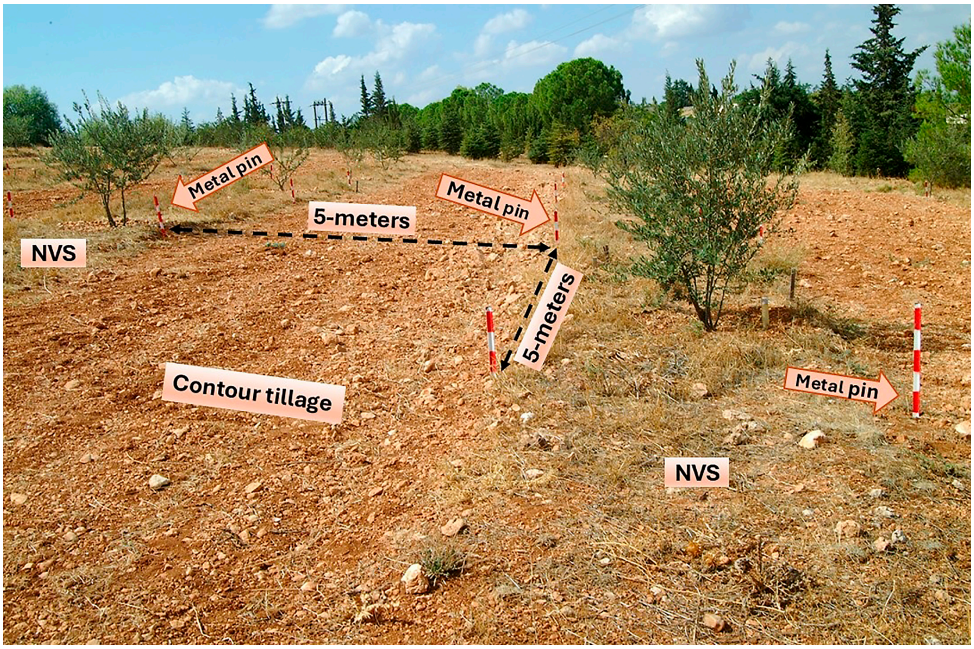


Figure 5. No-till NVSs and contour spacing, along with the alignment of metal erosion pins positioned at the borders of NVSs with the contour tillage tracks in Tal-Hadya.

This layout allowed us to track soil loss and displacement at the edges of the no-till NVSs and assess how contour tillage and NVSs influenced erosion across the hillslope.

To monitor the soil loss or movement over time at the Yakhour and Tal-Hadya sites, measurements were taken annually before spring tillage by assessing changes in soil levels relative to each site's zero point. Soil loss (below zero) occurs at the upper slope boundaries, while soil displacement or accumulation (above zero) occurs at the lower boundaries. Because the pins remained in place throughout the entire study period (2004–2008), they provided a reliable long-term record of soil erosion as well as displacement or buildup. This data was then used to calculate average annual soil loss in meaningful units, tons per hectare per year (t ha^{-1} yr^{-1}), enabling us to compare the impacts of mule-drawn versus tractor-based tillage on soil stability.

2.4. Determination of the Actual Soil Flux Using Aluminium Tracer Cubes

Following the method of [23], which has been widely used in the recent past [33,34], tillage-induced soil flux values (kg m^{-1}) were calculated by the following equation:

$$T_M = T_L \cdot D_T \cdot \rho_B$$

where T_M = soil flux (kg m^{-1}), T_L = average of aluminium tracers' displacement (m), D_T = depth of the till layer (m), and ρ_B = soil bulk density in the till layer (kg m^{-3}) at the time of the measurements.

Tractor-mounted plows were used three times a year in Tal-Hadya, while only one mule-drawn plow, "Faddan," was used in Yakhour in the spring.

2.5. Soil Sampling Procedure and Soil Analysis

Using a manual shovel, the soil sampling procedure was carried out in the contour till, downhill–uphill till, and no-till NVSs treatments through the three segments. Annually in spring, composite soil samples were collected at a depth of 0–15 cm in each segment at three random locations for each treatment. This involved 3 replicates multiplied by 3 segments, and for 3 treatments, resulting in 27 composite samples each spring (3 composite samples multiplied by 3 segments and 3 treatments).

First soil sampling was carried out in Tal-Hadya during the fall of 2003 and in Yakhour in the early spring of 2004 before carrying any plows. Sampling procedure continued every year following the same timescale in both sites.

Sampled soils were air-dried and divided into two batches. The first batch was passed through a 2 mm sieve and ground for chemical analysis at the ICARDA soil lab. The other batch was stored in sealed polyethylene bags in a cool and dry place for physical analysis. Chemical and physical analyses were carried out as follows.

2.5.1. Soil Chemical Analysis

Soil organic carbon was determined by the method of [35] and converted to SOM by multiplying by 1.724. Available phosphorus was determined by the Olsen bicarbonate method [36]. Mineral N, inorganic calcium carbonate ($CaCO_3$) or calcium carbonate equivalent (CCE), and extractable (ammonium acetate extractable) potassium (K) were measured [37]. The pH and electrical conductivity (pH and EC, respectively) were determined from a 1:1 (soil:water) suspension [37]. Cation exchange capacity (CEC) was determined with 1 M ammonium chloride solution in ethanol/water (60:40 v/v) at pH 8.2 [38].

2.5.2. Soil Physical Analysis

Soil texture was determined by the pipette method [39], which was performed in duplicate. Soil bulk density (Mg m^{-3}) was measured for the aggregates' bulk density by paraffin coating and water displacement [40] for soil aggregate fractions 10–20 mm.

Aggregate size distribution was determined by macro-aggregation dry sieving [41]. The mean weight diameter (MWD) index was calculated to characterize the soil mass size distribution [42]. Following macro-aggregation dry sieving, a micro-aggregation of the water-stable aggregates was obtained [13]. Water-stable aggregation was measured by wet sieving 50 g soil to provide the percentage of water-stable aggregates retained on a 0.5 mm sieve [43]. Aggregate size distribution and percentage of water-stable micro-aggregates were determined only for the 5–10 mm aggregate sizes.

Soil structural stability was assessed using macro-aggregate analysis, a key indicator of soil health and resistance to erosion. A detailed analytical simulation procedure was conducted on composite soil samples collected from the no-till NVSs treatment site in Yakhour. Soil samples were oven-dried and dry-sieved using ten sieve sizes (0.05 mm, 0.10 mm, 0.20 mm, 0.50 mm, 1.00 mm, 2.00 mm, 4.00 mm, 5.00 mm, 10.00 mm, and 20.00 mm). The soil mass retained on each sieve was recorded and expressed as a percentage of the total sample.

To illustrate improvements in soil structural stability [44,45], the standard deviation (STDEV) function was computed based on the integrated cumulative fractions of dry soil aggregate size distribution across different sieve sizes. Values were reported in grams and converted into percentages (%). These percentage values were then used to calculate cumulative fractions, which were subsequently integrated with the corresponding sieve sizes to derive the STDEV.

2.6. Statistical Analysis

The results were statistically analyzed by Genstat v-12.0 software (VSN International, UK), using general analysis of variance, where replicates of each treatment were considered a block structure and measured parameters as variates.

3. Results

3.1. Soil Flux

Soil fluxes resulting from tillage were assessed from 2004 to 2008 and averaged in kg/tillage/pass due to differences in tillage intensities and frequencies (one mule pass/year in Yakhour and three tractor passes/year in Tal-Hadya). Actual soil displacement was used to quantify tillage erosion and understand the impacts of the tillage process on soil displacement in two research fields that differ in their microtopography, steepness, soil type and color, depth, and degradability.

Table 2 summarizes the mean soil losses based on the aluminum cubes' displacement as described in the material and method part (Section 2.3.1) in conditions of two different slope steepnesses, 31–35% and 11–13%, in Yakhour and Tal-Hadya, respectively.

Table 2. Four-year averages of soil flux for 2003–2008 expressed in (kg soil/m/tillage pass) assessed by aluminum tracer cubes and soil loss and displacement expressed in (ton $ha^{-1}yr^{-1}$) measured by erosion pins in Tal-Hadya and Yakhour with tractor-mounted and mule-drawn tillage, respectively.

Sites	Tillage Type	Slope (%)	Soil Flux (SF) (kg Soil/m/Tillage Pass)				Soil Loss and Displacement (ton $ha^{-1}yr^{-1}$)	
			Tillage Direction			Net Flux	Loss	Displacement
			Contour (CSF)	Downhill (DSF)	Uphill (USF)	(NSF)	Contour	
Tal-Hadya	Tractor	11–13	44.3	102.4	16.4	86.0	14.92	10.5
Yakhour	Mule	31–35	22.7	52.5	8.4	44.1	11.26	9.47

The means of contour soil flux (CSF) resulting from tractor-mounted and mule-drawn uphill–downhill tillage presented significantly higher values in Tal-Hadya (44.3 kg soil/m/tillage pass) versus Yakhour (22.7 kg soil/m/tillage pass) (Table 2). Downhill soil flux (DSF) exhibited significantly higher values in Tal-Hadya (102.4 kg soil/m/tillage pass) with tractor-mounted tillage versus Yakhour (52.5 kg soil/m/tillage pass) with mule-drawn tillage. The data indicate that the soil fluxes uphill were lower than those downhill at the Tal-Hadya and Yakhour sites.

The uphill soil flux (USF) was two-fold higher (16.4 kg soil/m/tillage pass) with tractor-mounted tillage at the Tal-Hadya site compared to the uphill soil flux with mule-drawn tillage at the Yakhour site (8.4 kg soil/m/tillage pass). The overall means of net soil flux (NSF) resulting from tractor-mounted and mule-drawn uphill–downhill tillage presented significantly higher values in Tal-Hadya (102.4 kg soil/m/tillage pass) versus Yakhour (52.5 kg soil/m/tillage pass); nevertheless, the slope steepness in Yakhour (31–35%) was higher compared to the 11–13% slope in Tal-Hadya. Net soil flux (NSF)

displacements with downhill tillage indicate tillage severity, whether carried out by tractor or mule (Table 2).

The amounts of soil loss and displacement were averaged per ton $ha^{-1}y^{-1}$ based on the contour till track width of 5.0 m with a margin of error of ±0.1 m along ten parallel strips in Yakhour, spread over a 70 m distance, versus eight parallel strips in Tal-Hadya, spread over a 55 m distance. Significant amounts of soil loss were reported, 11.26 and 14.92 ton $ha^{-1}y^{-1}$ for Yakhour and Tal-Hadya, respectively, and displacement was reported as 9.47 and 10.50 ton $ha^{-1}y^{-1}$ in Yakhour and Tal-Hadya, respectively (Tables 1 and 2 and Figure 6).



(**a**) (**b**)

Figure 6. Metal erosion pins are aligned along the border lines between the NVSs and the contour tracks and positioned at the upper border (**a**) and the lower border (**b**) of the contour track, showing eroded and displaced soil, respectively.

3.2. Changes in SOM in the NVSs and Soil Chemical Properties

Table 3 presents the results of the soil chemical analysis from the most recent soil sampling during the spring of 2008 (0–15 cm depth) in Tal-Hadya and Yakhour. Prior to the start of the experiments, the average SOM content was reported to be 2.6% in Tal-Hadya [13] and 2.3% in Yakhour [2]. The statistical analysis of the SOM for the soil samples collected in April 2008 showed a significant (<0.001) increase to 3.0% and 3.1% for the no-till NVSs treatments compared to a decrease to 2.4% and 1.8% for the uphill–downhill treatments in Tal-Hadya and Yakhour, respectively. The contour treatment showed moderate average SOM values, 2.3% and 2.6% in Tal-Hadya and Yakhour, respectively. However, the values of SOM for the contour treatments of the mule-drawn and tractor-mounted tillage in Yakhour and Tal-Hadya remained at 2.3% and 2.6%, respectively, without changes.

The no-till NVSs treatment improved SOM, a key indicator of soil health that enhances other soil physical and chemical properties in the long term.

Analysis of soil pH and EC (1:1) showed no differences between treatments at both research sites, Yakhour and Tal-Hadya. Soil available P and mineral N reflected the fertilization history of the experiment. The soil extractable K values in Tal-Hadya were higher (252–330 ppm) across all treatments compared to those in Yakhour (70–125 ppm), while calcium carbonate content was moderately higher in Tal-Hadya than in Yakhour. These differences are attributed to the soil types described in Section 2.2.

Table 3. Analysis of SOM and other soil chemical properties for Tal-Hadya and Yakhour research sites for soils sampled during the spring of 2008, at depth 0–15 cm, after 4 years of conducting this research.

Sites	Treatments	SOM	pH (1:1)	EC (1:1)	Olsen-p	Extractable K	Min-N	$CaCO_3$
		%		dS/m	ppm	ppm	ppm	%
Yakhour	Overall site in 2004	2.3	N/A	N/A	N/A	N/A	N/A	N/A
	No-till NVSs	3.1	8.0	0.3	28	125	10	66
	Contour till	2.3	8.1	0.2	21	85	9	67
	Uphill–downhill till	1.8	8.1	0.2	15	70	9	69
Tal-Hadya	Overall site in 2004	2.6	N/A	N/A	N/A	N/A	N/A	N/A
	No-till NVSs	3.0	8.1	0.3	5	274	11	43
	Contour till	2.6	8.1	0.3	8	252	21	41
	Uphill–downhill till	2.4	8.2	0.3	8	330	13	35
F pr. for sites		0.062	<0.001	0.002	<0.001	<0.001	<0.001	<0.001
F pr. for treatments		<0.001	0.31	0.007	0.505	0.067	<0.001	0.096
LSD (p = 0.05) for sites		0.26	0.015	0.06	6.8	24.7	0.8	1.7
LSD (p = 0.05) for treatments		0.32	0.018	0.07	8.3	30.2	0.98	2.0
LSD (p = 0.05) for treatment × site		0.48	0.025	0.1	11.7	42.8	1.37	2.0
C.V for Rep. × Segments (%)		14.5	7.7	1.0	67.5	18.6	9.4	2.84

3.3. Changes in Soil Physical Properties and Soil Structural Stability

Analysis of soil texture revealed minor differences in soil clay (37–41%), silt (40–41%), and sand (19–22%) for both experimental sites in Yakhour and Tal-Hadya.

The largest aggregate fractions were retained on the 2.0 mm (19.85%), 4.0 mm (19.73%), and 10.0 mm (16.09%) sieves, revealing a predominance of large macro-aggregates in the soil. These results demonstrate enhanced soil structural stability under conservation management practices such as NVSs.

The index of mean weight diameter (MWD) showed higher values in the no-till NVSs (2.5 and 3.1) in Yakhour in Tal-Hadya, respectively, indicating improved soil structural stability. The calculated MWD values were lower (1.9 and 1.6 compared to 2.3 and 2.2) in Yakhour and Tal-Hadya, respectively (Table 4).

Table 4. Analyses of soil texture, soil aggregate bulk density (BD), percentage of water-stable aggregates (WSA), and mean weight diameter index (MWD) of the soils sampled in April 2008 from Yakhour and Tal-Hadya.

Sites	Treatments	Soil Texture			[1] BD	Water-Stable Aggregates		[2] MWD
		Clay	Silt	Sand		[3] Macro	[4] Micro	
		%			Mg/m^3	%		Index
Yakhour	No-till NVSs	38	41	21	1.26	40.0	36.2	2.5
	Contour till	39	40	21	1.28	25.7	20.6	1.9
	Uphill–downhill till	37	41	22	1.28	24.4	19.1	1.6
Tal-Hadya	No-till NVSs	38	40	22	1.26	58.0	48.6	3.1
	Contour till	38	43	19	1.28	36.9	33.7	2.3
	Uphill–downhill till	41	41	18	1.28	30.3	31.7	2.2
F pr. for sites		0.12	0.34	<0.001	0.0015	0.0015	<0.001	<0.001
F pr. for treatments		0.71	0.22	0.004	0.453	<0.001	<0.001	<0.001
LSD (p = 0.05) for sites		1.3	1.1	0.7	0.006	0.006	4.54	0.12
LSD (p = 0.05) for treatments		1.3	1.4	0.9	0.007	0.007	5.56	0.14
LSD (p = 0.05) for treatment × site		1.6	1.4	0.9	0.097	0.097	7.86	0.21
C.V for Rep. × Segments (%)		2.2	1.9	1.2	0.60	0.60	18.0	7.6

[1] BD: Soil aggregate bulk density by paraffin coating and water displacement ($Mg\ m^{-3}$). [2] Mean weight diameter (an index of dry aggregate distribution after sieving). [3] Percentage (%) of macro-aggregation: dry-sieved aggregates retained on 20.0, 10.0, 5.0, 4.0, 2.0, 1.0, 0.5, 0.2, 0.1, and 0.05 mm sieve sizes, expressed in percentage (%). [4] Percentage (%) of micro-aggregation: water-stable aggregates retained on 0.5 mm sieve size.

Table 5 presents the distribution and analysis of dried soil aggregates retained on a series of sieves ranging from 0.05 mm to 20.0 mm.

Table 5. Integration of cumulative fractions of percentage macro-aggregation of dried sieve aggregates retained on sieves (0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 4.0, 10.0, and 20.0 mm) to compute the standard deviation (STDEV) for averages of NVS treatment in Yakhour.

Macro-Aggregation	Sieve Sizes (mm)										
	0.05	0.10	0.20	0.50	1.00	2.00	4.00	5.00	10.00	20.00	Total (gr)
Aggregates retained on sieves (gr)	6.371	25.95	52.04	91.97	147.1	197.6	196.4	48.45	160.2	69.39	559.51
Aggregates retained on sieves (%)	0.64	2.61	5.23	9.24	14.77	19.85	19.73	4.87	16.09	6.97	100.00
Cumulative fractions	0.64	3.247	8.474	17.71	32.49	52.34	72.07	76.94	93.03	100.0	STDEV
Integrated cumulative fractions	0.006	0.032	0.085	0.177	0.325	0.523	0.721	0.769	0.93	1.0	0.381

Based on the STDEV procedure for the no-till NVSs treatment, a cumulative curve of the aggregates' size distribution was simulated for all three treatments in Yakhour and Tal-Hadya (Figure 7a,b) for the aggregates retained on sieves (%), i.e., 0.0–100, vs. their integrated cumulative fractions (0.0–1.0). Figure 7a,b illustrates the cumulative curves of soil aggregate size distribution from samples collected at a 0–15 cm depth in April 2008 at the Yakhour and Tal-Hadya research sites. These curves compare three tillage treatments: no-till NVSs, contour till, and uphill–downhill till. The computed STDEV values illustrate a comparative cumulative curve of dry aggregate size distribution for the contour till and uphill–downhill till treatments, which resulted in adverse changes in STDEV from the improved cumulative curves in the no-till NVSs treatments following SOM increases.

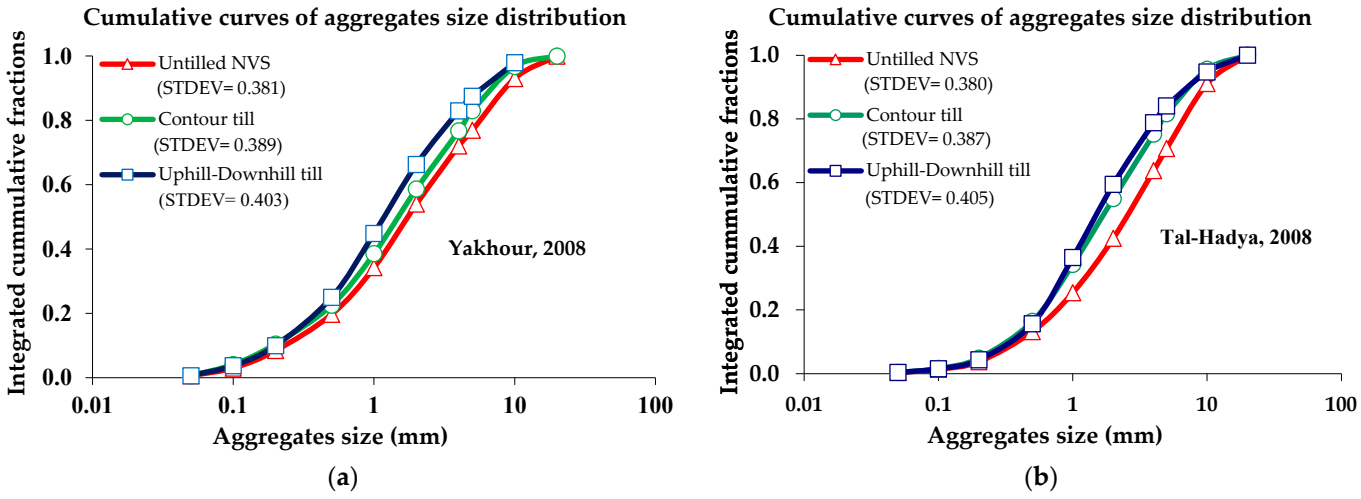


Figure 7. Changes in simulated cumulative curves of aggregate size distribution in the soil sampled at 0–15 cm depth in April 2008 for the different tillage practices at Yakhour (**a**) and Tal-Hadya (**b**) research sites.

Uphill–downhill tillage consistently produced a greater proportion of finer aggregates, indicated by a steeper curve at the lower particle size range. This suggests more extensive soil disaggregation, likely due to repeated mechanical disturbance and erosion processes.

Therefore, the standard deviation (STDEV) values were highest under this treatment (0.403 in Yakhour, 0.405 in Tal-Hadya), reflecting greater variability and instability in aggregate size distribution. The no-till NVSs showed the lowest STDEV values (0.381 in

Yakhour, 0.380 in Tal-Hadya), indicating more uniform and stable aggregate sizes. This no-till NVSs treatment significantly enhanced soil structural integrity, primarily through reduced mechanical dis-turbance and increased soil organic matter accumulation under natural vegetation cover.

However, contour tillage presented intermediate behavior, with STDEV values (0.389 in Yakhour, 0.387 in Tal-Hadya) and soil aggregate distributions that fell between those of the other two treatments. This indicates that contour tillage relatively reduces erosion and soil structural degradation compared with uphill–downhill tillage but still causes some degree of soil disruption.

4. Discussion

4.1. Impact of Tillage Types, Direction, and Steepness on Soil Flux

The NSF results indicated that the steeper slopes managed with mule-drawn tillage in Yakhour exhibited lower soil flux compared to the gentler slopes under tractor-mounted tillage in Tal-Hadya. This can be attributed to key differences in the tillage methods and their subsequent effects on soil erodibility. Mule-drawn implements operate at slower speeds and shallower depths, applying less ground pressure and causing less soil disturbance. This approach generally preserves soil structure and organic matter while creating a rougher, more heterogeneous surface microtopography, characterized by small ridges, clods, and minimal soil displacement. These features help reduce overland flow and trap sediment.

By contrast, tractor-mounted tillage, even on gentler slopes, involves higher speeds, deeper working depths, and much greater wheel loads. These conditions lead to intense soil disturbance, breaking down soil aggregates and producing a smoother, more uniform surface. Such a surface reduces roughness, decreases infiltration capacity, and makes the soil more prone to detachment and transport by surface runoff. Therefore, even on gentler slopes, plots worked with tractors experienced higher soil flux because of the combined effects of mechanical compaction and less structured surface protection.

Our findings from the soil flux assessment are consistent with those of other studies that have assessed the intensity of tractor tillage [6,23,32,46,47], finding that tillage direction significantly affects soil redistribution and contour tillage minimizes erosion while downslope tillage accelerates soil translocation and uneven deposition [48].

The low soil flux uphill was in line with the findings of [34,49], who concluded that the analysis of additional available data on soil translocation by moldboard tillage showed that downslope displacement distances were only significantly related to the slope gradient when tillage was carried out in the downslope direction. When the tillage was carried out in the upslope direction, the effect of slope gradient on upslope displacement distances was not significant.

The data of [2] provided clear evidence that mule-drawn tillage results in shallower and more-irregular plowing furrows, leading to less significant soil displacement compared to tractor-mounted tillage implements, which create consistent furrows of a specific width during tillage passes. Therefore, tractor-mounted tillage makes soil conditions more vulnerable to soil and water erosion. Although our findings demonstrate the positive impact of no-till NVSs and contour till on soil loss and displacement, we plan to introduce various soil conservation practices, such as cover crop management systems within the contour tillage tracks, in the next phase of this research. In our study, the limited spatial soil loss in the contour till treatment is confined within 5 m tracks (Figure 5) and can be recovered by redistributing soil upward using suitable machinery.

4.2. Impact of No-Till NVSs on SOM and Other Soil Chemical and Physical Properties

Although the Mediterranean climate, with its long, hot summers, promotes high rates of SOM mineralization, the continuous deposition of vegetation biomass on the soil surface under no-till NVSs, together with the decomposition of root systems, contributes to SOM accumulation. This effect is largely driven by plant roots, which play a key role in enhancing soil structure at the root–soil interface [50–52].

On the other hand, the microbial decomposition of organic residues releases a range of organic compounds and root exudates that enhance soil aggregation and improve the physicochemical environment for mineralization. This, in turn, increases nutrient availability for olive trees established within no-till NVS rows and facilitates the re-accumulation of soil organic carbon, contributing to the regulation of the dynamic soil carbon balance [53], and it helps to alter the dynamic carbon balance that can otherwise destabilize SOM [54,55] in degraded olive orchards in NW Syria in the future. Soil nutrient levels were compared between treatments (Table 3) to assess soil fertility, although this was not our primary focus.

The response of soil organic matter (SOM) varied among research sites due to differences in soil type and conditions. To better understand these effects, soil structural stability parameters, including macro- and micro-aggregation as well as the mean weight diameter (MWD), were evaluated as key contributors to SOM improvements under no-till NVSs treatments (Table 4). In Tal-Hadya and Yakhour, increases in SOM under no-till NVSs not only enhanced soil structural stability but also influenced bulk density (BD) and aggregate size distribution, as reflected in the cumulative curves (Figure 7).

The soil bulk density (BD) values measured for the 10–20 mm soil aggregate fractions by paraffin coating revealed significant values (0.0015) between the treatments, at 1.26 Mg/m^3 in the no-till NVSs treatments versus higher values of 1.28 Mg/m^3 in the contour till and uphill–downhill till treatments in Yakhour and Tal-Hadya.

Soils with higher organic matter content generally exhibit lower bulk density. However, changes in bulk density occur gradually and typically require long-term observation. Management practices that affect soil cover, organic matter, structure, compaction, and porosity can change bulk density. By contrast, excessive tillage speeds up the loss of organic matter, weakens soil aggregate stability, and makes soil more vulnerable to erosion [56], ultimately decreasing porosity and increasing bulk density.

4.3. Impact of No-Till NVSs on Soil Structural Stability

The percentage of calculated cumulative fractions (%) reflects the progressive summation of aggregate size from the smallest to the largest. These cumulative values provide insight into how the soil's physical structure is distributed across size classes [57].

The dominance of large macro-aggregates (>2 mm) in the NVS treatment emphasizes its positive role in maintaining soil structural integrity. The relatively low STDEV value (0.381) in our study indicates improved soil stability and well-aggregated conditions. These structural improvements with NVSs are likely to be due to reduced mechanical disturbance, increased root activity, and organic matter buildup, all of which help form and stabilize aggregates.

The data in Table 5 and Figure 7 support the conclusion that no-till NVS management fosters more resilient soil physical properties, boosting the soil's ability to resist erosion, retain moisture, and support sustainable land productivity on steep, erosion-prone slopes. The comparison of the soil aggregate size distribution curves for the three tillage methods—no-till NVSs, contour till, and uphill–downhill till—shows clear differences in aggregate stability influenced by tillage practices. The lower tillage intensity under contour till and the preservation of surface vegetation under no-till NVSs significantly enhance soil aggregate stability, which is essential for improving soil structure, reducing erosion, buffering surface

runoff, and increasing water infiltration and soil water retention, ultimately boosting long-term soil productivity.

Therefore, the higher aggregate stability under NVS and, to a lesser degree, contour tillage systems helps facilitate water infiltration, aeration, and resistance to erosion, key aspects of sustainable land management on sloped Mediterranean terrains.

Significant gains in soil stability and easily decomposed organic carbon have been reported under conservation practices, along with improved nutrient release [58–60]. In no-till NVSs treatments, changes in soil physical properties are expected to develop gradually over time. These improvements are mainly driven by the amount of organic biomass added to the soil [61,62], through roots or surface residues, and the subsequent decomposition processes. Plant roots, in particular, are vital for strengthening soil structure at the root–soil interface, aiding aggregate formation and overall soil resilience.

In many parts of the world, the moldboard tractor plow is considered the primary tool contributing to tillage erosion in intensified marginal crop production landscape systems [21]. However, other authors [6,23,25,63,64] concluded that all tillage implements, whether animal-drawn or tractor tillage, contribute to tillage erosion on steep slopes.

4.4. Engagement with PTD Farmers and Communities

Awareness campaigns and seasonal field days provided continuous feedback, which helped in refining technologies for local agro-ecological and socio-economic settings. Importantly, blending indigenous and local knowledge, especially about soil behavior, microclimate patterns, and historical land-use practices, improved the relevance, acceptability, and perceived usefulness of the introduced innovations. This combined approach demonstrates that community ownership in Yakhour is a key element for sustainable land restoration, explicitly connecting soil system health with the delivery of vital ecosystem services. By merging scientific insights with local knowledge and practices, the approach not only reduces serious biophysical threats, such as soil erosion, the loss of soil organic carbon, and declining agricultural productivity, but also strengthens and promotes resilience in soil systems that support both ecological functions and livelihoods in degraded agroecosystems.

5. Conclusions

The no-till natural vegetation strip (NVS) offered a competitive tillage system that encouraged the adoption of sustainable farming models while conserving environmental resources. It resulted in a substantial increase in soil organic matter (SOM) at both the Yakhour and Tel-Hadya research sites compared to contour and traditional uphill–downhill tillage methods. Although SOM buildup under contour tillage was lower than that under no-till NVSs, it was still significantly higher than that under uphill–downhill tillage. This highlights the advantages of minimizing soil disturbance and increasing soil cover. Contour soil flux (CSF) was lower in Yakhour, where mule-drawn contour tillage was used on steep slopes (31–35%), compared to Tel-Hadya, where tractor tillage on gentler slopes (11–13%) led to higher CSF. Over four years, net soil flux (NSF) indicated greater erosion and soil displacement under tractor tillage in Tel-Hadya.

Although steeper slopes are naturally more prone to erosion, our findings suggest that mule-drawn tillage (Yakhour) effectively reduces soil redistribution and loss, even on steep terrain, by limiting both lateral and vertical soil flux. This reduction results from the low-impact nature of animal-powered tillage, which preserves key properties of the soil system: it maintains soil structure and macroporosity, minimizes compaction-related reductions, and sustains a heterogeneous surface microtopography that disrupts soil processes. By contrast, tractor-mounted tillage (Tal-Hadya), even on gentler slopes, compromises soil system integrity through deep, high-energy disturbances and repeated wheel traffic,

causing aggregate breakdown, loss of structural stability, reduced soil moisture retention, and smoother, more vulnerable surfaces. These changes increase surface runoff and soil displacement, leading to higher soil flux despite favorable topography. Overall, the results show that management practices, especially tillage methods, can influence topographical effects and serve as main factors in determining soil system resilience and soil loss in traditional olive orchard landscapes.

In no-till NVS systems, plant roots improved soil stability through physical, chemical, and biological processes, enhancing aggregation, cohesion, and water retention. Olive roots in the rhizosphere play a vital role in stabilizing aggregates, supporting the soil structure and biogeochemical functions essential for productivity and ecosystem health. Compared to tractor tillage, NVSs increased SOM, improved soil physical properties, and decreased runoff and sediment loss, especially on steep slopes where vegetation served as natural barriers. Accumulated soils in contour furrows could be redistributed uphill to aid the recovery of displaced soil.

In Yakhour, where economic marginalization and weak policies hinder the adoption of sustainable land management, the PTD approach built trust and collaboration between ICARDA researchers and farmers, enabling the development of context-specific conservation strategies for restoring degraded olive-based systems in northwest Syria. Our research empowered local extension staff in Afrin, and extensive engagement with agricultural stakeholders through PTD approaches was also established. From 2003 to 2008 and beyond, these traditional tillage systems served as reference models for sustainable land management.

Notably, farmers in villages surrounding Yakhour have successfully implemented large-scale soil and water conservation (SWC) measures, which has resulted in significant improvements in olive productivity. A structured scoping analysis by researchers identified key socio-economic and institutional barriers to SWC adoption, informing a strategic implementation plan that has since gained strong support from national, regional, and international stakeholders, including ICARDA and other international partnership centers, emphasizing its relevance and potential for scaling across similar dryland agroecosystems.

This study addresses a critical gap in Mediterranean soil conservation research: the development of locally adapted and farmer-feasible strategies that reconcile productivity with sustainability in severely degraded olive-based agroecosystems.

By demonstrating the multifunctional benefits of integrated NVS–contour tillage systems in northwest Syria, we offered a scalable model for reversing land degradation and safeguarding long-term viability with the objective of mitigating human-induced land degradation in the hilly olive orchards of northwest Syria.

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Abbreviations

The following abbreviations are used in this manuscript:

NVSs	Natural vegetation strips
Contour till	Contour tillage
Uphill–downhill till	Uphill-downhill tillage
CSF	Contour soil flux
NSF	Net soil flux
SOM	Soil organic matter
MWD	Mean weight diameter
STDEV	Standard deviation of values dispersed from the average of mean
PTD	Participatory technology development

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