
Soil Physical Quality and Carbon Stocks Related to Weed Control and Cover Crops in a Brazilian Oxisol

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1. Introduction

The integration of weed management and cover crops as green manure plays an important role in several soil physical processes, influences carbon stocks and might be useful for minimizing soil physical degradation by compaction and hydric erosion.

According to Lal [1], soil degradative processes can be divided into physical (soil structure degradation, leading to crusting, compaction, erosion, desertification, anaerobiosis, environmental pollution and unsustainable use of natural resources), chemical and biological. Soil structure is an important soil physical property that affects all three degradative processes [1] and might be changed by weed control and cover crops management.

In an early report, Rufino et al. [2] investigated the relationships between management of a coffee crop and bare soil during five years on a Dystropherric Red Latosol with a 6% slope at Londrina. They observed that the soil losses in the coffee plantation were similar to bare soil (99.30 Mg ha⁻¹) in the first and second year post coffee planting. However, they noted that the soil losses decreased to 33.93 Mg ha⁻¹ from the fourth to fifth year. It was inferred that increasing soil cover between coffee rows and under the coffee canopy is important in reducing erosion susceptibility.

In another study conducted at Londrina, it was shown that high coffee population densities resulted in an increase in soil water content, soil organic matter, soil nutrient availability and a decrease in soil acidity and concentration of carbon in the soil microbial biomass (Pa-

van et al. [3]). They suggested that these results were due to the greater quantity of residues on the soil surface with higher coffee population density, which increased soil water content in both assessed layers.

In a Typical Dystropheric Red Latosol (617 g kg⁻¹ clay content) with 12% slope, Carvalho et al. [4] quantified the lowest soil losses (0.1098 Mg ha⁻¹ ano⁻¹) and sediment transportation (0.025 Mg ha⁻¹ mm⁻¹) in a system where the weed control was mechanical mowing. This obtained greater protection against soil erosion than, when the weed control was hand hoeing and the soil was exposed, increasing soil losses to 67.2434 Mg ha⁻¹ ano⁻¹ and sediment transportation to 0.022 Mg ha⁻¹ mm⁻¹. They also noted that weed control with post-emergence herbicide had an intermediate effect in relation to soil loss and sediment transportation.

Faria et al. [5] observed that, in bare soil, combined application of pre-emergence herbicide and systemic herbicide showed clear signs of surface crusting and sheet erosion associated with the formation of micro-rills and micro-knolls on the surface. As a consequence of this surface crusting there were increases in soil strength, quantified by precompression stress and soil load bearing capacity [6, 7].

Some studies carried out in tropical Oxisols and Ultisols [4 — 9] have shown the effect of weed control on soil physical, mechanical and biological properties. As reported earlier, in coffee plantations in the State of Paraná intense cultivation of coffee resulted in severe declines in soil organic matter contents and the use of large heavy farm equipment has produced compacted soils with poor structure that are susceptible to erosive rainfall [10]. Thus, cover crops like dwarf mucuna and peanut horse planted between coffee rows might be useful to decrease soil susceptibility to hydric erosion.

Dwarf mucuna [*Mucuna deeringiana* (Bort.) Merr] is a tropical legume and among the most successful species for using as a cover crop or green manure between coffee rows. It is a shrubby species of determinate growth, has a short or early cycle, and reaches a maximum height of about 40 to 50 cm [11]. Furthermore, the production of plant biomass between 4 – 6 Mg ha⁻¹, which minimizes the severe damage caused by water erosion, improves the root system by the decomposition of crop residues, reduces the time spent in the management of weeds, increases production and improves the nutrition of the coffee plants [12], consequently decreasing the cost of coffee production by decreasing fertilizer dependence.

Peanut horse [*Arachis hypogea*] is a legume with a long cycle (200 days between sowing to harvest). This ensures good coverage and protection of the soil [13] during all the periods of most intense rainfall (between October to February) [14], when the rainfall causes high erosion [15]. Furthermore, planting this crop between the lines of coffee favours biological fixation, increasing the cycling of nutrients and dry matter production to between 2200 and 2550 kg per hectare, which contributes to the maintenance of the soil moisture [13].

Furthermore, the impact of weed management on the total organic carbon concentration in soil might be affected per unit area or volume increase, as well as soil bulk density and thickness of soil layer [16].

The soil-water retention curve defines the relationship between the matrix pressure head and water content [17, 18, 19, 20]. Any soil-water retention curve has certain common fea-

tures that reflect the forces influencing the water retention [21]. Soil structure might influence these forces and change the behaviour of the soil-water retention curve.

The distinguishing properties of the soil-water retention curves depend on several factors, such as soil structure and aggregation, initial moulding water content, void ratio, type of soil, particle size distribution, mineralogy, stress history and soil compaction state. Among these factors, the stress history and initial moulding water content have the most influence on soil structure, which in turn dominates the nature of the soil-water retention curve and governs the air-entry value [18]. Authors have also shown that sandy clay till soil has two levels of structure: a macro-level structure and a micro-level structure and that both levels of structure are present in natural and compacted clayey soils.

Dexter [22] proposed the slope “S” of the soil-water retention curve at the inflection point as a measure of the micro-structural porosity of the soil for assessment of soil physical quality. This author also showed that the S-index was related to particle size distribution, soil bulk density, soil organic matter and root growth. This index, according to Dexter [22], is mostly due to microstructural porosity, and therefore, S governs many of these principal soil physical properties directly.

Although, some studies done in tropical soils suggest that the same reference value of S-index might be used for assessment of soil physical quality, this study has the hypothesis that the changes in the soil-water retention curve can change the references and responses of this index. Also, the changes in soil physical quality and carbon stocks under different weed management and cover crops in coffee plantations have not yet been investigated in Brazil.

Thus, our hypothesis is that weed control and the use of cover crops as a green manure between coffee rows changes the weed diversity and density, soil cover, soil carbon stocks and soil physical quality. Therefore, this chapter evaluates and provides information about the effects on soil total carbon stocks and soil physical quality caused by weed control and cover crops used as a green manure at different soil depths of a Latosol in a coffee plantation, in comparison to the soil under native forest.

2. Study site description and characterization

Since 2008, weed control and cover crop experiments have been conducted at the Agronomic Institute of Paraná (IAPAR) Experimental Station Farm in Londrina County, State of Paraná, Brazil (Latitude 23° 21' 30" S; Longitude 51° 10' 17" W of Greenwich).

The climate is Cfa – humid subtropical, according to Köppen’s classification. The average temperature in the coldest month is lower than 18 °C (mesothermal) and in the hottest months is higher than 22 °C, creating a hot summer, with a low frequency of frost and a tendency to be rainy in the summer months, although without a dry season [14].

According to geomorphological mapping for the State of Paraná [23], Londrina is located in the morfoescultural unit Sedimentary Paraná Basin, morfoescultural units Third Plateau and morfoescultural sub-units Londrina Plateau.

The soil in the experimental area is derived from basalt and is classified as a Typical Dystric Ferric Red Latosol according to the Brazilian Soil Classification System [24]; Typic Haplor-

thox according to USDA soil taxonomy [25] and Ferralsol [26]. The slope of the study site is nearly level at 3%, and altitude is 550m above sea level.

The natural forest is amongst secondary mixed hardwood forest, close to the experimental area and the soil there provides a benchmark for soil quality. Some of its physical properties are shown in Table 1.

The soil particle-size distribution was determined by the pipette method [27], by chemical dispersion with a 5 mL 1 N sodium hydroxide solution in contact with the samples for 24 hours. Physical dispersion was accomplished by 2 hours, in a reciprocating shaker, which shakes 180 times per minute in a 38mm amplitude.

Field capacity and permanent wilting point were measured in the laboratory and corresponds to water contents remaining at the soil samples after saturation and equilibrated to matric potential - 33 kPa and - 1500 kPa, respectively, in a ceramic plate inside a pressure chamber.

Soil particle density was determined using a volumetric flask [28]. Total porosity was calculated by the soil bulk density to particle density ratio [29, 30].

Depth	Clay	Silt	Sand	SOC	FC	PWP	Bd	Pd	TP
cm	g kg ⁻¹		g dm ⁻³		cm ³ cm ⁻³		kg m ⁻³		cm ³ cm ⁻³
2 – 7	780	160	60	29.98	0.35	0.29	0.91	2.78	0.67
12 – 17	800	140	60	19.44	0.42	0.36	1.00	2.79	0.64
22 – 27	810	140	50	18.41	0.42	0.36	1.08	2.81	0.61
32 – 37	810	140	50	15.36	0.43	0.37	1.13	2.82	0.60

Depth: depth of sampling; SOC: soil organic carbon; FC: field capacity; PWP: permanent wilting point; Bd: bulk density; Pd: particle density and TP: total porosity. Averages from four replicates.

Table 1. Physical properties and total organic carbon content of a Typical Dystroferic Red Latosol under native forest adjacent to the study area at IAPAR in Londrina, North of State of Paraná.

The clay fraction dominated in all depths of this Dystroferic Red Latosol. The soil contained 250 – 280 g kg⁻¹ of iron extractable by citrate-dithionite-bicarbonate, with hematite as dominant iron oxide, 620 – 650 g kg⁻¹ kaolinite and 20 – 40 g kg⁻¹ Al-interlayered vermiculite [10].

The soil had a homogeneous structure, low soil bulk density, high total porosity and macroporosity and exhibited a granular structure like coffee powder throughout the profile, as described early by Kemper & Derpsch [31].

The coffee plantation was established about 30 years ago and the soil management history of the site included a conventional tillage system, the primary operation was disk ploughing (approximately 25cm soil depths) and the secondary was two disks acting to 15cm. Between 1978 to 2007 the weed control between coffee rows was done with disk harrowing and hand hoeing.

3. Experimental design, weed control and cover crops

The experimental area has been planted with Mundo Novo plants, spaced 3.50m between rows and 2.00m between plants, since 1978.

In 2008, cover crops and weed management systems were established in a randomized complete block design with four replicates. Each plot has two inter-rows and has an area of 112m² (7m × 16m) for each treatment (28 plots in total). The experimental design further included a split-plot, with each weed control and cover crop in the inter-rows as the main-plot factor and the soil sampling depths (2–7 cm, 12–17 cm, 22–27 cm and 32–37 cm) as a split-plot.

The weed and cover crops management systems (TREATMENTS) were as follows:

1. hand weeding (HAW): performed with the aid of a hoe, when the weed reached 45 cm height, between August 2010 and July 2011 was performed four times.
2. portable mechanical mower (PMOW): with the aid of a portable knapsack mechanical mower
3. pre-emergence and post-emergence herbicides (HERB): A) pre-emergence: oxyfluorfen at a rate 4.0 L ha⁻¹ of commercial product at 240 g L⁻¹ (0.96 Kg active ingredient ha⁻¹), applied three times since beginning of the experiment, in November 2008, October 2010 and September 2011; B) post-emergence herbicides: glyphosate, at a rate 4.0 L ha⁻¹ of commercial product at 360 g L⁻¹ (1.44 Kg active ingredient ha⁻¹) applied six times (January, April, October and December 2009, April and December 2010); in March 2011 carfentrazone-ethyl was used as post-emergence herbicide at a rate 100 m L ha⁻¹ of commercial product at 400 g L⁻¹ (0.04 Kg active ingredient ha⁻¹).
4. cover crop peanut horse (*Arachis hypogaea*) used as a green manure (GMAY): was sown annually on October 23/2009; 14/2010 and 27/2011.
5. dwarf mucuna (*Mucuna deeringiana*) (Bort.) Merr used as a green manure (GMMD): was sown annually in October 23/2009; 14/2010 and 27/2011.
6. no-weed control between coffee rows (NWCB): the weed plants were left to grow freely between coffee rows.
7. no-weed control between coffee rows or under canopy of the coffee plants (weed check -WCCK).
8. native forest (NAFT): adjacent to coffee cultivation is a secondary mixed hardwood forest, located about 500m from experimental area.

Between each coffee row, two rows of the cover crops were sown annually at the beginning of the spring in October (23/2009; 14/2010 and 27/2011) and cut at flowering stage within the production cycle of the coffee.

It was observed in the field, that the species *Mucuna deeringiana* (Bort.) Merr grew faster than *Arachis hypogaea* until the end of December (sowing to flowering), after this stage the soil covered by these two species was similar.

4. Soil sampling and analyses

The soil sampling and analyses were performed in 2011 (the third year of this experiment) to assess the effects of weed control and cover crops on soil structure. The undisturbed soil samples were collected from the centre of the inter-rows between coffee plants (1.75m from the coffee stem) using a mechanical extractor and inox rings, 5cm high and 5cm in diameter. Also, to calculate the total carbon stocks, disturbed soil samples were collected under the coffee canopy at the same depths.

As reported previously, the undisturbed soil samples were collected at depths 2 – 7 cm, 12 – 17 cm, 22 – 27 cm and 32 – 37 cm. These depths were chosen for sampling because the surface layers are more relevant when assessing the impact of management on carbon stocks and are more frequently modified directly by cultivation [16]. These authors showed that the layers between 0 and 18 cm were most influenced by management. Furthermore, these layers are more influenced by weed control in coffee plantations, as shown earlier by Alcântara & Ferreira [9] and Araujo-Junior et al. [6, 7]. The selection of the fixed sampling depth, as done in this study, is somewhat arbitrary, but it must be identical for all profiles being compared and include the soil layer most susceptible to the influence of management [16].

The photos 1A and 1B show the no-weed control between coffee rows and dwarf mucuna used as a green manure and cover crop. Cover crops provide a good soil cover and protect the soil against hydric erosion and soil surface crusting. The soil cover with peanut horse (Figure 1C) and weed control with herbicides provided lower soil cover (Figure 1D).

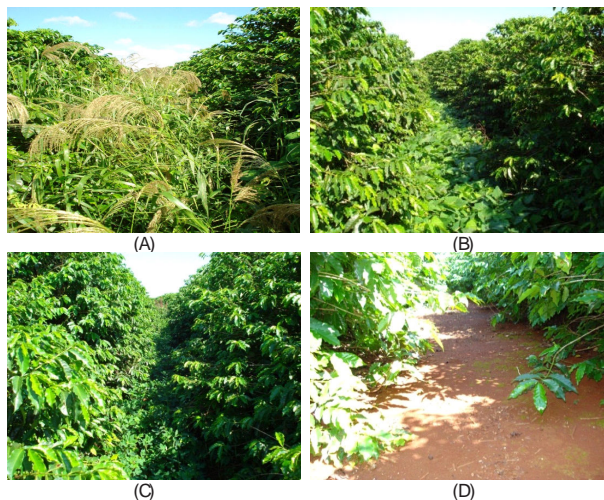


Photo 1. Experimental plots: (A) weed check no-weed control between coffee rows and under coffee canopy, (B) plants of dwarf mucuna (*Mucuna deeringiana*) used as a cover crop and green-manure, (C) peanut horse (*Arachis hypogaea*) and (D) herbicides.

5. Total soil organic carbon and carbon stocks

Total soil organic carbon was determined by wet digestion following organic oxidation by $\text{Cr}_2\text{O}_7^{2-}$ in acid [32]. The total soil organic carbon concentrations in kg Mg^{-1} were obtained directly from chemical analyses for the two sites of sampling (under the coffee canopy and between coffee rows). Total soil organic carbon masses in each soil layer in Mg ha^{-1} were calculated from the thickness of the soil layer (0.10m) and the average soil bulk density in each layer, according to Equation 1, proposed by Ellert & Bettany [16].

$$M_{\text{COT}} = \text{conc} \cdot \rho_b \cdot T \cdot 10\,000 \text{ m}^2\text{ha}^{-1} \cdot 0.001 \text{ Mg kg}^{-1} \quad (1)$$

Where, M_{COT} total soil organic carbon mass per unit area (Mg ha^{-1}), conc is total soil organic carbon concentration (kg Mg^{-1}), ρ_b is the soil bulk density (Mg m^{-3}) and T thickness of soil layer (m).

6. The soil-water retention curve and its properties

Evaluation of soil physical quality includes measurements of the soil-water retention data and its properties performed in quadruplicate. Undisturbed soil samples were prepared for the exact size of inox rings. These soil samples were saturated with water for 48 hours. After that, undisturbed soil samples were equilibrated to a matric potential expressed as pressure head h (cm) of 20cm, 40cm, 60cm and 100cm on a suction table [33] (Eijkelkamp Equipment, P.O Box 4, 6987 ZG Giesbeek Nijverheidsstraat 30, 6987 EM Giesbeek) and 330cm, 1,000cm, 5,000cm and 15,000cm in a ceramic plate inside a pressure chamber (Soil Moisture Equipment Corp., P.O. Box 30025 Santa Barbara, CA 93105) [34].

To calculate soil bulk density, undisturbed soil samples were dried in the oven at 105–110 °C for 48 hours to determine dry soil weight per unit volume [35, 36]. The volumetric soil water content was estimated using gravimetric soil water content times soil bulk density [37].

The soil microporosity was determined for the soil samples equilibrated to a matric potential - 6 kPa in a suction table, which separated the pores with effective diameter greater than 50 μm , drained from the cores (macropores). The soil macroporosity was calculated by the difference among total porosity and microporosity, which corresponds to water drained between 0 to 60 cm pressure head.

The soil-water retention curve is the functional relationship between water pressure head (cm) or soil matric potential (Ψ) versus soil water content ($\text{cm}^3 \text{ cm}^{-3}$) was obtained for each undisturbed soil sample. The soil-water retention was fitted through the van Genuchten [17] model with Mualen [38] constraint ($m = 1-1/n$) described by the Equation 2, using software Soil Water Retention Curve (SWRC) [39].

$$\theta = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{[1 + (\alpha \Psi)^n]^{1-1/n}} \quad (2)$$

Where, θ , θ_{res} and θ_{sat} represent the volumetric, residual and saturated soil water contents ($\text{cm}^3 \text{cm}^{-3}$), respectively; α , m and n are the parameters of the fitted model that are related to scaling factor and the shape of the fitted curve; Ψ is the pressure head (cm).

The angular coefficient of the soil-water retention curve at inflection point (soil physical quality [S index]) was calculated by Equation 3 [22].

$$S_{index} = -n (\theta_{sat} - \theta_{res}) \left[\frac{2n-1}{n-1} \right]^{-\left(\frac{1}{n}-2\right)} + \theta_{res} \quad (3)$$

Data for soil cover, soil bulk density and total soil organic carbon were submitted to analysis of variance through the software SISVAR [41], considering a split plot design, comparing different weed management and cover crops in each soil depth. Linear regressions were obtained for soil macroporosity and soil physical quality S-index to obtain the lower boundary limit for this index.

7. Results and discussion

The results supported that in Oxisol planted with coffee plantation the weed diversity and density, soil cover, soil carbon stocks and soil physical quality measured by S index and macroporosity are related to weed control and cover crops.

Seven weed species were identified in the coffee plantation and were submitted to different weed control and cover crops between coffee rows and under the coffee canopy in May 2011 (Table 2). Although the soil in the present study has a clayey texture, the number of weed species was relatively small compared to the previous study of a coffee plantation assessed in the summer season in a tropical region (December 2007) [42].

Carter & Ivany [43] highlighted that the soil type and kind of tillage can significantly influence weed seed bank composition. They also explained that reduced physical protection and aggregate entrapment in sandy, compared to clay textured soils, would allow weed seeds to move to deeper soils depths (12cm), where seed dormancy would be independent of soil texture. In addition to this, Carter & Ivany [43] *apud* Albrecht and Pilgram showed that soil textures are mainly related to soil-water retention and can significantly influence weed seed density, weed composition and seed size, through selective pressure on available water capacity.

The low density and diversity of weed species observed in this study (Table 2) was probably due to low temperature, with a mean monthly temperature of 17.7°C and mean precipitation of 93mm. However, in May 2011 the rain distribution was erratic, with only 7.6mm of precipitation, which impaired the weed germination, growth and development.

A greater diversity and density of weed plants was observed in the soil between coffee rows, compared to under the canopy (Table 2). This suggests that the coffee canopy promoted weed suppression.

SCIENTIFIC NAME AND WEED SPECIE	Weed management and cover crops in a coffee plantation													
	HAWE		PMOW		HERB		GMAY		GMMD		NWCB		WCKC	
	BCR	UCC	BCR	UCC	BCR	UCC	BCR	UCC	BC	UCC	BC	UCC	BCR	UCC
									R		R			
Portulaca oleracea L. Purslane								X		X				
<i>Digitaria insularis</i> (L.) Fedde Sourgrass	X		X		X							X		X
Brachiaria decumbens Signal grass												X		X
Sida rhombifolia Arrowleaf sida														X
<i>Talinum paniculatum</i> (Jacq.) Gareth. Fameflower		X		X	X	X	X	X	X	X			X	X
Momordica charantia L. Bitter melon			X	X								X		X
Phyllanthus tenellus Roxb. Leafflower	X	X	X	X	X	X	X	X	X	X		X		X

HAWE: hand weeding; HERB: pre plus post-emergence herbicides; PMOW: portable mechanical mower; GMAY: cover crop peanut horse *Arachis hypogea*; GMMA: cover crop dwarf mucuna *Mucuna deeringiana*; NWCB: no-weed control between coffee rows; WCKC: weed check. BCR: between coffee rows; UCC: under coffee canopy.

Table 2. Weed species distribution under different management and cover crops in a coffee plantation at two positions, between coffee rows and under the coffee canopy in May 2011.

Among the management adopted, a greater density and diversity of weed plants (Table 2) was detected in the no-weed control between coffee rows and weed check. The absence of soil disturbance in these weed management systems allows formation of a bigger and more diverse weed seed bank in soil [43, 44, 7]. However, the former authors suggested the diversity is not directly related to higher infestation levels.

The species fameflower and leafflower were observed in almost all treatments, except in the no-weed control between coffee rows (Table 2).

8. Soil cover

The weed control and cover crops had a significant effect on soil cover values offered by weed plants between coffee rows and under the coffee canopy (Figure 1). For the assessment in May 2011, soil cover by weed plants and cover crops between coffee rows was in the following order: NWCB = WCKK > HAWE = PMOW > GMAY = GMMA > HERB. However, it should be noted that managements HAWE and PMOW also promoted a good soil cover at this time of year.

Between coffee rows, no-weed control and weed check (without weed control between coffee rows and under canopy) were most effective in soil protection, whereas the weed control with herbicides was less effective in soil protection. Intermediate levels of effectiveness were observed for the hand weeding, portable mechanical mower and green manures.

Under the coffee canopy, significant differences were not evident among most of the managements. Greater soil cover was obtained by hand weeding, dwarf mucuna, no-weed control between coffee rows and weed check (without weed control between coffee rows and under canopy) (Figure 1).

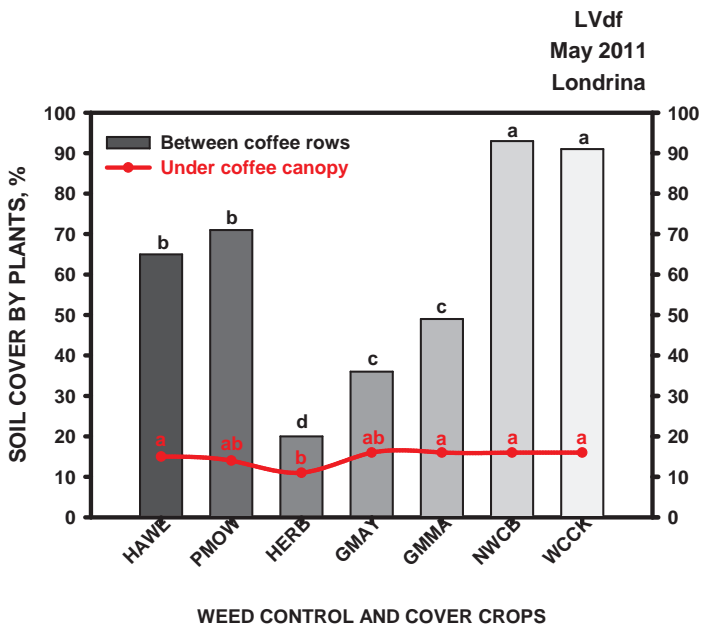


Figure 1. Soil cover by weed and cover crops in a coffee plantation between coffee rows and under coffee canopy in May 2011. HAWE: hand weeding; HERB: pre plus post-emergence herbicides; PMOW: portable mechanical mower; GMAY: cover crop peanut horse (*Arachis hypogea*); GMMA: cover crop dwarf mucuna (*Mucuna deeringiana*); NWCB: no-weed control between coffee rows; WCKK: weed check.

These results show the potential that weed plants have to provide protection between coffee rows against the direct impact of raindrops, thus reducing the potential for loss of water and soil. Despite the high water infiltration rate of Dystrocherric Red Latosol in Londrina (70mm h^{-1}), there is an intense rainfall erosivity index, with over $1,000\text{ MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ [2, 15]. Therefore, this soil can experience losses exceeding 100 tons/ha on bare soil and 33 tons/ha where crops are grown [2]. These authors showed that the squaring operation (Post-harvest coffee) is critical to soil losses in coffee crops grown, due to removal of lower leaves and soil protection. Thus, weeds and cover crops cultivated between coffee rows might be used to protect the soil against direct raindrop impact and reduce water and soil losses in coffee plantations.

9. Soil bulk density

The soil samples from the coffee-cultivated plots subjected to different weed management and cover crops between coffee rows had a higher bulk density at four depths, when compared to the soil samples from native forest soil (Table 3). Some previous studies have shown this increase in the soil bulk density under coffee plantation in relation to native forest [7, 9].

The soil bulk density for Latosol at 2–7 cm, 22–27 cm and 32–37 cm depths were not significantly varied between different weed and cover crops management. However, at 12–17 cm depths obvious differences of soil bulk density were detected. The soil bulk density for Latosol under HAWE, NWCB and WCK weed managements and both cover crops used as green manure, resulted in higher packing of solid particles of the soil (Table 3). The higher bulk densities at 12–17 cm depth might be due the stress concentration applied by tyres and equipment used for weed control in the past, which promoted a higher degree of physical degradation and packing of solid particles of the soil.

Nevertheless, neither soil bulk densities found in the present study were considered higher than the critical soil bulk density (1.20 kg dm^{-3}) for coffee root growth established by Araujo-Junior et al. [7] in Latosol with 560 g kg^{-1} clay. These results are in agreement with Streck et al. [45], who obtained the critical soil bulk density, based on soil physical quality S-index, for seven Latosols under different land uses with clay content between 160 to 760 g kg^{-1} .

For the soil in this study, Derpsch et al. [46] suggested the value equal to 1.20 kg dm^{-3} for problems with root growth and soil aeration are not probable. On the other hand, according to these authors, values of soil bulk density higher than 1.25 kg dm^{-3} might restrict root growth.

In a Dystrocherric Red Latosol with 800 g kg^{-1} clay, Tormena [47] observed that soil physical quality measured by S-index decreased as soil bulk density or compaction increased as a result of reducing macropores volume, with a consequent alteration on the pore size distribution. They found that at 1.16 kg dm^{-3} there are restrictions on soil physical quality associated with soil resistance to root penetration. However, they pointed out that using S-index in-

stead of soil bulk density values has the advantage of getting similar S values in soils of different particle size distribution.

Native forest / weed and cover crops	Soil bulk density, kg dm ⁻³			
	Depths, centimetres			
	2 – 7	12 – 17	22 – 27	32 – 37
Native forest	0.91 A	1.00 A	1.08 A	1.13 A
Hand weeding	1.10 B	1.16 C	1.16 B	1.14 A
Portable mechanical mower	1.11 B	1.11 B	1.12 B	1.15 A
Herbicides	1.11 B	1.10 B	1.19 B	1.18 A
Peanut horse <i>Arachis hypogaea</i>	1.12 B	1.23 C	1.18 B	1.13 A
Dwarf mucuna <i>Mucuna deeringiana</i>	1.12 B	1.19 C	1.21 B	1.19 A
No-weed control between coffee	1.08 B	1.18 C	1.14 B	1.09 A
Weed check	1.07 B	1.20 C	1.17 B	1.15 A

Averages followed by the same uppercase letters compare different treatments in each soil depth.

Table 3. Soil bulk density for Latosol samples collected between coffee rows in four depths under different weed control and cover crops managements.

For seven Oxisols in the South of Brazil under different land uses Streck et al. [45] showed lower values for soil bulk density under native forest than for the soil under direct drilling. They showed no relationship between clay content and dispersible clay in water using soil physical quality S-index. However, they found an exponential decay relationship between S-index vs. soil bulk density and S-index vs. precompression stress. Although Tormena et al. [47] did not comment on the kind of relation between S-index and soil bulk density, it was possible to note similar behaviour to exponential decay.

10. Total soil carbon stocks

Figure 2 shows the total soil organic carbon stocks for a Dystróferric Red Latosol at four depths, under natural forest and coffee plantation, submitted to different weed controls and cover crops.

The soil under native forest contained lower carbon stocks compared to the soil under coffee plantation submitted to different weed management systems. This is likely due to the lower soil mass per unit area under native forest and also the large amount of weed dry mass added during thirty years, resulting in soil organic carbon accumulation in the soil under the coffee plantation (Figure 2).

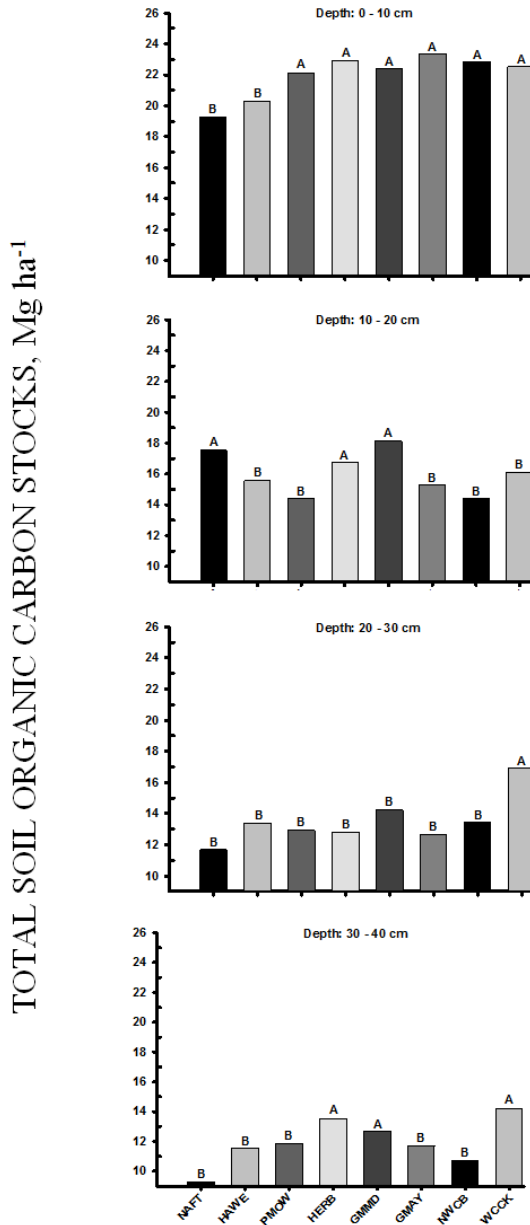


Figure 2. Total soil organic carbon stocks for a Dystroferic Red Latosol at four depths, under natural forest and coffee plantation. NATF: native forest; HWE: hand weeding; HERB: pre plus post-emergence herbicides; PMOW: portable mechanical mower; GMMD: dwarf mucuna (*Mucuna deeringiana*); GMAY: peanut horse (*Arachis hypogea*); NWCB: no-weed control between coffee rows; WCK: weed check.

In coffee plantations, the planning of weed control, with the input of cover crops as a green manure, restored the carbon stocks to similar levels as the native forest. Another possible explanation for the higher stocks of carbon in the coffee plantation is physical protection of organic matter by aggregates and organomineral interactions [49] because this Typical Dystroferic Red Latosol (Typic Haplorthox) has a clay fraction that is dominated by hematite and phyllosilicate as kaolinite [10]. The organomineral interactions, such as iron and aluminium oxides and the surface functional groups of organic matter, interfere with the decomposition of organic matter by microbial processes, even under conventional tillage [49].

Based on information supported by Castro Filho et al. [48], in experiments of crop succession in conventional tillage and direct drilling over 14 years, Bayer et al. [49] estimated the total carbon stocks at 0–20 cm depths and the rate of carbon inputs for clayey Latosol from IAPAR. They found 27.40 to 29.00 Mg C stock ha⁻¹ under conventional tillage and 31.87 to 32.30 Mg C stock ha⁻¹ under direct drilling at a rate 0.24 to 0.48 Mg ha⁻¹ year⁻¹.

At 0 – 20 cm depth, our results were: NAFT: 36.79 Mg C stock ha⁻¹; HAWE: 35.86 Mg C stock ha⁻¹; PMOW: 36.50 Mg C stock ha⁻¹; HERB: 39.65 Mg C stock ha⁻¹; GMAY: 37.63 Mg C stock ha⁻¹; GMMMA: 40.57 Mg C stock ha⁻¹; NWCB: 37.28 Mg C stock ha⁻¹ and WCCK: 38.64 Mg C stock ha⁻¹. Generally, the conversion of native forest into crops can promote losses of soil carbon stocks. However, this study showed that with integrated weed management and cover crops between coffee rows the carbon stocks can be maintained or increase.

The carbon stocks under coffee plantation were higher than those estimated by Bayer et al. [49] for the tillage treatments, based on results obtained by Castro Filho et al. [48]. These results might be due to the lower decomposition rates between coffee rows or greater biomass inputs from weed populations and cover crops. Also, the high coffee population density might contribute to lower soil temperature and increase in soil organic carbon in the coffee plantation, as reported earlier by Pavan et al. [3].

The total soil carbon stocks at 10 to 20 cm depths for NAFT were similar to HERB and GMMMD. Calegari et al. [49], in a long-term experiment supported by results for a clayey Rhodic Hapludox with 720 g kg⁻¹ clay, from Pato Branco (Southwestern of State of Paraná), found that the weed provided some increase in soil organic carbon compared to burning. Also, they observed the effects of several winter crops and tillage treatments over 19 years. They found 68.86 Mg C ha⁻¹ under no-tillage and 65.21 Mg C ha⁻¹ under conventional tillage between 0 to 20 cm depths. Another important result found by these authors, was that independent of soil tillage, the total soil organic carbon stocks decreased in the following order: lupin > oat > radish > vetch > wheat. Although lupin was intermediate in dry mass production compared to others. These results highlight that winter cover crops help increase the soil carbon stocks compared to wheat [50].

Early reports from experiments done at IAPAR, between 1964 and 1978, showed that organic matter content decreased by approximately 45% through coffee cultivation, compared to native forest [31]. However, in that time, the coffee plantations had mechanized weed control by tillage, which increased soil losses by removing organic substances and nutrients.

However, current uses of integrated weed management systems and cover crops between coffee rows can promote higher organic matter accumulation on the soil surface, increasing protection against soil erosion and nutrients losses.

The use of integrated weed management systems [5, 7, 9], coffee population density [3] and cover crops have been suggested to play an important role in soil carbon stocks [47 to 49]. The results found in this study, suggest that integrated weed management and cover crops between coffee rows helps the maintenance of soil carbon stocks.

It was observed that the cover crop peanut horse provides good carbon accumulation through the root system. In comparison, assessments carried out in 2010 and 2011 suggest the values of the total soil organic carbon under the cover crop peanut horse increased by 4 g dm^{-3} at 0 – 10 cm depth (unpublished data).

11. Soil physical quality

The soil-water retention curve for the Genuchten-Mualem equation for the Latosol submitted to different weed control and cover crops in a coffee plantation at four depths was significant at a 1% probability level, for t-Student test. The coefficient of determination (R^2) ranged from 0.71 to 0.99.

The residual soil-water content (θ_{res}) ranged from $0.26 \text{ cm}^3 \text{ cm}^{-3}$ for the samples collected from WCK at 2 – 7 cm depth, to $0.40 \text{ cm}^3 \text{ cm}^{-3}$ for the HERB at 22 – 27 cm depth. Based on this information, it was possible to see that weed control with HERB increased soil water retention at high-pressure heads (15,000 cm col H_2O) and this management promoted close pore-size distribution. On the other hand, the WCK promoted lower water retention, which indicates high pore diameter distribution on soil samples under this management.

The saturated soil-water content (θ_{sat}) ranged from $0.68 \text{ cm}^3 \text{ cm}^{-3}$ for the soil samples collected from NAFT at 2 – 7 cm depth, to $0.52 \text{ cm}^3 \text{ cm}^{-3}$ for the HERB at 22 – 27 cm depth. These results suggest higher total porosity of soil samples from NAFT and lower in HERB.

The value of α ranged from 0.0292 to 0.8065 ($1/\text{cm}$) at which the retention curve becomes the steepest, as reported earlier by van-Genuchten [17]. The value of the parameter “n” ranged from 1.2386 for NAFT land use at 12 – 17 cm depth to 1.8321 for HAWE weed control. The smaller value of n represents a less steep soil-water retention curve [17] and “m” from 0.1927 for the soil samples under NAFT at 12 – 17 cm depth to 0.4338 for the samples under HERB (22 – 27 cm).

In general, the soil physical quality of samples from Latosol quantified by S-index under coffee plantation and native forest at four depths (Figure 3) were higher than the lower boundary limit established by the regressions based on macroporosity $0.10 \text{ cm}^3 \text{ cm}^{-3}$ considered as critical for soil aeration (Figure 4).

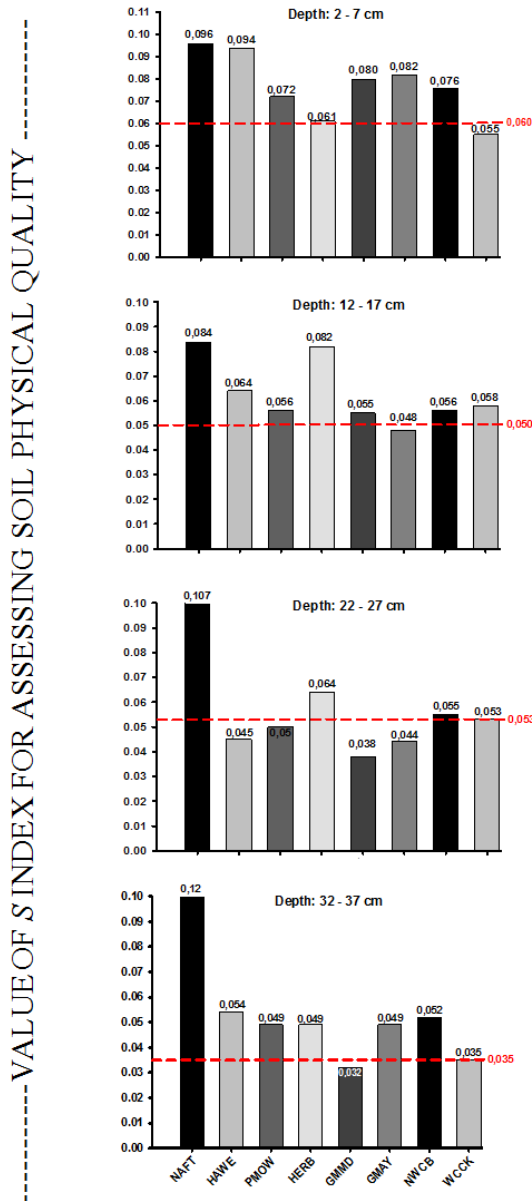


Figure 3. Soil physical quality “S index” for a Dystroferic Red Latosol in 2–7 cm, 12–17 cm, 22–27 cm and 32–37 cm layers, under natural forest and coffee plantation. NATF: native forest; HAWE: hand weeding; HERB: pre plus post-emergence herbicides; PMOW: portable mechanical mower; GMMD: dwarf mucuna (*Mucuna deeringiana*); GMAY: peanut horse (*Arachis hypogea*); NWCB: no-weed control between coffee rows; WCCK: weed check. The dotted horizontal line represents the critical value for S index in each soil layer.

It should be noted that values of S-index obtained in the present study are higher than the reference values suggested by Dexter [22] and found by many studies for Brazil's tropical soils [47, 51, 52]. In an overview of the relationship between S-index and soil physical properties (particle size distribution, bulk density, total porosity, macroporosity) from 2,364 soil samples with a wide range of clay content, Andrade & Stone [53] found that lower boundary limit for S-index is equal to 0.045. This proved to be adequate to separate soils with good structure and soils with a tendency to have poor soil structure, where values of $S \leq 0.025$ indicate physically degraded soils.

Dexter [22] suggested that the boundary between soils with good and poor soil structural quality occurs at values of approximately $S = 0.035$. Values of $S < 0.020$ are clearly associated with very poor soil physical quality in the field. Though, in this study we fitted soil-water retention curves using volumetric soil water content, which promoted higher S values, in agreement with Maia [52].

In the present study, the soil-water retention curve was adjusted for volumetric water content to improve the response of S-index to soil compaction. Under soil compaction, there are changes in volumetric water content and there is no change in gravimetric water content, which can improve the sensitivity of S-index.

Dexter [22] and Maia [52] suggested that the soil-water retention curve must be fitted by gravimetric soil water content to use the reference values established by the former. Although it could equally be defined using the volumetric water content, changing reference values for assessing soil physical quality as suggested in the present study.

In all depths, the highest soil physical quality S-index was observed for soil under natural forest (Figure 3), which is due to the absence of stress history, which was observed by high macroporosity and lowest soil bulk density (Table 3). These results highlight that although the adoption of weed control without machine traffic and cover crops as a green manure between coffee rows ameliorates slightly those harsh effects on soil quality, the impacts of the coffee plantation in relation to the soil under native forest are highly significant.

The soil physical quality quantified by S-index at 2 — 7 cm depths in plots under hand weeding was similar to the value observed in the soil under native forest (Figure 3). This result might be due the effect of the hoe, which loosens the soil surface, promoting an increase in the total porosity and a decrease in soil bulk density (Table 3).

After three years studying a Rhodic Paleudalf (Nitossolo Vermelho distroférrico) with 600g kg^{-1} clay under crop rotation and chiselling, Calonego & Roslem [51] observed a higher S-index value as a result of better soil management compared to the beginning of their experiment. They observed mainly soil physical quality improvements on the soil surface, due to the chiselling and loosening of the soil and also as a result of greater root growth in this soil layer.

At 22 — 27 and 32 — 37 cm depths, soil physical quality S-index in plots under dwarf mucuna (*Mucuna deeringiana*) (Bort.) Merr had lower values than the critical limit (Figure 3). These findings must be due to the stress history caused by the use of the mechanical rotary tiller and disk harrowing as part of weed control between coffee rows in the past, before the ex-

periment installation. In clayey soil in Northern Paraná, the excessive use of heavy ploughing harrow equipment compacted the subsurface layers, accelerated erosion, decreased infiltration rate, inhibited root development and reduced crop productivity [31, 56].

Similar results were obtained by Calonego & Rosolem [51], mainly in the 27.5 to 32.5 cm layer under triticale plus pearl millet. This characterizes a soil with poor structural quality, with the lowest $S = 0.019$. They suggested that crop rotation involving only monocotyledonous species, limited the cultivation effect on the soil structure to the first 20cm of the soil depth. Although some cover crops have appeared to improve soil protection against erosion and compaction, improve water infiltration rate, soil-water retention and soil carbon stocks, some of them did not show a beneficial effect at deeper soil layers, since the root system is concentrated at the soil surface.

In a Cerrado Red Latosol with 420 g kg^{-1} clay under direct drilling over four years Silva et al. [55] observed that the sills of the active parts of the disk plough and disk harrow increased soil strength and reduced the saturated hydraulic conductivity in layer below the sills of this equipment.

In deeper soil layers (22 — 27 cm and 32 — 37 cm) the differences among the S-index calculated for the Latosol samples under native forest and for coffee plantation were greater (Figure 3), which suggests that these depths had lower soil physical quality. These results might be due to the lower organic carbon content in coffee plantation, which favours closer packing of solid soil particles, as a result of decreased macroporosity and increased soil bulk density, [7] and consequently decreases soil physical quality index in comparison to soil without stress history (native forest). Furthermore, the organic matter content reflects the degree of soil degradation in clayey soil derived from basalt rocks [56]. A decrease in organic matter content over the time reflecting the inadequate land use was observed.

In the past, measurements of the same experimental field have shown that the reduction of soil organic matter due to tillage operations can contribute to the destruction of natural porosity and create a compact layer in clay soils in the North of the State of Paraná [31]. On the other hand, in surface layers, the weed and cover residues are left as mulch, so the differences in soil physical quality index were less marked compared the soil under native forest.

12. Relationship between S-index and soil macroporosity

Figure 4 shows the relationship between the soil macroporosity and S-index for the soil under different weed management, cover crops in a coffee plantation and in soil under native forest. For all depths, the S-index increased linearly with increasing soil macroporosity (Figure 4). These results are in agreement with Andrade & Stone [53] who observed that S-index increased with total porosity and macroporosity.

The regression lines fitted to all the data in Figure 4 explained 70% to 88% of the variance in S-index. All regressions for the Dystropherric Red Latosol were significant at 1% probability level, by t-Student test. Based on these equations, the S-index of the soil surface (2 — 7 cm depth) in-

creased less as macroporosity increased. On the other hand, at 32 — 37 cm depth the soil physical quality quantified through S-index increased in greater proportion with soil macroporosity.

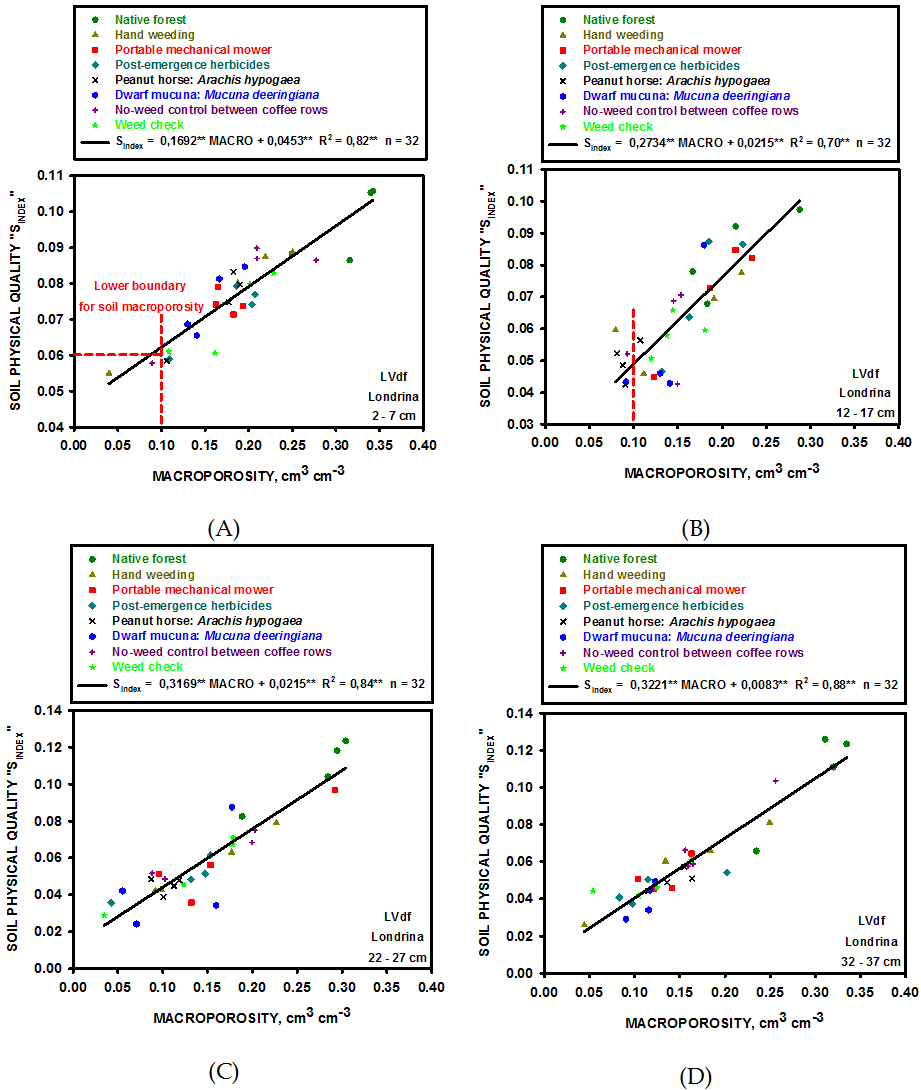


Figure 4. Relationship between soil macroporosity and S-index for a Dystroferic Red Latosol in four soil depths, under natural forest and coffee plantation. The lower boundary for soil macroporosity considered was 0.10 cm³ cm⁻³ (A) soil samples taken from 2 – 7 cm depth; (B) 12 – 17 cm depth; (C) 22 – 27 cm depth and (D) 32 – 37 cm depth.

The regressions lines in Fig. 4 A to 4 D were used to define the lower boundary for soil physical quality for Latosol cultivated with coffee plantation and might be used for pre-

dicting soil physical quality (S-index) through macroporosity of this Latosol under different weed control and cover crops. With inadequate soil management, a flattened soil-water retention curve was observed, with a reduction in the slope of this curve at the inflection point [21, 20, 42]. Thus, it can be inferred that soil compaction changes pore diameter, but not all pores are reduced similarly [20, 21, 42, 45, 47, 51 – 54]. Typically, compacted Oxisols have low macroporosity and total porosity and, as a consequence, have low infiltration rate [31].

Many studies have shown that the macropores (pores with effective diameter greater than 50 μm) are reduced first under stress. Then, compaction has a great influence on macropore flow, but there have been few attempts to quantify these effects [20]. Han et al. [54] found that characteristics of pore diameter at the inflection point were related to the hydraulic conductivity. Due to that, we relate the S-index with macroporosity (Figure 4) and use this relation to define the lower boundary limit for S-index for four depths.

13. Conclusions

The results supported the hypothesis that weed control and cover crops between coffee rows change the weed diversity and density, soil cover, soil carbon stocks and soil physical quality measured by S-index and macroporosity. Also, the weed control and cover crops between coffee rows ameliorate slightly the harsh effects of the coffee crop system on total soil carbon stocks and soil physical quality in the North of the State of Paraná.

Adjustment of the soil-water retention curve changed the references and responses of the S-index. Based on S-index, it was observed that the soil under coffee plantation, submitted to different weed controls and cover crops as a green manure between coffee rows without traffic machines, contributed to preserve soil physical quality in soil depths between the surface and 40cm, except the plots under the cover crop dwarf mucuna at 22 – 27 cm and 32 – 37 cm soil depths. Therefore, the integration of weed management and cover crops must be recommended to help maintain carbon stocks and improve soil physical quality between coffee rows.

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