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Effects of Biochar and Cattle Manure under Different Tillage Management on Soil Properties and Crop Growth in Croatia

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Abstract: The negative environmental impact of conventional agriculture threatens agroecosystem stability and food security. Therefore, searching for optimal soil management practices is crucial for maintaining and improving soil functions. This work aims to determine the impact of conventional and conservation tillage on Stagnosols in a semi-humid environment in Marija Magdalena (Croatia) during 2021 and 2022. Under each tillage treatment, subplots were biochar, cattle manure, and control (split-plot design). The conservation tillage exhibits lower compaction in addition to conventional tillage. In 2021, at 0–15 cm and 15–30 cm depths, control plots had the highest bulk density (BD), while biochar plots had the lowest. In 2022, biochar and manure treatments under conventional tillage had significantly higher BD than those under conservation tillage. Penetration resistance did not exceed 2 MPa in all treatments. Soil water content was high in conservation treatments at 0–15 cm. Water-stable aggregates were higher in biochar and manure plots under both tillage treatments. Maize yield was higher in conservation treatments in 2021 and in conventional during 2022. Manure and biochar in the conventional system showed a better impact on grain yields than under conservation. Conservation tillage in rain-fed farming maintains crop yields and reduces soil compaction.

Keywords: reduced tillage; soil amendments; soil compaction; grain yields; sustainable agriculture

Citation: Bogunovic, I.; Dugan, I.; Pereira, P.; Filipovic, V.; Filipovic, L.; Krevh, V.; Defterdarovic, J.; Matisic, M.; Kisic, I. Effects of Biochar and Cattle Manure under Different Tillage Management on Soil Properties and Crop Growth in Croatia. *Agriculture* **2023**, *13*, 2128. https://doi.org/10.3390/agriculture13112128

Academic Editors: Riccardo Scotti and Hu Zhou

Received: 15 September 2023
Revised: 23 October 2023
Accepted: 9 November 2023
Published: 11 November 2023

1. Introduction

Soil is a limited natural resource essential for human life. Soils support numerous ecosystem services. Soils provide food, wood, and fiber. They support the purification of water and the delivery of other diverse ecosystem services like transforming nutrients, substances, and water, the provision of a physical and cultural basis for humans and their activities, and the function of geological and archaeological archives [1,2]. In the context of food security, global threats like climate changes and wars, and the importance of soils in sustaining human life, soil provisioning services became the main focus in the scientific literature [3–6].

In acknowledgment of agricultural systems' importance, the food provided by soils still reaches more than 95% globally [7], providing about 90% of food calories and 80% of proteins and fats [8]. The sustainability of agricultural systems nowadays presents a significant issue of concern. Long-term conventional soil management in annual and perennial croplands significantly exacerbated land degradation processes [9,10]. According to Löbmann et al. [11], at least one-third of the global land is considered moderately to highly degraded, while in the European Union (EU), 60–70% of soils are considered degraded [12].

The leading causes of soil degradation in croplands were identified: frequent invertive tillage, wheel traffic, overuse of pesticides and mineral fertilizers, lack of organic amendments, and proper crop rotations [13]. Conventional agricultural practices decrease aggregate stability, biological activity, and soil fertility [14]. Frequent machinery traffic during tillage, sowing, and plant protection increases soil compaction and overland flow [15], often increasing diffuse pollution [16,17]. Conventional tillage negatively affects soil structure [18] and decreases hydraulic conductivity [19], which inhibits root development and reduces grain yields [20].

Distorted structure and elevated soil compaction in conventionally managed croplands are responsible for disturbed aeration and increased CO_2 emissions [21], increasing the negative impact on the climate crisis [22,23]. On the other hand, conservation management appears as an interesting alternative to conventionally managed soils. Conservation agriculture is a system of agronomic practices that include reduced tillage or no tillage, permanent organic soil cover by retaining crop residues, and crop rotations, including cover crops [24]. Conservation agriculture management is proven to reduce compaction [15], mitigate overland flow and sediment losses [17], reduce fuel and labor costs [25], and increase carbon sequestration [24].

Conservation agriculture regularly uses organic amendments to reduce soil degradation and improve soil properties [24]. Farmyard manure and biochar in the scientific literature are associated with positively impacting soil physical and chemical properties, and they can help in reducing nitrogen fertilizer losses [26,27]. Their impact on soil is mainly related to enhanced soil structural stability, higher porosity, reduced compaction, erosion, and overland flow, and elevated carbon. In contrast, benefits like higher nutrient availability, reduced toxic chemical load, facilitated biodiversity, reduced emission of greenhouse gases, and better water storage capabilities are also documented [28,29]. Root and microbial activities are also positively impacted [30]. Biochar use in some soils can be used as a crop residue strategy in a conservation agriculture system [31]. Choice of soil management can affect the loss of soil organic carbon content and the proportion of soil degradation and determine the soil production level and duration of its exploitation. The influence of soil management on soil physical properties and yields is well documented. Still, the results are frequently inconsistent, mainly because soil responses to agronomic practices are also influenced by climate, soil texture, and soil organic matter (SOM) [31]. Due to the primary use of universal solutions to site-specific conditions, the farmers often failed to obtain stable yields. Then, they reversed to transition into conservation agricultural practices. The solutions of conservation agriculture practices should be tested for specific pedological, geomorphological, and environmental conditions. Otherwise, the results will not support the easy transition of farmers toward sustainable practices. Hence, adopting site-specific soil conservation practices in croplands is extremely important to reduce the negative impact of conventional agriculture. The effect of the management of tillage and organic amendment (biochar, manure) on maize grain production in loam Stagnosols under semi-humid conditions needs to be better documented. Moreover, biochar trials are mainly set up in glasshouses, accelerating the need for more experiments under field conditions [31]. We thus hypothesized that (i) the conservation treatments enable the preservation of soil physical quality, preventing compaction; and (ii) adding organic amendments will provide a better soil structure and higher crop yields. This work aims to study (i) the impacts of tillage and amendment treatment on compaction, structure, and soil water content and (ii) to identify the most appropriate soil management for maize grain yields.

2. Materials and Methods

2.1. Study Site

The study area is located in northwestern Croatia (45°55′ N; 15°44′ E; elevation—211 m above sea level) in the village of Marija Magdalena (Figure 1). It is predominantly a hilly area, and land besides natural forests is covered mainly by croplands and orchards. The slope inclination in the study area is 11°. The climate of the study area is temperate continental. The mean annual temperature is 11.2 °C, and the total average precipitation is 970 mm. The studied years (2021 and 2022) are similar to the average 1995–2020 (Figure 2). The study area's soil is classified as Stagnosols [32] loam in topsoil and clay loam in subsoil (Figure 1). The general properties are shown in Table 1.

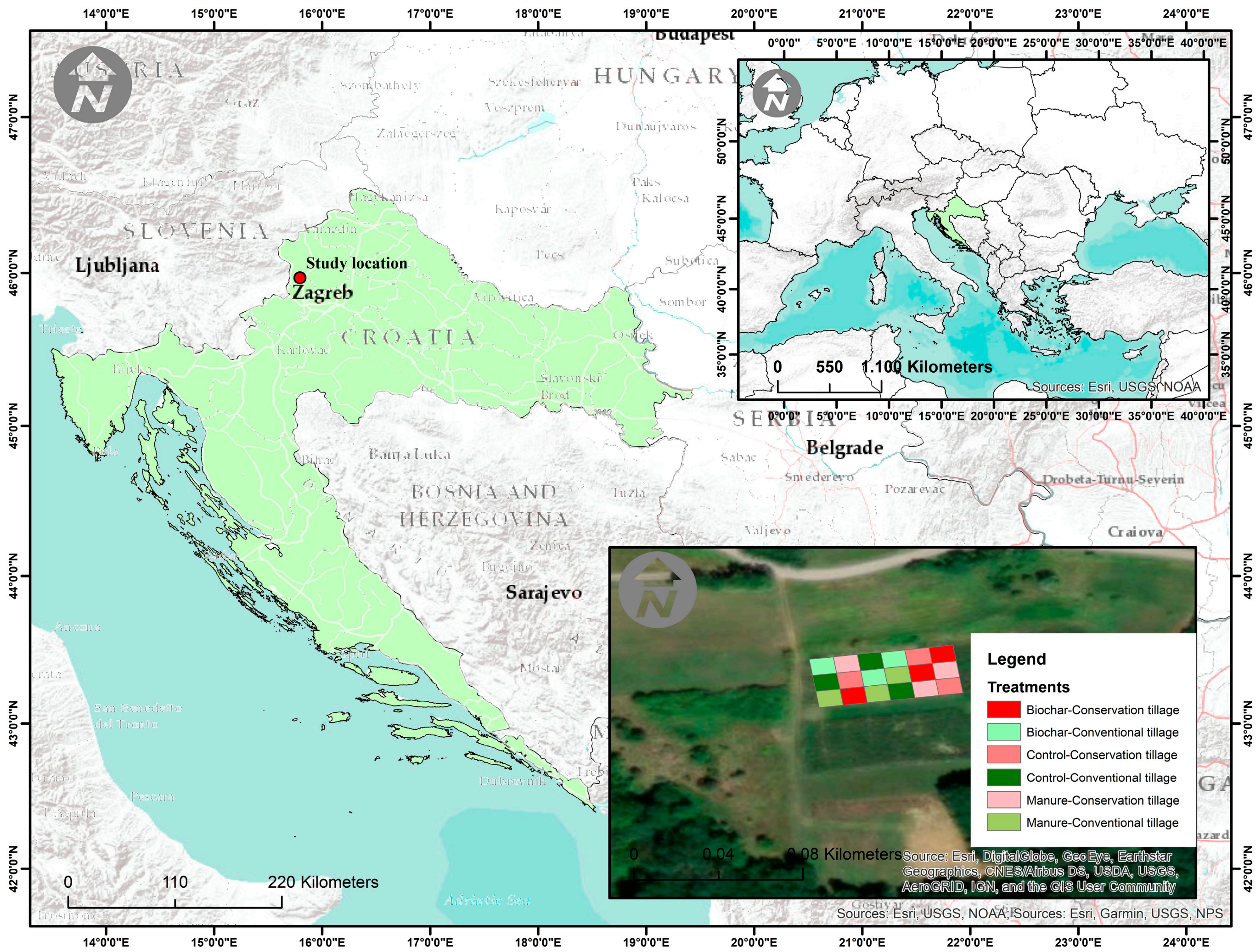

Figure 1. Location and design of the experiment in Croatian and Central European relations.

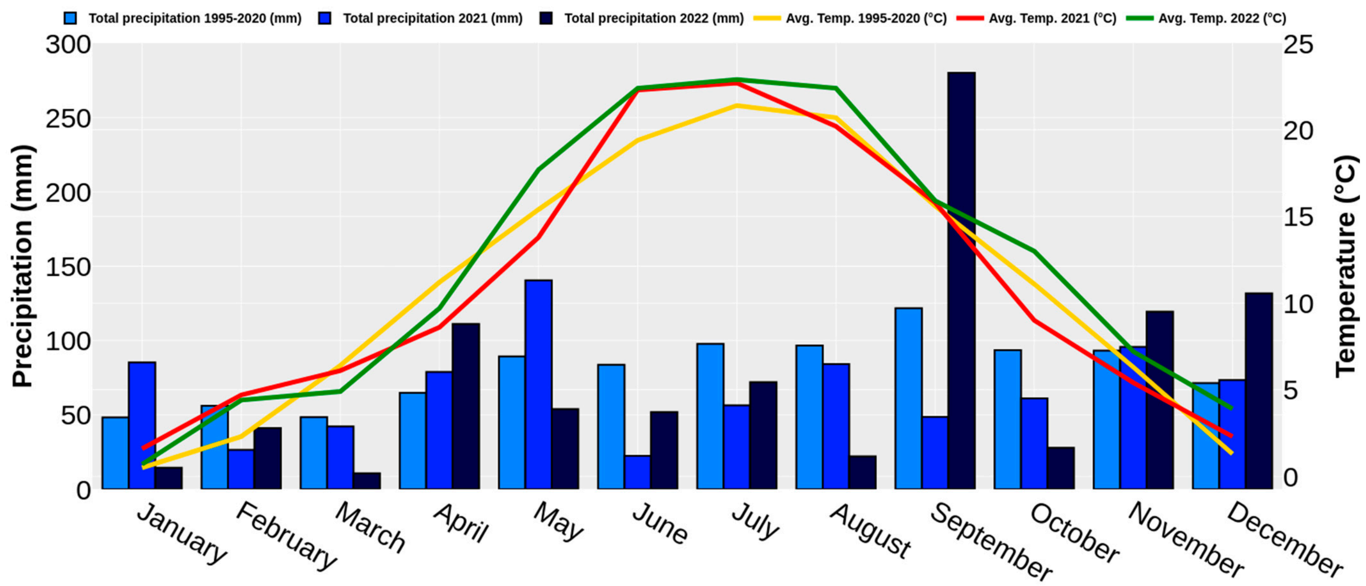

Figure 2. Monthly precipitation and temperature throughout the experimental period along the long-term average.

Table 1. Soil properties at 0–35 and 35–70 cm depths.

Soil properties	0–35 cm	35–70 cm
pH in H_2O	7.29	5.10
P_2O_5 (mg kg^{-1})	163	42
K_2O (mg kg^{-1})	282	79
Organic matter (%)	3.37	1.9
Bulk density (g cm^{-3})	1.26	1.34
Water holding capacity (%)	44.04	30.68
Clay (%)	23.2	39.9
Silt (%)	30.4	21.0
Sand (%)	46.4	39.1
Texture	Loam	Clay Loam

2.2. Experimental Design and Management Practices

The experimental plots were established in the autumn of 2020 and consisted of a split-plot design with tillage as the primary treatment and amendment application as sub-treatment (Figure 1). Two tillage treatments were considered (8 m wide and 18 m long): conventional and conservation tillage (Figure 1). Conventional tillage involves moldboard plowing to a depth of 30 cm and preparation of the seedbed with a roto-harrowing to an 8 cm depth before seeding. Conservation tillage treatments consist of loosening (non-invertive) to a depth of 30 cm and harrowing to a depth of 8 cm. Both treatments incorporated plant residues into the soil. The crops grown on each experimental plot were maize (*Zea mays* L.) during both seasons (2021–2022), as well as 2020 under non-irrigated cultivation.

Primary tillage (plowing and loosening) for maize was implemented during November in the previous autumn, and supplementary tillage followed in April before planting. Between-row cultivation measure was not performed during the research period. In each tillage treatment, three sub-treatments (8 m wide and 6 m long) (Figure 1) were established: without any addition—control, biochar, derived from wood, with a dose of 40 t ha^{-1}, and the addition of cattle manure (40 t ha^{-1}). Biochar and manure were added only during primary tillage performed in November 2020. Their basic properties are presented in Table 2.

Table 2. Basic properties of used manure and biochar.

Property	Cattle Manure	Biochar
H_2O	79.67	66.24
Dry matter (%)	20.33	33.76
pH	8.85	8.33
Organic matter (%)	81.93	91.64
N (%)	0.85	0.33
P_2O_5 (%)	0.232	0.15
P (%)	0.101	
K_2O (%)	0.665	0.46
K (%)	0.552	
Ca (%)		1.37
Mg (%)		0.09
Fe (mg kg^{-1})		223
Mn (mg kg^{-1})		360

2.3. Penetration Resistance and Yield Measurements, Soil Sampling, and Laboratory Analysis

We determined soil sampling in all plots during May 2021 and 2022. Each plot was sampled with six cores. In total, 18 random points were selected for sampling at each treatment. Soil was sampled at 0–15 cm and 15–30 cm depths using 100 cm^3 cylinders. Overall, a total of 108 soil samples were collected per sampling date (2 tillage × 3 amendment × 3 replicates × 2 depths × 3 repetitions). The undisturbed soil samples were transported to the laboratory and dried in the oven at 105 °C for 48 h to measure bulk density (BD) and determine soil water content (SWC). Penetration resistance (PR) measurements were carried out simultaneously in the vicinity of the sampling point using a cone penetrometer (Penetrologger, Eijkelkamp, Giesbeek, The Netherlands), which measures PR at each cm. The PR data were grouped in soil layers 0–15 and 15–30 cm, respectively. In total, 15 sampling points per treatment (90 per sampling date) were measured at 0–15 cm and 15–30 cm depths.

Additional undisturbed soil samples (0–15 cm) were collected and stored in rectangular plastic boxes to determine soil structural properties. Undisturbed soil samples were prepared by hand [33] and, after air-drying for one week at room temperature (25 °C), were dry-sieved in a sieve shaker for 30 s [34] to obtain particular aggregate size fractions (<0.25, 0.25–0.5, 0.5–1.0, 1.0–2.0, 2.0–4.0, 0.4–0.5, and 0.5–0.8 mm) and calculate mean weight diameter (MWD) using the following formula for calculation after weighting each aggregate size:

$$\mathrm{MWD} = \sum_{i=1}^{n} xi \times wi, \tag{1}$$

where xi is the mean diameter of any particular size range of aggregates separated by sieving, and wi is the weight of aggregates in that size range as a fraction of the total dry weight of soil used. Eijkelkamp's wet sieving method derived from Kemper and Rosenau [35] was used to determine water-stable aggregates (WSAs) with Eijkelkamp's wet sieving apparatus on all previously dry-sieved samples in the particle size range 1.0–2.0 mm. The percentage of WSAs was received with the equation:

$$\mathrm{WSA} = \frac{Wds}{Wds + Wdw} \times 100, \tag{2}$$

where WSAs is the percentage of stable water aggregates, Wds is the weight of aggregates dispersed in dispersing solution (g), and Wdw is the weight of aggregates dispersed in distilled water (g).

Samples and penetration measurements were collected/measured from non-traffic areas on each plot. Each year during the harvest, six passes of the harvester per treatment were performed to determine the maize grain yields. Afterward, the grain was cleaned and weighed, and the obtained values were corrected to a 14% grain moisture content.

2.4. Statistical Analysis

Before statistical analysis, data were checked for normality with the Kolmogorov—Smirnoff test. Normal distribution of the data was considered at a $p > 0.05$. Bulk density, WSA, and PR followed the Gaussian distribution, while SWC, MWD, and crop yield data were box-cox- and logarithmic-transformed to meet normality requirements, respectively. A two-way ANOVA design was applied. If significant differences were identified at a $p < 0.05$, Duncan's post hoc test was applied. Statistical analyses were computed with SAS 9.3 software package (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Soil Water Content, Bulk Density, and Penetration Resistance

Over two years of management practices consisting of tillage and amendment management, our experiment showed significant interactions on several soil physical properties in each soil depth layer (Table 3). During 2021, conservation tillage improves SWC and soil compaction properties at the topsoil layer. At 0–15 cm depth, significantly higher PR was measured at control than at manure plots under conservation tillage. Control plots at conservation tillage had significantly higher PR than control under conventional tillage. At 15–30 cm depth, biochar and control have significantly higher PR than at manure plots under conservation tillage. Under a conventional tillage system, differences are insignificant, with the PR highest at the biochar (1.23 MPa) and the lowest at the manure (1.04 MPa) plots.

Table 3. Results of two-way ANOVA considering penetration resistance (PR), soil water content (SWC), and bulk density (BD). Different letters after mean values in the columns represent significant differences at $p < 0.05$.

Depth	Tillage	Amendment	PR (MPa)		SWC (% vol)		BD (g cm^{-3})	
2021				$\bar{x}$		$\bar{x}$		$\bar{x}$
0–15 cm	Conventional	Biochar	0.71 abc		40.2 a		1.32 ab	
		Control	0.86 bc	0.77 c	40.3 a	40.4 ab	1.37 a	1.35 a
		Manure	0.76 bc		40.8 a		1.35 ab	
	Conservation	Biochar	0.92 ab		42.8 a		1.29 b	
		Control	1.07 a	0.89 c	42.1 a	42.0 a	1.34 ab	1.31 b
		Manure	0.66 c		41.1 a		1.30 b	
F			8.700		1.12		4.76	
p			0.0003		0.331		0.012	
15–30 cm	Conventional	Biochar	1.23 b		37.8 ab		1.37 ab	
		Control	1.15 b	1.15 b	36.7 b	38.5 bc	1.40 a	1.38 a
		Manure	1.04 b		41.0 ab		1.37 ab	
	Conservation	Biochar	1.58 a		30.9 c		1.28 c	
		Control	1.50 a	1.40 a	39.8 ab	37.5 c	1.32 c	1.29 b
		Manure	1.11 b		41.6 a		1.27 bc	
F			6.800	1.404	2.843	1.618	0.06	3.56
p			0.010	0.028	0.035	0.021	0.033	0.031
2022								
0–15 cm	Conventional	Biochar	0.76 a		36.5 a		1.30 a	
		Control	0.72 a	0.74 c	35.1 a	35.74 a	1.27 ab	1.29 c
		Manure	0.74 a		35.6 a		1.31 a	
	Conservation	Biochar	0.92 a		36.5 a		1.20 b	
		Control	0.85 a	0.87 c	33.8 a	35.17 a	1.22 b	1.21 d
		Manure	0.86 a		35.2 a		1.22 b	
F			0.769		0.062		0.351	
p			0.383		0.940		0.041	

Table 3. *Cont.*

Depth	Tillage	Amendment	PR (MPa)		SWC (% vol)		BD (g cm^{-3})	
15–30 cm	Conventional	Biochar	1.02 c	1.11 b	35.6 ab	34.36 a	1.41 ab	1.42 a
		Control	1.16 abc		34.3 abc		1.44 a	
		Manure	1.14 bc		33.2 bc		1.42 a	
	Conservation	Biochar	1.53 a	1.43 a	38.7 a	34.75 a	1.37 ab	1.37 b
		Control	1.50 ab		29.9 c		1.39 ab	
		Manure	1.25 abc		35.7 ab		1.34 b	
F			13.310	2.589	4.104	0.184	0.390	0.58
p			0.0004	0.011	0.021	0.668	0.028	0.037

In 2021, at 0–15 cm depth, conservation tillage seems to conserve more water in the soil, although the differences are insignificant. At 15–30 cm depth under conservation tillage, manure plots recorded significantly higher SWC than biochar plots (Table 3). Bulk density differs between treatments in both depths. Generally, the conservation tillage exhibits lower compaction in addition to conventional tillage. More specifically, control plots have the highest BD at 0–15 cm and 15–30 cm depths, while biochar plots have the lowest BD.

During 2022, the tillage and amendment treatments significantly impacted BD at 0–15 cm depth. Biochar and manure treatments under conventional tillage have significantly higher BD than those under conservation tillage. At 15–30 cm depths, BD at manure plots is significantly higher at conventional tillage than at conservation. Regarding the PR and SWC at 15–30 cm depth, significant differences in SWC occur under conservation tillage where control plots recorded significantly lower SWC than biochar and manure plots. Differences among amendments in PR did not occur under both tillage managements. Biochar plots under conventional tillage recorded significantly lower PR than those under conservation tillage.

3.2. Soil Structural Properties

Soil structural properties during 2021 and 2022 are presented in Figure 3. In 2021, only non-significant differences between treatments in the cases of MWD and WSAs occur. Biochar and manure plots recorded higher MWD and WSAs than control plots on both tillage treatments (Figure 3a,b). Conservation tillage plots recorded slightly higher WSAs than conventional plots (Figure 3b). During 2022, on both tillage treatments, the amendment did not significantly modify the MWD (Figure 3c). Conventional tillage has a slightly higher MWD than conservation tillage plots. Biochar and manure plots at conventional tillage management recorded significantly higher WSAs than control plots (Figure 3d). In the conservation tillage system, manure treatment recorded significantly higher WSAs than other treatments in the conservation tillage system. Generally, the stability of the soil in 2022 is on a higher level compared with 2021.

3.3. Maize Grain Yields

The yields are presented in t ha^{-1} at 14% moisture content. In 2021, the highest maize yield was detected in conventional tilled manure plots (8.86 t ha^{-1}), followed by conservation control plots (8.47 t ha^{-1}) (Figure 4). The lowest was noted at conventionally tilled biochar plots (5.98 t ha^{-1}). Comparing the tillage effect, the maize grain yields did not significantly differ. Conventional tillage recorded 7.04 t ha^{-1} and 7.63 t ha^{-1} at conservation tillage. In 2022, conservation-tilled control and conventional-tilled biochar reached the highest yield (10.50 t ha^{-1}; 10.08 t ha^{-1}), followed by conventional-tilled control (9.54 t ha^{-1}) and manure plots (9.24 t ha^{-1}). The lowest yields were noted at conservation manure plots (8.29 t ha^{-1}). The tillage effect was not significant. Conservation tillage plots (9.20 t ha^{-1}) recorded lower yields than conventional (9.62 t ha^{-1}).

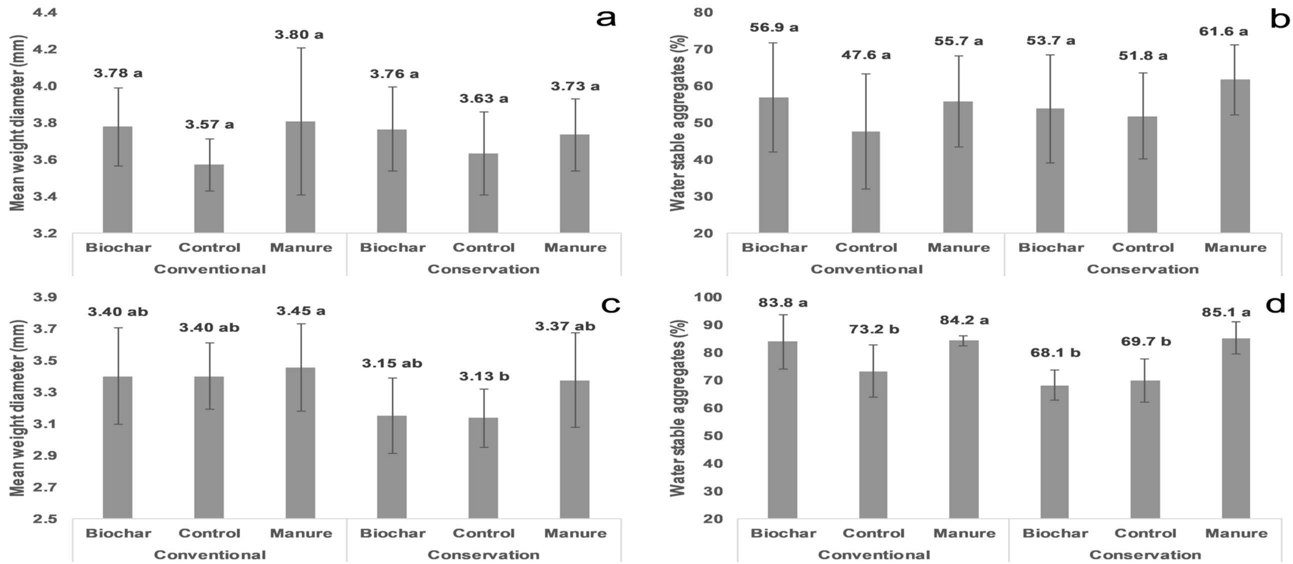

Figure 3. Effect of tillage and amendments treatments on (**a**) mean weight diameter in 2021, (**b**) water-stable aggregates in 2021, (**c**) mean weight diameter in 2022, and (**d**) water-stable aggregates in 2022. Different letters represent significant differences at $p < 0.05$. Hanging bars represent standard deviation.

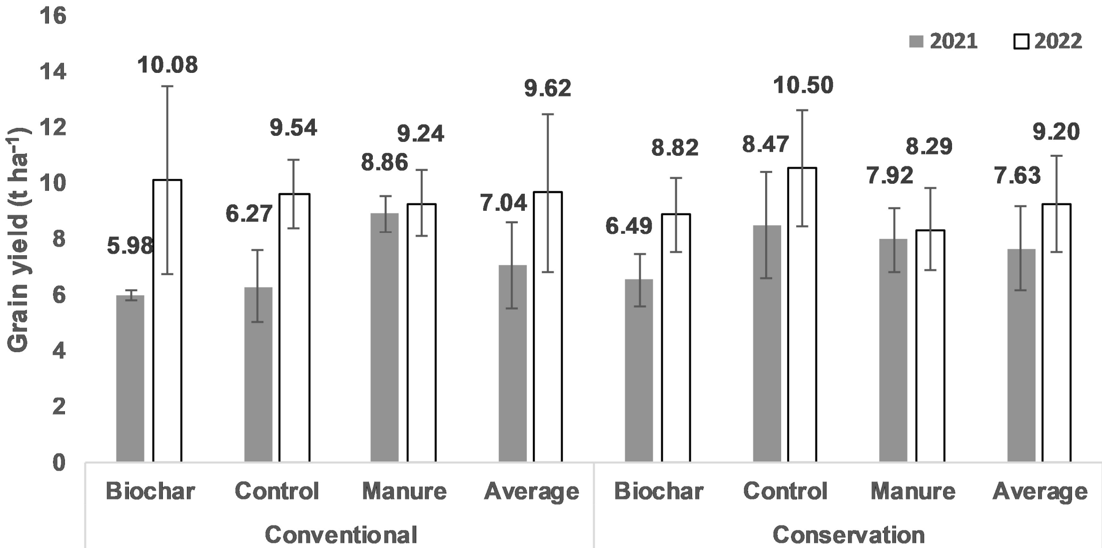

Figure 4. Maize grain yield on different treatments in the 2021 and 2022 agricultural year. Hanging bars represent standard deviation.

4. Discussion

4.1. Impact on Soil Properties

Conventional agriculture in continental European conditions, specifically the Pannonian region, produces food (second-most significant region regarding the share of agricultural land use in Europe but first in productivity) for international markets in croplands, for the most part, covered by bare soils due to frequent use of conventional practices, i.e., conventional tillage and herbicides [10,36,37]. Conservation agricultural practices are rarely applied and cover small areas. Proper soil management practices are critical aspects of the sustainability of agroecosystems, and there is a need to research which conservation management strategies are sustainable. The frequency and severity of climate and weather extremes are increasing, making the last two decades to have far-reaching effects inside and outside of the European Union. Further, economic losses from more frequent climate-related extreme events are increasing, averaging over EUR 12 billion annually [38]. In order to raise the climate challenge, climate neutrality by 2050, and an emissions reduction target of at least 55% by 2030, there are mechanisms to combat what the European Council sees as “an existential threat”. The present research is focused on adapting regional agriculture solutions in a “no regret” manner, as the Global Commission on Adaptation sees them—solutions worth pursuing regardless of the ultimate climate path [38]. Soil degradation is one of the consequences of conventionally managed soils, and soil carbon loss, soil compaction, and erosion contribute to soil degradation [39] but also result in variable and decreased yields, negatively impacting farmers’ incomes [40–42]. At the same time, another type of damage (floods, downstream sedimentation of lakes and rivers) significantly damages infrastructure, the environment, and society [43].

This study demonstrates that conservation tillage practices (soil layers were kept at the same level throughout the year) applied in continental Croatia on rain-fed croplands resulted in lower soil bulk density, while the maize grain yields were not decreased. The measurements during 2021 and 2022 confirmed that conventional tillage on the experiment increased compaction levels (measured by BD) by 3% and 7% on 0–15 cm and 15–30 cm depths, respectively, making these land management practices less sustainable. Soil tillage is seen as a key factor for growing conditions and crop performance, and it is performed mainly to optimize soil productivity by modifying its properties [44]. Tillage has been a major cause of soil degradation since the first agricultural revolution [45]. Several researchers confirm the fact that conventional tillage with frequent invertive tillage operations leads to elevated soil compaction levels [9,15,36,37,46]. Such negative soil status reduces the long-term productivity of soils since it negatively influences the various physiological processes in soil and modifies soil properties such as organic matter or microbial properties [47]. Conventional tillage often decreases the bulk density of soil in the early stages of plant growth [44]. However, until the end of the vegetation season, the compaction level in conventional tillage systems is several times higher due to settling, unstable soil structure, and additional traffic events [48,49]. Our results were consistent with previous studies that reported higher compaction under conventionally plowed than under conservation loosening tillage [21,37,50]. However, the significant justification between treatments is often missing [51] due to the low sensitivity of BD properties to tillage treatments. Penetration resistance is generally low during both years of research and does not exceed values higher than 1.6 MPa on both tillage treatments. The low PR level is primarily due to the high SWC in the soil during both years of research since their relation is usually highly correlated. Such PR values do not inhibit normal growth when using the accepted limit of 2 MPa for normal root development [52]. Lower PR at topsoil and higher at subsoil is similar to other studies [37,53] and is very likely a consequence of the tillage depth that can affect soil structure, pore system, and water retention. Finally, tillage management’s impact on SWC was insignificant in the present study. High SWC can explain this during the hydrologically good years 2021 and 2022. It is already noted that conservation tillage management reveals a higher beneficial effect on water conservation in arid environments on textured lighter soils than on heavy soils in humid environments [54].

In the Pannonian Croatia research area, biochar and manure caused several advantages in both tillage management systems. Farmyard manure, over millennia, and biochar, over the last several decades, have been used as examples of good agricultural practices in several agricultural production types like carbon farming, regenerative agriculture, or organic farming. Present research here confirms the same. The plots with the addition of biochar or manure recorded a more favorable structure and lower compaction. A similar idea is noted in several other studies in continental [55] or Mediterranean [56] environments on silty clay [21], clay [56], sandy loam [55], and sandy [57] soils. When used regularly, organic sources from biochar and manure elevate soil carbon concentrations, making several beneficial impacts on soil like higher aggregate stability [56,58], which increases soil resistance to settling and traffic. Secondly, manure and biochar increase water retention, infiltration, and aggregate stability [59], although several improved soil properties in the present study record insignificant positive changes in addition to control plots. This situation may be due to the duration of the experiment. Some authors indicate that manure effects are often small or insignificant in short-term studies (less than four years) under field conditions [60–62]. This may explain some of our non-significant relations in soil physical properties between manure and biochar in addition to control plots. When looking at the whole, present research shows that biochar has similar benefits to manure for enhancing soil physical properties and can complement other organic amendments for improving soil structure and reducing soil compaction. These findings are important not only for provisioning services but also for land degradation mitigation. At the research site in Pannonian Croatia, conventional tillage was the only management strategy used by farmers, while mineral fertilizers dominated in addition to organic ones. Such management occurred from the 1960s. Such improper management can increase total erosion and facilitate sediment transport downstream; this has already been proven in several erosion and rainfall simulation studies on the same soil type and environment as in the present research [15,63–65]. As demonstrated in the current research, it is necessary to revise the study's focus. This work did not follow potential erodibility or soil erosion. Still, the positive impact of conservation tillage on soil structural properties and soil compaction level can support the conclusion that sustainable management practices that can halt and reverse land degradation in present pedological and environmental conditions are using organic amendments and non-invertive tillage.

4.2. Impact on Maize Grain Yields

Grain yield was generally high compared to the world average of 5.8 t ha^{-1} in 2021 [66]. As reported previously, conventional farming produces higher yields than organic farming [67]. In the present research, tillage and amendments had implications on maize grain yield during both years. No significant differences were observed during both years. During 2021, conservation tillage plots (7.63 t ha^{-1}) have higher yields in addition to conventional (7.04 t ha^{-1}), and vice versa in 2022 (9.20 t ha^{-1} and 9.62 t ha^{-1}). Previous works reported that maize crop yields increase under conservation loosening tillage compared to conventionally plowed tillage [68] and vice versa [54]. The results suggest that crop yields were more affected by climate factors than tillage management. The crop yield depends on the interaction between rotation, management practices, soil properties, genotype, environment, and their complex interactions [54,69]. Climate is likely responsible for differences in maize grain yields. In dry environments, crop yields are usually higher under conservation tillage management because of the high water retention compared to conventional tillage management. In contrast, in semi-humid conditions, conventional tillage treatments can produce higher crop yields [70]. Despite extensive research, the impact of tillage management on maize crop yields remains unclear to date.

A similar scenario occurs when studying the amendment's impact on maize grain yields. In conventional tillage plots, the manure plots have the highest yields in 2021, and the biochar in 2022. In conservation plots, the control treatment has the highest yields during both years. We hypothesize that this could be attributed to the initial high nutrient content in the investigated field and the high organic matter content (Table 1). Together with sufficient rainfall during the vegetation season, it is very likely that a treatment effect is overlapped. An adequate supply of nutrients for maize plants in the study soils is achieved, considering the mean plant P and K uptakes of 24 kg P ha^{-1} and 120 kg K ha^{-1} [71]. However, this situation needs to be investigated further.

5. Conclusions

The Stagnosols in rain-fed croplands in Pannonian Croatia are less sustainable when conventionally tilled. The absence of organic amendments like biochar and manure aggravates the situation, increasing the compaction rates and decreasing the aggregate size and stability. Vertical non-inversion tillage in rain-fed farming maintains crop yields and reduces soil compaction. However, biochar and farmyard manure are recommended in studied croplands where the soil is conventionally tilled since it improves soil properties regardless of the tillage management. Those findings show that the tillage management types studied here can be classified as conservation > conventional and manure > biochar > control among amendment treatments from a soil conservation and land degradation mitigation perspective. Implementing conservation tillage could also achieve efficient management for stable yields since it significantly does not differ from conventional management. In conventional tilled soils, amendment shows an increase in yields, while for conservation tilled soils, more research is desirable. It can be concluded that non-invertive conservation tillage and organic fertilization contribute to better land use management in annual croplands in Pannonian Croatia.

Author Contributions: Conceptualization, I.B. and P.P.; methodology, I.B., I.D. and P.P.; software, M.M., I.D. and I.B.; validation, M.M., I.D., P.P., V.F., L.F., V.K., J.D., I.K. and I.B.; formal analysis, I.B., M.M., I.K. and I.D.; investigation, I.B. and I.D.; resources, I.B.; data curation, I.B.; writing—original draft preparation, I.B.; writing—review and editing, M.M., I.D., P.P., V.F., L.F., V.K., J.D., I.K. and I.B.; visualization, I.B. and I.D.; supervision, I.B. and P.P.; project administration, I.B.; funding acquisition, I.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Partnership for Research and Innovation in the Mediterranean Area ('the PRIMA Foundation') through the "Soil Health and Agriculture Resilience through an Integrated Geographical information systems of Mediterranean Drylands" project (grant agreement number 2211) (SHARInG-MeD).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author.

Acknowledgments: The authors are grateful for the support of Family Farm Ivan Dugan.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the result.

References

1. Paul, C.; Kuhn, K.; Steinhoff-Knopp, B.; Weißhuhn, P.; Helming, K. Towards a standardization of soil-related ecosystem service assessments. *Eur. J. Soil Sci.* **2021**, *72*, 1543–1558. [CrossRef]
2. Rodrigues, A.F.; Latawiec, A.E.; Reid, B.J.; Solórzano, A.; Schuler, A.E.; Lacerda, C.; Fidalgo, E.C.C.; Scarano, F.R.; Tubenchlak, F.; Pena, I.; et al. Systematic review of soil ecosystem services in tropical regions. *R. Soc. Open Sci.* **2021**, *8*, 201584. [CrossRef] [PubMed]
3. Pereira, P.; Bašić, F.; Bogunovic, I.; Barcelo, D. Russian-Ukrainian war impacts the total environment. *Sci. Total Environ.* **2022**, *837*, 155865. [CrossRef] [PubMed]
4. Pereira, P.; Zhao, W.; Symochko, L.; Inacio, M.; Bogunovic, I.; Barcelo, D. The Russian-Ukrainian armed conflict impact will push back the sustainable development goals. *Geogr. Sustain.* **2022**, *3*, 277–287. [CrossRef]
5. Rosenzweig, C.; Mbow, C.; Barioni, L.G.; Benton, T.G.; Herrero, M.; Krishnapillai, M.; Liwenga, E.T.; Pradhan, P.; Rivera-Ferre, M.G.; Sapkota, T.; et al. Climate change responses benefit from a global food system approach. *Nat. Food* **2020**, *1*, 94–97. [CrossRef]
6. Malhi, G.S.; Kaur, M.; Kaushik, P. Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review. *Sustainability* **2021**, *13*, 1318. [CrossRef]
7. Borrelli, P.; Robinson, D.A.; Panagos, P.; Lugato, E.; Yang, J.E.; Alewell, C.; Wuepper, D.; Montanarella, L.; Ballabio, C. Land use and climate change impacts on global soil erosion by water (2015–2070). *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 21994–22001. [CrossRef]
8. Viana, C.M.; Freire, D.; Abrantes, P.; Rocha, J.; Pereira, P. Agricultural land systems importance for supporting food security and sustainable development goals: A systematic review. *Sci. Total Environ.* **2022**, *806*, 150718. [CrossRef]
9. Prăvălie, R. Exploring the multiple land degradation pathways across the planet. *Earth-Sci. Rev.* **2021**, *220*, 103689. [CrossRef]
10. Bogunovic, I.; Filipovic, L.; Filipovic, V.; Kisic, I. Agricultural Soil Degradation in Croatia. In *Impact of Agriculture on Soil Degradation II: A European Perspective, The Handbook of Environmental Chemistry*, 1st ed.; Pereira, P., Muñoz-Rojas, M., Bogunovic, I., Zhao, W., Eds.; Springer International Publishing: Cham, Switzerland, 2022; Volume 121, pp. 1–34. [CrossRef]
11. Löbmann, M.T.; Maring, L.; Prokop, G.; Brils, J.; Bender, J.; Bispo, A.; Helming, K. Systems knowledge for sustainable soil and land management. *Sci. Total Environ.* **2022**, *822*, 153389. [CrossRef]

12. European Commission. *Caring for Soil Is Caring for Life–Ensure 75% of Soils Are Healthy by 2030 for Food, People, Nature and Climate*; Independent expert report; Publications Office of the European Union: Luxembourg, 2020; 82p. [CrossRef]
13. Bogunović, I.; Filipović, V. Mulch as a nature-based solution to halt and reverse land degradation in agricultural areas. *Curr. Opin. Environ. Sci. Health* **2023**, *34*, 100488. [CrossRef]
14. Bogunovic, I.; Kljak, K.; Dugan, I.; Grbeša, D.; Telak, L.J.; Duvnjak, M.; Kapović Solomun, M.; Kisić, I.; Pereira, P. Grassland management impact on soil degradation and herbage nutritional value in a temperate humid environment. *Agriculture* **2022**, *12*, 921. [CrossRef]
15. Bogunovic, I.; Pereira, P.; Kisic, I.; Sajko, K.; Sraka, M. Tillage management impacts on soil compaction, erosion and crop yield in Stagnosols (Croatia). *Catena* **2018**, *160*, 376–384. [CrossRef]
16. Dugan, I.; Pereira, P.; Barcelo, D.; Telak, L.J.; Filipovic, V.; Filipovic, L.; Kisic, I.; Bogunovic, I. Agriculture management and seasonal impact on soil properties, water, sediment and chemicals transport in a hazelnut orchard (Croatia). *Sci. Total Environ.* **2022**, *839*, 156346. [CrossRef] [PubMed]
17. Dugan, I.; Pereira, P.; Defterdarovic, J.; Filipovic, L.; Filipovic, V.; Bogunovic, I. Straw Mulch Application Enhanced Soil Properties and Reduced Diffuse Pollution at a Steep Vineyard in Istria (Croatia). *Land* **2023**, *12*, 1691. [CrossRef]
18. Mondal, S.; Chakraborty, D. Global meta-analysis suggests that no-tillage favourably changes soil structure and porosity. *Geoderma* **2022**, *405*, 115443. [CrossRef]
19. Patra, S.; Parihar, C.M.; Mahala, D.M.; Singh, D.; Nayak, H.S.; Patra, K.; Reddy, K.S.; Pradhan, S.; Sena, D.R. Influence of long-term tillage and diversified cropping systems on hydro-physical properties in a sandy loam soil of North-Western India. *Soil Tillage Res.* **2023**, *229*, 105655. [CrossRef]
20. da Silva, G.F.; Calonego, J.C.; Luperini, B.C.O.; Chamma, L.; Alves, E.R.; Rodrigues, S.A.; Putti, F.F.; da Silva, V.M.; de Almeida Silva, M. Soil—Plant relationships in soybean cultivated under conventional tillage and long-term no-Tillage. *Agronomy* **2022**, *12*, 697. [CrossRef]
21. Bogunovic, I.; Pereira, P.; Galic, M.; Bilandzija, D.; Kisic, I. Tillage system and farmyard manure impact on soil physical properties, CO_2 emissions, and crop yield in an organic farm located in a Mediterranean environment (Croatia). *Environ. Earth Sci.* **2020**, *79*, 70. [CrossRef]
22. European Commission. *Farm to Fork Strategy, for a Fair, Healthy and Environmentally-Friendly Food System*, 1st ed.; European Union: Bruxelles, Belgium, 2020. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:ea0f9f73-9ab2-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed on 5 September 2023).
23. European Commission. *Proposal for a Regulation of the European Parliament and of the Council Establishing the Framework for Achieving Climate Neutrality and Amending Regulation (EU) 2018/1999 (European Climate Law)*, 1st ed.; European Union: Bruxelles, Belgium, 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020PC0080 (accessed on 5 September 2023).
24. Palm, C.; Blanco-Canqui, H.; DeClerck, F.; Gatere, L.; Grace, P. Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **2014**, *187*, 87–105. [CrossRef]
25. Chatterjee, R.; Acharya, S.K.; Biswas, A.; Mandal, A.; Biswas, T.; Das, S.; Mandal, B. Conservation agriculture in new alluvial agro-ecology: Differential perception and adoption. *J. Rural. Stud.* **2021**, *88*, 14–27. [CrossRef]
26. Sun, H.; Chen, Y.; Yi, Z. After-Effects of Hydrochar Amendment on Water Spinach Production, N Leaching, and N_2O Emission from a Vegetable Soil under Varying N-Inputs. *Plants* **2022**, *11*, 3444. [CrossRef] [PubMed]
27. Chen, S.; Li, D.; He, H.; Zhang, Q.; Lu, H.; Xue, L.; Feng, Y.; Sun, H. Substituting urea with biogas slurry and hydrothermal carbonization aqueous product could decrease NH_3 volatilization and increase soil DOM in wheat growth cycle. *Environ. Res.* **2022**, *214*, 113997. [CrossRef] [PubMed]
28. Dwibedi, S.K.; Pandey, V.C.; Divyasree, D.; Bajpai, O. Biochar-based land development. *Land Degrad. Dev.* **2022**, *33*, 1139–1158. [CrossRef]
29. Rayne, N.; Aula, L. Livestock Manure and the Impacts on Soil Health: A Review. *Soil Syst.* **2020**, *4*, 64. [CrossRef]
30. Liu, S.; Pu, S.; Deng, D.; Huang, H.; Yan, C.; Ma, H.; Razavi, B.S. Comparable effects of manure and its biochar on reducing soil Cr bioavailability and narrowing the rhizosphere extent of enzyme activities. *Environ. Int.* **2020**, *134*, 105277. [CrossRef]
31. Nyambo, P.; Chiduza, C.; Araya, T. Effect of conservation agriculture on selected soil physical properties on a haplic cambisol in Alice, Eastern Cape, South Africa. *Arch. Agron. Soil Sci.* **2022**, *68*, 195–208. [CrossRef]
32. IUSS—WRB. *World Reference Base for Soil. Resources 2014: International Soil. Classification System for Naming Soils and Creating Legends for Soil. Maps*; Word Soil Resources Reports No. 106; FAO: Rome, Italy, 2014.
33. Dıaz-Zorita, M.; Perfect, E.; Grove, J.H. Disruptive methods for assessing soil structure. *Soil Tillage Res.* **2002**, *64*, 3–22. [CrossRef]
34. Le Bissonnais, Y.L. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *Eur. J. Soil Sci.* **1996**, *47*, 425–437. [CrossRef]
35. Kemper, W.D.; Rosenau, R.C. Aggregate stability and size distribution. In *Methods of Soil Analysis*; Klute, A., Ed.; American Society of Agronomy, Inc.: Madison, WI, USA, 1986; pp. 425–442. [CrossRef]
36. Kovács, G.P.; Simon, B.; Balla, I.; Bozóki, B.; Dekemati, I.; Gyuricza, C.; Percze, A.; Birkás, M. Conservation Tillage Improves Soil Quality and Crop Yield in Hungary. *Agronomy* **2023**, *13*, 894. [CrossRef]

37. Dekemati, I.; Simon, B.; Bogunovic, I.; Vinogradov, S.; Modiba, M.M.; Gyuricza, C.; Birkás, M. Three-Year Investigation of Tillage Management on the Soil Physical Environment, Earthworm Populations and Crop Yields in Croatia. *Agronomy* **2021**, *11*, 825. [CrossRef]
38. European Commission. Forging a Climate-Resilient Europe—The New EU Strategy on Adaptation to Climate Change. In *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels (24.02. 2021)*; European Union: Bruxelles, Belgium, 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0082 (accessed on 5 September 2023).
39. Ferreira, C.S.; Seifollahi-Aghmiuni, S.; Destouni, G.; Ghajarnia, N.; Kalantari, Z. Soil degradation in the European Mediterranean region: Processes, status and consequences. *Sci. Total Environ.* **2022**, *805*, 150106. [CrossRef] [PubMed]
40. Chabert, A.; Sarthou, J.P. Conservation agriculture as a promising trade-off between conventional and organic agriculture in bundling ecosystem services. *Agric. Ecosyst. Environ.* **2020**, *292*, 106815. [CrossRef]
41. Sardar, A.; Kiani, A.K.; Kuslu, Y. Does adoption of climate-smart agriculture (CSA) practices improve farmers' crop income? Assessing the determinants and its impacts in Punjab province, Pakistan. *Environ. Dev. Sustain.* **2021**, *23*, 10119–10140. [CrossRef]
42. Al-Kaisi, M.M.; Lal, R. Aligning science and policy of regenerative agriculture. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1808–1820. [CrossRef]
43. Morris, G.L. Classification of Management Alternatives to Combat Reservoir Sedimentation. *Water* **2020**, *12*, 861. [CrossRef]
44. Orzech, K.; Wanic, M.; Załuski, D. The Effects of Soil Compaction and Different Tillage Systems on the Bulk Density and Moisture Content of Soil and the Yields of Winter Oilseed Rape and Cereals. *Agriculture* **2021**, *11*, 666. [CrossRef]
45. Baude, M.; Meyer, B.C.; Schindewolf, M. Land use change in an agricultural landscape causing degradation of soil based ecosystem services. *Sci. Total Environ.* **2019**, *659*, 1526–1536. [CrossRef]
46. Zhang, Z.; Peng, X. Bio-tillage: A new perspective for sustainable agriculture. *Soil Tillage Res.* **2021**, *206*, 104844. [CrossRef]
47. Beylich, A.; Oberholzer, H.R.; Schrader, S.; Höper, H.; Wilke, B.M. Evaluation of soil compaction effects on soil biota and soil biological processes in soils. *Soil Tillage Res.* **2010**, *109*, 133–143. [CrossRef]
48. Bogunovic, I.; Andabaka, Z.; Stupic, D.; Pereira, P.; Galic, M.; Novak, K.; Telak, L.J. Continuous grass coverage as a management practice in humid environment vineyards increases compaction and CO_2 emissions but does not modify must quality. *Land Degrad. Dev.* **2019**, *30*, 2347–2359. [CrossRef]
49. Telak, L.J.; Pereira, P.; Ferreira, C.S.S.; Filipovic, V.; Filipovic, L.; Bogunovic, I. Short-Term Impact of Tillage on Soil and the Hydrological Response within a Fig (*Ficus carica*) Orchard in Croatia. *Water* **2020**, *12*, 3295. [CrossRef]
50. Zhang, Y.; Wang, S.; Wang, H.; Ning, F.; Zhang, Y.; Dong, Z.; Wen, P.; Wang, R.; Wang, X.; Li, J. The effects of rotating conservation tillage with conventional tillage on soil properties and grain yields in winter wheat-spring maize rotations. *Agric. For. Meteorol.* **2018**, *263*, 107–117. [CrossRef]
51. Sharratt, B.; Zhang, M.; Sparrow, S. Twenty years of tillage research in subarctic Alaska: I. Impact on soil strength, aggregation, roughness, and residue cover. *Soil Tillage Res.* **2006**, *91*, 75–81. [CrossRef]
52. Taylor, H.M.; Gardner, H.R. Penetration of cotton seedlingn taproots as influenced by bulk density, moisture content, and strength of soil. *Soil Sci.* **1963**, *96*, 153–156. [CrossRef]
53. de Moraes, M.T.; Debiasi, H.; Carlesso, R.; Franchini, J.C.; da Silva, V.R.; da Luz, F.B. Soil physical quality on tillage and cropping systems after two decades in the subtropical region of Brazil. *Soil Tillage Res.* **2016**, *155*, 351–362. [CrossRef]
54. Alvarez, R.; Steinbach, H.S. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. *Soil Tillage Res.* **2009**, *104*, 1–15. [CrossRef]
55. Blanco-Canqui, H.; Hergert, G.W.; Nielsen, R.A. Cattle manure application reduces soil compactibility and increases water retention after 71 years. *Soil Sci. Soc. Am. J.* **2015**, *79*, 212–223. [CrossRef]
56. Mujdeci, M.; Isildar, A.A.; Uygur, V.; Alaboz, P.; Unlu, H.; Senol, H. Cooperative effects of field traffic and organic matter treatments on some compaction-related soil properties. *Solid Earth* **2017**, *8*, 189–198. [CrossRef]
57. Baiamonte, G.; Crescimanno, G.; Parrino, F.; De Pasquale, C. Effect of biochar on the physical and structural properties of a sandy soil. *Catena* **2019**, *175*, 294–303. [CrossRef]
58. Blanco-Canqui, H. Does biochar application alleviate soil compaction? Review and data synthesis. *Geoderma* **2021**, *404*, 115317. [CrossRef]
59. Hati, K.M.; Mandal, K.G.; Misra, A.K.; Ghosh, P.K.; Bandyopadhyay, K.K. Effect of inorganic fertilizer and farmyard manure on soil physical properties, root distribution, and water-use efficiency of soybean in Vertisols of central India. *Bioresour. Technol.* **2006**, *97*, 2182–2188. [CrossRef] [PubMed]
60. Sweeten, J.M.; Mathers, A.C. Improving soils with livestock manure. *J. Soil Water Conserv.* **1985**, *40*, 206–210.
61. Jokela, W.E.; Grabber, J.H.; Karlen, D.L.; Balser, T.C.; Palmquist, D.E. Cover crop and liquid manure effects on soil quality indicators in a corn silage system. *Agron. J.* **2009**, *101*, 727–737. [CrossRef]
62. Dunjana, N.; Nyamugafata, P.; Shumba, A.; Nyamangara, J.; Zingore, S. Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe. *Soil Use Manag.* **2012**, *28*, 221–228. [CrossRef]
63. Telak, L.J.; Pereira, P.; Bogunovic, I. Soil degradation mitigation in continental climate in young vineyards planted in Stagnosols. *Int. Agrophys.* **2021**, *35*, 307–317. [CrossRef]
64. Bogunović, I.; Hrelja, I.; Kisić, I.; Dugan, I.; Krevh, V.; Defterdarović, J.; Filipović, V.; Filipović, L.; Pereira, P. Straw Mulch Effect on Soil and Water Loss in Different Growth Phases of Maize Sown on Stagnosols in Croatia. *Land* **2023**, *12*, 765. [CrossRef]

65. Dugan, I.; Bogunovic, I.; Pereira, P. Soil management and seasonality impact on soil properties and soil erosion in steep vineyards of north-western Croatia. *J. Hydrol. Hydromech.* **2023**, *71*, 91–99. [CrossRef]
66. FAOSTAT. *Agricultural Production Statistics*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2023. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 14 September 2023).
67. Alvarez, R. Comparing productivity of organic and conventional farming systems: A quantitative review. *Arch. Agron. Soil Sci.* **2022**, *68*, 1947–1958. [CrossRef]
68. Goulart, R.Z.; Reichert, J.M.; Rodrigues, M.F.; Neto, M.C.; Ebling, E.D. Comparing tillage methods for growing lowland soybean and corn during wetter-than-normal cropping seasons. *Paddy Water Environ.* **2021**, *19*, 401–415. [CrossRef]
69. Ansarifar, J.; Wang, L.; Archontoulis, S.V. An interaction regression model for crop yield prediction. *Sci. Rep.* **2021**, *11*, 17754. [CrossRef] [PubMed]
70. DeFelice, M.S.; Carter, P.R.; Mitchell, S.B. Influence of tillage on corn and soybean yield in the United States and Canada. *Crop Manag.* **2006**, *5*, 1–17. [CrossRef]
71. Ciampitti, I.A.; Vyn, T.J. Understanding global and historical nutrient use efficiencies for closing maize yield gaps. *Agron. J.* **2014**, *106*, 2107–2117. [CrossRef]