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Liquid Bovine Biofertilizer and Cultivation Effects on the Porosity of a Typic Haplocambids as a Function of Cultivation and Dose

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ABSTRACT: The soil porous space is where processes related to gases and soil solution occur, and provides an adequate guide for agricultural practices. This study aimed to evaluate the integrated effects of cultivation and the application of liquid bovine biofertilizer on the porous network of a Typic Haplocambids *(Cambissolo Háplico Ta Eutrófico)* cultivated with figs (*Ficus carica* L.). Four treatments were evaluated (under fig cultivation with the application of 20, 40 and 60 % of biofertilizer through irrigation, a control treatment without biofertilizer and an additional treatment – soil under natural vegetation). Disturbed and undisturbed soil samples were collected in three soil layers (0.0-0.1, 0.1-0.2 and 0.2-0.3 m) with four replicates. The following physical properties were analyzed: particle-size distribution, soil bulk and particle densities, and soil water retention curve. The coefficient of intrinsic soil air permeability was calculated based on the equation that considers the decreasing pressure method. Soil porosity, pore continuity index and blocked porosity were calculated and pore length was estimated. Compared with the native forest, pore network quality is improved, if not maintained, when the soil is cultivated under the conditions described in this experiment. In the conditions of cultivation, the application of bovine biofertilizer, for supplying sediments that block or reduce the size of the pores, did not improve soil air permeability. The cases where pore network quality was worsened in soil porosity as a result of the applied treatments (Biofertilizer 20 %, Biofertilizer 40 % and Biofertilizer 60 % for the layer of 0.0-0.1 m and Biofertilizer 60 % for 0.1-0.2 m), although not considered critical to plant development, point to the need for specific management practices (for instance, avoid coarse residues in the biofertilizer before its application) to avoid soil degradation.

Keywords: soil physics, soil porosity, organic matter.

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INTRODUCTION

The knowledge on the geometry and magnitude of soil porous space is essential to understand soil water and solute dynamics, as well as gas diffusion (Ball et al., 2007). Plant development is significantly affected by the capacity of the soil to promote an adequate gas exchange between the rhizosphere and the atmosphere (Silva et al., 2009). Therefore, the quantification and the monitoring of properties related to the soil porous system are important to evaluate its physical functionality.

Intrinsic soil air permeability and pore continuity and length indices are parameters that influence soil gas and water flows. Thus, they are relevant for soil porous space characterization and the identification of changes in soil structure, since they are sensitive to the effects of management practices (Blackwell et al., 1990; Fish and Koppi, 1994; Cavalieri et al., 2009).

Soil porous system can be significantly altered by different factors, and frequently happens as a result of anthropic actions associated with land uses (Costa et al., 2014). Soil management practices have a great impact on soil aeration. Practices promoting soil disturbance with the use of plows tend to increase the volume of pores, soil permeability and air storage (Braunack and Dexter, 1989). In this scenario, the addition of organic material, like bovine biofertilizer, has been an anthropic alteration used to improve functional performance in the agricultural system (Kitamura et al., 2008). However, the magnitude of the alteration in structure and functionality of the soil porous system, caused by the addition of bovine biofertilizer, needs to be better detailed.

Comprehension of the existing relationships in the pore network induced by soil management is crucial for the prognosis of characteristics involving water, solutes and gas flow in the soil profile. Such understanding helps farmers and researchers more efficiently to develop an adequate management plan to be adopted in the production of a given crop (Lipiec et al., 2006).

This study was based on the following hypotheses: 1) cultivation, since it degrades soil properties related to porous geometry, worsens its quality compared with soil under natural vegetation; and 2) the application of bovine biofertilizer (organic matter) in soil under cultivation, since it acts as a cementing agent between soil particles, improves soil structure and, consequently, properties related to the porous system. Therefore, this study aimed to evaluate the integrated effects of cultivation and the application of a biofertilizer on the porous network of a *Cambissolo Háplico Eutrófico* cultivated with fig (*Ficus carica* L.).

MATERIALS AND METHODS

Studied area

The area is located at the Apodi Plateau, in the municipality of Limoeiro do Norte, Ceará, Brazil. The experimental area cultivated with fig (0.02 ha) has the geographic coordinates of 5° 10’ 57.64” S and 38° 0’ 45.97” W in its center, at an altitude of 145 m. The secondary native forest, taken as a reference, is located 400 m away from the cultivated area. The soil of the experimental area is classified as a *Cambissolo* Háplico *Ta Eutrófico* (Santos et al., 2013), corresponding to Typic Haplocambids (Soil Survey Staff, 2014), originated from the limestone of the Jandaíra Formation (Brasil, 1973). Selected soil properties are shown in table 1.

Experimental procedure

The experiment began in early October 2010 and was carried out in an open field, cultivated with fig and under biofertilizer application. The biofertilizer applied to the

Table 1. Soil physical characteristics

Use and management system	Layer	Sand	Silt	Clay	Natural clay	Textural class
	m	g kg^{-1}				
Biofertilizer (0 %)	0.0-0.1	539	269	192	131	Sandy loam
	0.1-0.2	518	252	230	145	Sandy clay loam
	0.2-0.3	466	254	280	184	Sandy clay loam
Biofertilizer (20 %)	0.0-0.1	517	288	195	126	Sandy loam
	0.1-0.2	508	265	227	163	Sandy clay loam
	0.2-0.3	460	271	269	187	Sandy clay loam
Biofertilizer (40 %)	0.0-0.1	525	281	194	143	Sandy loam
	0.1-0.2	495	264	241	156	Sandy clay loam
	0.2-0.3	475	250	275	188	Sandy clay loam
Biofertilizer (60 %)	0.0-0.1	542	261	197	158	Sandy loam
	0.1-0.2	488	244	268	152	Sandy clay loam
	0.2-0.3	460	257	283	193	Sandy clay loam
Forest	0.0-0.1	748	156	96	50	Sandy loam
	0.1-0.2	625	154	221	132	Sandy clay loam
	0.2-0.3	507	168	325	186	Sandy clay loam

Particle-size distribution analysis, clay content was determined through the pipette method, sand content through sieving and silt content through the difference between clay and sand fractions. Clay dispersed in water was determined using the same method adopted for particle-size distribution, but without the chemical dispersant. Sand (2.00 to > 0.053 mm); silt (0.053 – > 0.002 mm); clay (≤ 0.002 mm).

soil was produced through an anaerobic process, in plastic receptacles (volume of 200 L). A hose was attached to its lid with the other tip immersed in a receptacle with water until the height of 0.20 m, for gases outlet. The proportion for the biofertilizer production was 50 % (volume/volume) of the fermentation of the fresh bovine manure and water, for a period of 30 days.

Biofertilizer doses were formulated with the following proportions: T0, 0:5 – 0 % biofertilizer and 100 % water; T1, 1:4 – 20 % biofertilizer and 80 % water; T2, 2:3 – 40 % biofertilizer and 60 % water; and T3, 3:2 – 60 % biofertilizer and 40 % water. The biofertilizer was applied to the soil from October 2010 to August 2012, for a total of 23 months, over four crop cycles, with 46 applications, and 138 L of solution per plant. A localized drip irrigation system was used for the fertigation in the experiment, which was designed to operate with two emitter lines per plant row, with four emitters per plant, each with a mean flow rate of 4 L h^{-1}.

At the end of the experiment, the amount of organic material added to the soil through the 20, 40 and 60 % biofertilizer was approximately 0.182, 0.364 and 0.546 kg per m² of soil, respectively. Biofertilizer samples were for chemical characterization (Table 2).

Table 2. Chemical properties of the pure bovine biofertilizer (100 %) and the estimated doses, after diluted in water, in the different concentrations

Sample	N	P	K	Ca	Mg	S	Fe	Zn	Cu	Mn	B	Na	EC	C	C/N	pH
	g L^{-1}						mg L^{-1}						dS m^{-1}	%		
100 %	0.78	0.73	1.19	0.59	0.28	0.21	73.04	5.88	2.04	9.32	1.62	175	7.05	1.08	13.8	7.78
20 %	0.16	0.15	0.25	0.12	0.06	0.06	14.60	1.17	0.40	1.86	0.32	35	1.41	0.216	13.5	8.05
40 %	0.31	0.29	0.49	0.24	0.11	0.08	29.21	2.35	0.82	3.72	0.48	70	2.82	0.432	13.9	8.29
60 %	0.47	0.44	0.68	0.35	0.17	0.13	43.82	3.52	1.22	5.59	0.97	105	4.23	0.648	13.8	8.14

Fonte: Silva (2012).

In order to evaluate soil porous system quality, five soil scenarios were considered (under fig cultivation with the application of 20, 40 and 60 % biofertilizer through irrigation, a control treatment without biofertilizer and an additional treatment – soil under natural vegetation), in three soil layers (0.0-0.1, 0.1-0.2 and 0.2-0.3 m) (Table 2).

Analyses

Disturbed and undisturbed soil samples were collected in the previously mentioned layers. Disturbed soil samples were analyzed in the laboratory for granulometry and particle density. Undisturbed soil samples were collected using an Uhland soil sampler, in 0.05-m-high steel rings with a diameter of 0.05 m. These samples were analyzed in the laboratory for particle-size distribution, soil bulk and particle densities, soil water retention curve, total porosity, macroporosity, microporosity, intrinsic soil air permeability (K_{air}), pore continuity indices (K_1 and N) and average pore length (L_p).

In the particle-size distribution analysis, clay content was determined through the pipette method, sand content through sieving and silt content through the difference between clay and sand fractions (Gee and Bauder, 1986). Water dispersible clay was determined using the same method adopted for particle-size distribution, but without the chemical dispersant.

Soil particle density (ρ_p) was determined through the volumetric flask method (Blake and Hartge, 1986a) and soil bulk density (ρ_s) was determined using undisturbed soil samples, collected in cylinders of known volume, and dried at 105 °C until constant mass (Blake and Hartge, 1986b). Soil porosity was obtained through $P_T = [1- (\rho_s/\rho_p)]$, where P_T is the total porosity ($m^3\ m^{-3}$), and ρ_p and ρ_s are soil particle and bulk densities ($Mg\ m^{-3}$). Microporosity (pores with diameter ≤50 µm) was determined using Haines' funnel, through the application of a 6-kPa tension on the samples, until the water occupying these pores was drained (Danielson and Sutherland, 1986). Macroporosity was calculated by the difference between total porosity and volume of pores with a diameter smaller than 50 µm.

In the determination of the soil water retention curve, the saturation water content was considered equal to soil total porosity (P_T); Haines' funnel was used for low matric potentials (-2, -4, -6, -8 and -10 kPa) and Richards' porous plate apparatus (Klute, 1986) was used for the others (-33, -100, -300, -700, -1000 and -1500 kPa). The data were fitted to the mathematical model proposed by van Genuchten (1980), equation 1:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\varphi_m|)^n]^m} \quad \text{Eq. 1}$$

where θ_r and θ_s are, respectively, residual and saturation water contents ($m^3\ m^{-3}$), φ_m soil water matric potential (kPa), α is a scaling factor for φ_m, and m and n are parameters related to the curve shape. The software SWRC, version 2.0, was used, fixing θ_r and θ_s at the soil water contents measured in the laboratory at saturation

and at the tension of 1,500 kPa, respectively. The parameters α, m and n were fitted through the Newton-Raphson iterative method, with no dependence between m and n (Dourado Neto et al., 2000).

Intrinsic soil air permeability was determined through the decreasing pressure method (Kirkham, 1946; Neves et al., 2007; Silva et al., 2009; Silveira et al., 2011). A volume of air, corresponding to the pressure of 1 kPa in the reservoir, was passed through the volumetric ring containing an undisturbed soil sample, equilibrated at tensions of 2, 6, 10, 33 and 100 kPa. During the procedure, the decrease in pressure over time was measured, until the equilibrium with the atmospheric pressure, using the software PermeAr, v.1.0 (Silveira et al., 2011). Soil air permeability coefficient (K_{air}) was determined using equation 2:

$$K_{air} = \frac{2.3 \times L \times \eta \times V}{A \times P_{atm}} \times |S| \quad \text{Eq. 2}$$

where K_{air} is the soil air permeability coefficient (m^2), V is the air volume passing through the cylinder (m^3), η is the dynamic air viscosity (Pa.s), L is the height of the volumetric ring (m), A is the cross-section of the soil sample (m^2), P_{atm} is the atmospheric air pressure (Pa) and S is the angular coefficient of the linear regression of the pressure (ln of pressure) over time.

To obtain the pore continuity index, the values of intrinsic soil air permeability were related to the values of aeration porosity (ε_{air}) through the Kozeny-Carman equation, similarly to Ahuja et al. (1984), according to equation 3:

$$K_{air} = M\varepsilon_{air}^{N} \quad \text{Eq. 3}$$

where M (intercept) and N (slope) are empirical constants. The exponent N, according to the authors, is considered a pore continuity index, since it reflects the increase in K_{air} with the increase in ε_{air} (aeration porosity) or a decrease in pore tortuosity, and the increase in superficial area with the increase in the fraction of pores available to air flow. Aeration porosity (ε_{air}) was calculated by the difference between total porosity and the volumetric water content at each matric potential established. Equation 3, adjusted to the logarithmic form, results in equation 4:

$$log\ K_{air} = log\ M + N\ log\ \varepsilon_{air} \quad \text{Eq. 4}$$

where M and N values are then estimated from the linear regression of the relationship of log ε_{air} *versus* log K_{air}. The intercept of the line with the abscissa, in the graph relating air permeability with aeration porosity in the axis of log ε_{air}, can be used as a measure of the blocked porosity (ε_b), which corresponds to the ε_{air} value below which soil air flow stops due to the discontinuity in the aeration pore network. From equation 4, ε_b is expressed by equation 5:

$$\varepsilon_b = 10^{(-\log M)/N} \quad \text{Eq. 5}$$

Another index, K_1, was suggested by Groenevelt et al. (1984) to determine whether differences in K_{air} can be attributed only to differences in ε_{air} or if they can be partially attributed to other geometric aspects of the air-filled porous space, such as pore-size distribution, tortuosity and continuity. It is obtained through equation 6:

$$K_1 = \frac{K_{air}}{\varepsilon_{air}} \quad \text{Eq. 6}$$

The average pore length was calculated from the soil water retention curve. For the analysis, using the simplified capillary equation (Equation 7), it was considered a matric potential range from -8 to -12 kPa, i.e., pores with diameter between 25 and 37 µm.

Thus, the average pore length for this range (d), approximately 30 µm, corresponded to the matric potential of -10 kPa.

$$d(mm) = \frac{3}{\Phi(cm)} \quad \text{Eq. 7}$$

Then, the volume was calculated, which corresponds to the water displaced between the matric potentials of – 8 and -12 kPa. Pore length (L_p) was then calculated according to equation 8:

$$L_p = \frac{Vss}{Ap} \quad \text{Eq. 8}$$

where L_p is the average pore length, mm; Vss is the volume of the soil solution (mm^3) collected between the two matric potentials (kPa); and Ap is the average pore area, mm^2 ($\pi\ r_m^2$, where r_m is the average pore radius, mm, for the interval between the two matric potentials considered).

Statistical analysis was performed using the software Assistat, version 7.6 (beta) (Silva, 2013). The experimental data were analyzed in a completely randomized design, in a split-plot scheme, 5 × 3 × 4 (five treatments – under fig cultivation with the application of 20, 40 and 60 % of the biofertilizer through irrigation, a control treatment without biofertilizer and an additional treatment – soil under natural vegetation; three soil layers 0.0-0.1, 0.1-0.2 and 0.2-0.3 m; and four replicates). The Kolmogorov-Smirnov test, at 5 % of probability, was applied to verify data normality.

Since the experiment had two control treatments, one as a reference for biofertilizer application and another as a reference for soil cultivation, the F test was used for variance analysis and Dunnett's test at 5 % probability was used for means comparison, between means of the other treatments and the scenario of soil under secondary native forest, considering five treatments and four replicates.

RESULTS AND DISCUSSION

Soil air permeability

The statistical analysis for intrinsic soil air permeability (K_{air}), at the tension adopted by Alencar et al. (2015) to define the field capacity, 10 kPa, revealed significant difference between treatments in the layer of 0.0-0.1 m (Figure 1), and the soil under fig cultivation without biofertilizer application had greater area available to gas flow compared with the native forest.

An important, particular contribution of soil air permeability comes from wetting and drying cycles caused by fertigation, which participate in the genesis of stable aggregates, creating pores between aggregates, thus increasing the area for gas flow in the fertigated treatments (Sartori et al., 1985; Pagliai et al., 1987; Dalal and Bridge, 1996; Costa et al., 2014). The formation of pores between soil aggregates occurs as a result of physical forces. In this context, successive fertigation cycles become important factors, because they change the water regime in the soil, altering and/or intensifying natural processes, such as the reorganization of particles and changes in the porous system, which induce soil aggregation (Dalal and Bridge, 1996; Costa et al., 2014).

Biofertilizers have solid residues in suspension and, therefore, its application in the soil must have blocked the macropores or decreased their diameter (through deposition on the internal pore walls) over time, especially in the more superficial layers, with important pores for gas flow, reducing intrinsic soil air permeability compared with the control without biofertilizer application. In order to support what is supposed to have happened, the amount of organic matter added to the

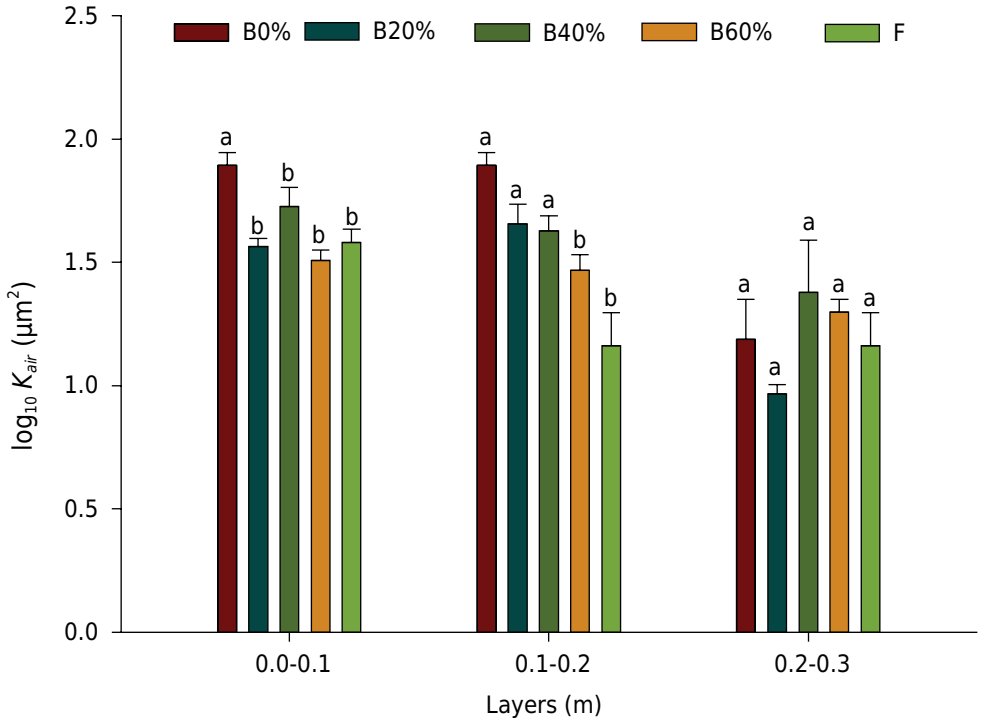

Figure 1. Intrinsic soil air permeability, with the errors of the means, for areas under fig cultivation and secondary native forest (B0% – Control; B20% – 20 % Biofertilizer; B40% – 40 % Biofertilizer; B60% – 60 % Biofertilizer; F – Native forest). Means followed by the same letter in the layer do not differ by Dunnett's test at 5 % probability.

soil through the 20, 40 and 60 % biofertilizer, at the end of the experiment, was approximately equal to 0.182 kg, 0.364 kg and 0.546 kg per m² of soil, respectively, which caused higher microporosity values for treatments with biofertilizer application (information on the porosity can be found in Alencar et al., 2015). Thus, the increase in the values of microporosity is an indication of obstruction or reduction in pore diameter by organic residues.

The pore-size distribution analysis using the soil water retention curve is an important tool to be used in monitoring the addition of biofertilizer. According to the results obtained by Alencar et al. (2015), the effect of biofertilizer on the obstruction/reduction of diameter of soil pores was evident.

In the 0.1-0.2 m layer (Figure 1), the effect of pore obstruction by residues from the biofertilizer was identified in smaller scale, being noticeable through the Dunnett's test at 5 % probability only in the treatment with higher amounts of biofertilizer applied to the soil. For the 0.2-0.3 m layer, there was no significant difference between the scenarios of cultivated soil and native forest, evidencing that pore obstruction or reduction in diameter must occur predominantly in the layers closest to where the biofertilizer is applied.

At the end of the experiment, the values of organic carbon obtained in the systems with native forest, B0%, B20%, B40% and B60% were 12.4, 15.7, 13.4, 15.0 and 14.8 g kg^{-1} (0.0-0.1 m); 7.2, 11.6, 11.5, 12.3 and 10.3 g kg^{-1} (0.1-0.2 m); and 6.0, 10.3, 10.2, 10.1 and 9.6 g kg^{-1}, respectively (Alencar et al., 2015). The similar values between treatments are due to the low amounts of C in the composition of the biofertilizer, because of the release of CO_2 and CH_4 in the biodigestion process (Medeiros and Lopes, 2006), the low C:N ratio, which favors rapid mineralization of the organic matter added to the soil (Giacomini et al., 2015), and the environmental conditions of the semiarid region, which do not favor a high supply of plant biomass in the native forest area (Alencar et al., 2015).

As previously mentioned, close to the application site, there is the effect of wetting and drying cycles, which contribute to the packing of particles, forming less porous intra-aggregate arrangements. In addition, Dexter (1988) claims that soil porosity increases from micro- to macroaggregates, because, besides the intra-aggregate porosity, there is a contribution from inter-aggregate pores. In the conditions of this study, this claim does not apply, because inter-aggregate pores were also blocked by the deposition of organic sediments from the bovine biofertilizer. Considering the reduction/obstruction of pores due to the addition of biofertilizer, it should be pointed out that the quality of the porous system for agricultural use was not compromised, since the functions of the soil with respect to the flow of water and gases remained satisfactory. In spite of that, it is recommended, as a management practice, to avoid coarse residues in the biofertilizer before its application.

Comparing cultivated areas with the native forest, cultivation did not degrade the pore network, since K_{air} values, depending on the treatments, are statistically equal to or higher than those found for the native forest area. It should be pointed out that management practices adopted in cultivated soils change the porous space, influencing the gas exchange environment in the root zone (Braunack and Dexter, 1989; Tormena et al., 1998; Rodrigues et al., 2011). Freire (2012) and Alves (2013) also found that the air permeability of Cambisols at the Apodi Plateau was improved when the soil was subjected to cultivation.

Thus, soil air permeability provides integrated knowledge on the effects of changes caused by cultivation in the internal structure of the soil, pore geometry, geometric variables (pore-size distribution, total porosity) and functional properties or processes, resulting in differences between treatments (Mentges et al., 2016; Reichert et al., 2016).

Soil K_{air} had positive correlation with the logarithmic fit in relation to the water matric potentials for all management scenarios studied (Figure 2). Thus, the application of higher water matric potentials allows more water to drain from the soil, resulting in an increase of the area available to gas flow, which confirms that intrinsic soil air permeability (K_{air}) has an inverse relationship with soil water content (Silva et al., 2009), i.e., as the soil dries, the pores previously occupied by water become natural pathways for air flow. Although the relationship is inverse, the fact that it is logarithmic indicates that the drying of the soil does not cause an increase of air permeability in the same proportion with which water tension varies, i.e., K_{air} increments are increasingly smaller for the same variation in soil water tension.

For all studied tensions, K_{air} values were higher than 1 μm^2 (log K_{air} = 0), which according to McQueen and Shepherd (2002) is considered critical to define non-functional porosity, the one where pores responsible for aeration are blocked and do not participate in the convective air transport. Such condition was not found in the evaluated management scenarios, in any of the applied tensions from 2 to 100 kPa.

The behavior of the relationship between soil air permeability (K_{air}) and the aeration porosity (ε_{air}) can be seen in Figure 3. Positive correlation and good fit (with r of at least 0.92 for the analyzed scenarios) were found between the variables for all studied systems and layers. The treatments with 20 %, 60 % and 40 % biofertilizer in the layers of 0.0-0.1 m, 0.1-0.2 m and 0.2-0.3 m, respectively, have higher K_{air} values for the ε_{air} considered critical to plant development, reported by Silva et al. (1994) as ε_{air} = 0.1 $m^3\ m^{-3}$ or log ε_{air} = -1.0 $m^3\ m^{-3}$. It should be pointed out that, unlike the situation discussed in Figure 1, in which the tension of 10 kPa was considered separately, here the linear relationship between K_{air} and ε_{air} treats the observations in a joint perspective, considering all the applied tensions, using the model of Ahuja et al. (1984). The results corroborate that which was verified in the previous analysis; the soil under cultivation, whether with or without biofertilizer application, has its pore network quality maintained or improved compared with the native forest scenario.

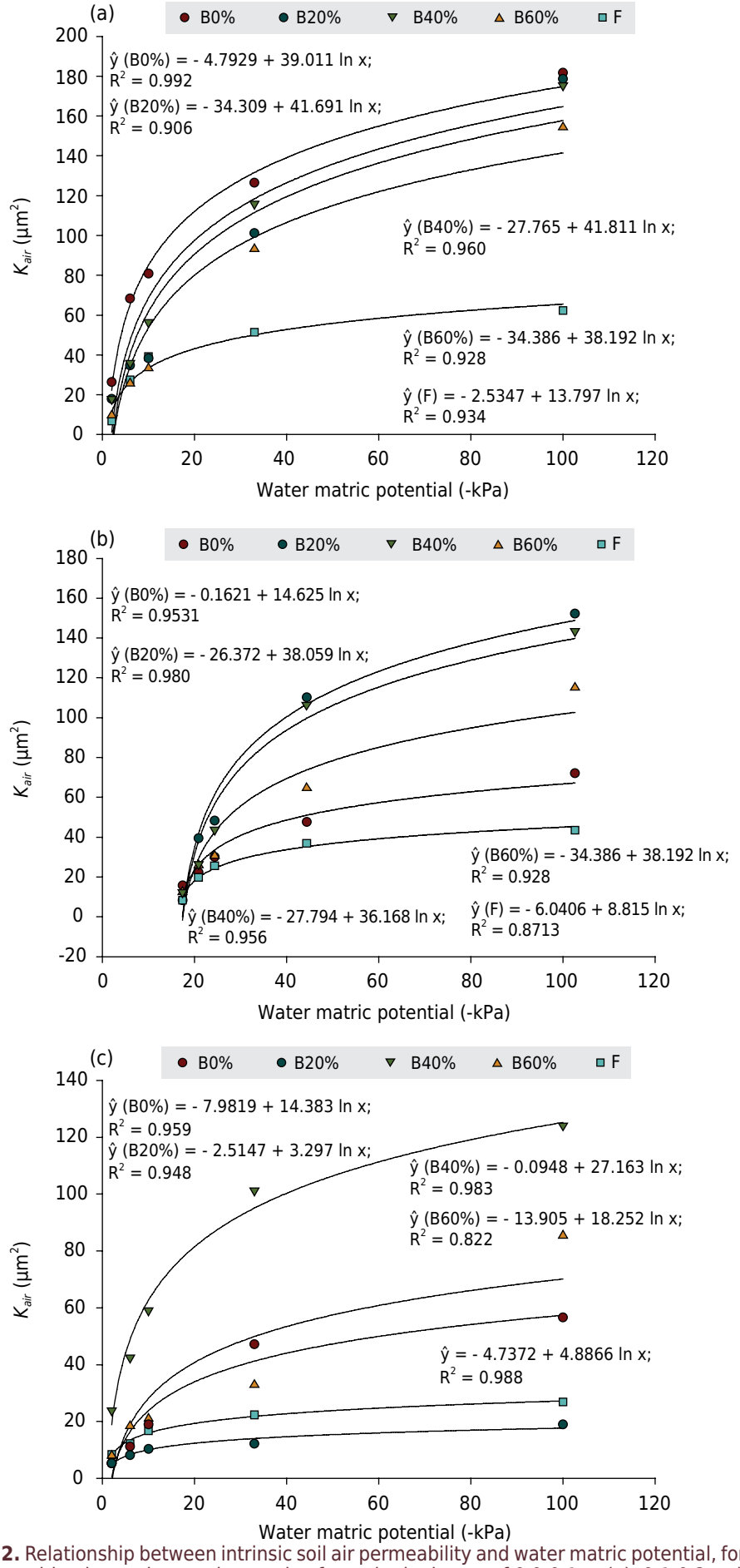

Figure 2. Relationship between intrinsic soil air permeability and water matric potential, for areas under fig cultivation and secondary native forest in the layers of 0.0-0.1 m (a), 0.1-0.2 m (b) and 0.2-0.3 m (c).

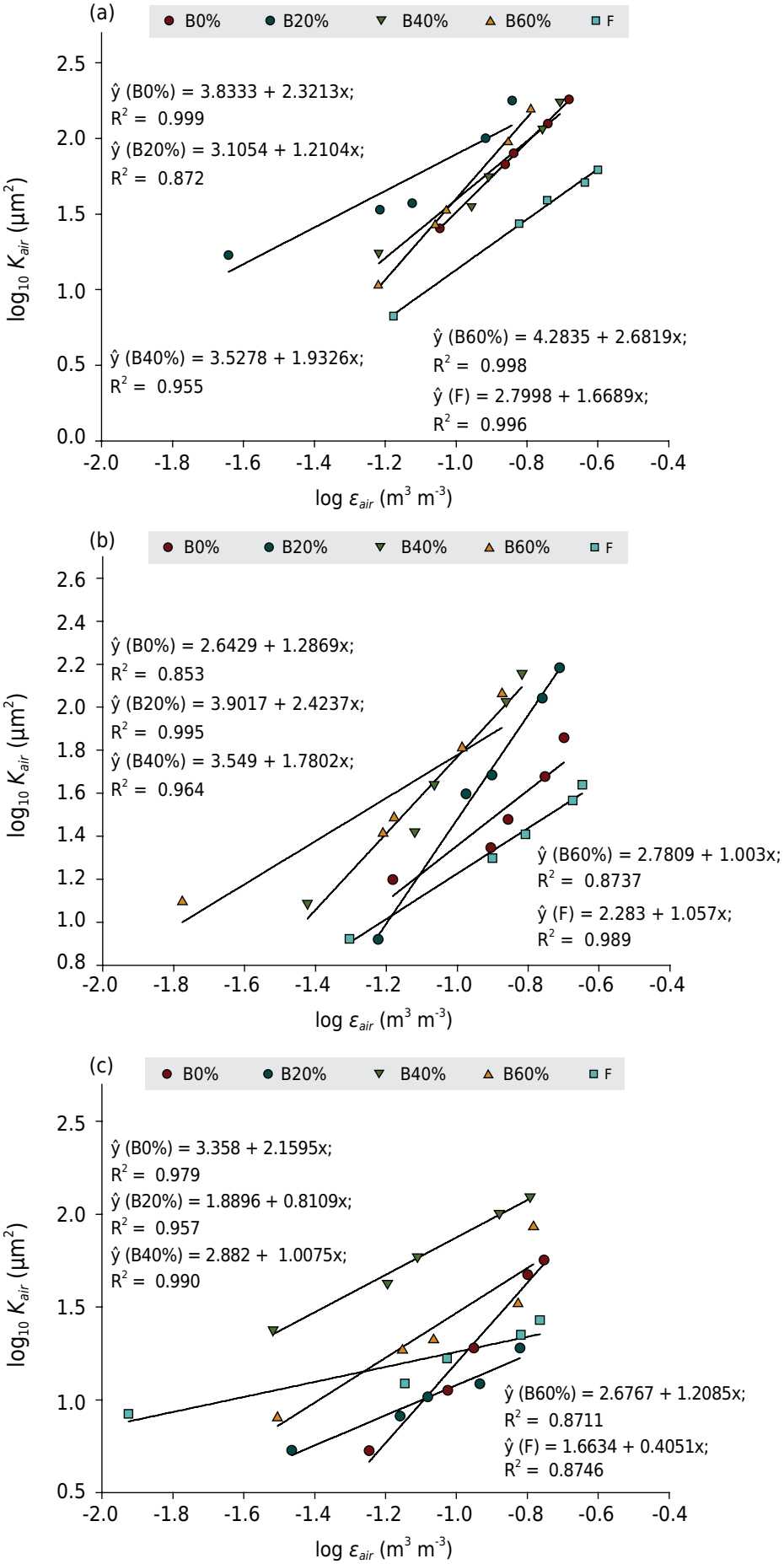

Figure 3. Logarithmic relationship between soil air permeability (K_{air}) and aeration porosity (ε_{air}) for areas under fig cultivation and secondary native forest in the layers of 0.0-0.1 m (a), 0.1-0.2 m (b) and 0.2-0.3 m (c).

Pore continuity indices (K_1, N) and pore length (L_p)

The K_1 indicate that, in general, the cultivated areas have higher pore continuity compared with the secondary native forest for the analyzed layers, similarly to that which was found for the parameter N (Table 3). It is noteworthy that, although the cultivated areas have increased the amount of soil micropores, the connectivity between pores was improved, which according to Freire (2012) is essential for an adequate gas exchange between soil and atmosphere.

N values (Table 4) indicated that the cultivated areas in general have pores more efficient for air flow compared with the native forest area, which according to Streck (2007) is of great importance to adequate gas exchange. Here, it is important to point out that the main soil aeration mechanism is diffusion, a kinetic-molecular phenomenon

Table 3. Pore continuity index (K1) for areas under fig cultivation and secondary native forest in the layers of 0.0-0.1 m, 0.1-0.2 m and 0.2-0.3 m, for the tension of 10 kPa

Use and management system	0.0-0.1 m	0.1-0.2 m	0.2-0.3 m
	$\log_{10} K_1$ (μm^2)		
Biofertilizer 0 %	2.74	2.33	2.29
Biofertilizer 20 %	2.69	2.57	2.09
Biofertilizer 40 %	2.65	2.70	2.88
Biofertilizer 60 %	2.55	2.66	2.39
Forest	2.33	2.22	2.25

Table 4. Parameters of the regression equation, $\log K_{air} = \log M + N \log \varepsilon_{air}$, and blocked porosity (εb) for areas under fig cultivation and secondary native forest, in the layers of 0.0-0.1 m, 0.1-0.2 m and 0.2-0.3 m

Use and management system	Layer	log M	N	R^2	ε_b
	m	μm^2			%
Biofertilizer 0 %	0.0-0.1	3.83	2.32	0.99	0.1
	0.1-0.2	2.64	1.29	0.85	0.8
	0.2-0.3	3.36	2.16	0.98	2.7
Biofertilizer 20 %	0.0-0.1	3.10	1.21	0.88	0.2
	0.1-0.2	3.90	2.42	0.99	2.4
	0.2-0.3	1.90	0.81	0.96	0.4
Biofertilizer 40 %	0.0-0.1	3.53	1.93	0.95	1.5
	0.1-0.2	3.55	1.78	0.96	1.0
	0.2-0.3	2.88	1.01	0.99	0.1
Biofertilizer 60 %	0.0-0.1	4.28	2.68	0.99	2.5
	0.1-0.2	2.78	1.00	0.87	0.2
	0.2-0.3	2.68	1.21	0.87	0.6
Forest	0.0-0.1	2.80	1.67	0.99	2.1
	0.1-0.2	2.28	1.06	0.99	0.7
	0.2-0.3	1.66	0.40	0.87	0.0

that does not necessarily depend on pore size, but on the connection between pores (Braunack and Dexter, 1989). Higher *N* values indicate soils with complex structure (Schjønning et al., 1999). In general, *N* values supported the results found by other indicators with respect to soil porosity (K_{air}, K_1 at the tension of 10 kPa), that pore network quality is notably better in the superficial soil layer of all studied systems, despite comments on the possibility of obstruction/reduction of pore diameter in cases where biofertilizer was applied.

The cultivated systems had higher volumes of blocked pores (ε_b) compared with the native forest, thus indicating that areas under fig cultivation have higher volume of non-functional pores, which are not available to gas flow. The treatments with the increasing doses of biofertilizer, as previously discussed, probably blocked soil pores in the superficial layers. In the case of soil under fig cultivation without biofertilizer application, soil disturbance caused clay particles to migrate and be deposited in the subsurface layer, which improved pore connectivity in the superficial layers. It is important to point out that the blocked porosity does not participate in the convective transport of water and air in the soil, which makes it independent of pore continuity, calculated considering those pores that effectively participate in the flow of water and gases in the soil.

Although most studies in the literature consider the correlation between organic C and porosity as direct, the increase in C is often not sufficient to mitigate the negative effects of anthropic activity, especially in the superficial soil layer. For instance, Mota et al. (2014) observed a direct correlation between organic C content and soil density, which at first contradicts the literature (Stock and Downes, 2008; Cunha et al., 2011), showing that the anthropic factor inhibited the role that carbon must play in soil resilience (Gregory et al., 2009). In this study, the addition of small-size particles, and not particularly carbon, was the main factor for the obstruction of part of the soil pores.

As for the average pore length (L_p) at the tension range from 8 to 12 kPa (Figure 4), in general, longer pores were observed in the soil under secondary native forest in

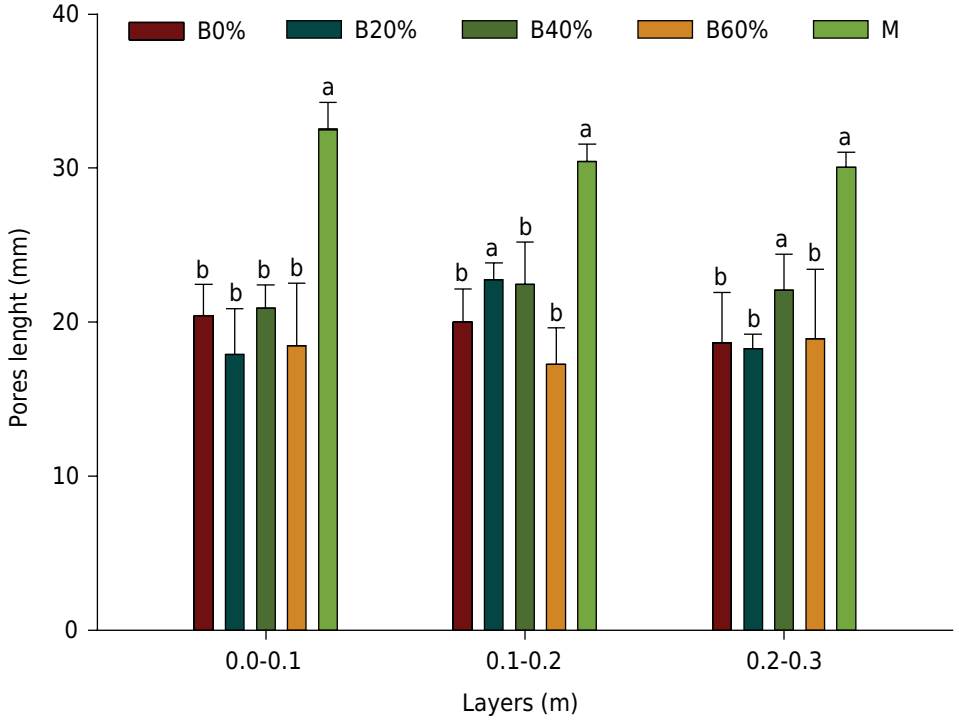

Figure 4. Average pore length, with the standard deviations from the mean, for areas under fig cultivation and secondary native forest. (B0% – Control; B20% – 20 % Biofertilizer; B40% – 40 % Biofertilizer; B60% – 60 % Biofertilizer; F – Native forest). Means followed by the same letter in the layer do not differ by Dunnett's test at 5 % probability. Tension of 10 kPa.

superficial and subsurface soil layers. The lower pore length in cultivated areas is related to soil disturbance. Although the treatment with native forest has longer pores, the pore continuity indices (K_1 and N) indicated that these pores are not connected or, at least, have high tortuosity. Thus, the index L_p did not prove to be a good indicator in the definition of soil air permeability. It should be pointed out that, although L_p had this limitation, it proved to be sensitive to variations caused by the management practices imposed on the soil. The average pore length was used only in the range from -8 kPa to -12 kPa, because the mean value approximately corresponds to the field capacity condition established for the least limiting water range, -10 kPa (Silva et al., 1994).

The comprehension on the dynamics of soil structure for this experiment was based on intensity-type properties, i.e., those that consider soil structural organization, dynamic aspects and processes that vary in space and time (Reichert et al., 2016). Thus, the intensity properties contributed to a better understanding of the alterations caused on soil structure by the treatments.

Agricultural systems are open from the thermodynamic perspective and tend to a stationary state, i.e., in dynamic equilibrium with the lowest production of entropy. From this point of view, the tendency is to converge to the improvement in structure, porous space and functions of the soil (Addiscott, 1995). Therefore, the minimum production of entropy leads the soil-plant system to self-organization and, consequently, to environmental sustainability (Vezzani and Mielniczuk, 2009).

The qualitative aspect of soil structure depends on the maintenance of an adequate balance between ordering and dissipation processes (Reichert et al., 2016). Therefore, from the thermodynamic point of view, the cultivated areas are found in situations very close to dynamic equilibrium, in conditions similar to or improved in relation to the secondary native forest. For the soil-plant system, according to Addiscott (1995), the steady state is characterized when there is a reduction of entropy due to the formation of structural units, formation of organic material, normal flow of water and gases, factors identified in the areas under cultivation, which, in combination, contribute to the development of the soil profile.

CONCLUSIONS

Compared to the native forest, pore network quality is improved, if not maintained, when soil is cultivated under the conditions described in this experiment.

In the conditions of cultivation, the application of bovine biofertilizer, which supply sediments that block or reduce the size of pores, did not improve soil air permeability.

The cases in which soil porosity was worsened due to the applied treatments (Biofertilizer 20 %, Biofertilizer 40 % and Biofertilizer 60 % for the layer of 0.0-0.1 m and Biofertilizer 60 % for 0.1-0.2 m), although not considered critical to plant development, indicate the need for the adoption of specific management practices (for instance, avoid coarse residues in the biofertilizer before its application) to avoid soil degradation.

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