

Review

Quantifying Root-Soil Interactions in Cover Crop Systems: A Review

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Abstract: Plant roots are an integral part of soil ecosystems and contribute to various services, including carbon and nutrient cycling, weathering, and soil formation. They also modify soil physical properties (e.g., soil water content, pore size distribution, and bulk density) and impact subsequent crops' growth. Cover crops have been reported to improve soil and environmental quality by reducing nutrient losses, improving soil water content, and increasing soil organic matter. Understanding the complex interactions between cover crop roots and soil (RS) is of utmost importance. However, cover crop RS interactions have not been critically reviewed. In this article, we investigated the nature of cover crop physical RS interactions and explored the emerging technologies for their study. We also assessed technologies that may be readily applied to the study of physical RS interactions in cover crop systems and discussed ways to improve related research in the future.

Keywords: cover crops; soil physical properties; root morphology; measurement techniques; tomography; rhizotrons



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1. Introduction

Roots are said to have succeeded rhizoid-based rooting systems in evolutionary history approximately 400 million years ago. This development caused plants to become increasingly involved in transforming terrestrial ecosystems by influencing carbon cycling and weathering of mineral parent materials [1]. Plant roots began to play a critical role in soil formation by re-shaping soil systems [2]. With this understanding, researchers have begun to redesign input-intensive agroecosystems to mimic natural ones where plants are valued, not only for what they produce for human consumption but also their ecosystem services [3]. Consequently, in recent decades, plants' employment for ameliorating soil physical constraints to crop production via root-soil (RS) interactions has received significant research attention [4–7].

Cover crops are the crops grown in agroecosystems for ecological services (e.g., soil cover, nutrient capture, fertility improvement, weed suppression) rather than a harvestable product [8,9]. The use of cover crops within grain crop rotations for improving soil physical properties, i.e., reducing soil compaction, improving pore size distribution, and forming biopores, has been validated by several studies [10–17]. In tandem with this, emerging technologies are now allowing for new insights into physical RS interactions that were previously unobservable through destructive sampling [11,18]. Thus, the aim of this review is three-fold: to briefly investigate the nature of cover crop physical RS interactions, to explore the landscape of emerging technologies for study of physical RS interactions, and finally to assess which technologies may be most readily applied to the study of physical RS interactions in cover crop systems.

2. Root-Soil Interactions and the Role of Cover Crops

In agroecosystems, roots perform three basic functions for the plants: support, water supply, and nutrient supply. Root activity is intimately tied to the plant water and nutrient

status, as well as internal carbohydrate supply, such that both root and shoot growth and development establish a functional equilibrium [19]. Roots also produce hormonal signals that rapidly regulate plant growth based on the rhizosphere condition [20]. For example, root meristematic cells integrate signals from the environment to cope with external constraints which requires the activation of hormone homeostasis and signaling pathways through transcriptional regulation.

Five processes govern root system morphology: emergence of new main axes, branching, axial growth (root elongation and direction), radial growth (thickening), and root senescence and decay [21]. These processes are internally regulated based on environmental conditions. Branching is primarily regulated by nutrient availability, with varied patterns depending on the type and nutrient availability [22]. Several tropisms regulate axial root growth. Gravitropism is commonly recognized as the dominant tropism in seminal roots but not lateral roots [22]. Recent studies in root growth have revealed that trematotropism—growth toward holes or voids—is differentially expressed across species [18,23]. Small cereals such as wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) tend to cross macropore channels. At the same time, corn (*Zea mays* L.) or soybeans (*Glycine max* L.) are more likely to colonize them and re-enter the bulk soil at lower depths which is explained by oxytropism.

Root morphology is also affected by soil water content. Bao et al. [24] demonstrated that seminal root's contact with moist surfaces induces the auxin-regulated formation of lateral roots to explore the wet soil. This response was referred to as “hydropatterning”. Water and nutrient uptake are not homogenous across the root axis [25]; some sections exhibit larger water and nutrient uptake levels, while others appear to be dormant [21]. Oxygen deficits decrease the rate of root growth and cause root death, while soil water deficits also reduce root elongation. However, they can increase the rooting depth and density in some species [26]. For example, field pea (*Pisum sativum* L.) and chickpea (*Cicer arietinum* L.) both increased their rooting depth in response to water deficiency, while soybeans roots showed no impact [27]. A similar differential response may exist for cultivars of the same species [28].

2.1. Roots as Affected by Changes in Soil Physical Properties

Soil physical factors also constrain root growth. Hard soil reduces the root elongation process [26,29]. The contact with hard soil increases radial root growth, building up pressure and weakening the soil [29]. This mechanism is called “inverse peristalsis” [30]. On the other hand, loose soils do not allow optimal root growth [31]. The degree of response to soil compaction is regulated by plant genetics. For example, common vetch (*Vicia sativa* L.) roots marginally explored compact soil layers compared to tillage radish (*Raphanus sativus* L. cv. ‘Early Mino’) and black oats (*Avena strigosa* Schreb. cv. ‘Pratex’) [11].

Increasing soil porosity benefits crop root systems. Subsoil macropores formed by shrinking and swelling of the soil [32,33], and biopores formed by soil fauna and plant roots, can increase soil aeration, water infiltration, and root access deeper soil water and nutrients [31,34–37]. Colombi et al. [18] and Pfeifer et al. [23] observed colonization of artificial macropores by plant roots. However, the above-ground biomass was not affected. Root colonization of soil macropores was also reported to reduce water uptake due to poor RS contact [38].

2.2. Soil Physical Properties as Affected by Root Growth

Soil physical properties constrain root growth and are shaped by root growth [39]. As roots experience resistance from the soil, axial and radial growth creates pressure that rearranges soil particles and pore spaces. Bodner et al. [10] proposed that various root sizes assume different growth strategies. Fine roots exploit existing pore pathways, increasing local soil drying, and coalescing aggregates. Coarse roots pioneer new channels between soil aggregates and densify the surrounding rhizosphere soil [40]. Local soil drying caused

by plant transpiration further enhances macroporosity since the increased frequency and amplitude of dry cycles create cracks and fissures in soil profile [32,33,41,42].

Initially, dense root growth can block soil pores and reduce hydraulic conductivity. Jotisankasa and Sirirattanachai [43] observed that the permeability of soil cultivated with vetiver grass (*Chrysopogon zizanioides* L.) reached a maximum at rooting densities of 6.5 and 6.0 kg m⁻³ in a silt soil and clayey sand, respectively; after this, these parameters decreased because roots occupying soil pores prevented water flow. Vergani and Graf [44] noted that K_{sat} increased initially after planting white alder (*Alnus incana* L.) but decreased when root volume density surpassed 0.1 cm³ cm⁻³. However, the maximum effect of root growth on aggregate stability took place at root densities greater than 2 cm³ cm⁻³. Aggregate stability is conceptually understood to maintain preferential flow paths [45]. However, some studies found an asynchronous relationship between aggregate stability and hydraulic conductivity [46]. Root death and decomposition are necessary for new biopores to emerge and serve as preferential pathways for root growth or water infiltration [33,42,45].

Root system impacts on soil macroporosity have received formidable research attention for their potential to alleviate subsoil compaction [4,12–14,18,33,47]. Reintam et al. [48] reported that *Cirsium arvense* L. reduced penetration resistance on abandoned farmland in Estonia. The root growth of *Cirsium arvense* demonstrated significant resilience to compaction since it increased root and shoot growth. In general, tap-rooted dicotyledonous species are more successful at penetrating compacted subsoils [37]. Alfalfa's (*Medicago sativa* L.) perennial root system has been found to increase soil aggregate stability, hydraulic conductivity, and macroporosity [42,47,49–51].

In addition to roots, plant residue and mulches also contribute to changes in soil physical properties through organic matter as the main ingredient for stabilizing soil aggregates [52–57]. Abiven et al. [58] reviewed the literature related to aggregate stability changes from different organic inputs. They found a clear separation in both the magnitude of increase in aggregate stability and the time-to-maximum as the organic inputs became more chemically complex. Initial increases in aggregate stability were strongly correlated with evolved CO₂, suggesting that microbial activity facilitates soil aggregates' stabilization. The organic inputs' chemical properties also stabilize aggregates by increasing inter-aggregate cohesion and hydrophobicity, thus protecting them from water destruction. However, microbial secretions tend to be larger polymers than those secreted by plants and thus are more effective at stabilizing aggregates [59].

2.3. Cover Crops as Physical Modifiers

Cover crops can be employed to provide ecological services that improve soil physical properties and agroecosystems' broader functioning [4,7]. Using plants to improve the soil environment has been called “bioengineering” [60], and in the context of decompacting the subsoil, “biodrilling” [4]. Yunusa and Newton [7] described this process as “soil priming”, whereby a “primer plant” can benefit the following crop's yield via modifications to the soil environment. Perenniality, coarse roots, and rapid root turnover rates are characteristics that Yunusa and Newton [7] suggest make for ideal primer plants.

Different species of cover crops can be selected depending on the ecological service to be provided. For example, cover crops with fine root systems increase pore spaces' heterogeneity in the soil, while coarse root systems predominantly increase soil macroporosity [10]. Nuttall et al. [5] tested the primer-plant hypothesis on several coarse-rooted plants. They found that birds-foot trefoil (*Lotus corniculatus* L.) and sulla (*Hedysarum coronarium* L.) increased the following wheat crop's exploration of the soil and water use efficiency. Similarly, alfalfa increased root growth of wheat in the 0–0.50 m horizons, but this did not result in a significant increase in wheat yield. Perkons et al. [6] compared the root growth of spring wheat and winter barley following two years of either chicory (*Cichorium intybus* L.) or oat and tall fescue (*Avena sativa* L.; *Festuca arundinacea* Schreb.) pre crop. Root growth was significantly greater for both spring wheat and winter barley below 125 cm when following chicory; the effect was more pronounced in winter barley where

the roots were longer. Contrary, root exploration in the topsoil was greater following the oat-fescue pre-crop, likely because oat and fescue have concentrated root systems in the upper soil horizons.

Bodner et al. [10] studied the impact of twelve different cover crop species on soil properties using root imaging. A significant positive relationship was found between root volume density (RVD; $\text{cm}^3 \text{ cm}^{-3}$) and field water content ($\text{cm}^3 \text{ cm}^{-3}$) such that at RVDs > 0.004 , the water content was maximized at $0.46 \text{ cm}^3 \text{ m}^{-3}$. A mixture of three cover crop species, including cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), and Hairy Vetch (*Vicia villosa* L.), along with some brassicas and legumes also maximized these parameters.

Using a sandy loam field soil packed in columns, Burr-Hersey et al. [11] grew commonly used cover crops (tillage radish, common vetch, and black oat) in sandy loam soil to evaluate their potential for biodrilling with X-ray computed tomography. They found that tillage radish and black oats' roots were able to penetrate a compacted subsoil layer. In contrast, vetch roots were restricted to the uncompacted zone. They concluded that tillage radish and black oats demonstrated root growth behaviors that are likely to reduce subsoil compaction and create biopores. Chen and Weil [13] studied the effect of cover crops on corn root growth under compacted and uncompacted conditions in the subsequent growing season. By counting the number of living roots at soil core break planes, they found that corn when grown after forage radish (*Raphanus sativus* var. *longipinnatus* cv. 'Daikon') had more roots in the 45 cm soil depth than corn grown after rapeseed (*Brassica napus* cv. 'Essex') or cereal rye. Forage radish has an aggressive taproot that can create subsoil biopores, and corn roots will preferentially colonize these to access subsoil water and nutrients instead of growing through the bulk soil [18]. Williams and Weil [14] monitored colonization of soil biopores by soybean roots using a minirhizotron. They observed that soybean roots colonized biopores left by the previous season's forage radish cover crop. At one field site where water was limiting, soybean yield was greatest after a canola-cereal rye cover crop where the combined services of biodrilling and reduced evaporative water loss were achieved, thus improving water availability and accessibility of the soybean crop.

Cover crops also improve soil aggregation [46,61,62]. Linsler et al. [63] used aggregate fractionation to determine changes in mean weight diameter for soil aggregates, using 2000, 1000, 250, and 53 μm sieves. They detected a 2-fold increase in large and medium-sized aggregates compared to a fallow treatment after 12 weeks. Steele et al. [46] reported that cover crops positively contribute to organic matter and aggregate stability (AS), and a significant correlation between organic matter and AS had been reported by Blanco-Canqui et al. [64]. Haynes and Beare [65] studied the impact of six cover crops AS, measuring organic matter and microbial biomass. They suggested that AS's improvements from encouraging microbial activity in the soil produce soil binding agents since AS was more closely related to microbial biomass than root biomass. Drury et al. [66] found improvements in soil physical properties in a no-tillage planting bed when a red clover cover crop was grown. Similarly, Chen et al. [67] found that tap-rooted cover crops in the Brassicaceae family could increase the least limiting water range (LLWR). The LLWR is an important indicator of soil quality and soil physical constraints on crop production. This parameter incorporates crop-limiting values of soil strength, aeration, and water supply to plant roots. Olibone et al. [68] also observed improvements in LLWR with cover crops in no-till, but this did not significantly change soybean yield.

3. Measurement Techniques

With roots being the "hidden half" of plants, they have long been understudied compared to above-ground plant growth and development [69]. To increase our understanding of RS interactions and leverage these principles to improve the management of cover crops and their ecological services, it is worth reviewing a range of RS measurement techniques used in past research. In the first part of this section, measurements that indirectly document RS interactions by measuring changes in roots or soil physical properties will be

reviewed; second, those measuring changes in both roots and the soil environment will be reviewed.

3.1. Techniques for Measuring Soil Physical Properties Associated with Roots

Changes in soil physical properties may be measured to infer root growth. For example, infiltrometers and hydraulic conductivity measurements are indirect ways of measuring soil macroporosity changes [70–73], which can be influenced by root biopores formation [14]. Bulk density, penetration resistance, water retention, and pore-size distribution (PSD) gives further insight into soil particles' arrangement in the soil profile [13,64,70,74]. Wet aggregate stability is highly correlated with organic matter content but less correlated with infiltration [46,64,75,76]. Studies that have used these techniques to measure changes in soil physical properties from cover crops are listed in Table 1.

Table 1. Impact of cover crops on soil physical properties (pb—bulk density; PSD—pore size distribution; K_{sat}—saturated hydraulic conductivity) measured using various techniques for indirect estimation of root-soil interactions.

Measurements	Cover Crop(s)	Effect	Ref.
Air permeability	<i>Brassica napus</i> cv. 'Essex'; <i>Raphanus sativus</i> var.; <i>longipinnatus</i> cv. 'Daikon'; <i>Secale cereal</i> cv. 'Wheeler';	Yes (+)	[77]
	<i>Secale cereale</i>	Yes (+)	[46]
Bulk density (pb) by Proctor	<i>Crotalaria juncea</i> ; <i>Glycine max</i> ; <i>Vicia villosa</i>	Yes (–)	[64]
Bulk density (pb)	<i>Brassica napus</i> cv. 'Essex'; <i>Raphanus sativus</i> var.; <i>longipinnatus</i> cv. 'Daikon'; <i>Secale cereal</i> cv. 'Wheeler'	No	[13,77]
	<i>Secale cereale</i>	No	[70,74]
	<i>Vicia sativa</i> ; <i>Vicia villosa</i> ; <i>Secale cereale</i>	Yes (–)	[76,78]
		Yes (–)	[46]
	<i>Triticum aestivum</i> ; <i>Vicia villosa</i>	No	[79]
Penetration resistance (cone penetrometer)	<i>Secale cereale</i>	Yes (–)	[76,80]
		No	[13,64,77]
Penetration resistance (micropenetrometer)	<i>Avena sativa</i> ; <i>Vicia sativa</i>	Yes (–)	[81]
Wet aggregate stability	<i>Sinapis alba</i> ; <i>Phacelia tanacetifolia</i> ; <i>Raphanus sativus</i> var.; <i>Oleiformis</i> ; <i>Trifolium alexandrinum</i>	Yes (+)	[63]
	<i>Hordeum vulgare</i> cv. 'Virden'; <i>Lolium multiflorum</i> cv.; 'Aubade'; <i>Secale cereale</i> cv. 'Danko'	Yes (+)	[82]
		Yes (+)	[46,64,70,76,83]
Dry aggregate size distribution		Yes (+/–)	[20]
Organic carbon	<i>Secale cereale</i> ; <i>Trifolium incarnatum</i> ; <i>Vicia villosa</i>	Yes (+)	[20]
		Yes (+)	[2,3,7,8,17]
		No	[70]
Water retention		Yes (+)	[76,78]
		No	[70,74,77]
In situ field capacity; Water retention	<i>Brachiaria ruziziensis</i> ; <i>Centrosema pubescens</i> ; <i>Cynodon nlemfuensis</i> ; <i>Paspalum notatum</i> ; <i>Psophocarpus palustris</i> ; <i>Pueraria phaseoloides</i> ; <i>Stizolobium deeringianum</i> ; <i>Stylosanthes guianensis</i>	Yes (+)	[70]

Table 1. Cont.

Measurements	Cover Crop(s)	Effect	Ref.
PSD via infiltration	<i>Secale cereale</i> <i>Sinapis alba</i>	Yes (+)	[10]
PSD via capillary rise		Yes (+)	[74]
PSD via water desorption		Yes (+)	[76]
		No	[79]
Mean Pore radius	<i>Festuca rubra</i> ; <i>Lotus corniculatus</i> ; <i>Medicago sativa</i>	Yes (+/–)	[84]
Resin-impregnated image analysis		Yes (–)	[84]
Least-limiting water range		Yes (+)	[77]
Constant head K_{sat}		No	[64,76,79]
Constant/falling head K_{sat}		No	[74]
Single-ring infiltration		Yes (+)	[74]
Double-ring infiltration		Yes (+)	[64,85]
Tension infiltration		No	[10]
Disc infiltration		Yes (+/–)	[84]
Infiltration (neutron moisture meter; time domain reflectometry)	<i>Trifolium alexandrinum</i>	Yes (+)	[86]
Simulated rainfall infiltration	<i>Avena sativa</i> ; <i>Secale cereale</i>	Yes (+)	[87]
		Yes (+)	[81]
Sprinkle infiltration	<i>Pisum sativum</i> var. <i>arvense</i> ; <i>Trifolium alexandrinum</i> ; <i>Trifolium incarnatum</i> ; <i>Triticum aestivum</i> ; <i>Vicia villosa</i>	Yes (+)	[83]
Marriot infiltration		Yes (+)	[46]

A couple of innovative measurement techniques are worth considering for future studies. De Almeida et al. [88] used a large rainfall simulator to find the stable infiltration rate of soils under soybean cultivation, whether conventionally tilled or no-tilled. In this method, infiltration rates can be estimated under field conditions. Surface residue does not need to be removed—unlike some infiltrometers, infiltration is measured according to the difference between incident rainfall and runoff.

Though not receiving much recent attention, changes in root growth across treatments can be obtained indirectly by measuring vertical root-pulling resistance (VRPR) [89]. Beck et al. [90] used VRPR with corn plants to estimate root system mass and root tensile strength more expediently than excavating. A similar technique was previously used in rice (*Oryza sativa* L.) to measure deep rooting and drought tolerance [91–93]. Since VRPR can be used to measure a selection of roots' morphological attributes, it could be used to measure changes in crop root growth due to changes in soil physical environment influenced by cover crop roots.

3.2. Techniques for Measuring Physical Root–soil Interactions

Root-soil research has predominantly relied upon three approaches to measuring root systems: 1. Excavation of the plant root system, 2. Extracting soil cores or monoliths to be further analyzed in the lab, and 3. Installing in-growth cores to monitor root growth into a given area over time [94,95]. These techniques help to learn about root biomass and length distribution in each area, root morphology, and to a lesser extent, the geometry or architecture of root systems. By taking multiple measurements for a season, one can acquire some level of understanding of root growth or turnover rates over time.

Digging trenches of various depths to expose the soil profile allows for several possible measurements to be taken. Perkons et al. [6] excavated a 2 m deep trench to measure rooting depth and spring wheat density following different pre-crops. To measure the presence of biopores, the field can be excavated to a given depth (ex. 45 cm) to clear a horizontal area where pores of a given size class are counted [6,47]. The horizontal area is often cleaned with a vacuum cleaner to leave a clear surface. The extraction of soil monoliths for analysis in the lab affords opportunities for both old and new measurement techniques to be used. Root length density and other physical parameters can be gleaned from washing the roots from soil cores and using image scanning technologies such as WinRhizo [10]. A pinboard can be inserted into a monolith and used to maintain the roots' spatial distribution as they are washed; this can indicate the root system architecture without spending much time in the field [96]. By horizontally breaking soil cores taken at a given depth, one can count the abundance of living roots protruding from the break's surfaces and infer root growth at different depths [13,97]. By vertically breaking soil monoliths, root growth inside biopores can be visually assessed, and high-resolution image analysis techniques can be incorporated to analyze 2D root growth [98]. Soil cores can also be impregnated with fluorescent resins for further scanning to study pore size, shape, and distribution [84].

Rhizotrons have been frequently used to study RS interactions because field rhizotrons and observation windows, like in-growth cores, allow for repeated study of root growth over time [95,96]. Minirhizotrons have been used to study root growth and root colonization of soil macropores and biopores in the field [14,42]. However, there are significant challenges associated with in situ rhizotrons. First, to get a representative understanding of a plant's root system, many observation ports—whether tubes or windows—need to be installed. This installation process causes significant disruption of the soil profile. A recommended period of 1–2 years ought to pass to re-establish a natural soil structure before measurements are taken [96]. Perhaps the greatest challenge is to ensure that roots or biopores will emerge near the observation port to capture root growth [99]. Though, this may be partially overcome by hand-planting directly over the installed rhizotron [14].

The setbacks of rhizotrons can also be overcome by using in situ endoscopy [99]. Athmann et al. [100] excavated a trench, dug horizontally into the soil profile at a depth of 105 cm, and used a mini videoscope to probe the insides of macropores >5 mm. below the free-hanging horizontal surface avoiding inside disruption of the biopores compared to inserting the videoscope from above. The videoscope could be inserted up to 10 cm into the biopore, and then the 10 cm section was cleared away for the videoscope to probe the next section above. Cover crop studies that used these techniques are listed in Table 2.

Table 2. Measurement techniques used in cover crop research for directly quantifying root-soil interactions (pb—bulk density; PSD—pore size distribution).

Cover Crops	Measurements	Instrumentation	Ref.
<i>Fagopyrum esculentum</i> ; <i>Lathyrus sativus</i> ; <i>Linum usitatissimum</i> ; <i>Melilotus officinalis</i> ; <i>Phacelia tanacetifolia</i> ; <i>Raphanus sativus</i> var. <i>Oleiformis</i> ; <i>Secale cereale</i> ; <i>Sinapis alba</i> ; <i>Trifolium alexandrinum</i> ; <i>Trifolium incarnatum</i> ; <i>Vicia sativa</i> ; <i>Vicia villosa</i>	Methylene staining; root scanning; PSD via tension infiltration; Root sampling (soil core); Water retention via tension infiltration	WinRhizo 4.1 (Regent Instruments, Quebec, QC, Canada)	[10]
<i>Raphanus sativus</i> var. <i>longipinnatus</i> cv. 'Daikon'; <i>Brassica napus</i> cv. 'Essex'; <i>Secale cereale</i> cv. 'Wheeler'	Root penetration (core-break); Penetration resistance (cone penetrometer); pb		[12]
<i>Secale cereale</i> ; <i>Raphanus sativus</i> cv. 'Daikon'; <i>Raphanus sativus</i> ; <i>Brassica rapa</i>	Minirhizotron, length of 1 m, outside diameter of 50.8 mm, 45° angle, 12 mm image intervals. Penetration resistance (cone penetrometer); Particle size analysis (hydrometer); pb	XYZ123 (Bartz Technology, Santa Barbara, CA, USA)	[14]

Tomography: All the techniques mentioned above require significant amounts of time spent either in the field or in the lab destructively hand-processing soil monoliths. With 3-dimensional tomographic technology, time may be redirected to digital image processing, and non-destructive sampling is possible with pot-based experiments. X-ray computed tomography (XCT) has received the most research attention [101], though neutron computed tomography (NCT), magnetic resonance imaging (MRI), and ground-penetrating radar (GPR) are being explored to counteract the challenges associated with XCT. XCT has been used most extensively to study pore networks in soil, specifically from earthworm activity [73,102]. Still, others have used it as a non-destructive method to study soil-structure [103], aggregation [104], and RS interactions [103,105,106]. All tomographic technologies require a sufficient level of contrast between the phase elements (e.g., soil, water, plant roots) to be distinguished. In XCT, X-ray beams are attenuated by materials of differing density and atomic number [107]. Thus, materials with similar physicochemical properties will have similar X-ray absorption and be more difficult to distinguish.

Sufficient contrast can be achieved when comparing air-filled pore space with the surrounding soil matrix; to this end, Munkholm et al. [108] successfully characterized soil pore space across different crop rotations and tillage management. On the other hand, sufficient contrast is not easily achieved when comparing plant roots and water-filled pores. In a pot-based experiment, Metzner et al. [109] found that increasing the pot size from 3.4×20 cm (“diameter” \times “height”) to 8.1×30 cm increased the amount of water pooling and decreased the effectiveness of XCT at capturing the root system. Contrast can be improved by using higher-resolution synchrotron microtomography, which, because of its higher power, increases monochromatization of the X-ray beams [110,111]. Some researchers have used contrast enhancement filters on open-source image analysis software like ImageJ to improve image quality [103]. However, this is unlikely to solve the challenges of larger pot sizes.

NCT differs from XCT as it measures the attenuation of charged neutrons instead of protons by various materials [112]. As NCT is highly sensitive to low molecular weight compounds, normal water results in a lot of beam hardening and scattering—two alternate fates of the imaging beams other than attenuation. Tumlinson et al. [112] found that sample sizes cannot exceed 2.5 cm in diameter if there is any water present. Meyer et al. [113] found that NCT accurately estimated soil pore size distribution except in soils with high clay or organic matter contents due to high shrinking/swelling potential. An additional challenge is the requirement of a radiation use permit at facilities carrying out this type of analysis. Another alternative is the MRI technology that measures radio waves’ attenuation instead of photons or neutrons and provides high contrast between water and roots. Metzner et al. [109] found that MRI could detect roots in saturated conditions where XCT was not, but it did not have as high resolution and so at times overestimated root length. Additionally, the MRI is restricted to soils with low iron levels [114].

GPR uses electromagnetic pulses sent from an antenna moved over the soil surface to detect the magnitude of reflected signals based on the nature of material below the soil surface. Processing the original radargrams requires five steps: radargram standardization, noise reduction, signal amplification, migration (Kirchoff), and Hilbert transformation [115]. Standardization of GPR indexes for estimating coarse root size and root biomass is still in its infancy. However, several studies have accurately estimated these parameters in the field [116–118]. It is limited based on the depth of analysis since reflected radio signals will grow weaker as depth increases. Some studies have also used GPR to measure soil water concentrations [119,120].

Alternative Methods: A couple of technologies offer unique insights into high-contrast imaging of root architectures, though not offering direct insight into cover crop RS interactions. Piñeros et al. [121] grew plants hydroponically on a vertical structure of mesh discs; the discs encouraged a more soil-like growth habit and helped retain the root system’s shape for imaging. Additionally, Downie et al. [106] tested the substrate Nafion for use as a transparent soil and found it behaved similarly to vermiculite. Due to both Nafion

and water's similar refractive indices, plants can be grown in a soil-like medium, and root architectures and morphology can be easily imaged. In both technologies, applications for RS interactions with cover crops are limited because they do not behave like soil. Nevertheless, they may differentiate root morphologies between cover crops and efficiently isolate species and cultivars to be further studied under field conditions.

Recently, a procedure for visual estimation of soil structure (VESS) has been standardized by Ball et al. [122]. Considering parameters such as soil strength, structure, porosity, and biological activity, Munkholm et al. [108] found that VESS values were highly correlated with corn yield at a long-term rotation-tillage trial. These sorts of “quick and dirty” methods have been used to successfully identify differences in soil quality due to tillage and cropping history [122]. They may be applied to cover crop systems to identify broad differences in treatments with a range of RS interactions.

4. Improving Future Root-Soil Research with New Technologies

After reviewing the studies on cover crop root–soil interactions (Table 1), what becomes clear is that observed changes in some soil physical properties are less consistent than others. That cover crops positively affect aggregate stability is well-established; that cover crops modify the soil's bulk density, strength, and water-holding capacity less clearly. Even studies that measured these parameters over several years of cover crop use did not detect significant changes [70]. Then, again, the likelihood of detecting changes in soil physical properties is highly dependent on the cover crop being studied. Unlike tap-rooted cover crops cereal rye is not likely to produce changes in field water content [10] or soil macroporosity [12] but may increase the PSD [32,41].

For this reason, procedures that first validate in a controlled environment the ecological service in question across a range of plant species may increase the efficiency of cover crop research effort. Transparent growth media [106,121] and the use of tomographic technologies to sequentially image root system growth and development [11] can be used to characterize cover crop root system architecture and response to different soil physical properties. The study by Burr-Hersey et al. [11] is particularly insightful in that Vetch (*Vicia sativa*) root growth did not respond favorably to soil compaction; black oats, on the contrary, demonstrated substantial resilience to compaction but has yet to be considered in the field studies on cover crop RS interactions. According to several field studies, Vetch produced some or no change in soil strength and compaction [64,76,78,79,81]. Still, the ecological service being studied (i.e., reduced soil compaction) should not be expected to change greatly since Vetch is not a fitting species to maximize this service provision. Thus, a better understanding of the RS interactions of a range of species used as cover crops is needed to design cover crops for better experiments.

Tomographic imaging allows studying root system growth under field conditions. Colombi et al. [18] sampled soil from wheat, corn, and soybean plots and successfully used XCT imaging to measure artificial macropores' exploitation rate by plant roots. This cannot perfectly substitute for the detail and insight gained through macropore endoscopy [100]—nor vice versa—but there are some obvious advantages. First, while endoscopy identifies macropore colonization, it does not additionally provide a map of the root system network; XCT can provide both, albeit on a smaller scale given size restrictions on the cores to be scanned. Second, endoscopy remains a highly destructive sampling method requiring full excavation of a soil trench and soil layers permeated by macropore channels. Reduced time spent in the field may be the largest barrier to expanded use of endoscopy. Nevertheless, endoscopy is an innovative measurement technique that cannot presently be replaced by tomography.

Tomographic imaging also provides an opportunity for high-resolution, non-destructive measurement of soil particle arrangement and pore space, which may clarify the variability or lack of significant differences found when measuring various soil physical properties. Demonstrating this, Cercioğlu et al. [101] sampled soil from cover crop and non-cover crop treatments for XCT scanning in addition to constant head K_{sat} measurements. While they

found a significantly greater number of XCT-measured macropores under the cover crop treatment, and while the number of macropores was positively correlated with K_{sat} , they could not detect a significant difference K_{sat} between the treatments. This ought to caution conclusions based on K_{sat} or other infiltration estimates of macroporosity since differences may be immediately absent from K_{sat} values but exposed through a more detailed analysis.

Finally, studies that integrate several parameters may better detect changes in soil physical properties from cover crop RS interactions. To this end, the work of Chen et al. [67] and Olibone et al. [68] in measuring changes to the LLWR from cover crops stands out. In contrast, many other studies measure the same parameters and considered alone, they do not provide as holistic an explanation of changes to soil physical properties produced by cover crops and how this may affect subsequent crop production. Like the LLWR, VESS scores integrate several parameters and may be suitable for cover crop studies. Though not entirely a cover crop system, the study by Liesch et al. [123] provides some indication that changes in VESS scores can be observed after several months of fall cereal rye growth. With their study, significant VESS changes were observed even when there were no significant differences in infiltration rates across treatments. Since infiltration rate is influenced by several factors [123] and depends on the time of year when sampling takes place [32,41,46,84]. Larger infiltration systems de Almeida et al. [88] that simulate field conditions may be better suitable to account for natural variability than small soil cores or infiltrometers. This is yet to be determined.

5. Conclusions

Cover crop RS interactions have been studied indirectly by measuring changes in soil physical properties, which have yielded varying results. The LLWR and VESS should be applied in future studies since they integrate several parameters into one metric. They should provide a more holistic explanation of soil physical properties' changes and suitability for crop production induced by cover crops. A few studies have labored to study cover crop and production crop roots in concert with changes in soil physical properties, and these have been highly insightful. Moving ahead, tomographic imaging technologies can be used to improve research quality through both these avenues of inquiry: when indirectly studying RS interaction through changes in soil physical properties, tomographic imaging increases the detail of analysis and can reveal treatment differences that were unobservable by other means; and when studying the direct interaction of roots and soil in cover crop systems, tomography allows for non-destructive, repeated imaging of root system growth and development in controlled environments, while also being employable to explore root networks under field conditions. Controlled environment studies should not be neglected. Cover crops may be more efficiently studied in controlled environments to substantiate which species most likely maximize the desired service provision. More comparative studies like those of Lal et al. [85], Bodner et al. [10], and Burr-Hersey et al. [11] that group plant species based on service provisions are needed.

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