

Review

Soil Physical-Hydrological Degradation in the Root-Zone of Tree Crops: Problems and Solutions

Simone Priori ¹, Sergio Pellegrini ², Nadia Vignozzi ² and Edoardo A. C. Costantini ^{3,4,*}

¹ Department of Agricultural and Forestry Sciences (DAFNE), University of Tuscia, Via S.C. de Lellis, 01100 Viterbo, Italy; simone.priori@unitus.it

² Consiglio per la Ricerca in Agricoltura e l'analisi dell'economia Agraria, Centro di Ricerca Agricoltura e Ambiente, Via di Lanciola 12a, Cascine del Riccio, 50125 Firenze, Italy; sergio.pellegrini@crea.gov.it (S.P.); nadia.vignozzi@crea.gov.it (N.V.)

³ Accademia dei Georgofili, Logge degli Uffizi, 50122 Firenze, Italy

⁴ Accademia Nazionale di Agricoltura, Via Castiglione, 40124 Bologna, Italy

* Correspondence: eac.costantini@gmail.com

Abstract: The diffusion of tree crops has continuously increased during the last decades all over the world. The market boost has favored the adoption of intensive and highly mechanized cultivation, often triggering the degradation of the soil physical-hydrological qualities, mainly through enhanced soil erosion and compaction. Several papers have been published on soil degradation and restoration strategies in specific perennial crops and environments. This review paper collects such studies showing the sensitivity of soil under tree crops to the degradation of their physical-hydrological qualities. Then it reports the state of the art on the methodologies used for the evaluation of the physical-hydrological qualities in the field and in the laboratory, also suggesting an improved methodology for estimating the actual available water capacity. Some updated and promising experiences to recover the physical-hydrological qualities of soil are then illustrated. In particular, subsoiling and placement of drainages, spreading of organic amendments, compost, biochar, using of cover crops, and biological inoculants. A key point in applying the restoration practices is that they should not only be specific for the soil and tree rooting system, but also tailored according to the ecosystem functions that need to be improved besides plant health and yield.

Keywords: structure; soil conservation; erosion; ecosystem services; plant available water; soil restoration



Citation: Priori, S.; Pellegrini, S.; Vignozzi, N.; Costantini, E.A.C. Soil Physical-Hydrological Degradation in the Root-Zone of Tree Crops: Problems and Solutions. *Agronomy* **2021**, *11*, 68. <https://doi.org/10.3390/agronomy11010068>

Received: 26 November 2020

Accepted: 28 December 2020

Published: 31 December 2020

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Soil degradation is a major global issue that affects about a third of all soils [1]. In intensively populated areas the situation can be even worse, as reported in the analysis of the state of soil health in Europe, which indicates that 60–70% of soils are unhealthy as a direct result of unsustainable management practices [2]. Farming can play an important role in safeguarding and maintaining the territory, but may also negatively affect soil health, under excessive land exploitation. Tree crops, in particular, may show high levels of soil degradation, especially due to water erosion [3].

In the last decades, the world surface of tree crops has expanded in many areas of the world, driven by the possibilities of higher economical incomes. According to FAO statistics (<http://www.fao.org/faostat/>), the world surface used for woody crops cultivation is about 130 million ha (2017), in particular fruit trees (68 million ha, including grape), nuts (25 million ha, including coconut), citrus (11 million ha), olive trees (10 million ha). From 2010 to 2018, the world cultivated area of fruit, nuts, citrus, and olive trees enlarged about 9.5%, 12%, 20% and 6%, respectively. If a proper tree crop cultivation, for instance, through a well-designed agroforestry system, may reduce soil degradation [4], many specialized plantations show signs of accelerated erosion [5,6]. Mechanization and bulldozing for slope regularization and rooting depth increasing have enabled farmers to industrialize

tree crops management and to cultivate marginal soils on hillslopes. Unfortunately, the strong mechanization of these crops has often implicated a profound modification of the soil natural profile and of surface and sub-surface hydrology [7].

In particular, heavy machineries used for land preparation and/or crop management, namely harvesting, soil cultivation, and crop protection, have caused deep impacts on soil physical properties [8]. After levelling and land preparation for new tree crop fields, the soil is often characterized by partial or total loss of structure, horizons mixing, rock fragments removal and no grass cover, which leave the surface bare and unarmoured. Deep ploughing and land levelling may also let outcrop the substratum or horizons with unfavourable properties, such as salinity. In this vulnerable condition, the soil is very susceptible to erosion in the short and medium term, and few storms can easily cause rapid soil losses until some hundreds of tons per hectare [7,9]. In the years after plantation, the cultivation system of tree crops, often in rows along the maximum slope, implying a single direction for all operations, including tillage, triggers the water runoff initiation, and then soil erosion. Compared with other land uses, the cultivation of fruit trees creates the most favourable conditions for severe soil loss; these conditions are the result of several factors, such as the common practice of planting along the maximum slope direction and the adoption of management practices that increase soil compaction [6]. Tractor traffic in the inter-rows of a tree crop planted in lines such as vineyards causes soil compaction and a slower infiltration rate, particularly along the wheel tracks, especially when the soil surface is cultivated and lack of a permanent or temporal grass cover [10]. Decreasing water infiltration increases surface runoff and reduces water storage, restricts root growth, causes a reduction in soil biota biomass, especially earthworms, and limits nutrients cycling [11]. In addition, the strong soil aeration due to the deep tillage and topsoil preparation for tree planting implies a strong organic matter mineralization and then a consequent soil organic carbon (SOC) depletion [8,12]. This is particularly evident when the new tree crop plantations involve deforestation or removal of semi-natural grassland and pastures, where the SOM reduction can exceed 30% [13,14]. The degradation of soil physical-hydrological features in the root-zone of tree crops causes the impairment of many soil ecosystem functions, including plant health, yield, and food quality, groundwater recharge, carbon sequestration, sediment, and water runoff regulation [15].

Specific characteristics of the root system of tree crops are the wider and deeper extension, as well as a longer life span respect to herbaceous crops. This implicates that deep soil horizons conditions play a much more important role in tree crops. Such soil horizons are generally called “limiting horizons” and they can have different causes of rooting restrictions. First of all, the bedrock depth is one of the most important limiting factors, in particular if the bedrock is massive and impossible to be explored by roots. The second most common factor that limits the rooting is the scarce oxygenation of the deep horizons, mainly due to waterlogging. The waterlogging can be either linked to a surficial water table that can temporarily or permanently occupy the soil pores, or to slow drainage of the infiltration water, due to impermeable or semi-impermeable layers. Scarce oxygenation and difficulties to rooting can also be due to compacted or hardened subsoil horizons. This can be the case of either mechanical compaction of the subsoil, or horizon hardening because of pedogenetic processes, such as precipitation of carbonates, gypsum and other salts, and iron oxides [16]. If the time needed to accumulate iron oxides generally overcomes the life of tree crops, compaction and accumulation of different salts within the rooting depth can occur rather rapidly, especially under irrigation, and affect the agronomic result.

A strong reduction in soil rooting ability affects plant vigour and in turn the economic life of crops, forcing plantations to be renewed in a short time. However, the frequent substitution of the plantation perpetuates a vicious cycle of soil degradation. Breaking this vicious circle and coping with degraded soils of tree crops implies a thorough knowledge of soil profile characteristics and of their interaction with the root system.

Several papers have been published on soil degradation and restoration strategies of specific perennial crops and agro-environments, but a review that compares, discusses and updates the diverse results and methodologies is still lacking. In this paper, we illustrate the inherent soil features that make soil more prone to degradation, giving particular emphasis and more details on dynamic physical-hydrological qualities, also suggesting an improved methodology for the estimation of the potential available water capacity (AWC). We then report some updated and promising experiences to recover the physical-hydrological functions of the soil. A set of mechanical, agronomical, and biological solutions are discussed, aimed at improving the soil profile in depth and restoring the functionality of the root system of tree crops.

2. Soils More Sensitive to Physical Degradation

Soil physical degradation is part of the broader concept of “soil degradation”, defined as “the general process by which soil health gradually declines and therefore it is less suitable for a specific purpose, such as crop production” [17], or as “a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries” [18]. Soil physical degradation mainly consists in a deterioration of structural characteristics [19] and can manifest as compaction, surface sealing and crusting, impeded drainage, poor aeration, often associated to limited water infiltration, high runoff volume, and accelerated erosion. Major physical degradation processes are generally triggered by intensive cultivation, frequent tillage operations and machinery traffic, as well as by chemical processes, mainly decrease of organic matter, salinization, and sodification [20]. Such processes, separately or in combination with each other, have major impacts on plant physiology and crop production. However, different soils show different susceptibility to various degradation processes, due to their specific inherent and dynamic properties.

The inherent, or use-invariant, properties are those that substantially do not change depending on conventional cultivation practices; the most important are soil texture, depth to hard bedrock and type of clay. Otherwise, dynamic or use-dependent properties may change over time in response to variations in land use or management. Dynamic properties include organic matter and nutrients content, salt accumulation, soil structural features, infiltration rate, groundwater table depth, and water holding capacity [21,22]. Under free drainage conditions, particle size distribution (texture), clay mineralogy, type and amount of salts and exchangeable ions, and organic carbon content are the soil properties that most affect soil structure. Soil organic matter (SOM) is known to play a crucial role in the maintenance and improvement of many soil properties and processes, basically because it affects soil structure formation and stabilization [23,24]. As a result, SOM reduces compaction susceptibility by increasing resistance to deformation [25] and increases water infiltration and conductivity, thus reducing runoff and erosion [26]. In addition, soil biological activity plays a basic role on soil structure formation and stability, because various agents (roots, macro and mesofauna, microbes, arbuscular mycorrhizae, enzymes, humus components) and processes (aggregation, root growth, burrowing, casting) are involved on its dynamics [27,28].

Based on these properties, different soils respond differently to external stresses. Soils under tree crops are recognized as at high risk of being endangered by physical degradation phenomena. Most of them are on slopes and frequently tilled, which makes them susceptible to soil erosion. Moreover, tree crops may be cultivated on shallow soils under climatic conditions characterized by intense rainfalls and high temperatures during the dry season, factors that can induce high soil erosion rates [29,30].

2.1. Soils Sensitive to Clay Dispersion

A high amount of monovalent cations in the soil exchange complex, namely sodium (Na^+) and potassium (K^+), increases clay minerals swelling and decreases attractive forces between clay particles. In particular, it is widely recognized that high levels of exchange-

able sodium in soil increase the dispersion of clay [31]. This implicates a weak structural development and stability, as well as low hydraulic conductivity, making these soils more susceptible to erosion and compaction (Figure 1). Sodicty decreases plant growth by hindering root expansion due to high soil strength and limiting gas exchange in the rhizosphere [31]. Saline soils, in which exchangeable sodium is not a problem, are usually well structured and water permeability is good [32], but a large accumulation of precipitated salts can even completely clog the pore system (petrocalcic, petrogypsic, petrosalic horizons). In addition, most fruit crops are highly sensitive to salinity since the excess of soluble salts in the root zone hinders soil water absorption. In saline and sodic soils all these constraints operate simultaneously to decrease the effective rooting volume, thus limiting the water available for plants. For all these reasons, saline and/or sodic soil horizons have deleterious effects on the root development of the tree crops, both directly for plant nutrition and indirectly for limitation of soil porosity and oxygenation.

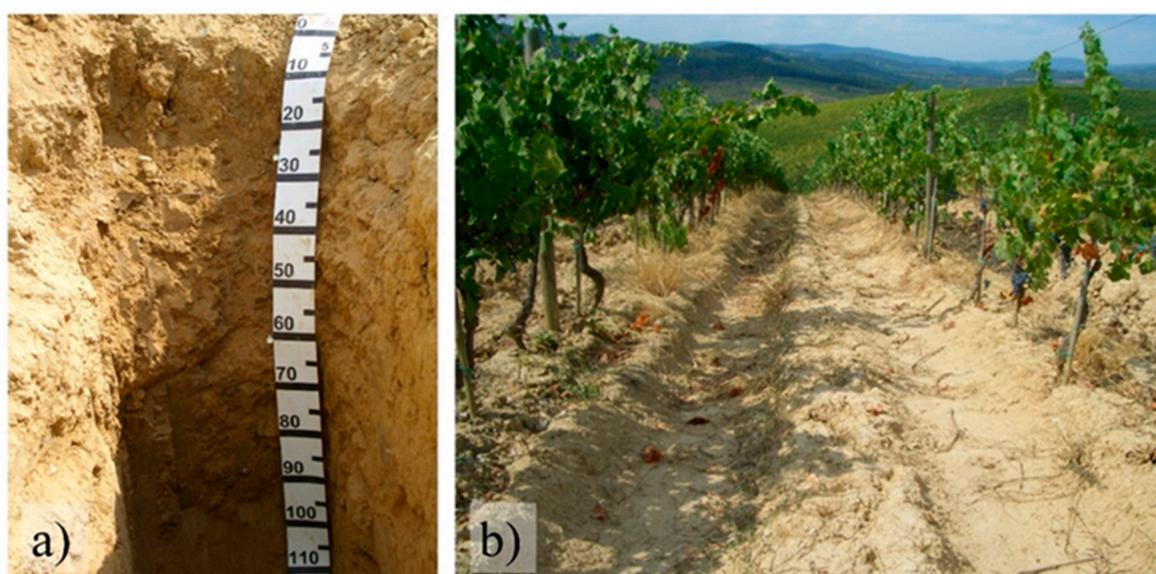


Figure 1. Soil compaction in a vineyard with sodic soil (clay loamy, pH: 8.9, ESP: 42.6) which limits the grapevine growth (b). On the left, the related soil profile, where the scarce structure of the soil horizons is evident (a).

K^+ can create similar effects as Na^+ on clay particles dispersion, and then soil aggregation, but it has received less attention than Na^+ for two reasons: (i) the impact of K^+ on clay dispersion is lower than Na^+ ; (ii) K^+ content is generally relatively low in salt-affected soils [33]. On the other hand, recent studies draw attention to elevated concentrations of K^+ and magnesium (Mg^{2+}) in soils, which arise naturally or because of fertilizing and irrigation with wastewater [33,34]. Several studies have demonstrated that elevated amount of exchangeable magnesium, higher than exchangeable calcium content, can cause structural deterioration in soils, very similar to that caused by Na^+ , and increasing compaction susceptibility and erodibility [35,36].

2.2. Soils Sensitive to Crusting

Soil crusting is a common physical degradation phenomenon of agricultural soils [37], having a negative impact on water infiltration, erosion, and soil–atmosphere gas exchanges. The mechanical action of raindrops, besides aggregates disruption, causes the compaction of the soil surface, with consequent porosity reduction. The single primary particles and microaggregates originating from the disruption of structural aggregates or “peds” cause the occlusion of the pores below the surface, then the drastic infiltration reduction triggers transport and deposition phenomena. All these processes lead to the formation on surface of a compact layer with low permeability (seal), from which the crust originates upon

drying [38]. Crusts consist in more compact, hard, and brittle layers at the soil surface and are particularly common in soils of arid and semiarid regions, with a thickness that usually ranges from less than 1 mm to 5 cm (Figure 2). These features not only decrease the size and the number of pores, but also modify the arrangement of the pore system [39,40].



Figure 2. Strong soil crusting on a silty loam soil, with loose structure, previously tilled for a hazelnut tree field preparation in Mediterranean area. The SOM content of this soil was less than 0.1%.

Soil crusting susceptibility depends on rainfall intensity, soil surface conditions, and inherent soil characteristics. In addition, soil tillage and the type of tool used strongly influence soil surface features and the risk of crusting [41]. For example, the use of power arrows for seedbed preparation produces small aggregates, more prone to disruption and particle dispersion, thus increasing the risk of crust formation.

Soil texture has a considerable influence on crust formation. Clay generally favours aggregation and reduces crust formation, although clay mineralogy and type and amount of soluble salts and of exchangeable cations can modify this generalization. Medium-textured (<20% clay) and soils rich in silt are usually more susceptible to crusting, especially when cultivated [42], while in sandy soils the amount of silt and clay, once dispersed, is often not sufficient to clog the pores at the soil surface [38]. SOM, on the contrary, being one of the most important stabilizing agents of the structure, reduces the crusting susceptibility [43]. Intense cultivation for tree crop preparation and low SOM content increase both soil crusting and erodibility (Figure 2). FAO [44] developed a soil crusting index (*CI*) based on the following equation:

$$CI = \frac{(1.5 * silt_{fine}) + (0.75 * silt_{coarse})}{(clay + 10 * SOM)}$$

where all the variables are reported in $g \cdot 100 g^{-1}$. The *CI* exceeds 2 for soils prone to intense crusting [44].

About the influence of clay mineralogy, it is known that when the dominant clay mineral is kaolinite, crusting susceptibility is lower, while soils containing expandable clays, illite, and micaceous minerals, are more prone to crusting [45]. As previously explained, Na^+ can play a key role on crust formation due to the capability to disperse clay. The raising to the soil surface of soluble salts, when present in large amounts, can also plug porosity and form crusts.

Soil coarse fraction also performs an important role in the crusting process. Rock fragments (gravel and stones) act as mulch material, protecting the surface aggregates from the raindrops impact, thus favouring water infiltration, and reducing runoff [46].

Surface crust formation can be considered to all intents and purposes as a compaction process, which however only affects a thin soil layer. Quite different is the case in which the pressures exerted by agricultural machineries induce a density increase up to several tens of centimetres depth, or when the use of mouldboard causes the formation of the plough pan below the lower limit of cultivation

2.3. Soils Sensitive to Compaction

Soil compaction is a ubiquitous problem that affects many fruit trees cultivation areas worldwide [47,48] and is responsible of the alteration of a wide range of soil functions, with consequences often detrimental to plant growth. In fact, when the soil is compacted, root growth is hindered, therefore, access to water and nutrients availability are severely limited [49]. A compacted soil shows reduced pore volume and size, pore connectivity, and water retention [50]. Compaction also reduces the volume of air-filled porosity and the consequent deficiency of oxygen may exacerbate the incidence of root diseases [51]. In some cases, scarce soil aeration caused by compaction induces plant iron-chlorosis due to production of exogenous soil ethylene [52].

A major cause of compaction in soils under fruit trees is due to the large use of agricultural machinery of ever-growing size and weight [53]. Soil compaction generally shows a decreasing trend with depth which is proportional to the applied burden, but it can be concentrated in parts of the soil horizons, when fragments of the massive substratum are mixed with structured horizons.

The degree of compaction not only depends on the type and size of machinery, but also on soil inherent vulnerability. The susceptibility of soil to compaction is function of its compressibility, namely “the ease with which a soil decreases in volume when subjected to a mechanical load” [54]. Soil compressibility is related to basic properties, such as particle size distribution and organic matter content [55]. According to several authors, coarse-textured soils are less susceptible to compaction than those with a fine texture [55,56]. In these soils, however, the alleviating processes due to the action of frost and to the drying-wetting cycles are less effective respect to the fine-textured ones, so the effects of compaction are likely to be more persistent [57].

In addition to texture, soil compaction susceptibility depends on stoniness. A content of more than 15–20% by volume of embedded gravel acts as a “skeleton”, thus protecting the fine earth fraction from compaction [58] and helping to preserve the functions related to macroporosity, such as hydraulic conductivity and gas exchange [59]. However, rock fragments can induce both positive and negative effects on the soil properties that regulate hydrological processes. As described in the previous sub-chapter, surface stoniness acts as a mulch, reducing crusting and evaporation, as well as favouring water infiltration. On the other hand, they reduce the volume available for water within the soil, and then the total AWC, as better explained in chapter 4. Moreover, increasing rock fragments decreases the water conducting area and thus the hydraulic conductivity in non-compacted soils, while the opposite occurs in the compacted ones [60,61]. Finally, soil compaction can also be a natural process, like in soil with a fragipan or subjected to hard-setting [62].

2.4. Soils Sensitive to Water Erosion

Soil water erosion is controlled by several factors, namely rainfall erosivity, soil erodibility, cover management, topography, and conservation practices. Soil erodibility, defined as the resistance to the impact of raindrops on the soil surface and to the shearing action of runoff water [63], can be considered an intrinsic soil property that mainly depends on soil structure, permeability, texture and SOC. In fact, the structure influences the erodibility since it is the shape, size, and stability of the aggregates that control the detachment of primary particles and water infiltration.

Several studies on soil erodibility showed that the diameter of the particles of the most erodible soil fraction is between 10 and 100 μm , in other words silt and fine sand [63,64]. When the quantity of finer particles (particularly clayey ones) is greater, the cohesion increases making soil less erodible; as aggregates of increasing resistance and size, and therefore more difficult to be disrupted and transported, are formed. Soils with high silt content have high erodibility values as a consequence of low structure stability; in these soils, primary particles are easily detached, so they have a high susceptibility to crust formation and to production of large runoff volumes [65]. The occurrence of a good topsoil structure is therefore crucial to limit erodibility. As previously described, high percentage of exchangeable Na^+ favours clay dispersion, increasing soil erodibility. On the contrary, the abundance of exchangeable Ca^{2+} , as well as Al^{3+} and Fe^{3+} cations tend to bind the clay particles, promoting soil aggregation and stabilization [66].

3. Assessment of Soil Physical–Hydrological Quality

Soil physical–hydrological features are strictly related to the water and nutritional status of the plants and deeply affect yield quantity and quality. The assessment of physical characteristics regards the inherent and dynamic soil characteristics of each soil horizon and the soil hydrological behaviour of the profile as a whole. While inherent soil features are not substantially affected by conventional soil management, particular attention must be paid to the dynamic ones. In particular, soil health is strictly related to structural conditions and many of the environmental damages in cultivated areas (erosion, desertification, etc.) are driven by soil structure degradation [19]. Actually, there is a close link between soil health and soil structure, since soil is a natural body which tends to self-organization in different forms according to local conditions [67]. The genesis of a specific type of soil structure is the main product of its natural self-organization, which characterizes a soil typology. Degrading soil structure implies creating a disequilibrium with local soil forming factors, the lowering of soil resilience, and hence of its health. By integrating many soil properties, soil structure determines soil fertility, soil biodiversity, nutrient cycling, carbon sequestration and the quantitative and qualitative regulation of water cycle [68,69]. Therefore, protecting the soil structure quality is crucial to ensure good soil functionality.

Soil structure may be defined either as “the shape, size and spatial arrangement of individual soil particles and clusters of particles (aggregates)” or as “the combination of different types of pores with solid particles (aggregates)” [19]. Actually, the spatial arrangement of solids and voids are complementary aspects of the soil structure [19]. The main types of soil structure are the granular, angular blocky, subangular blocky, platy, prismatic and columnar. There are also structureless conditions, and the latter are defined as single-grained or massive. Soil structure has a major influence on the type of pores and therefore on the movement of water and air, and on root growth.

3.1. Soil Structure Characterization

Distinct methods for the characterization of the solid phase arrangement or pore spaces are available and the results obtained are expected to differ in sensitivity, or relevance for soil functions. A first evaluation of soil structure is carried out in the field, following the instructions of soil survey manuals such as the FAO Guidelines [70]. Rabot et al. [68] in their review describe in detail and compare the various methods of measuring soil structure, distinguishing them according to the different perspective, solid phase vs pore space, starting from the field methods based on qualitative or semi quantitative measures, such as visual soil evaluation (VSE), up to the more precise lab methods as computer tomography imaging techniques. Advantages and limitations are highlighted for each method (Table 1) and at the end the authors suggest the pore space perspective, in particular imaging techniques, as the best method to evaluate the hydrological processes occurring in soils.

Table 1. Summary of the methods to assess soil structural characteristics. Modified from Rabot et al. [68].

Method	Measurement	Sample Size	Level of Expertise	Reproducibility	Duration	Cost
Whole profile evaluation	Qualitative	Horizon	High	Medium	Half an hour + pit	Low
Topsoil evaluation	Semi-quantitative	Full size of a spade and 20 cm depth	Medium	Medium	Half an hour	Low
Bulk density	Quantitative	Hundreds cm ³	Low	High	Half an hour + drying	Low
Aggregate size distribution and stability	Quantitative	Tens to hundred g	Medium	Low	A few hours	Low
Mercury porosimetry	Quantitative	A few cm ³	Low	High	A few hours	Medium
Water retention curve	Quantitative	Hundreds cm ³ to dm ³	Medium	High	Days to weeks	Medium
Gas adsorption	Quantitative	1 to tens mm ³	High	Medium	A few hours to days	Medium
Imaging techniques	Quantitative	1 cm ³ to dm ³	High	Medium	A few hours + sample preparation	High

Quantification of the pore space in terms of shape, size, continuity, orientation, and arrangement of pores in soil allows to define the complexity of soil structure and to understand its modifications induced by human activity. In the case of soils deeply ploughed before tree plantation, the total quantity of pores may decrease, as well as the proportion of elongated pores and the ratio between elongated plus irregular on the total, thus resulting in a worsening of soil internal drainage [71]. Characterisation of the pore system provides a realistic basis for understanding the retention and movement of water, gas exchange in soil, and the relationship between soil structure and biological and chemical properties (e.g., biological activity and turn-over of organic matter) [19].

Actually, soil structure characterization by image analysis of undisturbed soil samples (mainly X-ray computer tomography) provides excellent results but cannot directly assess soil structure stability and resilience [72], moreover this approach is expensive and restricted to specialized laboratories.

Aggregate size distribution and stability represent the ability of a soil to maintain its structure under the disruptive actions of water and mechanical stress [73]. These indicators are correlated with several soil functions, including gas exchange and C sequestration through physical protection of SOM [74,75]. Moreover, aggregate stability (AS) is a good indicator of soil erosion [76], since reduced AS increases susceptibility to crusting and runoff (Figure 3).

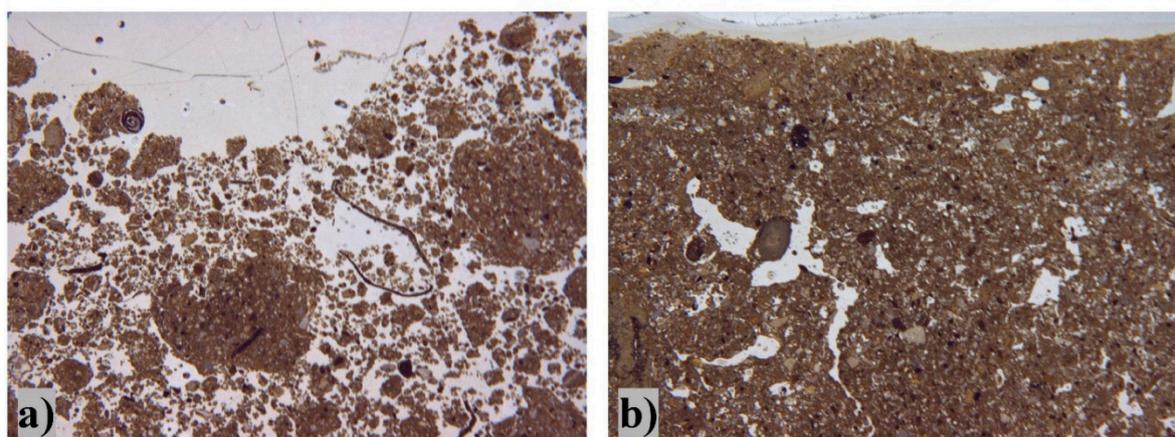


Figure 3. Macrophotographs of soil thin sections of a topsoil horizon one month after tillage without rainfall event (a), and the same soil 3 months after tillage and intense rainfall events (b). The horizontal length of a section is 32 mm.

There is no universally accepted laboratory method to determine aggregate size distribution and stability, but several approaches are currently used [77]. As a consequence, the results are rather sensitive to methodological details (type of sieving, duration, oscillation

frequency, loading rate) and poorly comparable. However, the determination of AS by wet sieving is the most widespread and, among the numerous variants, the procedure developed by Le Bissonnais [78] has been standardized and officially recognized (ISO 10930). AS has been endorsed by the “Soil Health Institute” (www.soilhealthinstitute.org) as an effective indicator of soil health, being very sensitive to changes in land use and management practices [79]. The analytical method accepted by the Soil Health Institute for its determination is the wet sieving procedure performed according to Kemper and Rosenau [80], but a new and fast procedure based on slaking effect and image recognition is currently under evaluation [81]. This procedure was developed using a smartphone application, named SLAKES. The app uses an image recognition algorithm that measures, at regular intervals over a 10-min period, the increasing area of soil aggregates immersed in water. Scientific publications of third parties proved that SLAKES is a reliable scientific method for quantifying AS; moreover, because of its simplicity and low cost, can be consistently and broadly implemented within the soil management community [82].

Nunes et al. [79] focused on the analysis of structural soil health indicators to assess the response to different tillage systems (mouldboard and chisel ploughing), no-tillage and perennial cropping systems. The authors initially selected AS, BD and penetration resistance (PR), but BD and PR did not result so sensitive as AS in evaluating soil structure quality. BD determination does not require high expertise or expensive equipment. Nevertheless, some difficulties during the sampling can occur that negatively affect the reliability of the measures. Moreover, BD is generally used to evaluate soil compaction, but is not so effective when related to soil functions such as water movement and retention or habitat for organisms. BD only provides a measure of total soil porosity, but no indications about pores size, shape and connectivity. As a matter of fact, the same BD value can assume a quite different meaning from functional viewpoint (Figure 4).

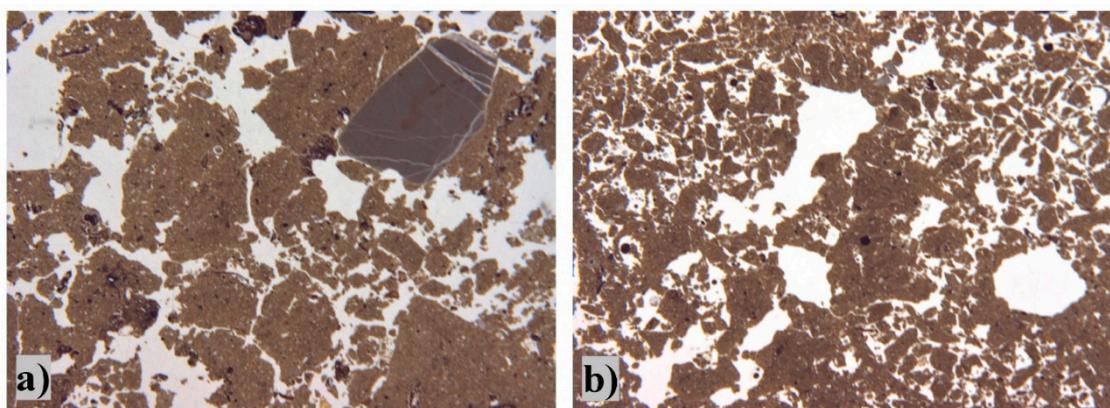


Figure 4. Macrophotographs of soil thin sections of two soils with the same bulk density, but quite different structure and pore distribution. (a) subangular blocky structure, (b) granular structure. The horizontal length of a section is 32 mm.

3.2. Soil Structure and Hydrological Behaviour

A suitable method for studying soil function related to water retention and transport is the measure of water retention curve (WRC). The sample sizes and the pores sizes investigated with this method are similar to the ones examined with imaging techniques. The WRC can be transformed into pore size distribution, and moreover it can be used to derive several indicators (Macropore volume—PMAC), air capacity (AC), relative field capacity (RFC), available water capacity (AWC), Dexter S-index) (Table 2) [83]. However, this method hardly provides information about what happens at the soil surface. For example, a soil crust of a few millimetres, hindering water infiltration and gas exchanges, may seriously affect soil hydrological functionality and crop production but can be hardly analysed with the WRC.

Table 2. Indicators calculated through water retention curves.

Water Retention Curve Indicators	Equations	Optimal Ranges [76]	Measure Units
Macropore volume (P_{MAC})	$= \theta_s (\psi = 0 \text{ kPa}) - \theta_m (\psi = -1 \text{ kPa})$	≥ 0.07	$\text{m}^3 \cdot \text{m}^{-3}$
Air Capacity (AC)	$= \theta_s (\psi = 0 \text{ kPa}) - \theta_{FC} (\psi = -10 \text{ kPa})$	≥ 0.14	$\text{m}^3 \cdot \text{m}^{-3}$
Available Water Capacity (AWC)	$= \theta_{FC} (\psi = -10 \text{ kPa}) - \theta_{WP} (\psi = -1500 \text{ kPa})$	≥ 0.15	$\text{m}^3 \cdot \text{m}^{-3}$
Relative Field Capacity (RFC)	$= (\theta_{FC} / \theta_s)$	0.6–0.7	-
Dexter S-index	$= -n(\theta_s - \theta_r)[(2n - 1)/(n - 1)]^{\frac{1}{n}-2}$	≥ 0.035	-

There is no single indicator able to provide exhaustive and reliable information on the physical-hydrological quality of a soil. As an example, Vignozzi et al. [84] used several soil physical indicators to study soil quality and hydrological conditions in a high-density olive orchard in Tuscany (Italy) under conservation tillage (CT) and natural grass cover (NC). Soil macroporosity characterization by image analysis highlighted soil structure degradation in the CT topsoil. BD and total macroporosity showed a similar trend; nevertheless, BD evidenced soil critical conditions for root growth only in the under-surface layer (10–30 cm) of CT. In this layer, AC reached a value lower than $0.10 \text{ m}^3 \cdot \text{m}^{-3}$, the recommended limit to prevent the occurrence of crop-damage or yield-reduction [85]. CT soil, characterized by very low AS and very high percentage of larger pores, was prone to collapse after an intense rainfall, as reported by Gucci et al. [86]. These authors also detected a drastic reduction of soil water infiltration associated to surface crusting.

Measuring water infiltration capacity, as well as permeability (hydraulic conductivity), is crucial to evaluate the hydrological functionality of soil structure. Both these properties indicate the ease with which water enters and flows through the soil. Infiltration refers to the soil surface, while permeability refers to the whole profile and can vary in each horizon. Any impediments, both on the surface and in depth, can strongly affect the soil hydrological behaviour and the water reserve for plants, an aspect particularly relevant in tree crops.

Soil water availability is the major constraint to tree crops productivity, especially in semiarid or sub-humid climatic conditions. In a study carried out in a mature olive grove in Southern Italy the impacts of two management systems (conventional—CS and sustainable—SS) on soil structure, hydraulic conductivity, and soil water content (up to 2 m depth) were evaluated [87]. In CS the surface was tilled two to three times per year, keeping the soil clear of grasses; in SS the soil surface was covered by spontaneous grasses which were mowed at least twice a year and the residues were left on the ground surface as mulch. CS, mainly adopted as dry farming technique to reduce water loss for evaporation and increase water infiltration, failed its objective. Despite the greater water consumption due to the grass cover, a higher water storage capacity was found in the SS. The best structural features of the SS soil improved water infiltration and permeability, so facilitating and accelerating the water storage also in the deeper layers (>1 m), a particularly relevant aspect for olive trees under rainfed conditions. On the contrary, CS caused drastic modifications of soil structure; important soil degradation phenomena were detected, namely crusting and plough pan formation at the lower limit of cultivation, both affecting the saturated hydraulic conductivity, which significantly decreased of two orders of magnitude [84].

In the cited studies, a large dataset of indicators was used to describe the soil hydrological behaviour. Nevertheless, an excessive number of indicators can increase collinearity as well as costs and time for measurements execution. Several authors, basing their selection on different criteria (expert judgement or statistical data reduction by multivariate techniques), developed minimum datasets of indicators for assessing soil quality [88] and effectiveness of restoration strategies [89]. More recently there has been a growing interest in (re-)using field visual soil evaluation (VSE) as an alternative to laboratory methods to characterize the impact of management on soil structure.

3.3. Visual Soil Structure Evaluation

Several visual methods to evaluate soil structure and soil quality have been developed and used for many years in different countries, mainly by agricultural extension service. VSE cannot reveal as much information on the geometrical arrangement of pores and constituents as computer tomography imaging, but assesses both the structural form and the structural stability [90] and can also provide information about soil resilience by some biological indicators [91]. This aspect is particularly important in view of an integrated and holistic assessment of soil health.

The most important approaches using visual soil evaluation have been reviewed by Bunneman et al. [88]. The VSE method can be divided into topsoil-focused spade methods and topsoil and subsoil focused profile methods. In the research context, the most used spade methods are the VSA (Visual Soil Assessment) [92] and the VESS (Visual Evaluation of Soil Structure) developed from the Peerlkamp method [90,93]. Among the soil profile methods, 'Profil Cultural' [94,95], SOILpak [96] and, most recently, the numeric visual evaluation of subsoil structure methods (SubVESS) [97] are used. Details of the methods have been published in a systematic review [98]. Recently, the VSE approaches have been used in soil evaluation and decision support system for soil management in tree crops, namely cherry trees in Germany [99], grapevines in northern Italy [100], almonds in Spain [101], and also to determine mechanical impacts of new forest plantations [102].

Generally, VSE techniques require inexpensive equipment and generate immediate results that correlate well with quantitative measurements of physical and biochemical properties, highlighting their potential utility. However, subjectivity is a limit for the adoption of these techniques and, when compared, the different methods sometimes led to different result in terms of soil physical quality [103]. Several properties related to soil structure are affected by different water contents. Defining the optimum range of water contents for visual soil evaluation and reducing the "operator dependent effect" should be a priority. For this purpose, more comparisons between scoring and field/laboratory measurements should be done.

Major benefits could be obtained in combining VSE with measurements of soil structure, i.e., integrating VSE in soil structure research, as these methods provide repeatable spatial information on large-scale aspects of soil structure that are difficult to obtain with other methods [72].

Further development of VSE could be achieved by combining it with sensing techniques at field or landscape scale in the context of precision farming. Combining VSE methods with visual crop evaluation may increase the agronomic relevance of VSE for identifying limiting soil conditions.

4. The Estimation of the Effective Available Water Capacity in the Root-Zone

The increase of plant water stress is one of the main and more frequent consequences of soil degradation [15,104], therefore, an estimation of the potential water availability that would be close to the reality is crucial to plan the measures for soil restoration and to verify their effects [89].

As is known, by AWC we mean the quantity of water available for plants in a range of values between the so-called hydrological constants ("field capacity" and "wilting point"); this quantity is usually expressed as volumetric fraction, percentage, or $\text{mm}\cdot\text{mm}^{-1}$ and, for the entire profile, in $\text{mm}\cdot\text{m}^{-1}$. The AWC concept was introduced with the aim of providing farmers with a practical criterion for assessing irrigation volumes [105]. Even in non-irrigated crops, however, the soil AWC is considered one of the main properties, being functional to all assessments of soil and land suitability in the agricultural, forestry, and environmental fields [106]. The AWC can be measured in different ways, but the most common method is the laboratory method, with sand box and pressure-plate extractors [107]. The AWC can also be estimated from easily measurable soil properties (e.g., texture, SOM), but the water retained at the tension corresponding to the so-called "field capacity" is more affected by the soil structural features [107]. Normal unit values of AWC in agricultural

soils vary between 5 and 25% by volume ($0.05\text{--}0.25\text{ mm}\cdot\text{mm}^{-1}$), depending on the texture, corresponding to a total of $50\text{--}250\text{ mm}\cdot\text{m}^{-1}$, since an unbounded rooting depth is generally assumed, and the rooting capacity of most plants is considered to be one meter [105].

A more accurate estimation, however, cannot ignore that the water actually available for plant transpiration depends on numerous factors. First of all, on the rooting depth, that is, the distance between the soil surface and a horizon or layer preventing radical penetration, for instance, a consolidated substrate, a cemented pedogenetic horizon, a layer very rich in salts, a water table [70]. Then there is the need to consider the quantity of skeleton, or coarse fragments (and its alteration state) present in the profile horizons, by subtracting the quantity of soil volume occupied by unaltered rock fragments, and finally the fraction of the volume of soil explored by the roots, that is, the soil mass that can actually be penetrated by roots [108]. This parameter is poorly considered or neglected in most soil assessments, in spite of the fact that the horizons of the profile can only be crossed from the roots in the parts where the macroporosity allows it, while the more compact masses remain practically rootless [106]. Soil horizons with difficult or only partial penetrability are particularly common in degraded and compacted soils due to improper management [15]. Impeding parts can be created either permanently or, more frequently, temporary, as when poorly structured soils are cultivated when too wet, especially with the mouldboard plough or with rotative tools, or are compacted by the passage of heavy machinery [47,49]. In these cases, many farmers try to increase soil macroporosity using rippers or other cultivators, which however can break the soil mass of the firm horizons until the working depth, but not in between the cutters.

4.1. Estimating Effective Available Water Capacity

The first step in estimating the effective available water capacity of soil is the calculation of the potential rooting capacity. The potential rooting capacity can be estimated through the sum of the values resulting from the following function:

$$Rc = Rd \times (1 - St) \times (1 - Cl) \quad (1)$$

where Rc (rooting capacity) is the volume of potential rooting, Rd (rooting depth) is the depth of rooting up to an impeding layer, St (stoniness) is the volume of the soil occupied by unaltered stones and Cl (clodiness) is the fraction of the volume of soil mass that cannot be penetrated by the roots, because compacted and massive [109]. In numerical values, Rc is expressed in unit volume (mm), Rd is the depth in mm, St and Cl are the equivalent in mm of the percentage volume of the mass occupied by the stones and the non-rootable soil mass, respectively. If the soil profile is made up of heterogeneous horizons, the calculation will have to be made for each individual horizon. Then the available water capacity of a soil can be related to the rooting capacity, instead of to the bulk soil.

For the calculation of Rc , the most difficult estimate parameter is certainly Cl , even though in the literature there are some references that can be followed for this purpose. The Soil Service of the USA has developed an empirical report indicating the bulk density values that limit plant growth, depending on both soil texture and structure [110]. The U.S. Natural Resources Conservation Service has produced a model and related software for estimating the main hydrological soil parameters, including AWC, which considers texture, amount of skeleton, compactness, salinity, and organic matter content, but not rootability [105].

A different approach is proposed by Dexter [62,111,112], which uses the S index, called the “Soil physical quality index”, derived from the slope of the water tension—volume curve. The threshold value of $S = 0.035$ corresponds to the boundary between good and poor physical quality of the soil and also between the soil compaction conditions that can be penetrated or not by the roots. The threshold value of S has a corresponding apparent density value for each soil textural class.

Pagliai and Vignozzi [113] used the micromorphometric approach to quantify the macroporosity and characterize the quality of the soil. Below 10% macroporosity, soils

were classified as compact and difficult to be penetrated from the roots. Finally, Ball et al. [93] proposed a field evaluation of the structural quality, through classes assigned with reference tables, to which it is possible to assign percentage values of soil rootability.

4.2. Relevance of an Effective AWC Estimation, a Case Study

The results of a research work carried out in some premium vineyards of Tuscany (Italy) can be used as an example to stress the practical relevance of a more realistic estimation of the soil AWC [114]. The four years trial highlighted that viticultural and oenological performance was positively related to soil water availability, with a rather high determination coefficient. This outcome was contrasting previous studies, which had indicated that the viticultural result of grape for red wines is generally limited by large water availability, as it causes lush growing at the expense of grape quality [115–117]. The explanation was related to the very low fertility of the experimental soils. Actually, the mechanical works carried out during the activities of surface preparation before planting had produced a deep upsetting of the original soil profiles and the stripping of the surface horizons. This had favoured the outcropping of stones and compacted deep soil layers in a variable amount, according to the local soil conditions before the mechanical work. Neither the successive soil ripping, nor the ordinary cultivation, had allowed to restore the excessive compaction throughout the soil profile horizons. Three soils showed good examples of degradation resulting from the earth movements. A *Haplic Cambisol* (*Calcaric, Skeletic*) according to WRB [16], clay-loamy and strongly gravelly (20–50%) with moderate AWC ($115 \text{ mm} \cdot \text{m}^{-1}$, corrected by the gravel content) and two *Endogleyic Stagnosols* (*Eutric, Clayic*), clayey, scarce gravelly, with moderate to high AWC ($130\text{--}170 \text{ mm} \cdot \text{m}^{-1}$). The three soils were poorly structured or massive, especially in depth; they showed few roots and a resistant consistence class throughout the profile, in contrast to the not degraded soils present in the same experimental vineyards. Although the AWC values of the three soils were similar or higher to the other more loamy or sandy soils under study, the monitoring of water content revealed significant lower values of available water during the growing seasons. Therefore, the rather good AWC values measured in these poorly structured clayey soils did not translate into a larger volume of water actually available to the vines. This was confirmed by stem water potential (Ψ_{stem}) and carbon isotopes ratio ($^{13}\text{C}/^{12}\text{C}$, or $\Delta^{13}\text{C}$) values, which indicated during the years of trial a stronger water stress, matching the requirement of the severe water stress class. Therefore, although corrected for the presence of skeleton, the AWC values of the studied soils were not reliable indicators of the effective plant water availability and should have been also corrected for the effective rooting capability of the soil mass, which was actually limited by poor soil aggregation and porosity.

5. Solutions to Restore Soil Physical-Hydrological Functions

Restoring optimal soil physical-hydrological characteristics after degradation is a complex and slow process, that can take many years. As described in the previous chapters, the soil physical-hydrological degradation under tree crops is mainly due to compaction, erosion, crusting, and soil deconstruction, and it is favoured by specific soil particle sizes and degradation processes, such as loss of organic matter and biological activity, salinization and sodification.

One of the most important and common degradation processes is soil compaction, mainly due to tractors traffic along inter-rows, for pruning, harvesting, and, especially, pest control [47,48]. The time needed to recover compacted soils was estimated by Froehlich et al. [118] from 5 to 18 years, depending on the soil type, degree of compaction and climate, whereas Webb (2002) [119] indicated around 100 years for full recover of heavy compacted soil in the U.S. Soil compaction can be reduced by several mechanical and natural methods involving subsoiling or strategic deep tillage, addition of exogenous organic matter, and use of cover crops, which are discussed in the following paragraphs.

5.1. Subsoiling

“Subsoiling” is defined as tillage below a depth of 35 cm [120], whereas “strategic deep tillage” is defined as a single or occasional practice with a deep ripper, rotary, spader, mouldboard plough or disk plough [121]. These techniques are very impactful on soil biology and should be avoided or used with great caution. Non-inversion subsoiling or strategic deep tillage can be used occasionally to loosen compact soil layers or to break hardpan, increasing soil macroporosity and internal drainage in compacted soils, without upsetting soil profile horizons. When these techniques are applied, soil is cut and sectioned, moved and crushed but soil biota is not much affected. The tillage depth, usually ranging from 40 to 100 cm, depends on the tree crops root system and the soil features, in particular the depth of eventual compacted layers or hardpans. Although there is a high risk to damage some roots of the tree crop, it is demonstrated that inter-row subsoiling has positive effects on plant growth and roots development, because of increasing macroporosity and water infiltration [120,122]. Clearly, the choice of the tool typology, the tillage depth, and the distance to the tree is basic to limit roots damage and to optimize the subsoiling practices. To improve the soil decompaction and aeration, vibrating subsoilers, formed from one to four shanks, have been developed [123–125]. These vibrating tools increase the decompaction capacity, reducing the draft force needed, and then fuel consumption [123,126].

Recently, “gas explosion subsoiling” tools based on pressured air has been designed [127,128]. These tools use a drilling pipe and high-pressure gas injection to shock soil body and then injects fertilizer. Fractures were generated after gas explosion and extended radially outward from the centre for about 40–60 cm. The effects on soil biota of this practice, however, is still unknown.

Subsoiling may be also associated with the use of amendments. In the case of soils with high sodicity, which tend to become massive and dense, subsoiling may incorporate slotting of gypsum (CaSO_4) or Ca-zeolites [129]. The release of Ca^{2+} from gypsum and Ca-zeolites, and the consequent replacement of Na^+ in exchangeable complex of the soil, directly prevents pH and ESP increasing, clay swelling and dispersion, and indirectly increases porosity, structural stability, and hydraulic properties, providing Ca^{2+} ions for exchange with Na^+ [130].

5.2. Surface and Sub-Surface Drainage

Before carrying on practices to restore degraded soils, it is mandatory to preserve soil from erosion through an optimal water runoff control. During the centuries, practices have been developed to prevent or mitigate flood events or unusual runoff on the fields, including a methodical use and maintenance of drainage furrows. During the last decades, however, the enlargement of the fields for mechanization and the scarce maintenance of the drainage channels have increased runoff and soil erosion, even during ordinary rain events. In tree crops on slope, like vineyards, olive groves, hilly and mountain fruit trees, the risk of soil erosion due to water runoff is usually extremely high. The global warming is increasing the extreme meteoric events, which are becoming more frequent and stronger [131]. In the sloping areas, more sensitive to soil erosion, is therefore crucial to project correct hydrological measures to intercept and divert excessive runoff, namely diversion ditches, swales, drainage canals, surface drains, diversion terraces, terrace channels, and bench terraces. The diversion ditches and the terrace channels are placed upslope of areas where protection is required, to intercept water and to divert in artificial waterways or along gently graded slopes. Diversion terraces are recommended on slopes from 8% to 20%, whereas bench terraces, supported by a barrier of rocks or other materials are more indicated for steeper slopes [132]. The presence of grass cover in the tree crops inter-rows mitigates soil erosion through the increasing of water infiltration and soil aggregates stability, as well as the decrease of runoff velocity [133–135]. Straw mulching of soil surface of vineyards and other tree crops is another method that guarantees good protection against soil erosion and runoff [29,136].

Increasing water infiltration in clayey and poorly drained soils is also fundamental to limit erosion due to water runoff. A mechanical method commonly used in tree crops on fine texture and cohesive soils to improve internal drainage is the “mole plough”. A mole plough is a long subsoiler (about 1 m deep) formed by a ripper blade (or leg) and a cylindrical foot that drags a mole bullet (plug or expander) to pierce and to compact the channel walls. The essence of mole ploughing is to produce continuous channels in subsoil that contain more than 30% of clay [137]. The efficiency and stability of mole drainage is largely dependent on soil type and soil moisture content during installation [138]. The channels should be re-formed at approximately 2- to 5-year intervals, and they are scarcely stable in soils with strong shrinking and swelling properties (Vertisols) and with dispersion and slaking properties (i.e., sodic soils) [137]. An alternative to mole plough in soils which cannot sustain a stable mole channel is the use of gravel to fill the mole channels. The name of this technique is “gravel mole drainage” [139]. Both the methods have been often used in soils on plain, to mitigate waterlogging, as an alternative to tile drains.

5.3. Organic Amendments

The restoring of good soil physical features is strictly connected to the improvements of soil biological and chemical characteristics. Regeneration of organic matter in soil increases biological activity, introducing a positive feedback on soil physical and chemical qualities. Among the available amendments, organic composted material, easier said compost (Figure 5), can be an excellent soil improver in terms of biological and chemical fertility, as well as soil physical properties in tree crops [140–143]. The term “compost” includes a mixture of several types of solid organic materials (manure, vegetal residue, straw, wastes derived by agro-food production, paper waste, etc.) that have been subjected to a controlled aerobic fermentation. It has undergone mesophilic and thermophilic temperatures, which significantly reduces the pathogens and weed seeds [144].



Figure 5. Compost produced in farm using manure, pruning residue, grape stalks, and marc, distributed by a manure spreader within a vineyard characterized by eroded and scarcely fertile soils.

Incorporating compost of good quality in soils that have lost their optimal functionality has been demonstrated to produce improvements to total porosity, aggregates stability and soil water retention capacity [140,141,145]. The decomposition of compost in soil produces polysaccharide compounds and then humic and fulvic acids, which act as glues to bond soil particles into aggregates [140]. Moreover, this organic matter addition in soil

stimulates microbial activity and fungal hyphae development that stabilize soil aggregates. In particular, it is demonstrated by several studies that the glomalin or glomalin-related glycoproteins, produced by fungal hyphae, have fundamental influence on soil aggregation and stabilization of aggregates, also in very degraded soils [146,147].

Clearly, the quality and characteristics of compost can be strongly variable because of nature of raw materials used, the duration and development of composting processes. This variability drives the effects on soil of compost addition, which could be also negative [148,149] if the composted materials are of poor quality, show excess of salts, include contaminated materials, or have chemical-physical characteristics not suitable in that context. Therefore, compost characterization, in terms of quality, stability, and maturity, represents the main requirement for its safe and fruitful use for agricultural purposes.

Another organic amendment that has been used in the last decades to restore organic matter in poor soils is “Biochar”. Biochar is formed by biological residues combusted at high temperatures under low oxygen conditions (pyrolytic process), resulting in a porous, low density carbon rich material. The large surface area and high cation exchange capacity enable sorption of contaminants, both organic and inorganic, in polluted soils [150]. From a physical point of view, many authors reported positive effects to incorporate biochar in soil, in particular a reduction of bulk density and an increasing of water holding capacity [151,152]. Other authors are somehow sceptical about the benefits of biochar on soil physical-chemical properties, and above all plant nutrition, as they state that the benefits are strongly dependent from the quality and typology of biochar [153,154]. Sandy soils appear to respond more to biochar than clayey soils [155]. There are several examples of the combined use of compost and biochar to recover soil physical and chemical fertility. Sánchez-García et al. [156] found that biochar applied alone does not increase nitrogen availability in soils of olive groves, whereas application of biochar and compost in combination showed a synergistic effect increasing microbial activity, organic carbon, and nitrogen availability. Regarding the biochar and compost blend, other authors found positive effects on soil physical quality, but deleterious effects on plant nutrition [157].

Hence, the benefits of the use of organic amendments in soils are strongly dependent on the quality and characteristics of the materials, both compost and biochar. In general, clear positive effects can be found in the use of organic amendments on degraded soils, particularly organic matter increasing, physical properties improvements, and higher biological activities. On the other hand, the benefits on plant nutrition are strongly dependent on the quality and chemical characteristics of the organic amendments (C/N ratio, pH, EC, trace elements, etc.). Finally, the improved soil conditions relate basically to the topsoil, while deep soil layers are only slowly affected by the practice.

5.4. Cover Crops

In tree crops, interrow cover crops (CC), also called “service crops” [158], are often used for several purposes, from prevention of erosion and compaction, as well as increasing of fertility and biodiversity, to practical agronomical issues as to ease tractors passage and harvest, cost reduction for soil management, weeds and pests control, nitrogen fixation, etc.

The adoption of CC in tree crops is crucial to fulfil the second and third principle of conservation agriculture, which foresees: (i) continuous minimum mechanical soil disturbance, (ii) permanent organic soil cover, and (iii) diversification of crop species grown in sequences and/or associations [159].

CC can be subdivided in two big groups:

- Temporary CC: generally annual variety of legumes, cereals and other species, yearly sowed and incorporated into the soil for green manure, or in some cases left on the surface as mulching.
- Permanent CC: perennial grass species, either sowed using selected varieties or natural grass cover, mowed from once to several times per year and left on the ground for mulching.

The importance of CC, in particular permanent CC, in the interrow of tree crops to control water erosion is widely accepted. Grass covered soils are less subjected to rain drop impact (splash erosion), water runoff is strongly reduced, while organic matter, soil biological activity, and topsoil AS increase (Figure 6) [145,160]. The organic carbon originated from roots exudates and the increase of microbial activity enhance soil aggregation through the bonding of primary soil particles [161]. Permanent grass cover tends to increase organic matter and AS after 2–3 years [65,162], however, a single tillage event can immediately decrease the aggregate resistance [163]. Permanent CC favours the organic carbon storage mainly in form of particulate, humic acids and humin [164], but generally reduces the nitrogen availability for plants [164,165]. In permanent CC of temperate zones, where seasonality occurs during the year, the upper soil horizons tend to dry more rapidly than in the tilled soil. Consequently, nitrogen mineralization decreases faster and stop early during the summer [166]. However, in rainfed tree crops, the effect of permanent CC on water (and nitrogen) availability is a debated issue. A study of Palese et al. [87] in rainfed olive orchards in Mediterranean area showed that permanent grass cover increased the water deep infiltration during winter, the soil microporosity and the pores connections, then improving water availability for plants. Other studies reported a reduction of plant water availability during vegetative period in inter-row permanent CC [167,168]. In soil-degraded areas, the negative effect of permanent CC on plant water stress could be accentuated, therefore such kind of soil recovering management should be carefully planned and the grass cover should be mowed several times per year. In these cases, it is crucial that the residues are left on the ground to armour the soil surface.



Figure 6. (a) Olive orchard with permanent grass cover, straw and pruning mulching. (b) Close-up of the topsoil under the mulch. Earthworms activity and good soil structuration are evident.

The decision for temporary CC aimed to improve soil quality is often a winning strategy in the context of seasonal climates characterized by limited water and nitrogen

availability [166,169,170]. Winter CC in the tree crops inter-rows allow to reduce erosion and nutrient leaching during rainy season, as well as to increase water infiltration [171]. On the other hand, during the sowing period and the first phases of CC growing, in autumn or spring, the scarce grass cover makes the soil more sensitive to erosion. The effective protection of temporary CC to erosion is therefore limited to a short period from 2 months (for spring sowing) to about 5 months (for autumn sowing). The incorporation of CC into the soil strongly increases the fresh organic matter available for microorganisms, promoting increase of biological activity and nutrients availability [157,169], as well as improving physical properties like BD and AS [145,168,172]. On the other hand, the incorporation of temporary CC into the soil by tillage increases more the mineralization of organic matter, and then the GHGs emission, than permanent grass cover. Compared to conventional tillage of inter-rows, temporary CC increase SOM as a consequence of higher carbon inputs, although some short-term experiments (1–2 years) of green manure showed no significant increases of soil SOM in comparison to tilled soil [163,173]. Other studies reported significant increases of soil C content using temporary CC than bare and tilled soils, but lower SOM increase than no tilled soils [169,174,175].

According to Morlat and Jaquet [172], the effects of green manure is mainly in the topsoil, usually from 0 to 30–45 cm, but it does not affect the physical and chemical characteristics of deeper horizons. Some grass species, characterized by deep rooting and high roots penetration strength, can be used to reduce compaction, and increase water infiltration of deeper soil horizons. Tap-rooted species like forage radish (*Raphanus sativus*), rapeseed (*Brassica napus*), turnip (*Brassica rapa*), Indian mustard (*Brassica Juncea*), and sunn hemp (*Crotolaria Juncea*) are used for bio-ploughing or bio-drainage, because of their ability to explore soil until a depth of 1 m and more [176,177].

Obviously, the ability of CC to improve soil fertility in tree crops is strongly dependent from their covering rate and development [158,163]. On the other hand, the success of CC on degraded soils in tree crops is not always expected. Usually, degraded soils in tree crops can have lost their surface horizons and most of chemical fertility for erosion, they can show high stoniness, or can be compacted or hardened. CC sowing and cultivation in these circumstances is difficult. In degraded soils, a wrong selection of species, a non-optimal seed-bed preparation, and bad meteorological conditions may have stronger negative impacts than on soils with good functionality [163]. In particular, the chemical composition of the residue of CC can have a great importance in the recovery of degraded soils, since they not only show very low SOM content but also very low C/N values, reflecting the composition of the organic constituents of the biomass [15]. Therefore, CC with high C/N residues may be difficult to be digested by soil biota and might need more time to increase SOM and glomalin, thus providing a positive feedback on soil structure and physical properties [178].

Coupling the management of CC with the use of proper organic amendments and fertilizers in degraded areas of tree crops could be a good strategy to guarantee the success of CC growing, and then their positive effects on restoring good soil functionality. In compacted soils, previous subsoiling techniques can also increase the positive effects of CC and organic amendments.

5.5. Bio-Inoculants

Bacterial and fungal inoculants have a potential to restore the fertility of degraded soils through the increasing of nutrient bioavailability and promoting soil aggregation through release of mucilaginous exudates and polysaccharides [179]. In the last decade, there has been an increasing demand for bio-inoculants, due to increasing cost of agrochemicals and demand for eco-friendly approaches in agriculture. In the global market, the sale of bio-inoculants and biostimulants in general show annual growth rates of approximately 10–12% [180]. Plant growth-promoting bacteria (PGPB) and arbuscular mycorrhizal fungi (AMF) are used for several purposes, like increasing plants resistance to abiotic stresses, salinity [181], drought [182,183], and nutrients deficiencies [184,185]. AMF root-symbiosis

is particularly important for enhancing the uptake of the relatively immobile and insoluble phosphate ions in soil, and then increasing the P nutrition of the plants [186]. Although the stimulation action of bio-inoculants seems to be more efficient in annual crops under greenhouse (vegetables, ornamentals), because of the higher application frequency and the favourable climatic conditions in controlled environment, some papers reported good results also in fruit tree crops [187].

Due to fixation, chelation, production of organic acid, siderophores, hydrophobins and glomalin protein, AMF and PGPB can enhance nutrient bioavailability and improve soil aggregation and aggregates stability. Hence, they can be used in reinstating both the chemical and physical fertility of degraded soil [179]. In other cases, PGPB and AMF were used in polluted soils to increase the efficiency of phytoremediation techniques [188] and found an important role in revegetation programs of old mining sites [147,189].

Success rate of bio-inoculants under field conditions mainly depends on the inoculation methods and the antagonistic or synergistic interaction with indigenous micro-biota. Co-inoculation of bacteria and fungi with organic fertilizers are more beneficial for reinstating soil fertility and organic matter content than single inoculum [179,190].

6. Conclusions

Several kinds of cropland are affected by soil degradation, but tree crops may show more evidently than annual herbaceous crops the effects of soil physical-hydrological deterioration, because of their deeper and wider rooting system, the longer life cycle, and the limited subsoiling agrotechniques that can be applied. Moreover, the deep mechanical impact of land preparation for tree crop plantation, namely deep ploughing, land levelling and, eventually, placement of artificial drainages, can lead to irreversible soil degradation due to mistakes in land preparation. Preliminary studies on physical-hydrological features of the whole soil profile and their spatial variability within field are needed to correctly plan the soil and land preparation before tree plantation. Such approach allows to minimize most of the troubles recurring in the tree crops, namely waterlogging, crusting, erosion, compaction, loss of organic matter and biological activity.

Although all soils are potentially subjected to these problems, particular attention should be given to soils more sensitive to physical degradation, which, in general, have fine texture, very scarce or very abundant coarse fragments, low organic matter, low calcium carbonate content, salinity with high sodium content. On top of that, soil depth and, in particular, rooting capacity, are fundamental features to indicate the soil physical-hydrological suitability for tree crops. This paper proposes an estimation of the effective soil available water that corrects the AWC with the volume occupied by stones and the volume of soil clods that cannot be penetrated by roots, because of compaction and/or cementation.

Several solutions to restore soil-physical degradation in tree crops are reported in literature and summarized in the last chapter of this review. They mainly involve mechanical techniques, such as subsoiling and artificial drainages, organic amendments, both external (compost, biochar) and internal (cover crops), as well as use of biological inoculants. The choice of the best strategy and restoration practices should not only be soil specific, but also tailored according to the ecosystem functions that need to be improved besides food production. For instance, groundwater recharge can be enhanced by improving soil infiltration and internal drainage by means of a proper ripping that is also aimed at decreasing soil compactness and increasing rootability. Carbon sequestration can be enhanced through the adoption of cover crops sowed to ameliorate soil structure and water infiltration and storage.

Finding the right solutions for the improvement of physical and hydrological soil qualities of tree crops needs the investigation of the whole soil profile, and in general is a more demanding activity than in herbaceous crops. On the other hand, the higher profitability and time lasting of tree crops justify a higher investment to combat soil degradation and to increase the crop agronomic efficiency and the functionality of the agroecosystem.

Author Contributions: E.A.C.C. and S.P. (Simone Priori) conceptualized the manuscript; S.P. (Sergio Pellegrini) edited the Section 2; N.V. edited the Section 3; E.A.C.C. edited the Section 4; S.P. (Simone Priori) edited the Section 5. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available in the cited publications.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AC	Air Capacity
AS	Aggregate stability
AWC	Available water capacity
BD	Bulk Density
Cl	Clodiness
MWD	Mean Weight Diameter
PMAC	Macropore volume
PR	Penetration resistance
Rc	Rooting capacity, is the volume of potential rooting
Rd	Rooting depth, is the depth of rooting up to an impeding layer
RFC	Relative Field Capacity
SI	Stability structure index
St	Stoniness, is the volume of the soil occupied by unaltered stones
WRC	Water Retention Curve

References

1. FAO; ITPS. *Status of the World's Soil Resources (SWSR)—Main Report*; Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils: Rome, Italy, 2015; p. 650.
2. Veerman, C.; Pinto Correia, T.; Bastioli, C.; Biro, B.; Bouma, J.; Cienciela, E. Caring for Soil is Caring for Life. In *Interim Report for the Mission Board for Soil Health and Food*; European Commission: Brussels, Belgium, 2020; p. 52.
3. Panagos, P.; Borrelli, P.; Meusburger, K.; Alewell, C.; Lugato, E.; Montanarella, L. Estimating the soil erosion cover-management factor at the European scale. *Land Use Policy* **2015**, *48*, 38–50. [[CrossRef](#)]
4. Hartemink, A.E. Soil erosion: Perennial crop plantations. In *Encyclopedia of Soil Science*; Taylor and Francis: New York, NY, USA, 2006; pp. 1613–1617.
5. Cerdan, O.; Govers, G.; Le Bissonnais, Y.; Van Oost, K.; Poesen, J.; Saby, N.; Gobin, A.; Vacca, A.; Quinton, J.; Auerwald, K.; et al. Rates and spatial variations of soil erosion in Europe: A study based on erosion plot data. *Geomorphology* **2010**, *122*, 167–177. [[CrossRef](#)]
6. Kosmas, C.; Danalatos, N.; Cammeraat, L.H.; Chabart, M.; Diamantopoulos, J.; Farand, R.; Gutierrez, L.; Jacob, A.; Marques, H.; Martinez-Fernandez, J.; et al. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena* **1997**, *29*, 45–59. [[CrossRef](#)]
7. Martínez-Casasnovas, J.A.; Ramos, M.C.; Ribes-Dasi, M. Soil erosion caused by extreme rainfall events: Mapping and quantification in agricultural plots from very detailed digital elevation models. *Geoderma* **2002**, *105*, 105–140. [[CrossRef](#)]
8. Costantini, E.A.C.; Agnelli, A.E.; Fabiani, A.; Gagnarli, E.; Mocali, S.; Priori, S.; Simoni, S.; Valboa, G. Short-term recovery of soil physical, chemical, micro-and mesobiological functions in a new vineyard under organic farming. *Soil* **2015**, *1*, 443–457. [[CrossRef](#)]
9. Cerdà, A.; Keesstra, S.D.; Rodrigo-Comino, J.; Novara, A.; Pereira, P.; Brevik, E.; Giménez-Moreira, A.; Fernández-Raga, M.; Pulido, M.; di Prima, S.; et al. Runoff initiation, soil detachment and connectivity are enhanced as a consequence of vineyards plantations. *J. Environ. Manag.* **2017**, *202*, 268–275. [[CrossRef](#)]
10. Polge de Combret-Champart, L.; Guilpart, N.; Merot, A.; Capillon, A.; Gary, C. Determinants of the degradation of soil structure in vineyards with a view to conversion to organic farming. *Soil Use Manag.* **2013**, *29*, 557–566. [[CrossRef](#)]
11. 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](#)]
12. Martínez-Casasnovas, J.A.; Concepcion Ramos, M. Soil alteration due to erosion, ploughing and levelling of vineyards in north east Spain. *Soil Use Manag.* **2009**, *25*, 183–192. [[CrossRef](#)]

13. Poeplau, C.; Don, A.; Vesterdal, L.; Leifeld, J.; Van Wesemael, B.; Schumacher, J.; Gensior, A. Temporal dynamics of soil organic carbon after land-use change in the temperate zone—carbon response functions as a model approach. *Glob. Chang. Biol.* **2011**, *17*, 2415–2427. [[CrossRef](#)]
14. Don, A.; Schumacher, J.; Freibauer, A. Impact of tropical land-use change on soil organic carbon stocks—a meta-analysis. *Glob. Chang. Biol.* **2011**, *17*, 1658–1670. [[CrossRef](#)]
15. Costantini, E.A.C.; Castaldini, M.; Diago, M.P.; Giffard, B.; Lagomarsino, A.; Schroers, H.J.; Priori, S.; Valboa, G.; Agnelli, A.E.; Akca, E.; et al. Effects of soil erosion on agro-ecosystem services and soil functions: A multidisciplinary study in nineteen organically farmed European and Turkish vineyards. *J. Environ. Manag.* **2018**, *223*, 614–624. [[CrossRef](#)] [[PubMed](#)]
16. IUSS Working Group WRB. World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. *World Soil Resour. Rep.* **2015**, *106*, 192.
17. Soil Science Glossary Terms Committee; Soil Science Society of America. *Glossary of Soil Science Terms*; ASA-CSSA-SSSA: Madison, WI, USA, 2008.
18. FAO. Available online: <http://www.fao.org/soils-portal/soil-degradation-restoration/en/> (accessed on 28 December 2020).
19. Pagliai, M.; Vignozzi, N. Soil porosity as an indicator of soil health. *Ann. Arid Zone* **2006**, *45*, 259–286.
20. Lal, R.; Hall, G.F.; Miller, F.P. Soil Degradation: I. Basic Processes. *Land Degrad. Rehabil.* **1989**, *1*, 51–69. [[CrossRef](#)]
21. Lal, R. (Ed.) *Soil Quality and Soil Erosion*; CRC Press: Boca Raton, FL, USA, 1998.
22. USDA-NRCS. Soil Quality: Selecting Physical Indicators to Assess Soil Function. In *Soil Quality Technical Note No.10*; Soil Quality National Technology Development Team, East National Technology Support Center, Natural Resources Conservation Service (NRCS): Greensboro, NC, USA, 2008.
23. Six, J.; Paustian, K.; Elliott, E.T.; Combrink, C. Soil structure and soil organic matter. I. Distribution of aggregate size classes and aggregated associated carbon. *Soil Sci. Soc. Am. J.* **2000**, *64*, 681–689. [[CrossRef](#)]
24. Obalum, S.E.; Chibuike, G.U.; Peth, S.; Ouyang, Y. Soil organic matter as sole indicator of soil degradation. *Environ. Monit. Assess.* **2017**, *189*, 176. [[CrossRef](#)]
25. Soane, B.D. The role of organic matter in soil compactability: A review of some practical aspects. *Soil Tillage Res.* **1990**, *16*, 179–201. [[CrossRef](#)]
26. Lal, R. Soil degradation by erosion. *Land Degrad. Dev.* **2001**, *12*, 519–539. [[CrossRef](#)]
27. Six, J.; Bossuyt, H.; Degryze, S.; Denef, K. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* **2004**, *79*, 7–31. [[CrossRef](#)]
28. Siddiky, M.R.K.; Kohler, J.; Cosme, M.; Rillig, M.C. Soil biota effects on soil structure: Interactions between arbuscular mycorrhizal fungal mycelium and collembola. *Soil Biol. Biochem.* **2012**, *50*, 33–39. [[CrossRef](#)]
29. Prosdocimi, M.; Cerdá, A.; Tarolli, P. Soil water erosion on Mediterranean vineyards: A review. *Catena* **2016**, *141*, 1–21. [[CrossRef](#)]
30. Biddoccu, M.; Ferraris, S.; Pitacco, A.; Cavallo, E. Temporal variability of soil management effects on soil hydrological properties, runoff and erosion at the field scale in a hillslope vineyard, North- West Italy. *Soil Tillage Res.* **2017**, *165*, 46–48. [[CrossRef](#)]
31. Edelstein, M.; Plaut, Z.; Ben-Hur, M. Water salinity and sodicity effects on soil structure and hydraulic properties. *Adv. Hortic. Sci.* **2010**, 154–160.
32. Richards, L.A. (Ed.) Diagnosis and improvements of saline and alkali soils. In *Agriculture Handbook 60*; USDA: Riverside, CA, USA, 1954; p. 160.
33. Rengasamy, P.; Marchuk, A. Cation ratio of soil structural stability (CROSS). *Soil Res.* **2011**, *49*, 280–285. [[CrossRef](#)]
34. Qadir, M.; Schubert, S.; Oster, J.D.; Sposito, G.; Minhas, P.S.; Cheraghi, S.A.; Murtaza, G.; Mirzabaev, A.; Saqib, M. High magnesium waters and soils: Emerging environmental and food security constraints. *Sci. Total Environ.* **2018**, *642*, 1108–1117. [[CrossRef](#)]
35. Keren, R. Specific effect of magnesium on soil erosion and water infiltration. *Soil Sci. Soc. Am. J.* **1991**, *55*, 783–787. [[CrossRef](#)]
36. Oster, J.; Jayawardane, N.S. Agricultural management of sodic soils. In *Sodic Soils: Distribution, Properties, Management and Environmental Consequences*; Sumner, M.E., Naidu, R., Eds.; Oxford University Press: Oxford, UK, 1998; pp. 125–147.
37. European Commission. *European Commission—Thematic Strategy for Soil Protection*; [SEC(2006)620] [SEC(2006)1165] [COM/2006/0231]; European Commission: Bruxelles, Belgium, 2006.
38. Loch, R.J.; Foley, J.L. Measurement of aggregate breakdown under rain: Comparison with tests of water stability and relationships with field measurements of infiltration. *Aust. J. Soil Res.* **1994**, *32*, 701–720. [[CrossRef](#)]
39. Pagliai, M.; Bisdom, E.B.A.; Ledin, S. Changes in surface structure (crusting) after application of sewage sludges and pig slurry to cultivated agricultural soils in northern Italy. *Geoderma* **1983**, *30*, 35–53. [[CrossRef](#)]
40. Usón, A.; Poch, R.M. Effects of tillage and management practices on soil crust morphology under a Mediterranean environment. *Soil Tillage Res.* **2000**, *54*, 191–196. [[CrossRef](#)]
41. Laker, M.C.; Nortjé, G.P. Review of existing knowledge on soil crusting in South Africa. In *Advances in Agronomy*; Academic Press: Cambridge, MA, USA, 2019; Volume 155, pp. 189–242.
42. Chesworth, W. Crusts, Crusting. In *Encyclopedia of Soil Science*; Chesworth, W., Ed.; Encyclopedia of Earth Sciences Series; Springer: Berlin/Heidelberg, Germany, 2008.
43. Morin, J. Improving Water Management in the Semi-arid Region of Cameroon. In *Study Report for the 1989 Season to GIARA (German-Israel Agricultural Research Agreement)*; Ministry of Foreign Affairs: Tel Aviv, Israel, 1989.
44. FAO. Methodology for assessing soil degradation. In *Report on the FAO/UNEP Expert Consultation*; FAO: Rome, Italy, 1978.

45. Collinet, J.; Valentin, C. Evaluation of factors influencing water erosion in West Africa using rainfall simulation. In *Challenges in Africa Hydrology and Water Resources*; IAHS Publ. No. 144; UKCEH Wallingford: Oxfordshire, UK, 1984; pp. 451–461.
46. Poesen, J.; Ingelmo, S. Runoff and sediment yield from topsoil with different porosity as affected by rock fragment cover and position. *Catena* **1992**, *19*, 451–474. [[CrossRef](#)]
47. Becerra, A.T.; Botta, G.F.; Bravo, X.L.; Tourn, M.; Melcon, F.B.; Vazquez, J.; Rivero, D.; Linares, P.; Nardon, G. Soil compaction distribution under tractor traffic in almond (*Prunus amygdalus* L.) orchard in Almería España. *Soil Tillage Res.* **2010**, *107*, 49–56. [[CrossRef](#)]
48. Ferrero, A.; Usowicz, B.; Lipiec, J. Effects of tractor traffic on spatial variability of soil strength and water content in grass covered and cultivated sloping vineyard. *Soil Tillage Res.* **2005**, *84*, 127–138. [[CrossRef](#)]
49. Duiker, S.W. *Effects of Soil Compaction*; Penn State Extension: University Park, PA, USA, 2004.
50. Horn, R.; Taubner, H.; Wuttke, M.; Baumgartl, T. Soil physical properties related to soil structure. *Soil Tillage Res.* **1994**, *30*, 187–216. [[CrossRef](#)]
51. Willett, M.; Smith, T.J.; Peterson, A.B.; Hinman, H. Growing profitable apple orchards in replant sites: An interdisciplinary team approach in Washington State. *Hort. Technol.* **1994**, *4*, 175–180. [[CrossRef](#)]
52. Perret, P.; Koblet, W. Soil compaction induced iron-chlorosis in grape vineyards: Presumed involvement of soil ethylene. *J. Plant Nutr.* **1984**, *7*, 533–539. [[CrossRef](#)]
53. Eckelmann, W.; Baritz, R.; Bialousz, S.; Bielek, P.; Carre, F.; Houšková, B.; Jones, R.J.A.; Kibblewhite, M.G.; Kozak, J.; Le Bas, C.; et al. Common Criteria for Risk Area Identification according to Soil Threats. In *European Soil Bureau Research Report No.20, EUR 22185 EN*; Office for Official Publications of the European Communities: Luxembourg, 2006; p. 94.
54. Bradford, J.M.; Gupta, S.C. Soil compressibility. In *Methods of Soil Analysis, Part 1: Physical and Mineralogical Properties*, 2nd ed.; Klute, A., Ed.; American Society of Agronomy: Madison, WI, USA, 1986; pp. 479–492.
55. Horn, R.; Lebert, M. Soil compactability and compressibility. In *Soil Compaction in Crop Production, Developments in Agricultural Engineering*; Soane, B.D., van Ouwerkerk, C., Eds.; Elsevier: Amsterdam, The Netherlands, 1994; Volume 11, pp. 45–69.
56. Imhoff, S.; Da Saliva, A.P.; Fallow, D. Susceptibility to compaction, load support capacity and soil compressibility of Hapludox. *Soil Sci. Soc. Am. J.* **2004**, *68*, 17–24. [[CrossRef](#)]
57. Nawaz, M.F.; Bourrié, G.; Trolard, F. Soil compaction impact and modelling. A review. *Agron. Sustain. Dev.* **2013**, *33*, 291–309. [[CrossRef](#)]
58. Rücknagel, J.; Götze, P.; Hofmann, B.; Christen, O.; Marschall, K. The influence of soil gravel content on compaction behaviour and pre-compression stress. *Geoderma* **2013**, *209*, 226–232. [[CrossRef](#)]
59. Verbist, K.; Baetens, J.; Cornelis, W.M.; Gabriels, D.; Torres, C.; Soto, G. Hydraulic conductivity as influenced by stoniness in degraded drylands of Chile. *Soil Sci. Soc. Am. J.* **2009**, *73*, 471–484. [[CrossRef](#)]
60. Kemper, W.D.; Nick, A.D.; Corey, A.T. Accumulation of water in soils under gravel and sand mulches. *Soil Sci. Soc. Am. J.* **1994**, *58*, 56–63. [[CrossRef](#)]
61. Magier, J.; Ravina, I. Rock fragments and soil depth as factors in land evolution. In *Erosion and Productivity of Soils Containing Rock Fragments*; Special Publication no. 13; Soil Science Society of America: Madison, WI, USA, 1984; pp. 13–30.
62. Dexter, A.R. Soil physical quality: Part II. Friability, tillage, tilth and hard-setting. *Geoderma* **2004**, *120*, 215–225. [[CrossRef](#)]
63. Renard, K.G.; Foster, G.A.; Weesies, D.A.; McCool, D.K.; Yoder, D.C. *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*, Agriculture Handbook No. 703; USDA: Washington, DC, USA, 1997.
64. Bonilla, C.A.; Johnson, O.I. Soil erodibility mapping and its correlation with soil properties in Central Chile. *Geoderma* **2012**, *189*, 116–123. [[CrossRef](#)]
65. Yang, X.; Gray, J.; Chapman, G.; Zhu, Q.; Tulau, M.; McInnes-Clarke, S. Digital mapping of soil erodibility for water erosion in New South Wales, Australia. *Soil Res.* **2018**, *56*, 158–170. [[CrossRef](#)]
66. Bronick, C.J.; Lal, R. Soil structure and management: A review. *Geoderma* **2005**, *124*, 3–22. [[CrossRef](#)]
67. Costantini, E.A.; Lorenzetti, R. Soil degradation processes in the Italian agricultural and forest ecosystems. *Ital. J. Agron.* **2013**, *4*. [[CrossRef](#)]
68. Rabot, E.; Wiesmeier, M.; Schlüter, S.; Vogel, H.J. Soil structure as an indicator of soil functions: A review. *Geoderma* **2018**, *314*, 122–137. [[CrossRef](#)]
69. Johannes, A.; Weisskopf, P.; Schulin, R.; Boivin, P. Soil structure quality indicators and their limit values. *Ecol. Indic.* **2019**, *104*, 686–694. [[CrossRef](#)]
70. Jahn, R.; Blume, H.P.; Asio, V.B.; Spaargaren, O.; Schad, P. *Guidelines for Soil Description*; FAO: Rome, Italy, 2006.
71. Costantini, E.A.C.; Barbetti, R.; Bucelli, P.; L'Abate, G.; Lulli, L.; Pellegrini, S.; Storchi, P. Land Peculiarities of the Vine Cultivation Areas in the Province of Siena (Italy), with Indications concerning the Viticultural and Oenological Results of Sangiovese Vine. *Boll. Soc. Geol.* **2006**, *6*, 147–159.
72. Guimaraes, R.M.L.; Lamande, M.; Munkholm, L.J.; Ball, B.C.; Keller, T. Opportunities and future directions for visual soil evaluation methods in soil structure research. *Soil Tillage Res.* **2017**, *173*, 104–113. [[CrossRef](#)]
73. Dexter, A.R. Advances in characterization of soil structure. *Soil Tillage Res.* **1988**, *11*, 199–238. [[CrossRef](#)]
74. Mangalassery, S.; Sjögersten, S.; Sparkes, D.L.; Sturrock, C.J.; Mooney, S.J. The effect of soil aggregate size on pore structure and its consequence on emission of greenhouse gases. *Soil Tillage Res.* **2013**, *132*, 39–46. [[CrossRef](#)]

75. Six, J.; Paustian, K. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. *Soil Biol. Biochem.* **2014**, *68*, 4–9. [[CrossRef](#)]
76. Barthès, B.; Roose, E. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. *Catena* **2002**, *47*, 133–149. [[CrossRef](#)]
77. Díaz-Zorita, M.; Perfect, E.; Grove, J.H. Disruptive methods for assessing soil structure. *Soil Tillage Res.* **2002**, *64*, 3–22. [[CrossRef](#)]
78. 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](#)]
79. Nunes, M.R.; Karlen, D.L.; Moorman, T.B. Tillage intensity effects on soil structure indicators. A US Meta-Analysis. *Sustainability* **2020**, *12*, 2071. [[CrossRef](#)]
80. Kemper, W.D.; Roseneau, R.C. Aggregate stability and size distribution. In *Methods of Soil Analysis: Part I: Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; Monogr. 9. ASA and SSSA: Madison, WI, USA, 1986; pp. 425–442.
81. Fajardo, M.; McBratney, A.B.; Field, D.J.; Minasny, B. Soil slaking assessment using image recognition. *Soil Tillage Res.* **2016**, *163*, 119–129. [[CrossRef](#)]
82. Flynn, K.D.; Bagnall, D.K.; Morgan, C.L.S. Evaluation of SLAKES, a smartphone application for quantifying aggregate stability, in high-clay soils. *Soil Sci. Soc. Am. J.* **2020**, *84*, 345–353. [[CrossRef](#)]
83. Reynolds, W.D.; Drury, C.F.; Tan, C.S.; Fox, C.A.; Yang, X.M. Use of indicators and pore volume-function characteristics to quantify soil physical quality. *Geoderma* **2009**, *152*, 252–263. [[CrossRef](#)]
84. Vignozzi, N.; Agnelli, A.E.; Brandi, G.; Gagnarli, E.; Goggioli, D.; Lagomarsino, A.; Pellegrini, S.; Simoncini, S.; Simoni, S.; Valboa, G.; et al. Soil ecosystem functions in a high-density olive orchard managed by different soil conservation practices. *Appl. Soil Ecol.* **2019**, *134*, 64–76. [[CrossRef](#)]
85. Pagliai, M. Soil porosity aspects. *Int. Agrophys.* **1988**, *4*, 215–232.
86. Gucci, R.; Caruso, G.; Bertolla, C.; Urbani, S.; Taticchi, A.; Esposto, S.; Servili, M.; Sifola, I.; Pellegrini, S.; Pagliai, M.; et al. Changes in soil properties and tree performance induced by soil management in a high-density olive orchard. *Eur. J. Agron.* **2012**, *41*, 18–27. [[CrossRef](#)]
87. Palese, A.M.; Vignozzi, N.; Celano, G.; Agnelli, A.E.; Pagliai, M.; Xiloyannis, C. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. *Soil Tillage Res.* **2014**, *144*, 96–109. [[CrossRef](#)]
88. Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; Deyn, G.D.; de Goede, R. Soil quality—A critical review. *Soil Biol. Biochem.* **2018**, *120*, 105–125. [[CrossRef](#)]
89. Costantini, E.A.C.; Branquinho, C.; Nunes, A.; Schwilch, G.; Stavi, I.; Valdecantos, A.; Zucca, C. Soil indicators to assess the effectiveness of restoration strategies in dryland ecosystems. *Solid Earth* **2016**, *7*, 397–414. [[CrossRef](#)]
90. Guimaraes, R.M.L.; Ball, B.C.; Tormena, C.A. Improvements in the visual evaluation of soil structure. *Soil Use Manag.* **2011**, *27*, 395–403. [[CrossRef](#)]
91. Boizard, H.; Peigné, J.; Sasal, M.C.; de Fátima Guimarães, M.; Piron, D.; Tomis, V.; Vian, J.-F.; Cadoux, S.; Ralisch, R.; Tavares Filho, J.; et al. Developments in the “profil cultural” method for an improved assessment of soil structure under no-till. *Soil Tillage Res.* **2017**, *173*, 93–103. [[CrossRef](#)]
92. Shepherd, T.G. *Visual Soil Assessment, Field Guide for Pastoral Grazing and Cropping on Flat to Rolling Country*, 2nd ed.; Horizons Regional Council: Palmerstone, New Zealand, 2009.
93. Ball, B.C.; Batey, T.; Munkholm, L.J. Field assessment of soil structural quality—A development of the Peerlkamp test. *Soil Use Manag.* **2007**, *23*, 329–337. [[CrossRef](#)]
94. Roger-Estrade, J.; Richard, G.; Caneill, J.; Boizard, H.; Defosse, P.; Manichon, H. Morphological characterisation of soil structure in tilled fields: From diagnosis methods to modelling of structural changes over time. *Soil Tillage Res.* **2004**, *79*, 33–49. [[CrossRef](#)]
95. Peigné, J.; Vian, J.-F.; Cannavacciuola, M.; Lefeure, V.; Gautronneau, Y.; Boizard, H. Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. *Soil Tillage Res.* **2013**, *127*, 13–25. [[CrossRef](#)]
96. McKenzie, D.C. Rapid assessment of soil compaction damage II. Relationships between the SOILpak score, strength and aeration measurements, clod shrinkage parameters and image analysis data on a vertisol. *Austral. J. Soil Res.* **2001**, *39*, 127–141. [[CrossRef](#)]
97. Ball, B.C.; Batey, T.; Munkholm, L.J.; Guimarães, R.M.L.; Boizard, H.; McKenzie, D.C.; Peigné, J.; Tormena, C.A.; Hargreaves, P. The numeric visual evaluation of subsoil structure (SubVESS) under agricultural production. *Soil Tillage Res.* **2015**, *148*, 85–96. [[CrossRef](#)]
98. Franco, H.H.S.; Guimarães, R.M.L.; Tormena, C.A.; Cherubin, M.R.; Favilla, H.S. Global applications of the Visual Evaluation of Soil Structure method: A systematic review and meta-analysis. *Soil Tillage Res.* **2019**, *190*, 61–69. [[CrossRef](#)]
99. Germer, S.; van Dongen, R.; Kern, J. Decomposition of cherry tree prunings and their short-term impact on soil quality. *Appl. Soil Ecol.* **2017**, *117*, 156–164. [[CrossRef](#)]
100. Ghiglieno, I.; Simonetto, A.; Donna, P.; Tonni, M.; Valenti, L.; Bedussi, F.; Gilioli, G. Soil Biological Quality Assessment to Improve Decision Support in the Wine Sector. *Agronomy* **2019**, *9*, 593. [[CrossRef](#)]
101. Soto, R.L.; Padilla, M.C.; de Vente, J. Participatory selection of soil quality indicators for monitoring the impacts of regenerative agriculture on ecosystem services. *Ecosyst. Serv.* **2020**, *45*, 101–157.
102. Collet, C.; Vast, F.; Richter, C.; Koller, R. Cultivation profile: A visual evaluation method of soil structure adapted to the analysis of the impacts of mechanical site preparation in forest plantations. *Eur. J. For. Res.* **2020**, *58*, 1–12. [[CrossRef](#)]

103. Mueller, L.; Kay, B.D.; Hu, C.; Li, Y.; Schindler, U.; Behrendt, A.; Shepherd, T.G.; Ball, B.C. Visual assessment of soil structure: Evaluation of methodologies on sites of Canada, China and Germany. Part I: Comparing visual methods and linking them with soil physical data and grain yields of cereals. *Soil Tillage Res.* **2009**, *103*, 178–187. [CrossRef]
104. Moreno-de las Heras, M.; Espigares, T.; Merino-Martin, L.; Nicolau, J.M. Water-related ecological impacts of rill erosion processes in Mediterranean-dry reclaimed slopes. *Catena* **2011**, *3*, 114–124. [CrossRef]
105. NRCS. *Procedure for Making Known Moisture Soil Samples for Irrigation Water Management Purposes*; Soil Technical Note 1; USDA: Portland, OR, USA, 2013. Available online: https://www.nrcs.usda.gov/wps/PA_NRCSCconsumption/download?cid=nrkseprd803007&ext=pdf (accessed on 28 December 2020).
106. Costantini, E.A.C. (Ed.) *Manual of Methods for Soil and Land Evaluation*; Science Publisher: Enfield, NH, USA, 2009; p. 549. ISBN 978-1-57808-571-2.
107. Kassel, D.K.; Nielsen, D.R. Field capacity and available water capacity. In *Methods of Soil Analysis Part 1: Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; ASA and SSSA: Madison, WI, USA, 1986; pp. 901–926.
108. Ugolini, F.C.; Corti, G.; Agnelli, A.; Piccardi, F. Mineralogical, physical, and chemical properties of rock fragments in soil. *Soil Sci.* **1996**, *161*, 521–542. [CrossRef]
109. Davie, S.; Isbister, B. *Identifying Soil Compaction*; Department of Primary Industries and Regional Development: Perth, Australia, 2018. Available online: <https://www.agric.wa.gov.au/soil-compaction/identifying-soil-compaction> (accessed on 15 November 2020).
110. Daddow, R.L.; Warrington, G. *Growth-Limiting Soil Bulk Densities as Influenced by Soil Texture*; USDA Forest Service: Washington, DC, USA, 1983; p. 17.
111. Dexter, A.R. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* **2004**, *120*, 201–214. [CrossRef]
112. Dexter, A.R. Soil physical quality: Part III: Unsaturated hydraulic conductivity and general conclusions about S-theory. *Geoderma* **2004**, *120*, 227–239. [CrossRef]
113. Pagliai, M.; Vignozzi, N. The soil pore system as an indicator of soil quality. *Adv. GeoEcol.* **2002**, *35*, 69–80.
114. Costantini, E.A.C.; Agnelli, A.; Bucelli, P.; Ciambotti, A.; Dell’Oro, V.; Natarelli, L.; Pellegrini, S.; Perria, R.; Priori, S.; Storchi, P.; et al. Unexpected relationships between $\delta^{13}\text{C}$ and wine grape performance in organic farming. *OENO One* **2013**, *47*, 269–285. [CrossRef]
115. Storchi, P.; Costantini, E.A.C.; Bucelli, P. The influence of climate and soil on viticultural and enological parameters of “Sangiovese” grapevines under non-irrigated conditions. *Acta Hort.* **2005**, *689*, 333–340. [CrossRef]
116. Scalabrelli, G.; D’Onofrio, C.; Macchia, A.; Rosellini, D.; Bertuccioli, M.; Boselli, M. Comportamento agronomico del vitigno Sangiovese in 11 zone del Chianti Classico. In *Proc. Int. Symposium “Sangiovese”*; ARSIA: Firenze, Italy, 2006; pp. 530–539.
117. van Leeuwen, C.; Tregoat, O.; Chone, X.; Bois, B.; Pernet, D.; Gaudillere, J.P. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? *OENO One* **2009**, *43*, 121–134. [CrossRef]
118. Froehlich, H.A.; Miles, D.W.R.; Robbins, R.W. Soil bulk density recovery on compacted skid trails in central Idaho. *Soil Sci. Soc. Am. J.* **1985**, *49*, 1015–1017. [CrossRef]
119. Webb, R.H. Recovery of severely compacted soils in the Mojave Desert, California, USA. *Arid Land Res. Manag.* **2002**, *16*, 291–305. [CrossRef]
120. Raper, R.L.; Bergtold, J.S. In-row subsoiling: A review and suggestions for reducing cost of this conservation tillage operation. *Appl. Eng. Agric.* **2007**, *23*, 463–471. [CrossRef]
121. Scanlan, C.A.; Davies, S.L. Soil mixing and redistribution by strategic deep tillage in a sandy soil. *Soil Tillage Res.* **2019**, *185*, 139–145. [CrossRef]
122. Medeiros, J.C.; Figueiredo, G.C.; Mafra, Á.L.; Rosa, J.D.; Yoon, S.W. Deep subsoiling of a subsurface-compacted typical Hapludult under citrus orchard. *Rev. Bras. Cienc. Solo* **2013**, *37*, 911–919. [CrossRef]
123. Shahgoli, G.; Saunders, C.; Desbiolles, J.; Fielke, J. The effect of oscillation angle on the performance of oscillatory tillage. *Soil Tillage Res.* **2009**, *104*, 97–105. [CrossRef]
124. Tomasono, R.; Cedrola, C.; Pagano, M.; Colorio, G.; Pochi, D. An oscillating subsoiler for loosening compacted soils in orchards. *Acta Hort.* **2011**, *919*, 147–152. [CrossRef]
125. Xirui, Z.; Chao, W.; Zhishui, C.; Zhiwei, Z. Design and experiment of a bionic vibratory subsoiler for banana fields in southern China. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 75–83.
126. Shahgoli, G.; Fielke, J.; Desbiolles, J.; Saunders, C. Optimising oscillation frequency in oscillatory tillage. *Soil Tillage Res.* **2010**, *106*, 202–210. [CrossRef]
127. Cho, Y.; Cho, H.; Ma, K.; Park, M.; Kim, B. Effect of subsoiling on soil physical properties and fruit quality in organic conversion kiwifruit (*Actinidia chinensis* ‘Haegeum’). *Acta Hort.* **2013**, *1001*, 347–352.
128. Xi, X.; Zhang, R. Design and Experiment of Orchard Gas Explosion Subsoiling and Fertilizer Injection Machine. *Int. J. Mech. Mechatron. Eng.* **2018**, *12*, 485–489.
129. Pal, D.K.; Bhattacharyya, T.; Ray, S.K.; Chandran, P.; Srivastava, P.; Durge, S.L.; Bhuse, S.R. Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India in redefining the sodic soils. *Geoderma* **2006**, *136*, 210–228. [CrossRef]

130. Lebron, I.; Suarez, D.L.; Yoshida, T. Gypsum effect on the aggregate size and geometry of three sodic soils under reclamation. *Soil Sci. Soc. Am. J.* **2002**, *66*, 92–98. [[CrossRef](#)]
131. Jones, A.; Stolbovoy, V.; Rusco, E.; Gentile, A.R.; Gardi, C.; Marechal, B.; Montanarella, L. Climate change in Europe. 2. Impact on soil. A review. In *Agronomy for Sustainable Development*; Springer: Berlin/Heidelberg, Germany, 2009. [[CrossRef](#)]
132. FAO. *Manual on Integrated Soil Management and Conservation Practices*; FAO Land and Water Bulletin 8: Rome, Italy, 2000; p. 230.
133. Martínez, J.R.F.; Zuazo, V.H.D.; Raya, A.M. Environmental impact from mountainous olive orchards under different soil-management systems (SE Spain). *Sci. Total Environ.* **2006**, *358*, 46–60. [[CrossRef](#)] [[PubMed](#)]
134. Marques, M.J.; García-Muñoz, S.; Muñoz-Organero, G.; Bienes, R. Soil conservation beneath grass cover in hillside vineyards under Mediterranean climatic conditions (Madrid, Spain). *Land Degrad. Dev.* **2010**, *21*, 122–131. [[CrossRef](#)]
135. Morvan, X.; Naisse, C.; Malam Issa, O.; Desprats, J.F.; Combaud, A.; Cerdan, O. Effect of ground-cover type on surface runoff and subsequent soil erosion in Champagne vineyards in France. *Soil Use Manag.* **2014**, *30*, 372–381. [[CrossRef](#)]
136. Corti, G.; Cavallo, E.; Cocco, S.; Biddoccu, M.; Brecciaroli, G.; Agnelli, A. Evaluation of erosion intensity and some of its consequences in vineyards from two hilly environments under a Mediterranean type of climate, Italy. In *Soil Erosion Issues in Agriculture*; InTech: Rijeka, Croatia, 2011; pp. 113–160.
137. Ondrasek, G.; Rengel, Z.; Petosic, D.; Filipovic, V. Land and water management strategies for the improvement of crop production. In *Emerging Technologies and Management of Crop Stress Tolerance*; Academic Press: Cambridge, MA, USA, 2014; pp. 291–313.
138. Tuohy, P.; Humphreys, J.; Holden, N.M.; Fenton, O. Runoff and subsurface drain response from mole and gravel mole drainage across episodic rainfall events. *Agric. Water Manag.* **2016**, *169*, 129–139. [[CrossRef](#)]
139. Mulqueen, J. The development of gravel mole drainage. *J. Agric. Eng. Res.* **1985**, *32*, 143–151. [[CrossRef](#)]
140. Cass, A.; McGrath, M. Compost benefits and quality for viticultural soils. In *Proc. Soil Environ. Vine Mineral Nutrition Symp*; American Society For Enology and Viticulture: San Diego, CA, USA, 2004; pp. 134–143.
141. Al-Widyan, M.I.; Al-Abed, N.; Al-Jalil, H. Effect of composted olive cake on soil physical properties. *Commun. Soil Sci. Plant Anal.* **2005**, *36*, 1199–1212. [[CrossRef](#)]
142. Mondini, C.; Fornasier, F.; Sinicco, T.; Sivilotti, P.; Gaiotti, F.; Mosetti, D. Organic amendment effectively recovers soil functionality in degraded vineyards. *Eur. J. Agron.* **2018**, *101*, 210–221. [[CrossRef](#)]
143. Baldi, E.; Cavani, L.; Margon, A.; Quartieri, M.; Sorrenti, G.; Marzadori, C.; Toselli, M. Effect of compost application on the dynamics of carbon in a nectarine orchard ecosystem. *Sci. Total Environ.* **2018**, *637*, 918–925. [[CrossRef](#)]
144. Brinton, W.F. Compost quality standards and guidelines. In *Final Report by Woods End Research Laboratories for the New York State Association of Recyclers*; New York State Association of Recyclers: New York, NY, USA, 2000.
145. Vignozzi, N.; Andrenelli, M.C.; L'Abate, G.; Pellegrini, S. Effect of management of topsoil structure. *EQA-Int. J. Environ. Qual.* **2018**, *31*, 11–15.
146. Bedini, S.; Pellegrino, E.; Avio, L.; Pellegrini, S.; Bazzoffi, P.; Argese, E.; Giovannetti, M. Changes in soil aggregation and glomalin-related soil protein content as affected by the arbuscular mycorrhizal fungal species *Glomus mosseae* and *Glomus intraradices*. *Soil Biol. Biochem.* **2009**, *41*, 1491–1496. [[CrossRef](#)]
147. Luna, L.; Miralles, I.; Andrenelli, M.C.; Gispert, M.; Pellegrini, S.; Vignozzi, N.; Solé-Benet, A. Restoration techniques affect soil organic carbon, glomalin and aggregate stability in degraded soils of a semiarid Mediterranean region. *Catena* **2016**, *143*, 256–264. [[CrossRef](#)]
148. Ramos, M.C. Metals in vineyard soils of the Penedès area (NE Spain) after compost application. *J. Environ. Manag.* **2006**, *78*, 209–215. [[CrossRef](#)] [[PubMed](#)]
149. Cavagnaro, T.R. Biologically regulated nutrient supply systems: Compost and arbuscular mycorrhizas—a review. *Adv. Agron.* **2015**, *129*, 293–321. [[CrossRef](#)]
150. Beesley, L.; Moreno-Jiménez, E.; Gomez-Eyles, J.L.; Harris, E.; Robinson, B.; Sizmur, T. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environ. Pollut.* **2011**, *159*, 3269–3282. [[CrossRef](#)] [[PubMed](#)]
151. Mukherjee, A.; Lal, R. Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy* **2013**, *3*, 313–339. [[CrossRef](#)]
152. Burrell, L.D.; Zehetner, F.; Rampazzo, N.; Wimmer, B.; Soja, G. Long-term effects of biochar on soil physical properties. *Geoderma* **2016**, *282*, 96–102. [[CrossRef](#)]
153. Hardie, M.; Clothier, B.; Bound, S.; Oliver, G.; Close, D. Does biochar influence soil physical properties and soil water availability? *Plant Soil* **2014**, *376*, 347–361. [[CrossRef](#)]
154. Sorrenti, G.; Masiello, C.A.; Toselli, M. Biochar interferes with kiwifruit Fe-nutrition in calcareous soil. *Geoderma* **2016**, *272*, 10–19. [[CrossRef](#)]
155. Blanco-Canqui, H. Biochar and soil physical properties. *Soil Sci. Soc. Am. J.* **2017**, *81*, 687–711. [[CrossRef](#)]
156. Sánchez-García, M.; Sánchez-Monedero, M.A.; Roig, A.; López-Cano, I.; Moreno, B.; Benitez, E.; Cayuela, M.L. Compost vs. biochar amendment: A two-year field study evaluating soil C build-up and N dynamics in an organically managed olive crop. *Plant Soil* **2016**, *408*, 1–14. [[CrossRef](#)]
157. Bass, A.M.; Bird, M.I.; Kay, G.; Muirhead, B. Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems. *Sci. Total Environ.* **2016**, *550*, 459–470. [[CrossRef](#)] [[PubMed](#)]
158. Garcia, L.; Celette, F.; Gary, C.; Ripoche, A.; Valdés-Gómez, H.; Metay, A. Management of service crops for the provision of ecosystem services in vineyards: A review. *Agric. Ecosyst. Environ.* **2018**, *251*, 158–170. [[CrossRef](#)]

159. Kassam, A.; Friedrich, T.; Derpsch, R.; Lahmar, R.; Mrabet, R.; Basch, G.; Serraj, R. Conservation agriculture in the dry Mediterranean climate. *Field Crop. Res.* **2012**, *132*, 7–17. [[CrossRef](#)]
160. Zuazo, V.H.D.; Pleguezuelo, C.R.R. Soil-erosion and runoff prevention by plant covers: A review. In *Sustainable Agriculture*; Springer: Berlin/Heidelberg, Germany, 2009; pp. 785–811.
161. Six, J.; Elliott, E.T.; Paustian, K.; Doran, J.W. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. *Soil Sci. Soc. Am. J.* **1998**, *62*, 1367–1377. [[CrossRef](#)]
162. Belmonte, S.A.; Celi, L.; Stanchi, S.; Said-Pullicino, D.; Zanini, E.; Bonifacio, E. Effects of permanent grass versus tillage on aggregation and organic matter dynamics in a poorly developed vineyard soil. *Soil Res.* **2016**, *54*, 797–808. [[CrossRef](#)]
163. Priori, S.; D’Avino, L.; Agnelli, A.E.; Valboa, G.; Knapic, M.; Schroers, H.J.; Akca, E.; Tangolar, S.; Kiraz, M.E.; Giffard, B.; et al. Effect of organic treatments on soil carbon and nitrogen dynamics in vineyard. *EQA-Int. J. Environ. Qual.* **2018**, *31*, 1–10.
164. Agnelli, A.; Bol, R.; Trumbore, S.E.; Dixon, L.; Cocco, S.; Corti, G. Carbon and nitrogen in soil and vine roots in harrowed and grass-covered vineyards. *Agric. Ecosyst. Environ.* **2014**, *193*, 70–82. [[CrossRef](#)]
165. Sánchez, E.E.; Giayetto, A.; Cichón, L.; Fernández, D.; Aruani, M.C.; Curetti, M. Cover crops influence soil properties and tree performance in an organic apple (*Malus domestica* Borkh) orchard in northern Patagonia. *Plant Soil* **2007**, *292*, 193–203. [[CrossRef](#)]
166. Celette, F.; Findeling, A.; Gary, C. Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate. *Eur. J. Agron.* **2009**, *30*, 41–51. [[CrossRef](#)]
167. Ruiz-Colmenero, M.; Bienes, R.; Marques, M.J. Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. *Soil Tillage Res.* **2011**, *117*, 211–223. [[CrossRef](#)]
168. Gómez, J.A.; Llewellyn, C.; Basch, G.; Sutton, P.B.; Dyson, J.S.; Jones, C.A. The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. *Soil Use Manag.* **2011**, *27*, 502–514. [[CrossRef](#)]
169. Ramos, M.E.; Robles, A.B.; Sanchez-Navarro, A.; Gonzalez-Rebollar, J.L. Soil responses to different management practices in rainfed orchards in semiarid environments. *Soil Tillage Res.* **2011**, *112*, 85–91. [[CrossRef](#)]
170. Gómez, J.A. Sustainability using cover crops in Mediterranean tree crops, olives and vines—Challenges and current knowledge. *Hung. Geogr. Bull.* **2017**, *66*, 13–28. [[CrossRef](#)]
171. García-González, I.; Hontoria, C.; Gabriel, J.L.; Alonso-Ayuso, M.; Quemada, M. Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land. *Geoderma* **2018**, *322*, 81–88. [[CrossRef](#)]
172. Morlat, R.; Jacquet, A. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. *Am. J. Enol. Vitic.* **2003**, *54*, 1–7.
173. Steenwerth, K.; Belina, K.M. Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. *Appl. Soil Ecol.* **2008**, *40*, 359–369. [[CrossRef](#)]
174. Garcia-Franco, N.; Albaladejo, J.; Almagro, M.; Martínez-Mena, M. Beneficial effects of reduced tillage and green manure on soil aggregation and stabilization of organic carbon in a Mediterranean agroecosystem. *Soil Tillage Res.* **2015**, *153*, 66–75. [[CrossRef](#)]
175. Montanaro, G.; Xiloyannis, C.; Nuzzo, V.; Dichio, B. Orchard management, soil organic carbon and ecosystem services in Mediterranean fruit tree crops. *Sci. Hortic.* **2017**, *217*, 92–101. [[CrossRef](#)]
176. Canadell, J.; Jackson, R.B.; Ehleringer, J.B.; Mooney, H.A.; Sala, O.E.; Schulze, E.D. Maximum rooting depth of vegetation types at the global scale. *Oecologia* **1996**, *108*, 583–595. [[CrossRef](#)]
177. Chen, G.; Weil, R.R. Penetration of cover crop roots through compacted soils. *Plant Soil* **2010**, *331*, 31–43. [[CrossRef](#)]
178. Zhong, Z.; Wang, W.; Wang, Q.; Wu, Y.; Wang, H.; Pei, Z. Glomalin amount and compositional variation, and their associations with soil properties in farmland, northeastern China. *J. Soil Sci. Plant Nutr.* **2017**, *180*, 563–575. [[CrossRef](#)]
179. Rashid, M.I.; Mujawar, L.H.; Shahzad, T.; Almeelbi, T.; Ismail, I.M.; Oves, M. Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils. *Microbiol. Res.* **2016**, *183*, 26–41. [[CrossRef](#)] [[PubMed](#)]
180. Xu, L.; Geelen, D. Developing biostimulants from agro-food and industrial by-products. *Front. Plant Sci.* **2018**, *9*, 1567. [[CrossRef](#)] [[PubMed](#)]
181. Moreira, H.; Pereira, S.I.; Vega, A.; Castro, P.M.; Marques, A.P. Synergistic effects of arbuscular mycorrhizal fungi and plant growth-promoting bacteria benefit maize growth under increasing soil salinity. *J. Environ. Manag.* **2020**, *257*, 109982. [[CrossRef](#)]
182. Behrooz, A.; Vahdati, K.; Rejali, F.; Lotfi, M.; Sarikhani, S.; Leslie, C. Arbuscular mycorrhiza and plant growth-promoting bacteria alleviate drought stress in walnut. *HortScience* **2019**, *54*, 1087–1092. [[CrossRef](#)]
183. Bulgari, R.; Franzoni, G.; Ferrante, A. Biostimulants application in horticultural crops under abiotic stress conditions. *Agronomy* **2019**, *9*, 306. [[CrossRef](#)]
184. Smith, S.E.; Jakobsen, I.; Grønlund, M.; Smith, F.A. Roles of arbuscular mycorrhizas in plant phosphorus nutrition: Interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. *Plant Physiol.* **2011**, *156*, 1050–1057. [[CrossRef](#)]
185. Berruti, A.; Lumini, E.; Balestrini, R.; Bianciotto, V. Arbuscular mycorrhizal fungi as natural biofertilizers: Let’s benefit from past successes. *Front. Microbiol.* **2016**, *6*, 1559. [[CrossRef](#)]
186. Roupheal, Y.; Franken, P.; Schneider, C.; Schwarz, D.; Giovannetti, M.; Agnolucci, M.; Colla, G. Arbuscular mycorrhizal fungi act as biostimulants in horticultural crops. *Sci. Horticult.* **2015**, *196*, 91–108. [[CrossRef](#)]
187. Basile, B.; Roupheal, Y.; Colla, G.; Soppelsa, S.; Andreotti, C. Appraisal of emerging crop management opportunities in fruit trees, grapevines and berry crops facilitated by the application of biostimulants. *Sci. Horticult.* **2020**, *267*, 109330. [[CrossRef](#)]

188. Gamalero, E.; Lingua, G.; Berta, G.; Glick, B.R. Beneficial role of plant growth promoting bacteria and arbuscular mycorrhizal fungi on plant responses to heavy metal stress. *Can. J. Microbiol.* **2009**, *55*, 501–514. [[CrossRef](#)] [[PubMed](#)]
189. Chen, B.D.; Zhu, Y.G.; Duan, J.; Xiao, X.Y.; Smith, S.E. Effects of the arbuscular mycorrhizal fungus *Glomus mosseae* on growth and metal uptake by four plant species in copper mine tailings. *Environ. Pollut.* **2007**, *147*, 374–380. [[CrossRef](#)] [[PubMed](#)]
190. Ramakrishna, W.; Yadav, R.; Li, K. Plant growth promoting bacteria in agriculture: Two sides of a coin. *Appl. Soil Ecol.* **2019**, *138*, 10–18. [[CrossRef](#)]