

Critical soil bulk density for soybean growth in Oxisols

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Abstract. The aim of this study was to evaluate the critical soil bulk density from the soil penetration resistance measurements for soybean root growth in Brazilian Amazon Oxisols. The experiment was carried out in a greenhouse using disturbed soil samples collected from the northwest of Para characterized by different texture. The treatments consisted of a range of soil bulk densities for each soil textural class. Three pots were used for soybean growth of and two for the soil penetration resistance curve. From the fitted model, the critical soil bulk density was determined considering the penetration resistance values of 2 and 3 MPa. After sixty days, plants were cut and root length, dry mass of root, and dry mass of shoots were determined. At higher bulk densities, the increase in soil water content decreased the penetration resistance, allowing unrestricted growth of soybean roots. Regardless of soil texture, the penetration resistance of 2 and 3 MPa had a slight effect on root growth in soil moisture at field capacity and a reduction of 50% in the soybean root growth was achieved at critical soil bulk density of 1.82, 1.75, 1.51, and 1.45 Mg m⁻³ for the sandy loam, sandy clay loam, clayey, and very clayey soil.

Keywords: soil compaction, soil penetration resistance, soil texture, *Glycine max* L.

INTRODUCTION

The soybean (*Glycine max* L.) has been highlighted as the main crop responsible for the advance of the agricultural frontier in the Amazon region with a significant increase in the cultivated area in this region. An example is the State of Para, where the area with cultivated soybean increased from 2 650 ha in 2000 to 120 000 ha in 2012. Estimates indicate that the Northeast Para has a potential of nearly two million hectares for cropping soybean. However, the predominant soil management in the region is the conven-

tional tillage system with regular ploughing and disking. The use of conservation management practices, such as conservation tillage, is still limited in the region.

Therefore, the perspective that this scenario contributes to adverse changes in the landscape, mainly related to soil degradation, specifically soil compaction, is becoming a concern. The yield perspectives can also be affected since the agricultural production potential is determined by factors related to soil and crop.

Soil cultivation with intensive use of machinery on bare soil is the primary agent of soil degradation, causing erosion and compaction. Among the soil compaction effects, there are an increase in bulk density and soil penetration resistance and a decrease in porosity and soil air permeability (Koolen, 1994). Soil bulk density is one of the most frequent soil physical indicators to evaluate soil compaction, and changes in this soil attribute can influence crop yield. Usually the relationship between bulk density and crop yield is parabolic with a maximum bulk density that depends on soil texture, crop, and climate (Czyż, 2004; Pabín *et al.*, 1991).

The soil bulk density from which the soil strength becomes so high that it reduces or prevents root growth is denominated critical bulk density (Reichert *et al.*, 2009), and its value depends mainly on soil textural class. Reichert *et al.* (2003) proposed critical bulk density for some textural classes: 1.30-1.40, 1.40-1.50 and 1.70-1.80 Mg m⁻³ for: clayey soils, clay loam soils, and sandy loam soils, respectively. However, some crops may grow even in compacted soils, depending on the plant characteristics (Rosolem *et al.*, 2002), and knowledge of these differences may support crop selection or soil management practices.

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In Brazil, numerous studies have shown that crops are affected by soil compaction, resulting from land use practices (da Veiga *et al.*, 2007; Reichert *et al.*, 2009; Seben Junior *et al.*, 2014; Suzuki *et al.*, 2013). However, these studies were performed in regions with weather conditions very different from the Amazon region, where information is still quite scarce. In this region, there has been no research trying to identify reference values for soil physical properties. In this work, we consider the possible effects of the increase in soil bulk density for soils located in a different climatic condition. This information may help to plan sustainable soil management practices combining high production and environmental conservation. Thus, the aim of this study was to evaluate the critical soil bulk density, from the soil penetration resistance, for soybean root growth in Brazilian Amazon Oxisols with different textures.

MATERIAL AND METHODS

The experiment was carried out in a greenhouse, from July to September 2011, at the Institute of Agricultural Sciences at the Federal Rural University of Amazon (UFRA), in Para, Brazil.

Disturbed soil samples were collected from four areas in two counties in the northwest of Para, which represents the main region of soybean production in this state. In all areas, the soils were classified as Oxisols (Embrapa, 2006). A heterogeneous set of soil clay content typical of the region was also selected. The soil particle size analysis performed with the pipette method (Gee and Bauder, 1986) is shown in Table 1.

Approximately 400 kg of soil from 0-0.20 m depth were collected in each area at 10 points to gather a composite sample. The soil samples were air-dried and sieved (2 mm). Subsamples were used for fertility analysis according to procedures described by Embrapa (2011). The fertility analysis (Oliveira *et al.*, 2015) showed that the soil was limed and fertilized according to the soybean crop requirements (Embrapa, 2010).

As treatments, different levels of soil bulk density (*BD*) were defined for each soil textural class. From the bulk density considered optimal for each soil, it was gradually

increased by about 0.1 Mg m⁻³ unit. Next, five *BD* levels were defined for the sandy loam and sandy clay loam soils (1.35, 1.40, 1.50, 1.60, and 1.70 Mg m⁻³) and three for the clayey (1.35, 1.40 and 1.50 Mg m⁻³) and very clayey soils (1.15, 1.24, and 1.30 Mg m⁻³). Only three levels were defined for the clayey soils because it was not possible to compact them above the latter limit.

A completely randomized experiment was designed with five replicates (N=80). Eighty cylinders of PVC (0.20 m high, 0.23 m in diameter) with perforated bottoms were filled with slightly moist, *ie ca.* 10%, soil to facilitate the compaction process. The soil samples were placed into the cylinders up to 0.20 m height and manually compressed with a 7 kg rammer in about 2 cm deep layers, to assure bulk density homogeneity. After the addition of each layer, the soil surface was slightly scratched for addition of the next layer in order to improve contact and prevent the formation of distinct layers. Additional details about the soil compaction methodology in the pots are provided by Oliveira *et al.* (2015).

Three of the five pots were used for soybean seeding (N=48) and two to collect undisturbed samples (N=32). In the pots designated for sampling, four samples were taken using cylindrical steel rings with dimensions of 0.05 m height and diameter, totalling 128 undisturbed samples. These samples were saturated, grouped (N=16) and then brought to equilibrium on the following matric potentials (Ψ): -0.003; -0.006; -0.01 MPa using table tension and -0.03; -0.06; -0.1; -0.3; -0.6 MPa in Richards chambers (Klute, 1986). The soil water content at -0.01 MPa Ψ was defined as the water content at field capacity (θ_{FC}).

After reaching the equilibrium at each potential, the samples were weighed and the soil penetration resistance (*PR*) was determined using an electronic penetrometer similar to that described by Figueiredo *et al.* (2011) with a 30° cone and base area of 0.1256 cm². The device was settled to register a reading every one second. The readings corresponding to 5 mm on the top and bottom were eliminated and an average was calculated for each sample. Finally, the samples were oven-dried at 105°C for 48 h for determination of *BD* and soil water content (θ) at each Ψ (Blake and Hartge, 1986).

Table 1. Results for particle size analysis for the soils sampled in two counties in Para state, north Brazil

Soil sampling site	Texture	Sand	Silt	Clay	Organic matter
		(g kg ⁻¹)			
Capitão Poço	Sandy loam	756.2	48.7	195.1	25.80
Paragominas	Sandy clay loam	663.3	110.0	226.7	37.13
Capitão Poço	Clayey	396.8	97.2	506.0	27.34
Paragominas	Very clayey	53.2	216.5	730.3	43.43

Sand = 2-0.05 mm, silt = 0.05-0.002 mm, clay < 0.002 mm.

For each soil, the *PR* results were adjusted in relation to the θ and *BD* using the non-linear model proposed by Busscher (1990):

$$PR = a \theta^b BD^c,$$

where: *PR* is the soil penetration resistance (MPa), θ the volumetric soil water content ($\text{m}^3 \text{m}^{-3}$), *BD* is the soil bulk density (Mg m^{-3}) and *a*, *b* and *c* are the model parameters.

From the model parameters, using the same equation, the critical soil bulk density (*BD*) was determined for the whole range of soil water content obtained from the matric potentials, considering the *PR* values suggested as critical for plant root growth: 2.0 MPa (Taylor, 1966) and 3.0 MPa (Horn and Baumgartl, 2000).

In the other three pots for each soil and *BD*, four soybean seeds of the cultivar BRS 'Sambaíba' were seeded at a depth of 0.015 m. After emergence, thinning was done leaving two seedlings per pot. Soils were kept at field capacity (soil water content at -0.01 MPa) by daily weighing and water addition using a watering can until reaching the desired weight in each pot.

Sixty days after emergence, in the R2 or blister stage (flowering), the plants were cut and the root system separated and washed with abundant water using a sieve (5 mm) as support. Root length (RL) according to Tennant (1975) and the dry mass of roots (DMR) after oven-drying at 60°C for 72 h were determined. Since the aim of this study was not to quantify the variables of soybean root growth, but to identify the *BD* values at which soybean root growth is severely limited, the data were transformed into relative values by dividing the maximum value obtained for RL and DMR by its values observed in each treatment (*BD*). The purpose was a clearer understanding of soybean root response to different levels of *BD*. The shoots were also oven-dried at 60°C for 48 h and weighed (dry mass of shoot = DMS) and related to DMR to assess if the above-ground part of the plants were affected by restrictive root growth.

The data analysis was performed using SAS (Statistical Analysis System, version 9.2). For the adjustment of the soil penetration resistance curve, the PROC NLIN was used. We analyzed the variance for RL and DMR data and, when significant, regression analysis between *BD* and the soybean growth variables was performed.

RESULTS AND DISCUSSION

The nonlinear model (Busscher, 1990) was highly significant ($p < 0.001$) and appropriate for the data distribution for all soil textural classes (Table 1). The model parameters explained >80% of the variability of *PR* as a function of θ and *BD*. Regardless of the soil textural class, the negative relation between *PR* and the soil water content (θ) and the positive relation to the soil bulk density (*BD*) were verified. This relation has already been reported and justified in several studies, which reported that the decrease in soil water content increases the cohesive forces among soil particles, especially with an increment in *BD* (Bengough and Mullins, 1990; Weber and Biskupski, 2008).

In Table 2, the *BD* and respective θ_{FC} for each soil are presented. Considering the soil water content (θ_{FC}), it was observed that, for the sandy loam, the *PR* was critical (> 2 MPa) only for the higher *BD*, at 1.70 Mg m^{-3} the *PR* was 3.48 MPa. For the sandy clay loam, the soil exhibited limitation due the high strength of *BD* of 1.6 Mg m^{-3} (2.13 MPa). At the lowest *BD*, the clayey soil at θ_{FC} reached a *PR* value of 2.38 MPa, which was reduced at *BD* of 1.4 Mg m^{-3} (1.66 MPa) and increased again at the highest *BD* (2.30 MPa). For the very clayey soil, only the lowest *BD* exhibited *PR* < 2 MPa. In this soil, the *BD* of 1.30 Mg m^{-3} reached a *PR* of 2.56 MPa, even with high soil water content (0.494 $\text{m}^3 \text{m}^{-3}$).

The higher the clay content, the higher the *PR*, as can be verified by the equations in Table 2. According to the equations, considering the same θ and *BD*, *PR* increases

Table 2. Soil bulk density (*BD*) treatments and water content at field capacity (θ_{FC}) for each soil and equations for the soil penetration resistance curve using a non-linear model (Busscher, 1990) for the evaluated soils

Soil	Treatment	Equation	R ²	F
Sandy loam	<i>BD</i>	$PR = 0.0053 \theta^{-1.276} BD^{8.910}$	0.92	386.9*
	θ_{FC}			
Sandy clay loam	<i>BD</i>	$PR = 0.0377 \theta^{-0.824} BD^{7.244}$	0.83	179.4*
	θ_{FC}			
Clayey	<i>BD</i>	$PR = 0.0553 \theta^{-2.348} BD^{4.005}$	0.95	397.3*
	θ_{FC}			
Very clayey	<i>BD</i>	$PR = 0.0103 \theta^{-5.485} BD^{6.275}$	0.97	713.8*
	θ_{FC}			

BD – soil bulk density (Mg m^{-3}), θ_{FC} – soil water content at field capacity ($\text{m}^3 \text{m}^{-3}$). *Significant at a 0.1% probability level ($p < 0.001$).

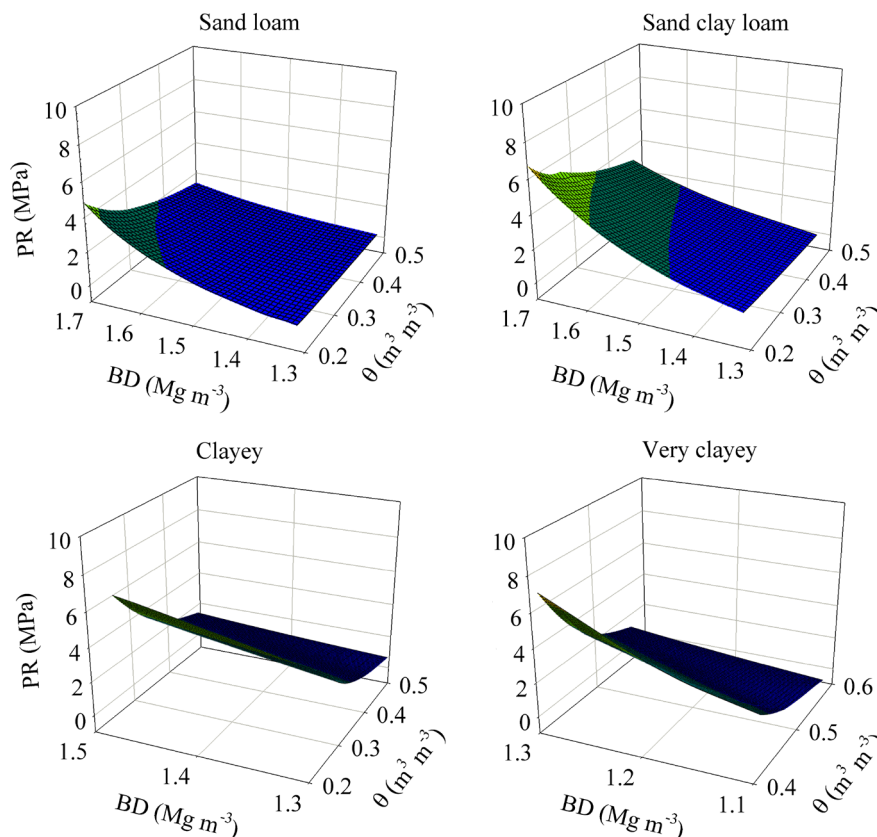


Fig. 1. Soil penetration resistance (PR) as a function of bulk density (BD) and soil water content (θ) for the evaluated soil textural classes.

substantially with the increasing clay content. Figure 1 shows that more clayey soils have higher PR values even for higher θ and lower BD . This behaviour is due to the higher clay content resulting in higher friction and cohesion among the soil particles, causing the increase in PR (Tormena *et al.*, 2008). Hence, soils with high clay content can reach PR values restrictive to plant growth sooner, with variations in θ or BD , compared with sandier soils.

The BD is a value in which the soil strength becomes so high that it reduces or prevents root growth (Rosemberg, 1964). The higher the BD , regardless of the soil texture and PR , the higher the soil water content (Fig. 2). This means that, when there is enough water available in the soil, it only imposes physical constraints to root growth, i.e. high penetration resistance, at high values of BD . In the very clayey soil (Fig. 2d), in conditions of lower θ ($< 0.40 \text{ m}^3 \text{ m}^{-3}$), soil imposes restrictions to root development at very low BD ($BD < 1.0 \text{ Mg m}^{-3}$). This BD range can be extended (Fig. 2) if the critical PR value of 3 MPa suggested by Horn and Baumgartl (2000) is considered. Thus, it is possible to establish a BD range from which the PR restricts root growth, taking into account the variation of θ .

Considering the soil water content at field capacity (θ_{FC}) and adopting the PR value of 2 MPa as critical, from the equations in Table 2, the BD were 1.65, 1.50, 1.35, and 1.22 Mg m^{-3} for the sandy loam, sandy clay loam, clayey, and

very clayey soils, respectively. However, if we take the PR value of 3 MPa, these values are elevated to 1.73, 1.59, 1.50, and 1.30 Mg m^{-3} . According to Tormena *et al.* (2008), the BD depends mainly on the soil particle size distribution. The high clay content of the very clayey soil gives it greater cohesion among particles, imposing constraints to root development at BD values much lower than for the

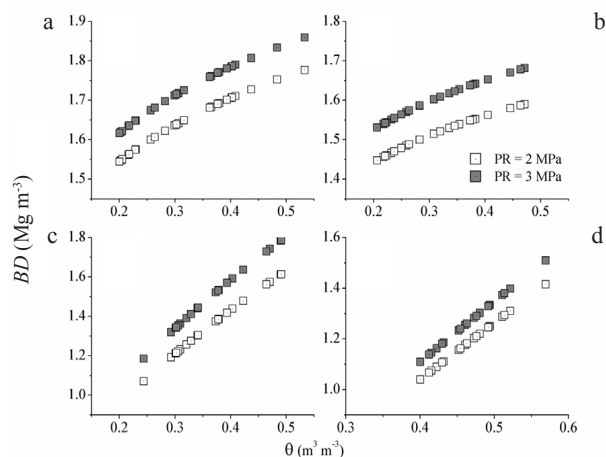


Fig. 2. Variation of critical bulk density (BD) related to soil water content (θ) in: a – sandy loam, b – sandy clay loam, c – clayey, and d – very clayey soils.

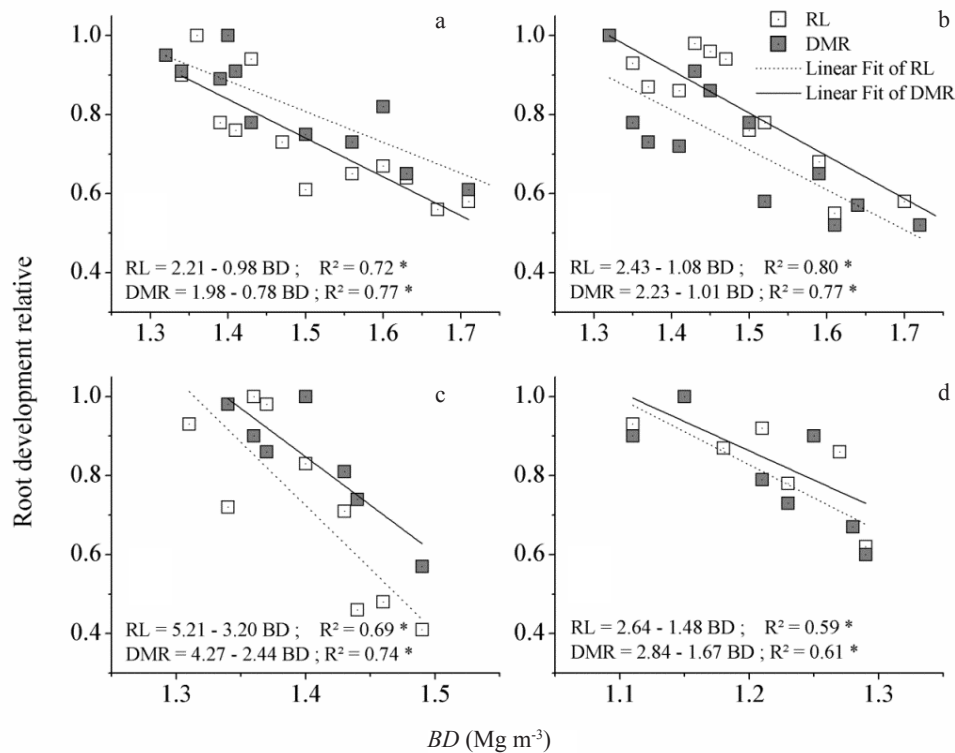


Fig. 3. Effect of soil bulk density (BD) on root length (RL) and dry mass of roots (DMR) of soybean in: a – sandy loam, b – sandy clay loam, c – clayey, and d – very clayey soils (d).

sandy clay loam soil (Fig. 2). Corroborating these results, Reichert *et al.* (2003) proposed intervals for BD for some soil textural classes as 1.30 to 1.40 Mg m⁻³ for clayey soils, 1.40 to 1.50 Mg m⁻³ for clay loam, and 1.70 to 1.80 Mg m⁻³ for the sandy loam.

To evaluate the critical BD for root soybean development, the Q1/2 index suggested by Dexter (1987) was used, which considers soil physical conditions critical when root growth is reduced to half of the maximum. For this, from the equations in Fig. 3, the values of BD in which root growth would be halved were 1.82, 1.75, 1.51, and 1.46 Mg m⁻³ for the sandy loam, sandy clay loam, clayey, and very clayey soils. Therefore, it can be noticed that the highest values of BD, defined in the treatments, were not sufficient to halve the RL, when the soil was maintained in the θ_{FC} . In fact, substituting in the adjustment equations (Fig. 3) the BD variable by the BD for 2 and 3 MPa, significant RL reduction was observed only for the sandy loam soil (41 and 49%), compared to sandy clay loam (19 and 35%), clayey (11 and 26%), and very clayey (17 and 6%) soils, considering the maximum RL.

The dry mass of roots (DMR) was positively related with the dry mass of shoots (DMS). Although this relationship was significant ($p < 0.01$, Fig. 4), the low coefficient of determination (R^2) indicated that the variability in the growth of the above-ground part of plants was possibly influenced by other variables than the root growth variation due the increase in BD.

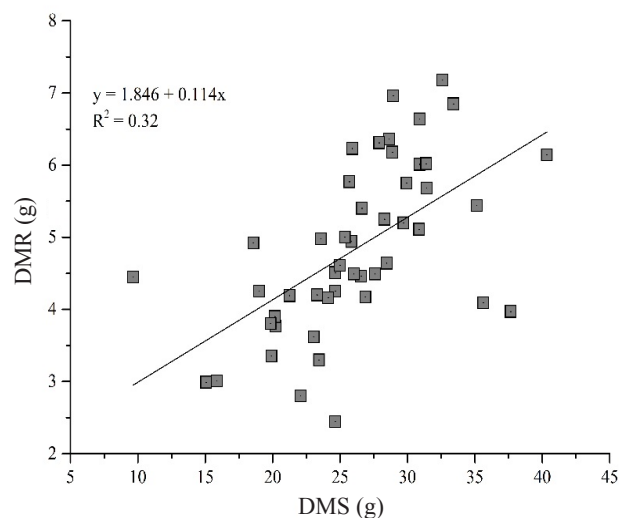


Fig. 4. Relationship between dry mass of roots (DMR) and dry mass of shoots (DMS) considering all soils (sandy loam, sandy clay loam, clayey, and very clayey) and bulk densities (treatments).

The highest values of BD for a 50% RL reduction, compared to the values of BD (2 and 3 MPa), indicate that the values of PR adopted as restrictive to plant growth were not sufficient to compromise the development of root soybean when the soil water content was adequate (θ_{FC}). This occurs because the suitable supply of water and nutrients in soil minimizes the effect of PR on plant growth (Beutler

and Centurion, 2003). Dexter (1987) claims that plants can grow normally under conditions of high soil penetration resistance ($PR > 4$ MPa) since there is adequate soil water availability.

Soil bulk density (BD) is considered a soil physical quality indicator and, studying the changes in PR with changes in BD and θ , may help by relating the possible changes in soil physical condition by the adoption of a particular soil management practice, such as the conventional system. The empirical relationship of this simple soil indicator and root soybean development could further be used in monitoring and appropriate management of soil structure and moisture content, for adequate growth and yield in the new cultivated lands in Brazilian Amazon.

In the present paper, the effect of increasing BD and a consequent increase in PR for the soybean root growth was evaluated only in one condition of soil water content, field capacity. However, the results indicated that even when the moisture was adequate, the soil PR reached values considered limiting for the proper plant growth. Hence, after this preliminary study, further research is recommended to evaluate the effect of water stress in this region, since the results of many studies available should not be extended to this region due to differences in climatic conditions.

CONCLUSIONS

1. At higher bulk densities the increase in soil water content decreases penetration resistance, allowing unrestricted growth of soybean roots.

2. Irrespective of the soil textural class, the penetration resistance of 2 and 3 MPa, considered limiting for root growth, had a slight effect on soybean root growth, when soil moisture was maintained at field capacity.

3. Considering the analyzed soil textural classes, even with high soil moisture content, a reduction of 50% in the soybean root growth was noted at bulk density values of 1.82, 1.75, 1.51, and 1.45 Mg m⁻³ for the sandy loam, sandy clay loam, clayey, and very clayey soil, respectively.

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