RAPHAEL PASSAGLIA AZEVEDO

IMPROVEMENT OF PERENNIAL PLANTS ROOT-ZONE PHYSICAL ENVIRONMENT CAUSED BY SOIL CLASS-SPECIFIC DEEP TILLAGE METHODS

LAVRAS – MG

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Prof. Dr. Bruno Montoani Silva

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MELHORIA DO AMBIENTE FÍSICO DA ZONA RADICULAR DE PLANTAS PERENES CAUSADA POR MÉTODOS DE PREPARO PROFUNDO EM ESPECÍFICAS CLASSES DE SOLO

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para obtenção do título de Doutor.

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2023

À Deus.

À minha esposa Bruna e filho Benedito.

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“Ninguém faz bem o que faz contra a vontade, mesmo que seja bom o que faz.”

(Santo Agostinho)

O início da sabedoria é a própria ignorância”.

(Sócrates)

RESUMO GERAL

O preparo de solo promove alterações estruturais que proporcionam um ambiente favorável ao desenvolvimento das plantas cultivadas. As alterções nas propriedades físicas do solo devido ao preparo são amplamente relatadas na literatura, porém informações sobre métodos de preparos profundos, sobretudo em solos tropicais, são pouco relatadas. Ademais, as diferentes estruturas morfogenéticas, oriundas de diferentes classes de solo, proporcionam ambientes físicos distintos. Nesse contexto, a principal indagação que direcionou esse estudo foi: solos cujas estruturas são morfogenéticamente diferentes, quando sob o mesmo preparo, apresentarão um ambiente físico semelhante? Assim, a hipótesedesse desse estudo é que o efeito do preparo do solo sobre o ambiente físico do solo está sujeito à influência dos atributos intrínsecos da classe de solo. O objetivo foi avaliar o efeito das práticas de preparo do solo, considerando estratégias de preparo profundo, sobre a qualidade física do solo e como esses efeitos diferem nas três classes de solos com estruturas morfogeneticamente contrastantes. A área experimental está localizada no estado de Minas Gerais, Brasil. Os solos avaliados foram Cambissolo/Typic Dystrustept, Argissolo/Rhodic Hapludult e Latossolo/Rhodic Hapludox. Os preparos do solo foram: MT: sulcamento superficial (0.1 m) + coveamento (0.4 x 0.7 m); CT: aração seguida de duas gradagens (0.25 m) + sulcamento (0.25 m); SB: aração seguida de duas gradagens + subsolagem (0.45 m); DM: aração seguida de duas gradagens + enxada rotativa (0.6 m); e DM+Ca: aração seguida de duas gradagens + enxada rotativa (0.6 m) + calcário adicional. Foram avaliados a densidade do solo, resistência do solo à penetração, resistividade elétrica do solo, avaliação visual da estrutura do solo, indicadores físicos derivados da distribuição de poros por tamanho e o intervalo hídrico ótimo. A resistividade foi positivamente correlacionada com a densidade do solo em todo o conjunto de dados, em todas as classes de solo, e, individualmente no Typic Dystrustept com resistência à penetração. Isso confirma o potencial para a identificação de mudanças estruturais causadas pelo preparo profundo em solos tropicais. Os indicadores que melhor separaram os tratamentos foram capacidade de aeração, capacidade de campo relativa, macroporosidade, densidade do solo e índice S. A inserção da umidade crítica do solo para determinar o intervalo hídrico ótimo crítico possibilitou maior exatidão na definição da faixa de conteúdo de água no solo sem limitações às plantas. As classes de solo responderam de forma diferente aos preparos de solo aplicados, confirmando a hipótese testada. Os resultados possibilitaram sugerir um preparo específico para cada classe de solo, assim: Deep Mixing till (DM) para o Cambissolo (CX), Subsoiling (SB) ou Deep Mixing till (DM) para Argissolo (PV) e Conventional till (CT) para o Latossolo (LV).

Palavras-chave: Qualidade física do solo. Manejo do solo. Subsolagem. Resistividade elétrica do solo. Resistência do solo à penetração. Intervalo hídrico ótimo.

GENERAL ABSTRACT

Soil preparation promotes structural changes that creates a favorable environment for the development of cultivated plants. Changes in soil physical properties due to tillage are widely reported in the literature, but information on deep tillage methods, especially in tropical soils, is scarcely reported. Furthermore, the different morphogenetic structures arising from different soil classes provide different physical environments. In this context, the main question that guided this study was: will soils whose structures are morphogenetically different, when under the same tillage, present a similar physical environment? Thus, the hypothesis of this study is that the effect of tillage on the physical environment of the soil is subject to the influence of the intrinsic attributes of the soil class. The objective was to evaluate the effect of tillage practices, considering deep tillage strategies, on the physical quality of the soil and how these effects differ in the three classes of soils with morphogenetically contrasting structures. The experimental area is located in the state of Minas Gerais, Brazil. The evaluated soils were Cambissolo/Typic Dystrustept, Argissolo/Rhodic Hapludult and Latossolo/Rhodic Hapludult. Soil preparations were: MT: surface furrowing (0.1 m) + plant hole (0.4 x 0.7 m); CT: plowing followed by two diskings (0.25 m) + furrowing (0.25 m); SB: plowing followed by two diskings + subsoiling (0.45 m); DM: plowing followed by two diskings + rotary hoe (0.6 m); and DM+Ca: plowing followed by two diskings + rotary hoe (0.6 m) + additional limestone. Soil bulk density, soil resistance to penetration, soil electrical resistivity, visual assessment of soil structure, physical indicators derived from pore size distribution and least limiting water range were evaluated. Resistivity was positively correlated with soil density across the entire dataset, across all soil classes, and individually in Typic Dystrustept with penetration resistance. This confirms the potential for identifying structural changes caused by deep tillage in tropical soils. The indicators that best separated the treatments were aeration capacity, relative field capacity, macroporosity, soil density and S index. The inclusion of critical soil moisture to determine the critical optimal water range allowed greater accuracy in defining the range of water content in the soil without limitations to plants. The soil classes responded differently to the tillage applied, confirming the tested hypothesis. The results made it possible to suggest a specific preparation for each soil class, thus: Deep Mixing till (DM) for the Typic Dystrustept (CX), Subsoiling (SB) ou Deep Mixing till (DM) for the Rhodic Hapludult (PV) e Conventional till (CT) for the Rhodic Hapludult (LV).

Keywords: Soil physical quality. Soil management. Subsoiler. Soil electrical resistivity. Soil resistance to penetration. Least limiting water range.

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FIRST PART - INTRODUCTION

INTRODUÇÃO

O termo perene na agricultura remete a algo duradouro, permanente. Culturas perenes, portanto, são aquelas que não necessitam de replantio após a colheita pois permanecem em estado produtivo por longo período de tempo até a renovação da lavoura. O Brasil, em 2021, contabilizou cerca de 5,4 milhões de ha utilizados com cultivo de culturas perenes/permanentes, com maior destaque para a cafeicultura com 1,8 milhões de ha e citricultura com 694 mil ha (IBGE, 2022). Ainda, segundo IBGE (2022) em 2021 foram produzidas 2.993780 toneladas de café em grão e 18.799.744 toneladas de laranja no território nacional. Em relação a este cenário o estado de Minas Gerais representa 21% da área plantada com culturas perenes (1.145.575 ha), 8% da área de citros (56.668 ha) e 54% da área de café (1.002.787 ha) (IBGE, 2022).

Culturas perenes têm potencial para produzir economicamente por longos períodos, por exemplo, no Brasil é possível encontrar lavouras produtivas de café com 10 a 15 anos de idade (SILVA et al., 2021). O preparo do solo é a base para instalação das culturas, principalmente para aquelas que permanecerão no solo por muitos anos. Portanto o preparo do solo é fundamental para garantir uma instalação adequada, com bom desenvolvimento inicial e vida útil prolongada e produtiva para cultura.

A produção agrícola eficiente demanda técnicas que otimizem as condições para o desenvolvimento das culturas e utilização eficiente da água, sobretudo considerando as atuais variações nas condições climáticas. A capacidade do solo de reter e disponibilizar a água na zona radicular é importante para aumentar o rendimento das culturas e a eficiência do uso da água, reduzindo os efeitos do déficit hídrico durante o período de cultivo (JIAO et al., 2017), principalmente nos veranicos (CARVALHO et al., 2013).

As alterações nos atributos físico-hídricos do solo estão associadas ao manejo, uma vez que o armazenamento de água varia em função do volume de água que infiltra e dos fatores que colaboram para a sua permanência ao alcance do sistema radicular (SILVA et al., 2021). O manejo age sobre as propriedades físicas do solo, tais como densidade, distribuição de poros por tamanho e volume, resistência do solo à penetração, condutividade hidráulica, retenção e capacidade de disponibilizar água e ar, as quais podem afetar diretamente a produção. Nesse sentido, um adequado manejo do solo pode favorecer um ambiente físico com melhores condições para as plantas cultivadas.

Camadas adensadas (de origem pedogenética), que normalmente apresentam comportamento semelhante a camadas compactadas (pela ação antrópica), além de potencializarem o risco de erosão do solo (SOUZA et al., 2008), limitam o crescimento e desenvolvimento das culturas por restringirem a presença do sistema radicular à camada superficial (BENGOUGH et al., 2006; 2011), o que condiciona o desenvolvimento de raízes profundas somente a poros pré-existentes (WHITE; KIRKEGAARD, 2010).

Solos classificados como Argissolos e Cambissolos (SANTOS et al., 2013) ou Ultisols e Inceptsols (SOIL SURVEY STAFF, 2014) podem exibir propriedades físicas do solo negativos, restringindo o crescimento radicular de culturas perenes a um pequeno volume de solo próximo a superfície tornando as plantas mais vulneráveis às variações climáticas (CINTRA; LIBARDI, 1998; BUSSCHER et al., 2006; AHMAD et al., 2010; SCARPARE et al., 2019; HAMILTON et al., 2019).

Solos jovens, pouco intemperizados, como os Cambissolos, caracterizados pela presença de horizonte pedogenético Bi e horizonte diagnóstico B incipiente, pouco profundos (SANTOS et al., 2013) geralmente, apresentam condições físicas desfavoráveis ao crescimento radicular, devido à grande influência do silte e da mineralogia caulinítica e estrutura em blocos em Bi e maciça no horizonte C, que influenciam diretamente no adensamento natural e na restrição da infiltração da água (PEREIRA et al., 2010) devido a uma reduzida porosidade do solo. A classe dos Argissolos, por outro lado, engloba solos com evolução mais avançada, devido ao processo de argiluviação (translocação de argila), promovendo a concentração e acúmulo de argila no horizonte sub-superficial, caracterizando o horizonte pedogenético Bt e horizonte diagnóstico da classe B textural (SANTOS et al., 2013). Apesar de serem profundos o acúmulo de argila no horizonte B promove adensamento natural do solo (reduzida porosidade natural). Além disso, o predomínio da estrutura em blocos é uma característica desfavorável quantos aos atributos físico-hídricos do solo.

Estudos têm sugerido a possibilidade de inclusão de novas áreas, até então consideradas marginais ao sistema produtivo, pela adoção de manejos que propiciem uma maior exploração do subsolo pelas raízes das culturas (KIRKEGAARD et al., 2007; SERAFIM et al., 2013a; SILVA et al., 2015b). Práticas de manejo com objetivo de aliviar camadas adensadas, ou compactadas, são conhecidas como preparo profundo (*Deep Tillage*) (SCHNEIDER et al., 2017). Por criar condições que aumentam o volume de solo explorado pelas raízes da cultura, pode ser a solução para restrições existentes no subsolo, particularmente pelo aumento do uso da água (SCHNEIDER et al., 2017; SCANLAN; DAVIES, 2019, BARBOSA et al., 2020), uma vez que camadas mais profundas têm potencial para armazenar consideráveis conteúdos de água e nutrientes (KAUTZ et al., 2013; WIESMEIER et al., 2013; SCHNEIDER et al., 2017). Estudos realizados com esse tipo de manejo no Brasil com a cultura do café têm relatado sucesso, devido ao maior aprofundamento das raízes da cultura, o que tem possibilitado maior uso da água armazenada, trazendo como resultado altos rendimentos e longevidade dos cafeeiros cultivados em áreas de Cambissolos e Latossolos (SERAFIM et al., 2013a; 2013b; 2013c; SANTOS et al., 2014; SILVA et al., 2015a; SILVA et al., 2016; SILVA et al., 2017; OLIVEIRA et al., 2019; SILVA et al., 2019a; 2019b; BARBOSA et al., 2020, SILVA et al., 2021).

Para avaliar o efeito dos preparos de solo sobre a qualidade física do solo diversas ferramentas podem ser utilizadas. Entre elas a curva de retenção de água (WRC) da qual podem-se extrair vários indicadores da qualidade física do solo (SQI), derivados da distribuição de poros por tamanho. Destaca-se também a avaliação da resistência do solo à penetração (PR) por meio de penetrômetros, o intervalo hídrico ótimo (LLWR), e a Tomografia de Resistividade Elétrica (ERT).

O efeito do preparo do solo nas propriedades físico-químicas do solo, causado pelas alterações na estrutura do solo, podem ser observados na umidade; concentração de íons na solução, porosidade e densidade aparente do solo (Bd), o que leva a variações nos valores de resistividade elétrica do solo (ρ) (BESSON et al., 2004; SÉGER et al., 2009; BESSON et al., 2013; LOKE et al., 2013; ROSSI et al., 2013; KOWALCZYK et al., 2014). Resultados positivos do preparo de solo relacionados à melhoria dos atributos físico-hídricos e/ou da produtividade das culturas têm sido reportados em todo o mundo em diferentes classes de solos, como na Austrália (SCANLAN; DAVIES, 2019), na Índia (SINGH et al., 2019), nos EUA (HENRY et al., 2018) e no Brasil (SILVA et al., 2015a; BARBOSA et al., 2020; SILVA et al., 2021, REICHERT et al., 2021a; 2021b).

Jeřábek et al. (2017) e Piccoli et al. (2019), mensuraram a profundidade do “pé de arado” (camada compactada) a partir do uso da ERT, confirmada pela PR e Bd. Roodposhti et al. (2019) modelaram a variação da ρ em função da umidade e Bd, demostrando que para mesma umidade do solo o aumento da Bd resulta na redução da ρ. Melo et al. (2021) vão além ao explicarem o comportamento da umidade, Bd e ρ do solo, demostrando uma relação inversa entre ρ e densidade. Porém, para umidades superiores a 0,18 cm^3cm^{-3}, esse comportamento se torna o inverso em um Latossolo. Nesse sentido, a ERT pode ser considerada um dos métodos geofísicos mais eficazes para estudos agrícolas e ambientais (VANELLA et al., 2018). Além de ser um método não invasivo e rápido, é capaz de monitorar a variabilidade espacial e temporal de muitas propriedades químicas e físicas do solo (estrutura, umidade, composição de fluidos) (BANTON et al., 1997; SAMOUËLIAN et al., 2005; PICCOLI et al., 2019).

O LLWR tem sido amplamente relatado na literatura em vários estudos realizados em diferentes solos, culturas e sistemas de manejo que comprovam sua utilidade como ferramenta efetiva para indicador a qualidade física do solo (SILVA et al., 1994; TORMENA et al., 1999;

LAPEN et al., 2004; TORMENA et al., 2007; KAISER et al., 2009; GUBIANI et al., 2013; CHEN et al., 2014; MOURA et al., 2019). Estudos têm relatado aumento do LLWR sob a utilização do preparo profundo do solo em relação a outros manejos (KAHLON; CHAWLA, 2017) e em relação a solo de mata (PACHECO; CANTALICE, 2011). Por outro lado, o manejo também pode levar à degradação estrutural do solo, como relatado por Guimarães et al. (2013) que observaram redução do LLWR em área cultivada com citros em relação à mata nativa.

Neste contexto, esta tese pretendeu elucidar o seguinte problema de pesquisa: em solos diferentes, um mesmo manejo proporcionará resultados semelhantes?

Estudos com essa abordagem são escassos (COULOUMA et al., 2006; BORDONI et al., 2019, REICHERT et al., 2021a; 2021b), especialmente em solos tropicais com estruturas pedogenéticas contrastantes, e ao se tratar de métodos de preparo profundo do solo e culturas perenes. Em sua maioria, os trabalhos em que foi estudado o preparo profundo do solo são realizados em culturas anuais/cerais (SCHNEIDER et al., 2017) e ou não apresentam contraste na estrutura das classes de solo avaliadas (COULOUMA et al., 2006; BORDONI et al., 2019).

Hipóteses, objetivos e estrutura da tese

Baseado no que foi apresentado anteriormente as hipóteses desse trabalho foram: (i) ERT combinada ou não a outros atributos físicos é capaz de mostrar a eficiência de métodos de preparo profundo em classes de solo contrastantes quanto à estrutura morfogenética; (ii) solos com estrutura naturalmente adensada respondem melhor ao preparo profundo, apresentando maior alívio estrutural; (iii) a melhoria do ambiente físico-hídrico do solo para as plantas não dependem apenas do tipo de preparo, mas também dos atributos intrínsecos da classe de solo; (iv) a qualidade estrutural e armazenamento de água no solo para as plantas, além do tipo de preparo, estão sujeitos à influência dos atributos intrínsecos da classe de solo.

Assim, o objetivo geral dessa tese foi avaliar o efeito de métodos de preparo do solo na implantação de culturas perenes sobre a qualidade física do solo e disponibilidade de água para a planta, considerando como esses efeitos se diferenciam em três classes de solo morfogeneticamente contrastantes. Espera-se contribuir com informações de base científica para auxiliar a tomada de decisão quanto ao melhor método de preparo do solo em função da classe de solo. Os objetivos específicos foram: 1- Verificar o efeito dos preparos do solo sobre o alívio estrutural do solo; 2- Avaliar técnicas e ferramentas que possam identificar com clareza os efeitos dos preparos do solo em diferentes classes de solo sobre a qualidade estrutural do solo; 3- Identificar quais os indicadores físico-hídricos são mais sensíveis para detectar mudanças na estrutura do solo provocadas pelo método de preparo do solo; 4- Apontar quais atributos intrínsecos das classes de solo influenciam os efeitos dos preparos de solo; 5- Avaliar o efeito do preparo do solo em relação às propriedades físicas de retenção de água em três classes de solo sob diferentes métodos de preparo; 6- Identificar a melhor opção de preparo do solo em cada classe de solo com base nos indicadores físicos do solo.

Atendendo aos objetivos, essa tese foi estruturada em três artigos de pesquisa. No primeiro artigo, foi realizada uma investigação sobre o efeito do preparo do solo sobre o alívio estrutural em três classes de solo com estruturas morfogenética contrastantes. Nesse artigo foi discutido a eficiência de técnicas para avaliação do efeito do preparo, bem como os atributos intrínsecos das classes de solo interagem/influenciam o efeito do preparo. No segundo artigo, a avaliação dos efeitos do preparo sobre os indicadores da qualidade física do solo nas três classes de solo gerou um amplo conjunto de dados e indicadores extraídos da curva de retenção de água no solo, então uma seleção dos indicadores de qualidade física do solo foi realizada por meio de análise de componentes principais. Com isso, foi possível identificar que a classe de solo tem importantes implicações sobre o efeito do preparo. No terceiro artigo buscou-se a partir da modelagem do intervalo hídrico ótimo entender como o efeito do preparo em cada classe de solo impacta a disponibilidade de água para a cultura. Foi testada também a inserção de um fator fisiológico relacionado ao estresse hídrico para calcular o intervalo hídrico ótimo crítico (LLWR*), o qual possibilitou maior exatidão, pois considera o déficit hídrico no qual o potencial produtivo da planta não é comprometido. Nesse artigo, sugere-se, a partir do desempenho dos preparos de solo, um preparo mais adequado para cada classe de solo estudada.

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SECOND PART - PAPERS

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PAPER 1 – DEEP TILLAGE STRATEGIES IN PERENNIAL CROP INSTALLATION: STRUCTURAL CHANGES IN CONTRASTING SOIL CLASSES

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Abstract

Tillage modifies soil structure, which can be demonstrated by changes in the soil's physical properties, such as penetration resistance (PR) and soil electrical resistivity (ρ). The aim of this study was to evaluate the effect of deep tillage strategies on three morphogenetically contrasting soil classes in the establishment of perennial crops regarding geophysical and physical-hydric properties. The experiment was conducted in the state of Minas Gerais, southeastern Brazil. The tillage practices were evaluated in Typic Dystrustept, Rhodic Hapludult, and Rhodic Hapludox soil classes, and are described as follows: MT—plant hole; CT—furrow; SB—subsoiler; DT—rotary hoe tiller; and DT + calcium (Ca) (additional liming). Analyses of PR and electrical resistivity tomography (ERT) were performed during the growing season and measurements were taken in plant rows of each experimental plot. Undisturbed soil samples were collected for analysis of soil bulk density (Bd) at three soil depths (0–0.20, 0.20–0.40, and 0.40–0.60 m) with morphological evaluation of soil structure (VESS). Tukey's test ($p < 0.05$) for Bd and VESS and Pearson linear correlation analysis between Bd, ρ, and PR were performed. Soil class and its intrinsic attributes have an influence on the effect of tillage. The greatest effect on soil structure occurred in the treatments DT and DT + Ca that mixed the soil to a depth of 0.60 m. The ρ showed a positive correlation with Bd and with PR, highlighting that ERT may detect changes caused by cultivation practices, although ERT lacks the accuracy of PR. The soil response to different tillage systems and their effects on soil structure were found to be dependent on the soil class.

Keywords: deep mixing; subsoiling; soil electrical resistivity; resistance to penetration.

1. Introduction

Soil structure controls many processes in soils [1] therefore, understanding and knowing how to manage it can be beneficial for both agricultural production and the environment. Creating soil conditions favorable to root growth, with consequences on crop development and production, involves optimizing the supply of air, water, and heat from the soil by favoring uptake of water and nutrients [2]. High density layers (of pedogenetic origin), which normally behave in a manner similar to compacted layers (from human activity), not only increase the risk of water erosion [3,4], but also limit crop growth and development by restricting the root system to the surface layer [5], therefore making the development of deep roots subject to the conditions of preexisting pores [6] and much more vulnerable to dry conditions during the winter and short droughts during the rainy season, which are very common in Brazilian conditions.

Mechanical modifications in the soil subsurface for the purpose of alleviation of high density or compacted soil layers are known as deep tillage operations [7]. Deep tillage can increase the soil volume used by crop roots and may thus assist in resolving restrictions in the subsoil, especially by increasing water uptake [7,8,9]. This positive effect can transform marginal areas into productive systems [10,11,12] due to the resulting improvement in soil physical quality, soil function, and the provision of ecosystem services [13].

The research our team has been conducting over the last decade has resulted in positive results with the use of deep tillage, especially in non irrigated coffee [14]. The success of this system of management is due to the greater deepening of crop roots, allowing greater uptake of water from deep layers, resulting in higher yields and longevity of the coffee fields grown in areas of Cambissolos (Inceptisols) and Latossolos (Oxisols) [9,11,15-23]. However, from a soil physical environment perspective, the question arises as to whether the same soil management system will lead to similar results in different soil classes. Limited research data are available on the performance of deep tillage in soils with contrasting physical properties from tropical regions under perennial crop cultivation [24,25]. Most of the peer reviewed studies on deep tillage have been performed on annual/cereal crops [7] and/or these studies have not been performed on soil classes with contrasting structure [24,25]. No work has been found to evaluate the effect of tillage systems on soil classes with contrasting structures.

Changes in soil structure caused by tillage can affect soil chemical and physical-hydric properties, such as soil moisture, soil solution ionic concentration, soil porosity, and bulk density, which leads to variations in soil electrical resistivity (ρ) values [26-31]. Jeřábek et al. [32] and Piccoli et al. [33] used Electrical Resistivity Tomography (ERT) to identify the depth of soil “hardpans”, which then confirmed the data obtained by resistance to penetration and bulk density. Roodposhti et al. [34] discussed how ρ varies in accordance with soil moisture and bulk density, showing that at the same moisture content, increases in bulk density result in a reduction in ρ. The same was reported by Melo et al. [35], who observed an inverse relationship between ρ and bulk density. However, this relationship is inverted for soils with moisture contents greater than 18 $cm^3\ cm^{-3}$. In this respect, ERT is considered one of the most effective geophysical methods for agricultural and environmental studies [36]. In addition, it is a fast and non-invasive method that is able to monitor the spatial and temporal variability of many soil chemical and physical properties (structure, moisture, fluid composition) [33,37-40].

Thus, the hypotheses tested in this study were that (i) ERT, alone or in combination with other physical attributes, is able to show the efficiency of deep tillage methods in contrasting soil classes regarding structure; and, (ii) soils that have higher natural bulk density have a better response to deep mixing and exhibit greater structural alleviation. Our expectation is to find correlations between ρ and the other physical properties that will confirm the potential of ERT under field conditions. Therefore, the aims of this study were to (i) evaluate the effects of deep tillage systems on the establishment of a perennial crop related to the structural quality of three contrasting soil classes and intrinsic attributes; and, (ii) determine the changes in electrical resistivity caused by soil tillage, as well as to correlate ρ with soil physical properties.

2. Results and Discussion

2.1. Penetration Resistance (PR)

The results of PR for the Typic Dystrustept (CX), Rhodic Hapludult (PV) and Rhodic Hapludox (LV) soil classes under the different tillage treatments (minimal tillage—MT, conventional—CT, subsoiler—SB, deep mixing tillage—DT, and deep mixing tillage with supplementary liming—DT + Ca) are shown in the form of 2D maps in Figure 1. Figure 1 presents values of soil resistance to penetration (MPa) measured in a transect perpendicular to the plant row to highlight the effect of tillage. PR is an able and effective tool for assessing the physical status of the soil or a sequence of changes in soil structure [40-43] and was used for the presentation, discussion and comparison of results regarding the efficiency of the tillage methods, with a limit value for root development of 3 MPa [44,45].

The effect of the different soil tillage systems that caused reductions in PR was clearly observed in all the soil classes and treatments, shown in the maps by light colored centralized zones (RP less than 3 MPa). Dotted lines indicate the expected projection of the working area of each implement, which helps in perceiving the differences in the efficiency of tillage systems in each soil class, indicated by the PR values. In general, PR values less than 3 MPa were found between 1.6 and 2.0 m on the “x” axis (plant row) and vary in depth with the action of each implement, whereas the higher values (greater than 3 MPa) did not have a defined pattern of distribution, but were affected by the soil structure itself at depths where there was no effect of tillage (below 0.25 m) and near the surface (0–0.10 m), coinciding with the signs of machine traffic (Figure 1—red arrows). It should be noted that all the machine traffic locations could not be monitored due to the difficulty of controlling the machine and implementing traffic within the experimental area (Figure 1).

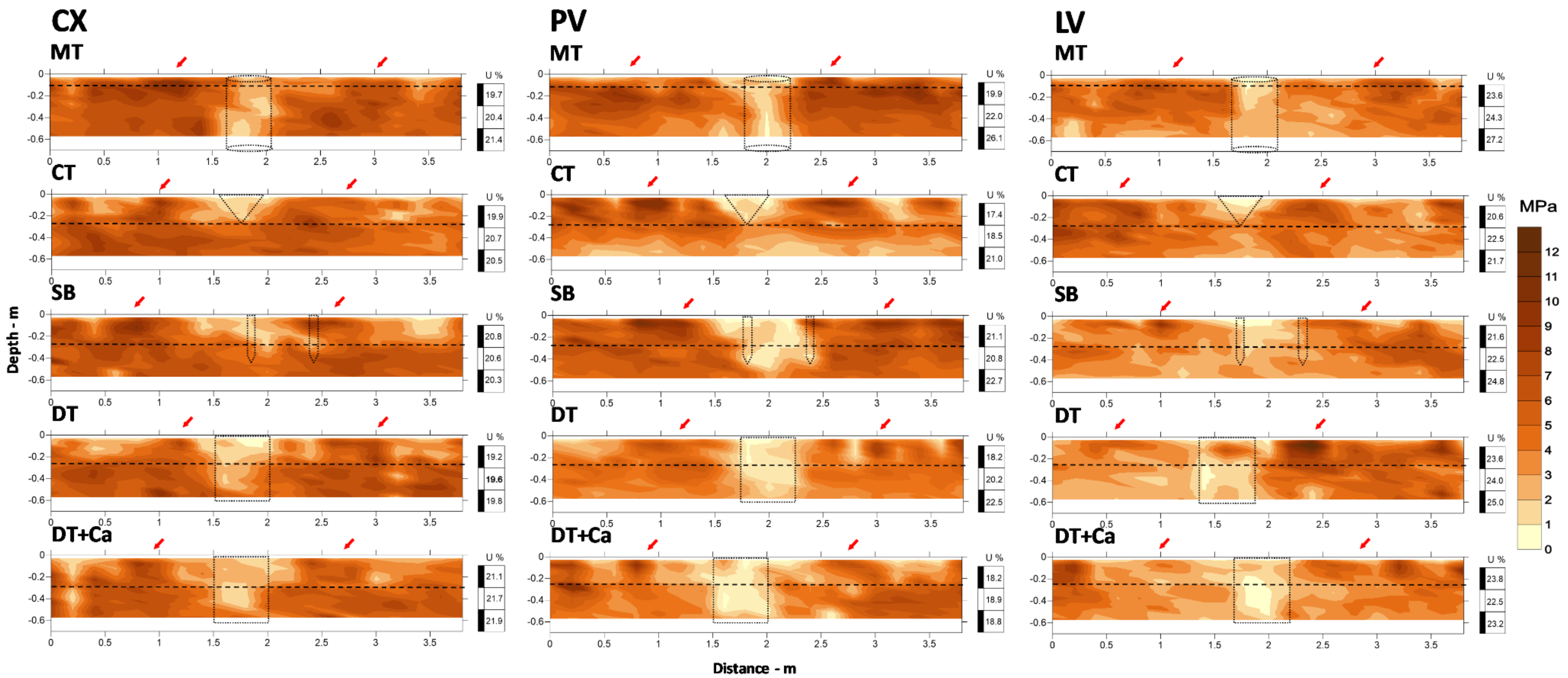

Figure 1. 2D maps of soil resistance to penetration for three soil classes (CX, PV, and LV) under five different soil tillage treatments. [MT: minimum tillage with a pit (0.4 m in diameter by 0.7 m deep); CT: conventional tillage (0.25 m deep); SB: subsoiler with booted ripper points on two shanks (0.45 m deep); DT: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep); DT + Ca: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep) + additional liming. The horizontal dashed line demarcates the working depth of the plow (approximately 0.25 m); dotted lines project the working area of the implements used; red arrows indicate the signs of machine traffic; U: soil moisture based on the weight (U, %) of each layer at the time of data collection. Measurements were performed eight months after tillage operations.

In relation to soil class, in general, the mean of PR throughout the sector was the lowest for LV—3.90 MPa, followed by CX—5.14 MPa and PV—5.55 MPa, respectively. Observation of the effect of the treatment in its working area, considering the distance of 1.5–2.5 m and depth that varies in accordance with each implement (MT—0.6 m, CT—0.25 m, SB—0.45 m, DT—0.60 m, and DT + Ca—0.60 m), showed that even 8 months after the implantation of soil tillage, the effects caused by it were clear, above all in PV, where there was a greater contrast of the PR values between the areas with tillage and without tillage, followed by CX and then by LV, where the contrast was less.

In the CX, the greatest tillage efficiency was achieved by MT and CT, which achieved 100% to the depth desired, with PR values less than or equal to 3 MPa, whereas the effect of the other treatments did not reach the depth expected (approximately 90%). This can be observed comparing the effect of tillage on MPa to the dotted lines that project the expected result. The efficiency of the implements in MT and CT may have been favored by the previous action of plowing and disking.

Under natural conditions, this soil (CX) exhibits physical restriction starting at 0.05 m, with reduction in the amount of sand and a doubling in the amount of silt fraction compared to the previous layer (0–0.05 m), favoring an increase in Bd (Table 1). This shallow physical restriction is an intrinsic property to most of the soils included in this class [46]. This may have led to an increase in mechanical resistance of the soil at the time of tillage. However, deep tillage aims at alleviating the high soil density observed in this layer for the purpose of improving the physical quality of the soil for crops [9]. Much of the references cited here [9,11,16,22] used soil tillage methods similar to those used in the present study in setting up coffee fields. Improvements in soil physical quality at depth one year after the implantation of the crop are reported and likely due to an increase in aeration capacity and in water availability in the Typic Dystrustept (Cambissolo Háplico Distrófico típico) under study. In the PV and LV soil classes, all the treatments had PR values less than or equal to 3 MPa in the working areas of the tillage implements. The contrast of the PR values within and outside the plant row, especially in CX and PV in comparison with LV, is noteworthy (Figure 1).

Table 1. Physical characterization of the soils of the experimental area.

Soil		**CX**			**PVd**			**LVe**		
Horizon		**Ap**	**Bw**	**BC**	**Ap**	**BA**	**Bt**	**Ap**	**Bo1**	**Bo2**
Depth	**m**	**0–0.05**	**0.05–0.15**	**0.15–0.60+**	**0–0.12**	**0.12–0.35**	**0.35–0.55+**	**0–0.10**	**0.10–0.60**	**0.60+**
Bd	g cm^{-3}	1.38	1.41	1.47	1.11	1.42	1.47	1.32	1.06	1.19
Pd		2.55	2.63	2.63	2.53	2.63	2.7	2.64	2.73	2.69
Tp	m^3 m^{-3}	0.49	0.45	0.48	0.54	0.46	0.46	0.54	0.57	0.53
FC		0.36	0.37	0.41	0.32	0.33	0.38	0.40	0.33	0.38
Mic		0.38	0.39	0.42	0.33	0.34	0.39	0.41	0.34	0.40
Mac		0.11	0.07	0.06	0.21	0.12	0.08	0.13	0.23	0.13
AC		0.25	0.17	0.15	0.41	0.28	0.18	0.26	0.43	0.28
Clay	%	41.7	35.5	35.5	44.8	46.9	67.3	50.6	65.5	68.6
Sand		41.9	28.4	28.4	40.6	38.9	24.0	29.6	21.3	20.1
Silt		16.5	36.1	36.1	14.5	14.2	8.64	19.7	13.1	11.3
Texture Class		Clay	Clay loam	Clay loam	Clay	Clay	Clay	Clay	Clay	Clay

CX: Typic Dystrustept; PV: Rhodic Hapludult; LV: Rhodic Hapludox. Bd: bulk density; Pd: particle density; Tp: total porosity; FC: field capacity estimated at −10 kPa; Mic: Microporosity estimated at −6 kPa; Mac: Macroporosity determined according to [47]; CA: soil aeration capacity determined according to Reynolds et al. [48]; Texture Class according to the Soil Survey Division [49].

CX and PV are soil classes with similar characteristics regarding high natural bulk density of horizons in the subsurface (B horizon), which explains the high values of PR. Cambissolos (Inceptisols) generally have physical conditions that are not favorable to plant development, mainly due to the greater silt in relation to clay fraction content that characterizes these less weathered soils. They are characterized by the subangular block structure in the B horizon and coherent massive structure in the C horizon, which have a direct effect on their naturally high bulk density [46], and this results in low soil porosity. Furthermore, the reduced thickness of the *solum* (A + B horizons) of the CX in this study is note worthy (Table 1). Argissolos (Ultisols in this study), however, have mature pedogenesis, promoting accumulation of clay fraction and occurrence of clay skins in the textural B diagnostic horizon [50], where the block structure predominates. Latossolos (Oxisols), for their part, have an advanced stage of weathering leaching and are deep soils [50]. Due to the high content of oxides, such as gibbsite, this soil class has granular structure, which promotes high macroporosity [51] and lower bulk density compared to CX and PV (Table 1), which explains the lower values of PR observed in Figure 1.

The results of this study indicate that the tillage systems were efficient in reducing the PR of the soils, notably within the working depth of the implements. This suggests that even soil classes that have naturally greater restriction for agricultural use, such as CX [46,52] and PV, if properly tilled, can show physical improvement, with PR values that do not limit crop growth (less than 3 MPa). Nevertheless, Figure 1 shows that the effectiveness of tillage systems may have been affected by the soil intrinsic attributes, both those related to mechanical resistance to penetration and those pertinent to natural reconsolidation of the soil [53,54].

Several studies [40-43] have suggested the development of a soil tillage efficiency indicator. Thus, we propose that the tillage systems efficiency be evaluated by comparing the areas/depths of the soil under mechanical intervention with lateral areas/depths not subjected to management practices. The indication criteria should also include reduction of PR in relation to the area not under management (considering a critical value for the crop or not) and the depth and width of the working area of the tillage system visualized by the 2D map of PR.

2.2.Electrical Resistivity Tomography (ERT)

Similar to PR, ρ values shown in the form of 2D maps (Figure 2), exhibited strong spatial variability in the transects of each treatment in the three soil classes. The quality of the ρ maps can be observed by the values in the lower right corner, which indicate the root mean square (RMSE) of each treatment in each soil class after inversion (Figure 2). Variation in theRMSE ranged from 9% to 15.8%, with a mean of 13.7% (Table 2).

Table 2. Summary of the parameters of inversion and root mean square (RMSE).

Soil	Treatment	no. of Points Rejected	no. of Points Used	RMSE %
CX	MT	13	148	15.7
	CT	45	116	15.8
	SB	10	151	14.6
	DM	19	142	14.5
	DM + Ca	14	147	14.0
PV	MT	12	149	14.3
	CT	3	158	9.0
	SB	4	157	14.5
	DM	3	158	14.1
	DM + Ca	11	150	14.7
LV	MT	4	157	15.2
	CT	2	159	14.5
	SB	6	155	15.5
	DM	5	156	9.0
	DM + Ca	3	158	10.7
Mean		10	151	13.7

Number of interations = 4; CX: Typic Dystrustept, PV: Rhodic Hapludult, and LV: Rhodic Hapludox; MT: minimum tillage with a pit (0.4 m in diameter by 0.7 m deep); CT: conventional tillage (0.25 m deep); SB: subsoiler with booted ripper points on two shanks (0.45 m deep); DM: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep); DM + Ca: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep) + additional liming.

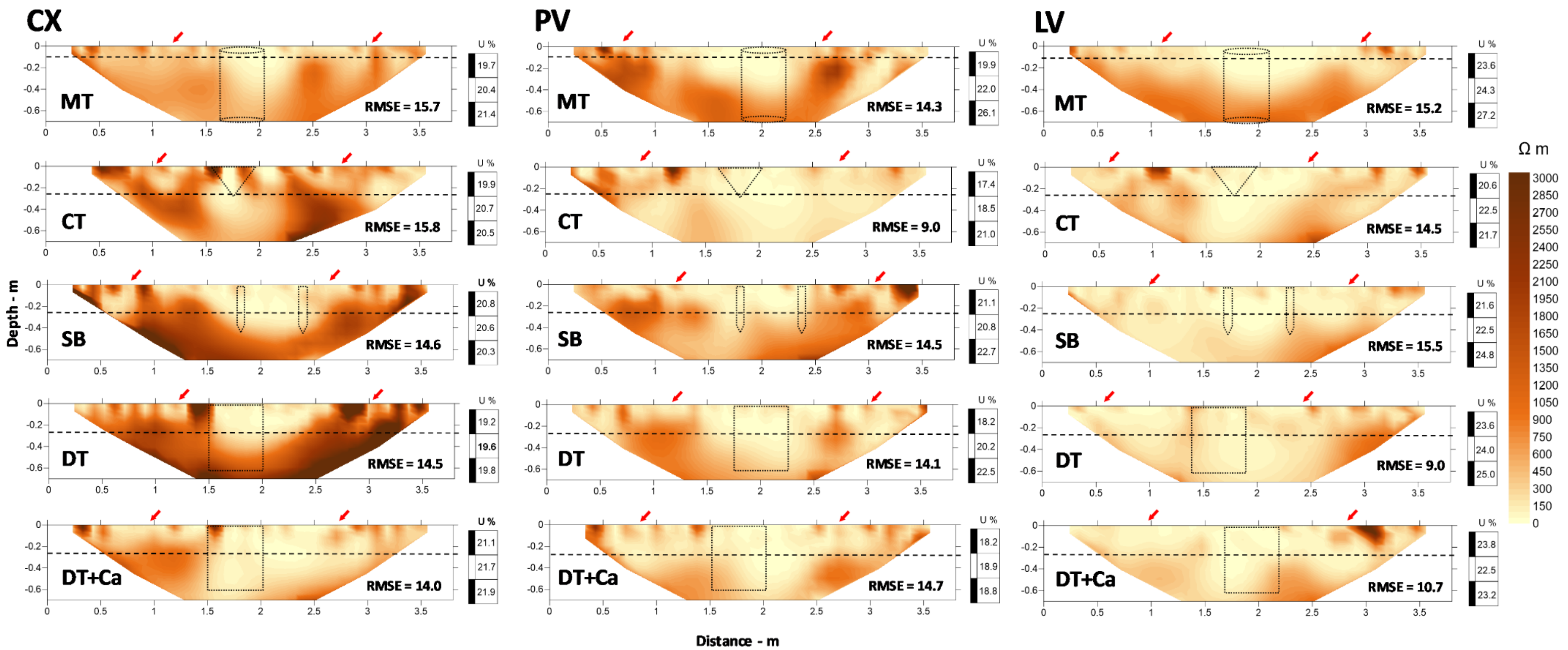

Figure 2. 2D maps of soil electrical resistivity for three soil classes (CX, PV, and LV) under five different soil tillage treatments.

[MT: minimum tillage with a pit (0.4 m in diameter by 0.7 m deep); CT: conventional tillage (0.25 m deep); SB: subsoiler with booted ripper points on two shanks (0.45 m deep); DT: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep); DT + Ca: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep) + additional liming. The horizontal dashed line demarcates the working depth of the plow (approximately 0.25 m); dotted lines project the working area of the implements used in each tillage treatment; U soil moisture based on the weight (U, %) of each layer at the time of data collection. Measurements were performed eight months after tillage operations.

In evaluation of soil structure after management practices, Besson et al. [26] observedRMSE was less than 10% after 4 to 6 interactions, just as in Besson et al. [28], withRMSE lower than 9%. However, when there is the possibility of a greater number of interactions, it is possible to achieve lowerRMSE, as in Garcia-Tomillo et al. [55], who observedRMSE varying from 1.20 to 1.70% for interactions ranging from 6 to 7. In the same way, Vanella et al. [36], studying the root soil interaction under irrigation systems, stipulated a value forRMSE of 16%, just as Jayawickreme et al. [56], when analyzing the water dynamics in the subsurface directed by land use, reported anRMSE of 15.75% in their maps.

The values ofRMSE found in our study are greater than those found in studies conducted in soils of temperate regions [26,28,36,55,56], which indicates the need for more studies involving soils of tropical regions. The greater error values in evaluations of ERT can be explained by the greater difficulty in establishing good contact between the electrodes and the dry soil, which affects electrical readings and the accuracy of inversion of resistivity [57,58]. In addition, soils with greater clay content, specially those having high activity clays, can form cracks during dry periods [59], producing noise that increase errors in readings. Abrupt changes in soil structure are another factor that can be source of noise and lead to an increase inRMSE, especially when associated to changes in porosity caused by soil management.

The ρ values ranged from 7 to 7000 Ωm; however, ρ values up to 3000 Ωm were used for creating the maps, understanding that values greater than that would pollute and could impede accurate interpretation of the images. This range of values can be considered high compared to that reported in the literature with similar objectives: 30–1680 Ωm [30], 150–1061 Ωm [55], 20–80 Ωm [32], and 0–500 Ωm [33]. Yet, all of these were in soils of temperate regions with no research reporting results for soils under tropical conditions. The highest amplitude of ρ values was observed in CX for the treatment with the subsoiler—SB (0.45 m depth), followed by PV also in the SB treatment, and LV in DT + Ca (Figure 2).

For all the soil classes and treatments analyzed, there was a tendency for an increase in ρ with an increase in depth, proceeding from less dense areas to denser ones. At depths where soil tillage occurred, from 1.5–2.5 m, approximately (x axis, Figure 2) and thus regions of greater structural alleviation (dotted lines), the lowest ρ values were observed (ρ less than 300 Ωm). In CX, it is possible to identify clear patterns of the effect of deep tillage, specially in the SB and DT treatments compared to the other treatments. The results of this study show that ρ maps can provide a better estimate of horizontal action as a function of implement being used than those obtained with PR maps (Figure 1). In PV, similar patterns to CX were observed, but were not so easily separated out from the background soil conditions. In contrast, in LV, it was not possible to distinguish clear patterns among any of the deep tillage treatments.

The greatest ρ values are in the no-tilled areas, especially below 0.25 m, the mean depth reached by the plow, and in some small areas near the surface, to approximately 0.10 m (Figure 2). Besson et al. [26] observed lower ρ values in machine traffic areas, with greater Bd, than in non-compacted areas, without, however, determining the exact position of the wheel tracks. In our study, the distribution of ρ was consistent with the values of PR except for the surface PR. The red arrows in Figure 1 demarcate high PR areas, which we indicated as signs of machine traffic. Our results showed that the ERT was unable to demarcate these same positions.

Changes in ρ under the conditions evaluated may largely be caused by changes in bulk density, moisture, and porosity [28,31]. Temperature variations may affect ρ values [26,29,38], and may even hinder the ability of data collection in the field [56]. However, for this study, which was performed under tropical conditions, we assumed that the temperature was stable during acquisition of ρ [60 cited by 26]. Zhou et al. [61] showed that the greatest changes in ρ take place at around and below 0 °C. In addition, another source of variation in ρ is the effect of integration of the hemisphere, which means that the results of ρ are affected by characteristics lateral to the ERT transect [27]. Variations in moisture also create difficulties in interpretation of the results [32,35,62].

Areas of greatest ρ below the depth of 0.25 m, especially in CX and PV, are consistent with the results of PR and with the morphological attributes of these soil classes that have naturally greater bulk density in the subsurface [46]. The ERT was able to identify changes caused by the different soil tillage methods, but it was unable to precisely demarcate the region changed by each tillage method. Studies performed for the purpose of detecting structural changes in agricultural areas show that ERT does not have sensitivity to abrupt variations in ρ, such as rock fragments or even high density clods surrounded by material of high porosity [27,30]. In addition, soil moisture has a predominant effect on ρ in detriment to structural changes [28,34,63]. Melo et al. [35] simultaneously studied the relationship among ρ, moisture content in the soil, and the degree of compaction in a Brazilian Typic Hapludox [64] and concluded that soil moisture content has a greater effect on ρ than the degree of compaction. It should be emphasized that 2D resistivity tomography was performed in the driest season of the year, winter, in which the last rainfall of 7 mm occurred 10 days before data collection (ERT and PR). In that period, the mean maximum temperature was 24 °C and the mean minimum was 10 °C, with relative humidity of 63.5%, which led to soil moisture below FC (Table 1, Figure 2).

Seladji et al. [62] observed that the relationship between bulk density and ρ is controlled by soil moisture, and is significant and negative when less than 0.25 g g^{-1} for French soils (Haplic Luvisol and Neoluvisol). Studies performed by Melo et al. [35] show that there is an inversion of interpretation of the relationship between bulk density and ρ with variation in moisture, specifically at the value of 0.18 m^3 m^{-3}, or approximately 13.4% moisture, based on weight in a Typic Hapludox [64] in the same region as this study, whereas most studies show a direct relationship between ρ values and soil porosity [32,38,65,66] under dry soil conditions. Melo et al. [35] showed that above this soil moisture content (0.18 m^3 m^{-3}), the relationship is reversed between ρ and porosity. Results of this nature are presented by Naderi-Boldaji et al. [67] and Piccoli et al. [33], who identified areas of alleviation of porosity by plowing areas of low ρ, whereas a compacted area (plow pan) was identified by high ρ.

The soil profile evaluated by the ERT may act as an insulating or conductive material depending on its moisture content. Moisture content is the main factor that controls ρ because the main mechanism responsible for conduction of electrical current in the soil is electrolysis [38]. Under high moisture conditions, the soil matrix will act as a resistive material and the water present in the pores as a conductor, whereas under low moisture, the air present in the pores leads to an increase in resistivity, and the soil matrix will be a conductor [35]. Therefore, under the conditions of increased bulk density and high moisture, there is a reduction in the amount of water stored due to the reduction in porosity. As a result, there is a greater amount of resistive material (soil matrix) and consequently high ρ in compacted locations [67]. In contrast, low ρ in porous areas suggests that the porous spaces may be filled with water, which increases conductivity. This mechanism presumably explains the low ρ values that predominate in the LV (Figure 2).

2.3. *Bulk Density (Bd)*

The results of the analysis of Bd carried out on PV, CX, and LV under different tillage systems (MT, CT, SB, DT, and DT + Ca) are shown in Figure 3, except for MT, because sample collection performed within the plant row would cause considerable damage to the plant. The soil tillage strategies affected Bd for the three soils in a different way. In CX there was a significant effect of the different tillage systems, which did not occur for PV and LV; nevertheless, there were differences among the depths for the three soil classes (Figure 3). In the PV, unlike the others, at the 0.20–0.40 m depth, all the treatments exceeded the critical bulk density limit, 1.32 and 1.30 $g.cm^{-3}$, 0.20–0.40 and 0.40–0.60 m, respectively (vertical red line–Figure 3), suggesting that its subsoil environment is more restrictive to plants. However, the use of treatments labeled “deep tillage” (DT and DT + Ca) reduced the Bd in relation to Bdc, especially compared to MT and CT treatments in the PV and LV soils. This result shows how effective soil tillage was in loosening the soil and physically improving the root environment. Few studies relate the morphological attributes of soil classes to plant growth or to management practices. Studies generally relate the soil physical properties to management practices only in the arable layer, 0–0.30 m on average, and do not consider the morphological attributes of each horizon in discussion or their effect on crop growth and productivity [68-71].

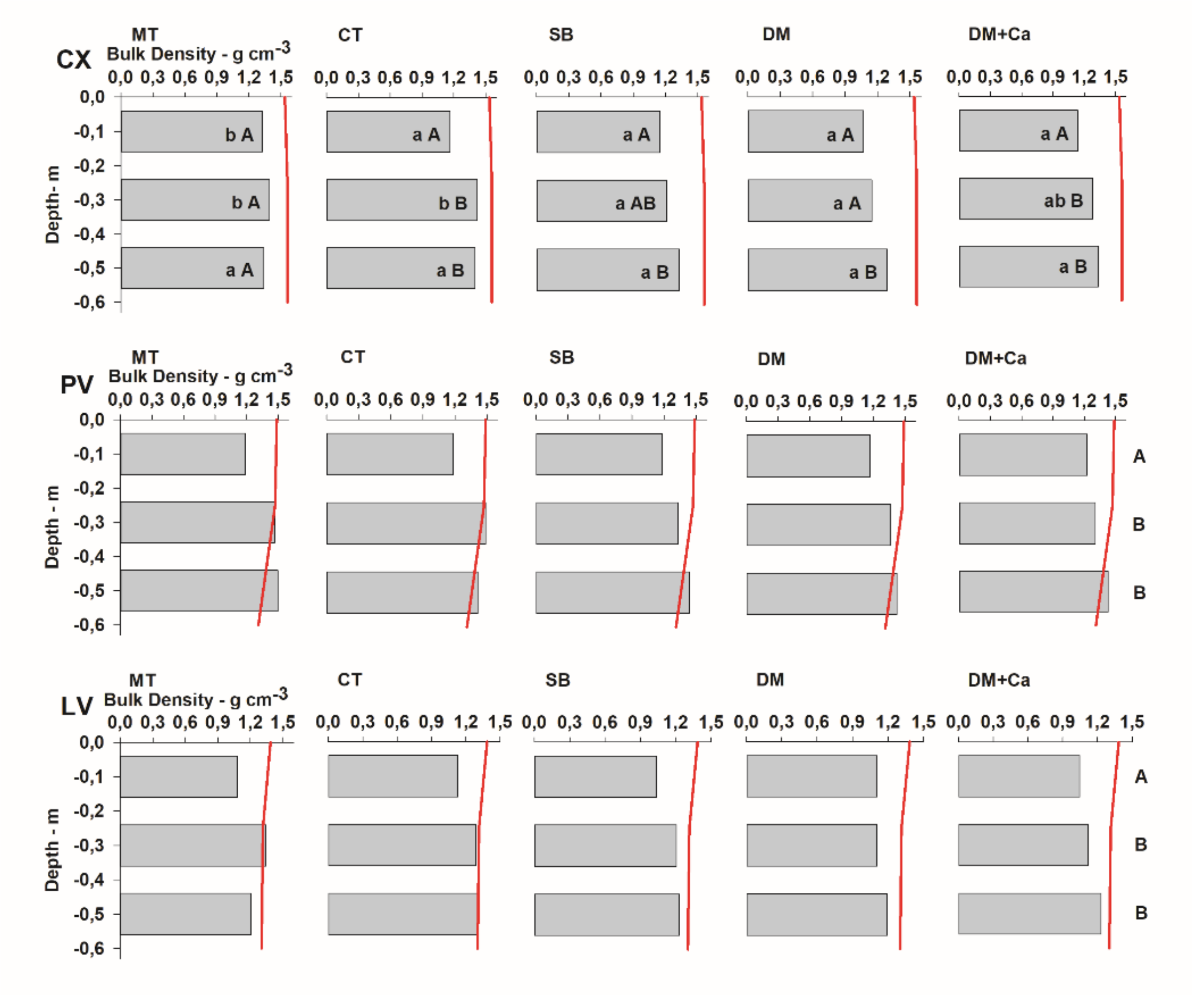

Figure 3..Bulk density (Bd) and critical bulk density (Bdc) (vertical red line) for three soil classes underdifferent soil tillage systems for a perennial crop. Measurements were performed seven months after tillage operations. Mean values followed by the same lowercase letters in the row and uppercase letters in the column do not differ from each other by Tukey's test ($p < 0.05$). MT: minimum tillage with a pit (0.4 m in diameter by 0.7 m deep); CT: conventional tillage (0.25 m deep); SB: subsoiler with booted ripper points on two shanks (0.45 m deep); DT: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep); DT + Ca: deep mixing tillage with rotary hoe tiller (0.5 wide by 0.6 m deep) + additional liming; Critical bulk density by according to Reichert [72]; (CX: Typic Dystrustept, PV: Rhodic Hapludult, and LV: Rhodic Hapludox).

In PV and LV, in general, the Bd increased with depth, without difference between the 0.20–0.40 m and 0.40–0.60 m layers. Lower Bd in the 0–0.20 m layer is associated with its greater organic matter content (Table 1). The absence of effect among the tillage systems on the Bd for the PV and LV soils can be explained by the lower sensitivity of Bd in detecting changes in structural alleviation. In addition to lower sensitivity of Bd, lower persistence of the effects of tillage in PV and LV is related to faster reconsolidation in these soils than in CX. Reconsolidation or the "agehardening" phenomenon [73-75] is a natural process that occurs in a slower way at depth than on the surface and mainly depends on accumulated rainfall [53,76] and wetting and drying cycles [77], even without machine traffic [78]. This phenomenon is the result of the rearrangement of soil particles, especially clay particles, in new positions of minimum free energy and strengthening of the cementation bonds in new points of contact between pairs of mineral particles [73]. This can explain why CX has slower reconsolidation, since PV and LV have greater clay in relation to silt content, a higher degree of weathering leaching, and greater concentration of Fe and Al oxides, which, for their part, accelerate such process [79].

Corroborating the fact that the effects of soil management in this study are not perceptible through Bd at 9 months after tillage, Reichert et al. [80] report that in a subtropical Argissolo (Ultisol), in less than one year, the effects of chisel plowing observed through changes in Bd disappeared, reaching a compaction condition similar to that of an area under a no-tillage system for 10 years. The authors attributed this effect to reconsolidation of the soil, due to mechanical disruption of the aggregates and their later rearrangement. Loss of the effect of soil management is also observed in Drescher et al. [81] through Bd in a period shorter than one year in a clayey Latossolo Vermelho (Oxisol). Nicoloso et al. [82] evaluated the effect of mechanical chisel plowing on a very clayey Latossolo (Oxisol) and noted a shortterm effect of the practice, without obtaining improvement in the physical conditions nine months after the operation. Scarpare et al. [83] evaluated deep tillage similar to the DT and DT + Ca treatments in a sandy-clay kaolinitic Latossolo (Oxisol) and observed reduction in Bd and increases in the density of the root system in soils under sugarcane cropping. However, the effect of this tillage on Bd persisted for one year, but was not observed in the second year. Those results differ especially from the results in our study, mainly due to variation in texture and mineralogy between the Latossolos (Oxisols). Bavoso et al. [84] evaluated the quality and the resilience of two Latossolos (Oxisols) and found that the soil with greater clay content had greater resilience. Peixoto et al. [85] used a machine learning algorithm to rank soil properties that are more sensitive in detecting structural changes due to soil tillage: PR was most important and Bd appeared in sixth place. This is in agreement with a previous study of Abreu et al. [86], who also showed greater sensitivity of PR in relation to Bd. In this respect, Simões et al. [76], evaluating the effect of subsoiling on an Ultisol on the east coast of North America, showed, through PR, evident reconsolidation in this soil class at 11 months after tillage. This effect is expected; as reported by Theadgill [40], for Ultisol, reconsolidation of greater density layers generally occurs in one year. Thus, Busscher et al. [41] observed loss of the effect of subsoiling in an Ultisol, with reconsolidation of around 75% in one year and 90% in two years. However, reconsolidation cannot clearly be observed in this study using PR (Figure 1).

In CX, the lower values of Bd are associated with mobilization of the soil by tillage, especially in the 0–0.20 m depth. In the other depths, Bd is consistent with the working depth of the implements. The Bd values of the surface layer (0–0.20 m) show that the effect of plowing and disking associated with the other implements led to significant reduction in Bd in relation to the MT treatment, where mechanical mobilization did not occur, just as in the subsequent layer, where SB, DT, and DT + Ca led to reduction in Bd compared to MT and CT. However, in the 0.40–0.60 m layer, the Bd values are not different, which corroborates the fact, described above, that it is possible that in the CX, the effective depth of the implement was not reached (Figure 1). The shallower C horizon, with no structure or with coherent massive material, helps to understand such effect. These results are can be used to show that deep tillage is important in reducing Bd and in structural alleviation of higher density soils. This beneficial effect was found in subsoiled soils in Germany [87,88] and in Brazilian Cambisols (Inceptisols) with the DT treatment [9,11,15,16] as long as the clay:silt ratio is greater than 0.3, as in the case of the present study (lowest ratio = 1.0). In soils with clay:silt ratios below 0.3, subsoiling has resulted in a collapse of the soil structure and in compaction [7].

Therefore, the lower sensitivity of the Bd measurement in detecting changes brought about by tillage in soils with more advanced weathering leaching processes and deeper *solum* (Figure 3, PV and LV) can be explained by the factors that act on reconsolidation. The response of the soil in returning to its state before tillage is affected by the organic matter content, texture, and mineralogy [79], as well as climate and weathering [84]. LV and PV have greater clay and Fe and Al oxides content than CX (Tables 1 and 2) and under environmental conditions of high rainfall, this leads to greater ability of rearrangement of particles, or reconsolidation [53]. Thus, CX, which is less weathered leached, exhibited a longer duration of the effects of tillage, i.e., it had lower reconsolidation or resilience capacity. Data compiled by Oliveira et al. [21] showed results in tropical Inceptisols and Oxisols (Cambissolos and Latossolos), i.e., porosity modifications may indicate improvements caused by soil tillage that remain up to five years after setting up the coffee crop. This indicates that Bd may not be a good indicator for making inferences regarding soil quality in accordance with the tillage treatment used.

2.4.Correlation between ρ and Other Soil Properties

Pearson correlation analyses are presented in Figure 4, which shows only those with significant correlations. Analyzing our entire dataset obtained from the three soil classes, we can observe positive correlations between PR and depth (r = 0.34) and between ρ and Bd (r = 0.19) (Figure 4A). Observed in that way, these results are diluted by the three soil classes. For that reason, we opted to separate the correlations by soil class, emphasizing the individuality of each one in its interactions. Thus, we can note an increase in the sensitivity of the analysis, observed by the increase in the correlation coefficient (r) in CX and PV (Figure 4B,C, respectively) by the emergence of significant correlations not otherwise perceived (Figure 4B) and the absence of significant correlations in LV. The lack of significant correlations in LV may be related to its greater resilience, i.e., its rapid ability to restructure itself [79,82,84,89] due to its high flocculating power induced by Al and Fe oxide minerals (gibbsite, goethite, and hematite) that favor the granular structure [51].

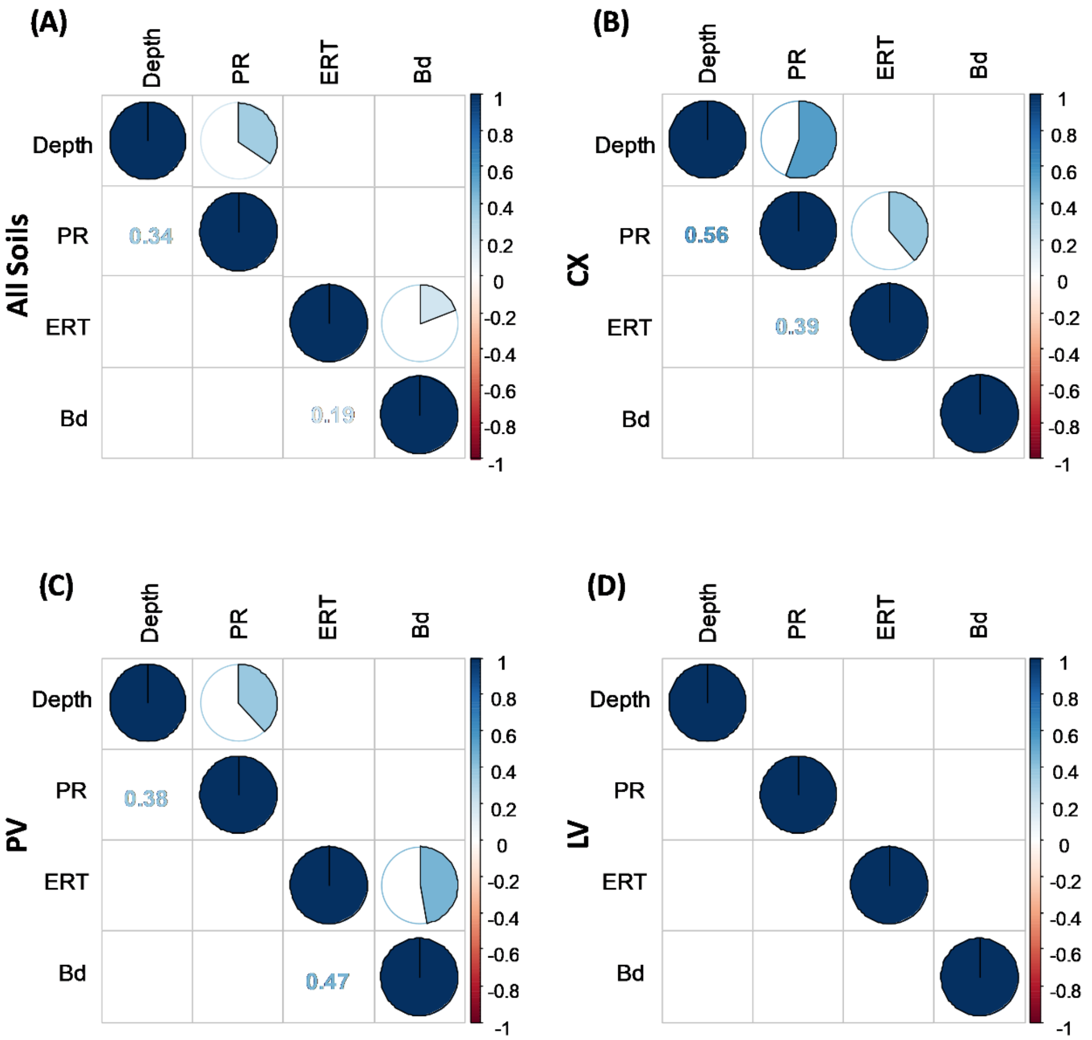

Figure 4. Representations of Pearson linear correlation coefficient for variables of sampling depth, penetration resistance (PR), soil electrical resistivity (RES), and bulk density (Bd), with data from all the soils evaluated (CX: Typic Dystrustept, PV: Rhodic Hapludult, and LV: Rhodic Hapludox) (A), and separately for each soil CX (B), PV (C), and LV (D). Only significant correlations are shown ($p < 0.05$); blue circles indicate positive correlations and red circles negative correlations; the upper off diagonal entry denotes the pie chart for the pairwise correlation level and the lower off diagonal entry denotes the corresponding pairwise correlation coefficient.

In observing ρ and its interdependence on the other soil attributes evaluated in this study, Figure 4 shows that ρ was affected by the physical properties of each soil class. In general, PR can be used to clearly distinguish the different soil tillage systems and their effects on PR [42,90,91]. In addition, according to Abreu et al. [86] and Peixoto et al. [85,92], PR is more sensitive than Bd in detecting compaction. PR and Bd positively correlated with ρ, r = 0.39 for PR in CX, and r = 0.47 for Bd in PV. These correlations indicate the capacity and the sensitivity of ERT as a tool to identify structural changes brought about by management systems in tropical soils, becoming an important alternative for studying temporal and spatial changes in a non-destructive manner, as previously observed by Piccoli et al. [33] in Inceptsols from Italy.

The correlation between ρ and Bd as found in the literature is negative [26,31,32,93], but also positive, as reported by Naderi-Boldaji et al. [67] and Piccoli et al. [33], which was already discussed above and explained by the effects of high soil moisture [35]. In regards to PR, Piccoli et al. [33] showed a positive correlation with ρ, whereas Jeřábek et al. [32] reported a negative correlation. The distribution of clay, silt, and sand fractions among the soil classes (CX, PV, and LV) were different and varied with depth (Table 1), and it appears that the effect of management practices may have superimposed some tendencies of correlation between ρ and texture (sand, silt, and/or clay). In contrast, Piccolli et al. [33] showed that the results of ρ were driven mainly by texture, ρ, and clay: r = 0.30, which was not observed in the present study.

The absence of correlation between PR and Bd can be explained by the marked effect of soil moisture on PR, which did not occur for Bd [33,94]. The correlation between PR and depth in CX and PV can be explained by the morphological attributes of these soil classes, which tend to have naturally higher density in subsurface horizons [41,50,91,95]. Both classes have a blocky structure (surface-surface contact) in the B horizon, observed during field work. Furthermore, in CX, in addition to the high values of Bd that increase with depth (Figure 3), the main factor that confers higher Bd is the increase in silt content below 0.05 m (Table 1) [52], sealing the pore system, with a consequent increase in PR (r = 0.56). In a different manner, in PV, the main attributes that caused higher Bd (Figure 3) are the increase in clay content and the presence of clay skins in the Bt horizon (Table 1). In addition, reduction in soil organic matter (SOM) in the subsurface layers increases PR, as well as Bd (Figure 3) [74]. Unlike CX and PV, LV has an advanced degree of weathering–leaching, with a deep and more homogeneous soil profile [50] due to its higher oxide content, including gibbsite, which confers good aggregation due to its very small and stable granular structure [51]. For that reason, in LV, the changes caused by management practices are less intense than genetic control of the soil structure, i.e., the soil management practices are not able to supersede the physical effect of the granular structure.

Comparing the effects of the tillage systems obtained by the different tools tested in this study (PR, Bd, and ESS) with the results achieved by ERT, we can affirm that the hypothesis of this study was partially confirmed, since ERT is sensitive to structural changes in the soil, but shows reduced accuracy in demarcating the modified area [27].

3. Materials and Methods

3.1. Characterization of the Study Area

The present study was conducted in the experimental area of the fruit growing sector of the Universidade Federal de Lavras (UFLA) in the Southeast region of Brazil. The climate in the region is Cwa according to the Köppen climate classification system [96], with hot and humid summers, cool and dry winters, mean annual temperature of 21.6 °C, and mean annual rainfall of 1339.5 mm, concentrated in the months from November to March, according to the data obtained in the period from 01/01/1998 to 01/01/2018 [97].

Due to geological complexity, there is great diversity of the parent material of the soils in the municipality of Lavras [98-100]. The campus of UFLA is in the Planalto Atlântico geomorphological unit, under the main influence of leucocratic granitic gneiss (LgG) and mesocratic granitic gneiss (MgG), and there are a wide variety of soil classes even in small areas. This allowed the selection of three classes of soil, classified by mapped by Curi et al. [101], according to Santos et al. [50] and US Soil Taxonomy [64]: Cambissolo Háplico Tb distrófico típico or Typic Dystrustept—CX; Argissolo Vermelho distrófico típico or Rhodic Hapludult—PV; and Latossolo Vermelho distrófico típico or Rhodic Hapludox—LV. These soils are well represented on a national (Brazil) scale (Latossolos—31.6%, Argissolos—26.9%, and Cambissolos—5.26%, Santos et al., [102]), and even on a worldwide scale when considering correlations with the orders in the US Soil Taxonomy classification system (Inceptisols—15%, Ultisols—8%, and Oxisols—8% [103]). The naturally high bulk density found in Inceptisols (Cambissolos) and Ultisols (Argissolos) is a prominent characteristic in these soil classes [41,46], as well as the very small granular structure present in Oxisols (Latossolos) of tropical regions [51]. Both these attributes contribute to the contrasting conditions found in these soil classes for crop growth in regard to root development and soil water availability.

Before the experiment was set up, undisturbed soil samples were collected from the soil horizons for physical characterization (Table 1), and disturbed samples for chemical characterization were collected at the depths of 0–0.2, 0.2–0.4, and 0.4–0.6 m (Table 3), according to standard methods described in Teixeira et al. [47]. The study areas were under fallow conditions for at least 5 years before the experiment was set up. In all three areas, weed control was carried out sporadically with use of herbicide or mechanical cutting. Each area comprises approximately 1200 m^2.

Table 3. Chemical characterization of the soils of the experimental area.

Soil		CX			PV			LV		
Depth	**m**	**0–0.2**	**0.2–0.4**	**0.4–0.6**	**0–0.2**	**0.2–0.4**	**0.4–0.6**	**0–0.2**	**0.2–0.4**	**0.4–0.6**
pH	H_2O	6.30	5.70	5.50	6.00	5.70	5.70	6.90	6.50	6.00
	$CaCl_2$	5.70	5.10	4.90	5.40	5.10	5.10	6.30	5.90	5.40
P–Mehlich-1	$mg\ kg^{-1}$	14.2	3.38	2.50	2.55	2.27	0.71	11.1	10.8	1.90
P–resin		25.4	5.73	1.18	10.9	5.25	3.41	10.4	4.76	3.45
K–Mehlich-1		94.0	45.4	32.5	133	103.0	71.7	66.5	38.9	23.4
Ca	$cmol_c\ kg^{-1}$	5.42	3.38	2.50	4.22	3.12	2.41	4.76	2.86	2.14
Mg		1.25	0.59	0.44	1.11	0.85	0.57	1.19	0.95	0.60
Al		0.00	0.06	0.15	0.00	0.00	0.00	0.00	0.00	0.00
H + Al		3.06	4.12	3.68	2.55	3.41	3.55	1.79	2.14	2.86
CEC_7		10.1	8.38	6.62	8.21	7.67	3.12	7.85	3.93	2.86
OC	%	1.40	0.90	0.90	1.80	1.10	0.80	1.10	1.10	0.60
SOM		2.41	1.55	1.55	3.10	1.90	1.38	1.90	1.90	1.03
BS		9.40	50.8	46.0	69.1	55.3	46.6	77.4	64.6	49.5
Al_{sat}		0.00	1.30	3.50	0.00	0.00	0.00	0.00	0.00	0.00

CX: Typic Dystrustept; PV: Rhodic Hapludult; LV: Rhodic Hapludox. CEC = cation exchange capacity; C = organic carbon; SOM = soil organic matter; BS = Base saturation; Alsat = Aluminum saturation.

3.2.Experimental Design and Treatments

The same experiment with five treatments and five replications was set up in the three soil classes in a completely randomized design, totalizing 75 experimental plots in the field. Each plot was composed of a plant row with six plants, occupying an area of 40.5 m^2. The choice of treatments was based on the main soil tillage systems used for establishing perennial crops in Brazil and on works developed by our research group [9,11,15,16,23]. The treatments included: MT—minimum tillage, without soil plowing, and surface furrow (0.10 m depth) for marking the plant row using a furrow opener + plant hole (0.40 m diameter by 0.70 m depth) using a soil borer auger; CT—conventional tillage, disk plowing (0.25 m) + two diskings (0.20 m) + furrow (0.25 m) using a furrow opener; SB—subsoiling, plowing (0.25 m) + two diskings (0.20 m) + subsoiler with booted ripper points on two shanks spaced at 0.50 m (0.45 m); DT—deep mixing tillage, disk plowing (0.25 m) + two diskings (0.20 m) + rotary hoe tiller (0.50

width by 0.60 m depth); DT + Ca—deep mixing tillage and supplementary liming, plowing (0.25 m) + two diskings (0.20 m) + rotary hoe tiller (0.50 width by 0.60 m depth) + additional liming at the depth of 0.40 to 0.60 m to reach 70% and 15% base saturation with Ca and Mg, respectively. For that purpose, liming was applied in the amounts of 3.91, 4.09, and 4.04 t ha^{-1} in the soils CX, PV, and LV, respectively. The rotary hoe tiller is a type of modified rotary hoe with a width of activity of 0.5 m, conducted in strips, composed of a vertical revolving tilling wheel that mixes the surface and subsurface horizons (BigMix® model AS-2, manufactured by Mafes Agromecânica) [104]. The area was tilled in the spring, on 29 November 2018, three days after the last rainfall of 20 mm.

Atemóia (*Annona cherimola* × *Annona squamosa*) was planted on 14 December 2018 at a spacing of 4.5 × 1.5 m, with 6 plants per plot. Soil amendment was performed with liming at the depth of 0 to 0.4 m to raise Ca and Mg saturation to 70% and 15% base saturation, respectively, except for MT, in which liming was performed in the plant hole. In addition, Braquiária Ruziziensis grass (Urochloa ruziziensis) was sown between rows and was periodically cut. Liming and fertilization recommendations were according to crop needs, as described in Rozane and Natale [105]. In this study, the effects of addition of complementary liming were only discussed for the DT treatment, since this study focused on analyzing the physical effects on the soil brought about by the different forms of deep tillage.

3.3. Variables Analyzed

3.3.1. Electrical Resistivity Tomography (ERT)

Electrical resistivity tomography (ERT) was used to determine the apparent electrical resistivity (ρa) of the soil in the field. The readings of ρa were obtained with a resistivity meter, model X5tal (Alto Energia, Belo Horizonte, Minas Gerais, Brazil), eight months after soil tillage. The Dipole–Dipole array was used because it has greater horizontal resolution [38] and it is useful for accessing morphological changes in the soil due to tillage [30,32]. In one plot of each treatment in each soil, the readings of ρa were taken in transects measuring 3.80 m, perpendicular to the plant row, between the 4th and 5th plant. The transect was composed of 21 rods (electrodes) at a distance of 0.19 m from each other, reaching a depth of 0.70 m, composed of 14 levels at a distance of every 0.05 m, with the first level at 0.09 m from the surface. Each transect in this arrangement resulted in 161 readings (n = 161), and a total of 2,415 ρa values were measured.

The data obtained through ERT compose a 2D section of apparent resistivity (ρa) for each treatment. Since they are not homogeneous soils, they do not contain an isotropic current distribution [38], and to resolve this modeling problem, the data were inverted using the Res2DINVDemo 4.9.17 software (Geotomo Software, Penang, Malaysia) [106] for obtaining true resistivity values (ρ). All the inversions of the ERT converged with 4 interactions, given the limitations imposed by the Demo version of the Res2DINV program. For that reason, to reduce the noise and the root mean square error (RMSE), the "RMSE error statistic" tool was used, which allows points with greater error or outliers to be excluded. We adopted a maximum error level of 16% for the following reasons: (i) weak signal/noise ratio in the dipole–dipole arrangement, especially when there are wide separations between pairs of current and potential electrodes [107] and (ii) dry soils may manifest cracks due to contraction movement [59], and this may produce anomalies in the current signal, hindering the readings.

The inversion method applied was the smoothness constrained method, using the mathematical Gauss–Newton least squares method [108]. Of the 161 points of apparent ρ, an average of 151 were used for the inversion and construction of the models that generated the maps.

After each measurement of ERT and PR, soil samples were collected along the transect at the depths of 0–0.2, 0.2–0.4, and 0.4–0.6 m for determination of soil moisture by the laboratory oven method.

3.3.2. Penetration Resistance in the Field (PR)

Soil mechanical resistance to penetration (PR) in the field was measured by the cone index using an impact dynamic penetrometer (IAA/PLANALSUCAR-STOLF) with a cone tip at a 30° angle and basal diameter of 1.28 cm [94,109], eight months after soil tillage. The dimensions of the cone tip are in accordance with Standard S313.3 of the American Society of Agricultural and Biological Engineers [110]. Evaluation of PR was considered as reference for comparison with the ρ analysis. For that purpose, in each soil in the same plot of each treatment in which ρ was evaluated, a transect was established measuring 3.80 m, parallel to that described in Section 3.3.1. The distance between the transects of PR and ρa was 0.20 m. The measurements of PR were obtained on the same date as those of the ρa. Twenty (20) points were checked for PR along the transect at a distance of 0.20 m from one to another to the depth of 0.60 m. On an electronic spreadsheet, the PR data were clustered at each 0.05 m of depth. This made for a total of 240 values of PR per transect, resulting in 3,600 values recorded.

3.3.3. Bulk Density (Bd)

Bulk density (Bd) was determined on undisturbed soil samples in volumetric rings (0.025 m height by 0.06 m diameter) collected using an Uhland sampler [111] seven months after soil tillage. Four samples (replicates) were taken at a spacing of 0.20 m from one to another in the center of each layer (0–0.20, 0.20–0.40, and 0.40–0.60 m), taking the center of the planting furrow as a reference in the three replications of each treatment in each soil, for a total of 540 samples. In the laboratory, the samples were dried in a laboratory oven at 105–110 °C for 48 h to obtain soil dry mass (SDM), and Bd ($g.cm^{-3}$) was calculated as the ratio between SDM and its volume.

The critical bulk density (Bdc) values based on soil texture were plotted together with the Bd values for comparison of the results. Critical bulk density refers to the variation in Bd values when the least limiting water range (LLWR) is zero (Bdc LLWR). The Bdc LLWR values were different for each soil texture class based on previous studies and compiled in Reichert et al. [89] in a pedotransfer function (Bdc LLWR = 0.00078 clay + 1.83803).

3.4.Statistical Analyses

The ρ values were exported from the Res2DINVDemo 4.9.17 (Geotomo Software, Penang, Malaysia) (Geotomo, 2017) after being inverted and filtered for the SURFER 13.6.618 software (Golden Software, Golden, USA), just as the PR data for linear interpolation by triangulation, in order to obtain 2D maps for each treatment in each soil.

The Bd and VESS data were tested regarding normality, independence, and homogeneity of variance. Upon meeting these presuppositions, analysis of variance (ANOVA) tests were carried out, and means were compared (Tukey's test, $p < 0.05$) for each soil class. For ANOVA, a completely randomized design (CRD) was adopted, with four replications for Bd and five replications for VESS. For Bd, a mixed linear model was used to compare the depths within each soil class.

To evaluate the ability of ERT in detecting changes caused by soil management practices, Pearson linear correlation analysis was performed between ρ, PR, Bd, and the sampling depth. The PR and ρ data were extracted from a subset of data corresponding to the soil layer collected for analysis of Bd to compose the correlation matrix.

4. Conclusions

Our results showed that the soil response to different tillage systems and their effects on soil structure is dependent on soil class. Differently from most of the other papers, we demonstrated, by several aspects, the importance of soil class and soil structure on the effects of different tillage systems. Given their influence, we understand that soil classification and characterization of soil structure are crucial to better understand the dimension of the effects of different tillage systems.

The soil tillage strategies reduced resistance to penetration and electrical resistivity, as observed in the 2D maps. The greatest effect on soil structure, which led to better physical quality, was brought about by the treatments with deep tillage that mixed the soil in the 0–0.60 m layer (DT and DT + Ca), and ensured greater structural alleviation. This is best observed in the Inceptisol and in the Ultisol, in which the contrast between the areas mobilized and not mobilized by soil tillage was greater. In the Oxisol, due to its high structural quality, a natural condition brought about by its unique and stable microgranular structure, the effect of the treatments was not expressive, not overcoming the genetic control of the soil class. Therefore, deep tillage strategies should consider the morphogenetic conditions of the soil class in decision making processes for two reasons: (i) to avoid unnecessary tillage operations and (ii) to indicate operations for increasing soil quality by improving soil functions and ecosystem services.

The VESS did not show sensitivity to define differences among the soil tillage systems, probably due to the short time space between soil tillage and when VESS was carried out. Bulk density was not a good indicator of the structural changes caused by tillage strategies in the Rhodic Hapludult and the Rhodic Hapludox, since these soils tend to reconsolidate more quickly. Bulk density is therefore more sensitive in the Typic Dystrustept, a younger soil under tropical conditions. Soil electrical resistivity was positively correlated with bulk density throughout the dataset considering all the soil classes, and positively correlated with resistance to penetration in the Inceptisol. This study confirmed the potential for identification of structural changes caused by deep tillage in tropical soils on a field scale, and for characterization and monitoring of agricultural management practices. Future studies may concentrate on application of geophysical techniques to assist in the use of precise agriculture practices for efficient management of resources and increase in crop yield, which assists in decision making.

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Appendix A – Supplementary material

Results and Discussion

Visual Evaluation of Soil Structure (VESS)

Regardless of the tillage method and the class of soil, there were no differences in the VESS scores, except for MT, which exhibited scores in the following order for the soil classes: PV > LV > CX, in regard to physical quality (Table S4). In relation to the treatments, there were no differences in PV, whereas for LV and CX, the MT had a lower result for soil quality. In spite of that, scores of 1 and 2 are classified as "good" and do not require intensive management [112]. It should be noted that even though soil turnover did not occur in the MT treatment, there was surface furrowing (0.10 m) and boring of the plant hole, which cause rupture of the structure and mixture of the soil horizons.

Table S4. Visual evaluation of soil structure (VESS) under different soil tillage systems in three soil classes.

Treatments	**CX**	**PV**	**LV**
Minimum-till+Pit – MT	1.74 c B	1.08 a A	1.33 b B
Conventional – CT	1.17 a A	1.09 a A	1.10 a A
Subsoiling – SB	1.00 a A	1.05 a A	1.06 a A
DeepMixing – DM	1.02 a A	1.00 a A	1.07 a A
DeepMixing+Ca – DM+Ca	1.00 a A	1.00 a A	1.00 a A

Mean values followed by the same lowercase letters in the row and uppercase letters in the column do not differ from each other by Tukey's test ($p < 0.05$). CX: Typic Dystrustept, PV: Rhodic Hapludult, and LV: Rhodic Hapludox.

The absence of differences in relation to soil tillage systems CT, SB, DT, and DT+Ca is directly related not only to the implement used, but also to the plowing and disking that were performed beforehand, creating uniformity in the 0-0.25 m layer, the working depth of the plow, and eliminating the stress history [113] in all the soil classes. It is important to emphasize that the soil classes in this study were under fallow conditions for at least 5 years up to the time tillage was performed; they did not exhibit restrictions regarding fertility and had little mechanical disturbance, which allowed establishment of plant cover. At the time analysis was performed, PV was the soil with the greatest density and vigor of spontaneous vegetation, with predominance of *Brachiaria decumbens*, just as in CX, though with much lower vigor and density. In LV, *Panicum maximum* predominated. It should be highlighted that the presence of grass roots favors the formation and maintenance of macropores, with heterogenization of the porous space that is related to the growth of fine roots [114], which can explain the differences in the MT score (Table S4).

The three soil classes evaluated in the study [101] have differences in the degree of pedogenesis, which is reflected in their intrinsic attributes, such as soil depth, structure, and bulk density. These natural properties should be considered when carrying out VESS. The attributes intrinsic to the very clayey Oxisols (Latossolos) of tropical regions may become a confounding factor for the VESS. Its greater gibbsite content promotes good aggregation and high macroporosity associated to its very stable microgranular structure [51]. Ultisols (Argissolos) and Inceptisols (Cambissolos), with angular and subangular block structure in this study, respectively, tend to break down into larger particles and with greater difficulty. These are characteristics that can directly affect evaluation in VESS, without necessarily compromising the soil functions and ecosystem services of these soil classes.

Materials and Methods

Visual Evaluation of Soil Structure (VESS)

The soil structure was visually evaluated according to the Visual Evaluation of Soil Structure (VESS) method developed by Ball et al. [112] and adapted by Guimarães et al. [115]. Soil blocks of 0.25 m depth, 0.10 m thickness, and 0.20 m width were collected from the center of the plant row of each experimental plot (n = 75), four months after soil tillage. The structure was evaluated, attributing scores from 1 (good soil structural quality) to 5 (poor structural quality) according to the criteria available in Guimarães et al. [115].

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PAPER 2 – INTERACTIONS BETWEEN INTRINSIC SOIL PROPERTIES AND DEEP TILLAGE IN THE SUSTAINABLE MANAGEMENT OF PERENNIAL CROPS

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Abstract: Choosing the adequate management system is essential for sustainable agricultural practices. Yet, soil-specific properties at the subsurface are seldom considered when choosing the adequate tillage system. This study assessed the effect of tillage depth on physical-hydraulic properties in three contrasting soil classes in the establishment of perennial crops. Tillage practices were evaluated in soils with natural dense layers (Inceptisols and Ultisols), and soils with very small and stable granular structure (Oxisols). From least to most aggressive, tested tillage systems included: surface furrowing + plant holes (MT); plowing followed by two diskings + furrowing (CT); plowing followed by two diskings + subsoiling (SB); and plowing followed by two diskings + rotary hoeing (DM). DM caused the greatest modification in soil structure, especially at the surface. Physical indicators with greatest explanatory power were aeration capacity (AC), relative field capacity (RFC), macroporosity (Pmac), bulk density (Bd), and the S index (Sgi). Soil classes responded differently to soil tillage systems. DM was most effective in soils with densified layers (Inceptisol and Ultisol). Effects were less expressive in the studied Oxisol. The choice of optimal tillage strategies should consider soil-specific properties, especially in greater depths, to guarantee more productive and sustainable crop systems.

Keywords: tillage systems; soil tillage; soil conservation, conservationist management; subsoiling; *Annona sp*.

1. Introduction

Plants use soil as a growth medium, as it provides them water, oxygen, and nutrients. The soil structure and its correlated physical-hydraulic properties are responsible for many ecosystem services, since they are related to heat flow, water retention, soil organisms, availability of nutrients and carbon stocks [1-4]. Understanding the dynamics of these properties is essential to guarantee sustainable agricultural activities without reducing productivity [5]. Ideally, agricultural soils should constitute an environment favorable to adequate plant growth, biological activity, and the supply of water and oxygen [6].

The depth to which water can easily percolate and roots can effectively grow is defined as effective soil depth. Reduced depths negatively affect plant growth by restraining drainage and physically hindering root growth [7]. It can have natural causes, such as the nature of the soil class itself, or have anthropic origin, being induced by soil compaction [8-9]. Shallow effective depths make soils more prone to erosion and reduce productivity, thereby reducing biomass production and carbon preservation in soils. For that reason, adequate site-specific management practices are important for the sustainability of crop systems [10].

Soil tillage should always aim to improve the root growth environment [11]. Traditionally, the physical changes resulting from soil tillage occur at depth 0-0.2 m. However, some soils have an underlying natural dense layer, unaffected by superficial tillage. Other soil classes might experience subsurface compaction under intensive cropping. That is, tillage affects soil classes differently. Depending on soil properties, certain tillage methods may not improve root growth significantly, or may even reduce the effective depth of soils, which is not ideal. The subsurface soil layers have recognized potential for storing and providing water and nutrients to crops [12-14]. Therefore, soil management practices must account for soil-specific properties, focusing on maximizing the volume of the soil explored by plant roots in order to increase crops' resilience to erosion and climatic variations [15-17]. This is especially true for perennial crop systems, as soils are only tilled once.

Deeper tillage may provide an effective solution for mitigating physical-hydraulic restrictions of soils with dense underlying layers [18]. Deeper soil tillage prior to sowing in association with other management practices have made it possible for the root system of the plants to explore a greater volume of soil [14,19,20]. Deeper root systems give plants access to more nutrients and water, thus minimizing the effect of regional water deficit, dry-spells and other unexpected climatic events, which should become more frequent with climate change.

Deep tillage has shown to be effective in improving the physical-hydraulic properties and/or crop yield, as reported in studies about different soil classes in Australia [18], in India [9], USA [21], and Brazil [8,22]. In addition, confirmation of increase in sugarcane yield and root growth, greater soil aeration and moisture content [23,24], and reduction in resistance to penetration [25] have also been reported.

Conversely, an absence of positive results for sugarcane yield in Oxisols in Brazil has also been observed [26]. This indicates that different soil classes can respond differently to tillage practices, due to differences in properties such as structure, pore size distribution, effective depth, and densification. These differences play an important role in greater depths, where there is less influence of organic matter, and mineralogy and texture will have more influence over soil's structure and its resulting physical-hydraulic properties. Naturally, soil classes greatly affect root development in depth.

The problem is that few studies evaluate these soil properties at the subsurface and relate them to plant growth or to management systems. Generally, the effects of management practices are only assessed in the 0-0.30 m layer, and the influence of physical-hydraulic properties of deeper horizons on crop growth and production are seldom considered [27-34]. Even more so for perennial crops.

Increasing the sustainability of agricultural practices is an urgent need, and involves adopting the adequate management practices based on soil- and site-specific properties. Hence, the aim of this study was to assess the effect of tillage systems on the physical quality of different soil classes at greater depths. The central hypothesis of this study was that improvement in the physical-hydraulic environment of soils depends not only on the type of tillage, but also on intrinsic properties of soil classes, especially in deeper horizons, sometimes neglected in soil management studies.

2. Materials and Methods

2.1.Study area

The study was conducted in the experimental area of the Fruit Farming sector of the Federal University of Lavras (UFLA), in the southeast of Brazil. The climate of the region is classified as Cwa, according to the Köppen system [35], with hot and humid summers and cool and dry winters. The mean annual temperature is 21.6°C and mean annual rainfall is 1339.5 mm, concentrated between November and March, according to data obtained in the period from January 1 of 1998 to January 1 of 2018 [36]. Unseasonable hot and dry periods can occur during the rainy period, intensifying water deficit.

The study site is in the geomorphological unit of the Atlantic Plateau. Granite-gneisses are the predominant lithology and native vegetation is represented by semi-perennial rainforest. Three soil classes were selected, mapped in detail and classified by Curi et al. [37]. By the Soil Taxonomy [38], they were classified as Typic Dystrustepts (CX), Rhodic Hapludults (PV) and Rhodic Hapludoxes (LV). According to the Brazilian Soil Classification System [39], as Cambissolo Háplico Tb distrófico típico (CX), Argissolo Vermelho Distrófico típico (PV), and Latossolo Vermelho Eutrófico típico (LV). The topography is strongly rolling in the CX, moderately udulated in the PV, and gently udulated in the LV. These soils are highly representative of Brazil (Latossolos – 31.6%, Argissolos – 26.9%, and Cambissolos – 5.26%) [39], and even worldwide (Inceptisols - 15%, Ultisols - 8%, and Oxisols - 8%) [40].

The structure was granular in the A horizon of all the studied soil classes. CX and PV presented blocky structure in their Bw and Bt horizons, respectively, and LV had granular structure in its Bo horizon [37]. The natural subsurface densification found in the Inceptisols and Ultisols is characteristic of these soil classes in this region [37,40,41]. Another common feature is the granular structure that is very small, rounded, and stable, present in the *solum* of the Oxisols [43]. These contrasting properties tend to affect root development of the crops, especially perennial crops, and the availability of water in the soil.

2.2.Characterization of the soils studied

Before setting up the experiment, undisturbed samples were collected from the horizons of each soil profile for physical-hydraulic characterization (Table 1). Disturbed samples were also collected for chemical characterization at the depths of 0-0.2, 0.2-0.4, and 0.4-0.6 m (Table 2). Analyses followed the standard methods described in Teixeira et al. [44].

The study areas remained fallow for 5 years before setting up the experiment. Weed control was carried out sporadically with the use of herbicide or through mechanized cutting. Each area had 1200 m^2.

Table 1. Physical-hydraulic characterization of the soils before setting up the experiment.

Property / Depth		CX			PV			LV		
		Ap	**Bw**	**BC**	**Ap**	**BA**	**Bt**	**Ap**	**Bo1**	**Bo2**
	m	**0-0.05**	**0.05-0.15**	**0.15-0.60+**	**0-0.12**	**0.12-0.35**	**0.35-0.55+**	**0-0.10**	**0.10-0.60**	**0.60+**
Bd	$g\ cm^{-3}$	1.38	1.41	1.47	1.11	1.42	1.47	1.32	1.06	1.19
Pd		2.55	2.63	2.63	2.53	2.63	2.7	2.64	2.73	2.69
TP	m^3m^{-3}	0.49	0.45	0.48	0.54	0.46	0.46	0.54	0.57	0.53
FC		0.36	0.37	0.41	0.32	0.33	0.38	0.4	0.33	0.38
Mic		0.38	0.39	0.42	0.33	0.34	0.39	0.41	0.34	0.4
Mac		0.11	0.07	0.06	0.21	0.12	0.08	0.13	0.23	0.13
AC		0.25	0.17	0.15	0.41	0.28	0.18	0.26	0.43	0.28
Clay	%	42	36	36	45	47	67	50	66	69
Sand		42	28	28	41	39	24	30	21	20
Silt		16	36	36	14	14	9	20	13	11

CX – Typic Dystrustepts; PV – Rhodic Hapludults; LV – Rhodic Hapludoxes; Bd – soil bulk density; Pd – particle density; TP – total porosity; FC – field capacity estimated at -10 kPa; Mic – microporosity estimated at -6 kPa; Mac – macroporosity; AC – aeration capacity of the soil determined according to Reynolds et al. [45].

Table 2. Chemical characterization of the soils before setting up the experiment.

Property	Depth m	CX 0-0.2	CX 0.2-0.4	CX 0.4-0.6	PV 0-0.2	PV 0.2-0.4	PV 0.4-0.6	LV 0-0.2	LV 0.2-0.4	LV 0.4-0.6
pH	H_2O	6.30	5.70	5.50	6.00	5.70	5.70	6.90	6.50	6.00
	$CaCl_2$	5.70	5.10	4.90	5.40	5.10	5.10	6.30	5.90	5.40
P–Mehlich-1	mg kg^{-1}	14.2	3.38	2.50	2.55	2.27	0.71	11.1	10.8	1.90
P–resin		25.4	5.73	1.18	10.9	5.25	3.41	10.4	4.76	3.45
K^+		94.0	45.4	32.5	133	103.0	71.7	66.5	38.9	23.4
Ca^{2+}	$cmol_c$ kg^{-1}	5.42	3.38	2.50	4.22	3.12	2.41	4.76	2.86	2.14
Mg^{2+}		1.25	0.59	0.44	1.11	0.85	0.57	1.19	0.95	0.60
Al^{3+}		0.00	0.06	0.15	0.00	0.00	0.00	0.00	0.00	0.00
H+Al		3.06	4.12	3.68	2.55	3.41	3.55	1.79	2.14	2.86
CEC		10.1	8.38	6.62	8.21	7.67	3.12	7.85	3.93	2.86
SOM	dagkg^{-1}	2.41	1.55	1.55	3.10	1.90	1.38	1.90	1.90	1.03
BS	%	9.40	50.8	46.0	69.1	55.3	46.6	77.4	64.6	49.5
Al_{sat}		0.00	1.30	3.50	0.00	0.00	0.00	0.00	0.00	0.00

CX – Typic Dystrustepts; PV – Rhodic Hapludults; LV – Rhodic Hapludoxes; CEC – cation exchange capacity at pH 7; SOM – soil organic matter; BS – base saturation; Alsat – aluminum saturation.

2.3.Experimental design and treatment

Four treatments and three replications were tested in a completely randomized design, for a total of 60 experimental plots. Each plot was composed of one plant row containing 6 plants, occupying an area of 40.5 m^2. The treatments corresponded to different manners of soil tillage for establishing the perennial crop, using different equipment: minimum tillage – surface furrowing (0.10 m depth) for marking off the plant row using a ridger + plant hole (0.40 m diameter by 0.70 m depth) with a plant hole auger (MT); conventional tillage – disk plowing (0.25 m), two diskings (0.20 m) + furrowing (0.25 m) using a ridger (CT); subsoiling – disk plowing (0.25 m), two diskings (0.20 m) + subsoiler with a wedge tip of two shanks spaced at 0.50 m (0.45 m) (SB); deep mixing tillage – disk plowing (0.25 m), two diskings (0.20 m) + soil deep tillage device (0.50 m width by 0.60 m depth) (DM). The deep tillage device is a type of modified rotary hoe with width of action of 0.50 m, composed of a vertical cutting tine blade wheel that mixes the surface and subsurface horizons, BigMix® AS-2 model, manufactured by Mafes Agromecânica [46]. The experimental area was tilled in the spring, on November 29, 2018, 3 days after the last rainfall of 20 mm.

Atemoya (*Annona cherimola* × *Annona squamosa*) was planted on December 14, 2018, at a spacing of 4.50 × 1.50 m, with 6 plants per plot. The soil was amended with limestone, calculated for the depth of 0 to 0.40 m with the purpose of raising the saturation of Ca^{2+} and Mg^{2+} to 70% and 15%, respectively, except for MT, where liming was performed in the plant hole. In addition, *Brachiaria ruziziensis* (*Urochloa ruziziensis*) grass was sown between the rows, which was maintained through periodic cutting. Recommendation for liming and fertilization was done according to crop demands [47].

2.4. Water retention curve (WRC)

To evaluate the effect of the treatments on the physical-hydraulic properties of the soils, undisturbed samples (6.5 cm diameter by 2.5 cm height) were collected at the center of the depths of 0-0.2, 0.2-0.4, and 0.4-0.6 m using an Uhland sampler. Sampling was done seven months after the soil preparation practices. After preparation of the samples and slow saturation with distilled water, they were placed under sequential suction at matric potentials (h) of -2, -4, and -6 kPa using perforated plate funnels (Büchner funnels) and of -33, -100, -500, and -1500 kPa using a Richards´ pressure chamber [48]. After reaching equilibrium, the samples were weighed and dried in a laboratory oven at 105-110 °C for 24 hours to obtain the soil dry matter and to calculate the moisture content (θ) at each potential.

Water retention curves (WRC) were fitted using the model proposed by van Genuchten (Eq. 1) with the Mualem restriction [49,50], with assistance of the software RETC version 6.02 [59], where “n” and “m” are parameters related to the slope of the curve and “α” is an empirical parameter related to the shape of the WRC.

$$\theta = (\theta s - \theta r)[1 + (\alpha h)n]^{-m} + \theta r \quad (1)$$

where:
θ: volumetric water content according to matric potential ($m^3\ m^{-3}$);
θs: volumetric water content in saturation ($m^3\ m^{-3}$);
θr: residual volumetric water content ($m^3\ m^{-3}$);
h: matric potential in module (cm);
α and n: model fitting parameters; and
m: fitting parameter obtained by the Mualem restriction [m=1-(1/n)].

2.5.Soil physical quality indicator

Due to the extensive set of data and of indicators taken from the WRC, a selection of the soil physical quality indicators was made through principal component analysis (PCA) using all the indicators obtained by the WRC. For each tested soil class and tillage system, the indicators obtained were the following: PWP – water content at the permanent wilting point estimated at -1500 kPa; FC – water content at field capacity estimated at -10 kPa; PAW – plant available water capacity calculated by the difference between FC and PWP; AC – aeration capacity; RFC – relative field capacity; Pmac – macroporosity (pores with diameter > 50 µm); Pmic – microporosity (pores with diameter < 50 µm); TP – total porosity; Bd – soil bulk density; d.median – median pore diameter; d.mode – mode pore diameter; d.mean – mean pore diameter; Sd – standard deviation of pore distribution; skewness – skewness of pore distribution; kurtosis – kurtosis of pore distribution; Sgi – S index of Dexter (2004); and EI_paw – integral energy of the PAW [52].

With the assistance of the R software, the function "PCA" contained in the "FactoMineR" package was used for the principal component analysis (PCA). The results of the PCA indicators were extracted using the function "get_pca_var(res.pca)" included in the "factoextra" package. The matrix of the squared cosine (cos^2) was assessed, representing the quality of the indicator. A high cos2 means good representation of the indicator by the principal component (PC) on the PCA axis. Based on Andrews et al. [53] and Dunteman [54], indicators that had values of $cos^2 > 0.80$ were selected; namely, AC, RFC, Pmac, Bd, and Sgi (Table 1). These indicators are further explained in the following sections.

Table 3. Values of "cos²" extracted from the PCA containing physical-hydraulic indicators of the three soil classes (CX, PV, and LV) under four management systems (MT, CT, SB, and DM) at three depths (0-0.2, 0.2-0.4, and 0.4-0.6 m).

Indicator	Principal Components				
	Dim.1	**Dim.2**	**Dim.3**	**Dim.4**	**Dim.5**
Plant height	0.029	0.001	0.633	0.029	0.078
Root collar diameter	0.008	0.060	0.637	0.011	0.043
PWP	0.697	0.016	0.002	0.276	0.000
FC	0.650	0.110	0.010	0.160	0.048
PAW	0.196	0.351	0.006	0.164	0.174
AC	**0.952**	0.002	0.010	0.003	0.026
RFC	**0.970**	0.003	0.006	0.001	0.007
Pmac	**0.952**	0.000	0.010	0.005	0.024
Pmic	0.548	0.195	0.013	0.152	0.065
TP	0.603	0.080	0.040	0.117	0.133
Bd	**0.812**	0.005	0.001	0.006	0.037
d.median	0.555	0.311	0.006	0.092	0.016
d.mode	0.316	0.548	0.018	0.074	0.002
d.mean	0.655	0.200	0.003	0.097	0.026
Sd	0.302	0.354	0.072	0.006	0.168
Skewness	0.360	0.424	0.029	0.024	0.132
Kurtosis	0.133	0.155	0.048	0.046	0.001
S_{gi}	**0.892**	0.064	0.002	0.000	0.023
Eipaw	0.396	0.426	0.013	0.012	0.104

Dim = dimension; PWP = water content at the permanent wilting point; PAW = plant available water capacity; AC = aeration capacity; RFC = relative field capacity; Pmac = macroporosity; Pmic = microporosity; TP = total porosity; Bd = soil bulk density; d.median = median pore diameter; d.mode = mode pore diameter; d.mean = mean pore diameter; Sd = standard deviation of pore distribution; skewness = skewness of pore distribution; kurtosis = kurtosis of pore distribution; Sgi = S index; and EI_paw = integral energy of the PAW.

2.5.1. Aeration Capacity (AC)

AC is defined as the water content obtained by the difference between the water content at saturation [θ_S (ψ = 0 m)] and the water content at field capacity [θ_{FC} (ψ = 1 m)] [45]. AC indicates the volume of pores responsible for rapid drainage of water and aeration of the soil; values lower than 0.10 m^3m^{-3} indicate a deficit in soil aeration, which can decrease plant yield [55].

2.5.2. Relative Field Capacity (RFC)

RFC is a non-dimensional indicator obtained by the ratio between water content in field capacity and at saturation (θFC/θS). It represents soils' air and water storage capacity in relation to the total porosity, here represented by θS [45].

The ideal balance between AC and the water capacity of soils occurs between 0.6 ≤ RFC ≤ 0.7. In this range, microbial production of nitrate is maximized [56]. RFC values < 0.6 indicate limited water availability in soils, while RFC values > 0.7 indicate limitation of aeration. Both situations hinder the production of microbial nitrate and plant development [57,58].

2.5.3. Macroporosity (Pmac)

Pmac (m^3m^{-3}) is the volume of pores greater than 50 µm. It can also be defined as the difference between θ_S and $\theta_{0.6}$ ($\psi = 0.6$ m) [59-62]. Values of Pmac between 0.05 and 0.1 m^3m^{-3} are considered optimal, whereas values lower than 0.04 m^3m^{-3} indicate soils degraded by compaction or densification [63,64].

2.5.4. Microporosity (Pmic)

Pmac (m^3m^{-3}) is the volume of pores less than 50 µm. It can also be defined as the $\theta_{0.6}$ ($\psi = 0.6$ m) [59-62].

2.5.5. Total Porosity (TP)

TP (m^3m^{-3}) is the volume of pores less than 50 µm. It can also be defined as the $\theta_{0.6}$ ($\psi = 0.6$ m) [59-62].

2.5.6. Soil Bulk density (Bd)

Bd (g cm^{-3}) is defined as the quotient between the soil dry matter and the cylinder volume. Critical values of Bd are based on the texture of the soil class. The critical Bd (Bdc) refers to the variation in Bd values when the least limiting water range (LLWR) is zero. Such values were compiled by Reichert et al. [65] in a pedotransfer function (Bdc LLWR = 0.00078 clay + 1.83803) for Brazilian conditions, which was used as a comparative reference.

2.5.7. S Index (Sgi)

S_{gi} (non-dimensional) was determined according to Dexter [66] and represents the slope of WRC (g g^{-1}) at the inflection point. Limiting values were established based on the study of Andrade and Stone [67] involving a wide variety of Brazilian soil classes and proposing the value of 0.045 as the limit between soils of good structural quality and those with a tendency to degradation, and values ≤ 0.025 for physically degraded soils.

2.5.8. Pore distribution per volume

Soil pore distribution per volume was determined according to [45]. The function of normalized pore distribution was obtained by the ratio between the slope of the WRC and the slope at the inflection point of the WRC (Eq. 2).

$$S^*(h) = \frac{S_v\,(h)}{S_{vi}} = \frac{m(\alpha h)^n[1 + m^{-1}]^{m+1}}{[1 + (\alpha h)^n]^{(m+1)}}; 0 \leq S^*(h) \leq 1 \qquad (2)$$

where:
S*(h): normalized pore distribution;
S_v (h): slope of the soil water retention curve;
S_{vi}: slope of the inflection point of the soil water retention curve;
h: matric potential; and
α, n, and m: fitting parameters obtained in modeling of the WRC, by Eq. 1.

The models of S*(h) were compared by the “localization” parameters: median diameter (d.median), mode diameter (d.mode), and mean diameter (d.mean); and the “shape” parameters: standard deviation (Sd), skewness, and kurtosis. Parameter calculated following [45].

2.6.Statistical Analysis

Since the treatments include different soil tillage depths, the statistical analysis was performed according to sampled soil depth. An analysis of variance (ANOVA) was performed in a completely randomized design, using a factorial arrangement with two factors (soil classes and soil tillage methods).

To compare the soil tillage methods and their effects on different soil classes, the normality, independence, and homogeneity of variance were tested for all studied variables, including: soil physical quality indicators (AC, RFC, Pmac, Bd, and Sgi), and location and shape parameters of the pore distribution (d.median, d.mode, d.mean, Sd, skewness, and kurtosis). Upon verifying these assumptions, ANOVA and means comparison tests (Tukey’s test, $p > 0.05$) were carried out for each soil depth.

In search of possible correlations between the management systems and the initial development of the atemoya plants, the root collar diameter (base of the stem) and plant height prior to pruning were measured eight months after planting, and these measurements were compared to the soil quality indicators.

Pearson’s linear correlation analysis was carried out between plant height and root collar diameter and the soil physical quality indicators per sampling depth. Principal component analyses (PCA) were performed for each depth to evaluate distinctions and similarities between soil classes and soil tillage systems. All statistical analyses were done using R software [68].

3. Results

3.1.Parameters of the normalized pore volume distribution function

The normalized functions of the pore volume distribution (S*(h)) for each soil management system in each soil class and depth are shown in Figure 1. No significant differences were found at depth 0.0-0.2 m between CX and LV. For PV, the S*(h) curve for DM tillage was displaced to the right. This indicated an increase in the frequency of greater diameter pores compared to the other tillage treatments. This displacement reached a value of 667 µm, which is 3.1 times higher than CT and 1.9 times higher than MT and SB (Figure 1, B).

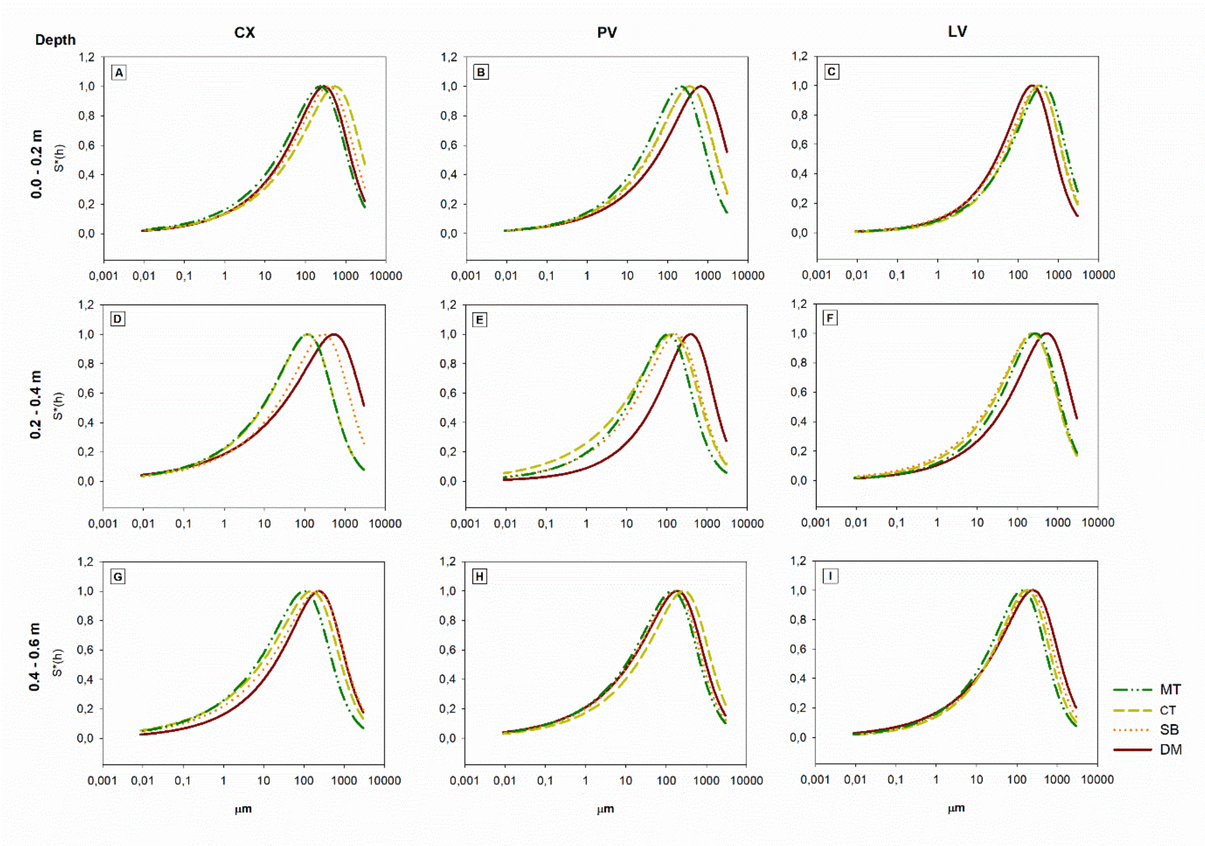

Figure 1. Normalized function of the pore volume distribution for different management systems in three soil classes: Typic Dystrustepts (CX), Rhodic Hapludults (PV) and Rhodic Hapludoxes (LV). *MT – minimum tillage; CT – conventional tillage; SB – subsoiling; DM – deep mixing tillage.

The difference between the types of tillage was most evident at the 0.2-0.4 m depth, where the displacement of S*(h) curves to the right is observed for DM tillage in all soil classes (Figure 1, D, E, and F). For CX, DM (542.3 µm) led to an increase of 4.5 times in relation to MT and CT, and of 1.8 times compared to SB. For soil classes PV and LV, there was greater homogeneity of differences. Most frequent pore diameters for DM were 2.9 times greater in relation to MT, CT and SB in the PV For LV, they were 2.1 times greater in relation to MT, CT and SB.

Between depths 0.4-0.6 m, small differences were seen among soil tillage treatments. A gradual increase in the displacement of curves to the right was observed with the increase of depth and aggressiveness of tillage for CX and LV. DM stood out compared to the other tillage treatments (Figure 1, G and I). This increase occurred in the following order: MT, CT, SB, and DM (101, 153, 216, and 231 µm in CX; and 139, 176, 211, and 254 µm in LV).

Comparing soil classes, the DM tillage altered the deepest layers of CX and LV, increasing the diameter of the most frequent pores at depths 0.2-0.4 and 0.4-0.6 m. However, for PV, DM obtained greater values of most frequent pore diameter at the 0.0-0.2 and 0.2-0.4 m depths, with values of 667.1 and 392.6 µm, respectively, but did not show significant differences at depth 0.4-0.6 m. Perhaps the DM had not reached this depth.

The localization parameters (d.median, d.mode, and d.mean - µm) and shape parameters (Sd, skewness, and kurtosis) for the normalized pore distribution are shown in Figure 2. DM was the tillage system that caused the greatest modification in soil structure, exhibiting highest frequency of pores (d.mode) with diameter greater than 300 µm, especially in the 0.2-0.4 m layer, regardless of soil class (Figure 2, D, E, and F). In addition, DM exhibited greater d.median and d.mean in relation to the other treatments. These results indicated that the DM tillage has greater capacity for altering the structure of soils at depth, rupturing even the densified layers naturally found in the CX and PV up to 0.4 m.

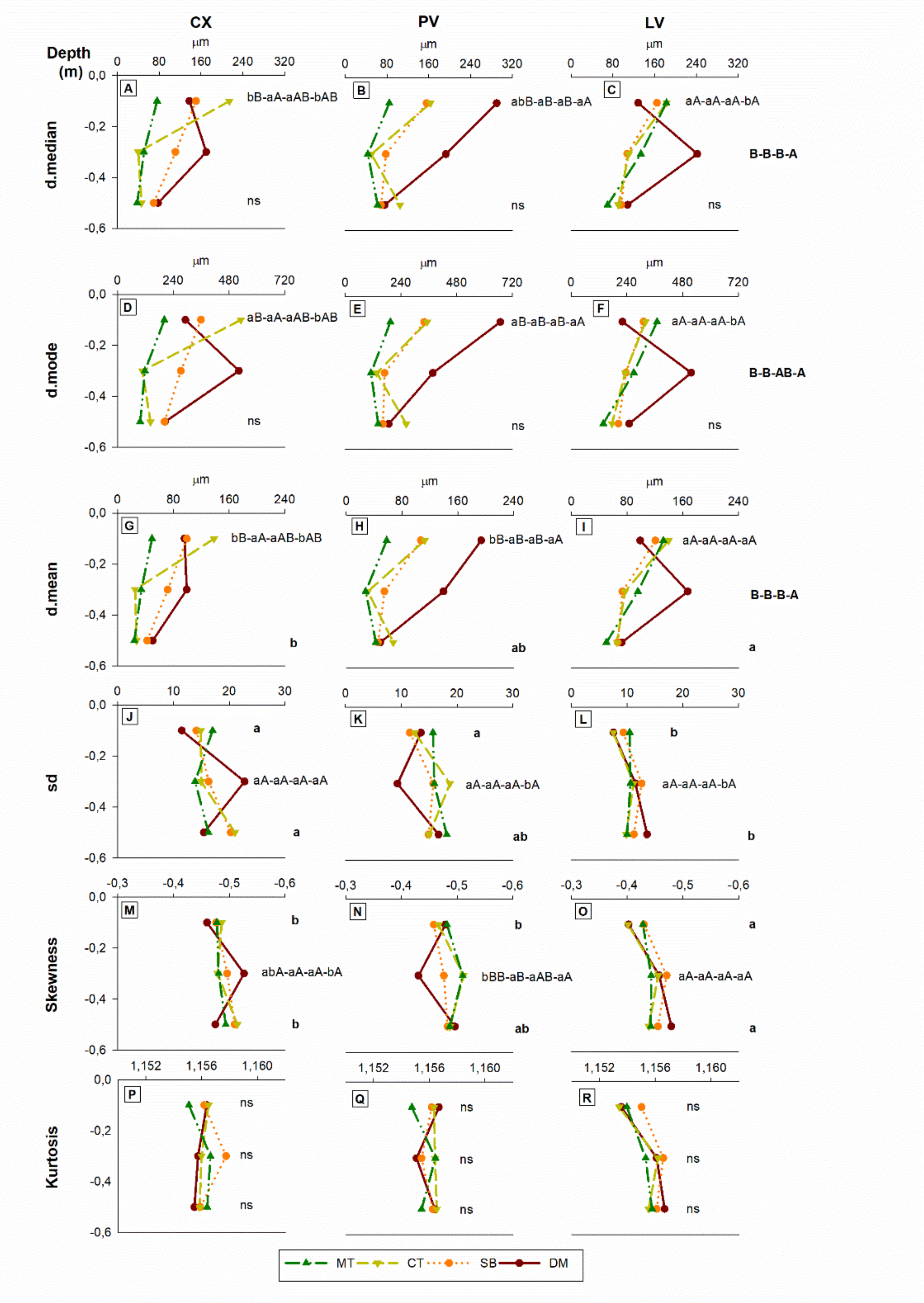

Figure 2. Localization parameters (d.median, d.mode, and d.mean - µm) and shape parameters (Sd, skewness, and kurtosis) for the normalized pore volume distribution functions for different management systems and three soil classes: Typic Dystrustepts (**CX**), Rhodic Hapludults (**PV**) and Rhodic Hapludoxes (**LV**). **MT** – minimum tillage; **CT** – conventional tillage; **SB** – subsoiling; **DM** – deep mixing tillage. *Lowercase letters compare soil classes; uppercase

letters compare management systems, both within each soil depth. Uppercase and lowercase letters in sequence represent interaction between the soil class and management system factors. Letters outside the plots represent the significance of each factor separately.

In general, deep tillage methods obtained higher mean pore diameter values than conventional tillage (CT), including in LV, which had higher total porosity compared to CX and PV (Figure 2; Table 1).

Results for the Sd shape parameter indicated that the treatments had no effect on soil classes – uppercase letters (Figure 2 J, K, and L), in spite of the significant effect of the test. Furthermore, comparing the effect of the treatment in each soil class, only DM presented significant differences, which were greater in CX than in PV and LV. Kurtosis did not show statistically significant differences. For all the soil tillage treatments in all the soil classes and depths, a leptokurtic distribution was obtained; i.e., curves sharper in the center and with longer tails compared to the normal log distribution [45].

3.2.Physical indicators

The analyses of variance performed on the physical indicators of soil quality did not show significant interaction ($p < 0.05$) between the soil class and management system factors. Therefore, the statistical analysis exclusively involved the mean values of these factors. That is, the mean values of results per management system were calculated and compared. Management system means are presented in the lower part of plots in Figure 3 (only when significant). The same was done for soil classes: the means of results per soil class were calculated and compared. Means per soil class are represented by gray bars in Figure 3.

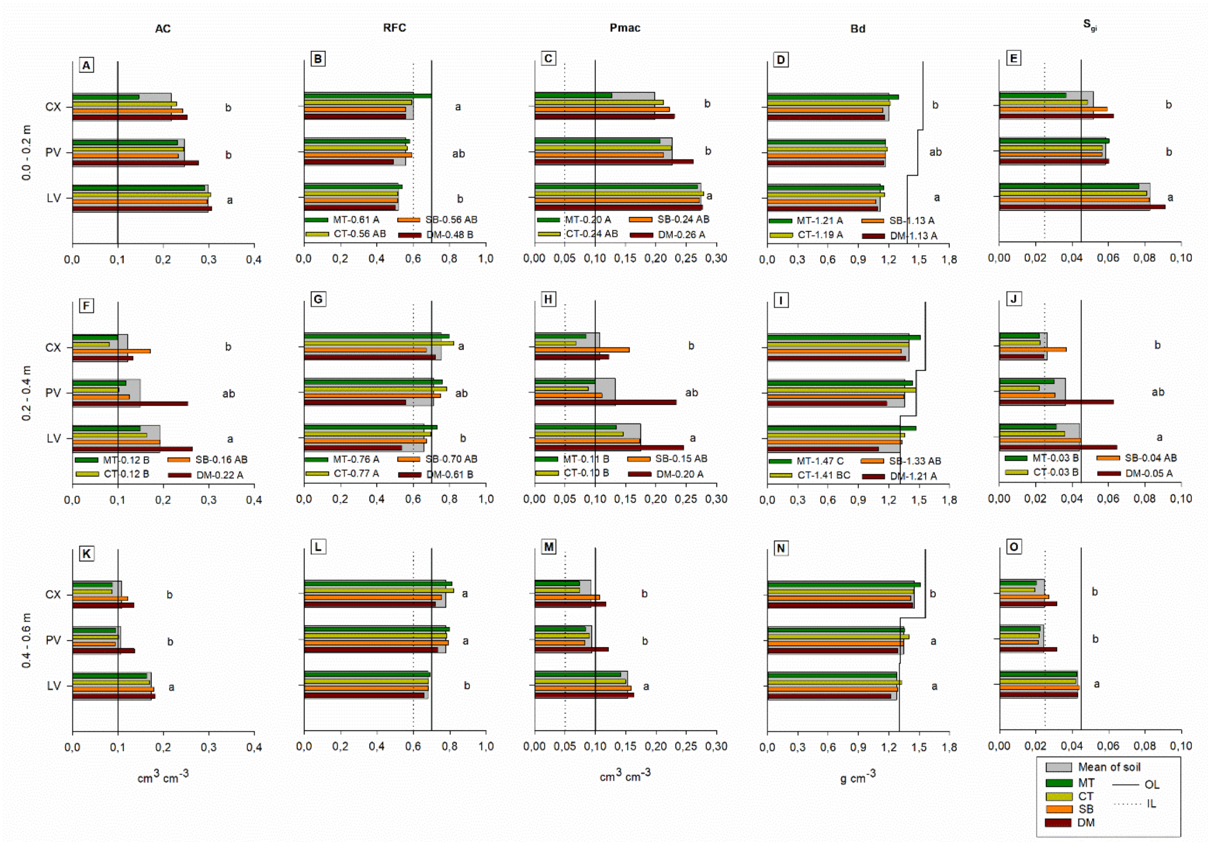

Figure 3. The effect of tillage systems in physical indicators of soil quality at different depths in three soil classes: Typic Dystrustepts (**CX**), Rhodic Hapludults (**PV**) and Rhodic Hapludoxes (**LV**). **MT** – minimum tillage; **CT** – conventional tillage; **SB** – subsoiling; **DM** – deep mixing tillage; **AC** –aeration capacity; **RFC** – relative field capacity; **Pmac** – macroporosity; **Bd** – soil bulk density; **S$_{gi}$** – S index. **OL** and **IL** – optimal and inferior limits defined by the literature, respectively. *Lowercase letters in the vertical direction compare result means per soil class, represented by the gray horizontal bar; uppercase letters compare result means per management system, presented below each plot, when significant.

DM presented the best results. It improved properties related to soil structure in all soil depths of classes. DM increased values of AC, Pmac, and Sgi, and reduced Bd values. LV was the soil class that presented the best results, regardless of the management system (Figure 2).

The DM treatment in LV had the worst RFC results (Figure 2 B, G and L). This indicated excess of large pores, which was corroborated by AC (Figure 2 A, F and K). An excess of larger diameter pores substantially increases drainage, reducing water storage capacity. It also reduces soil-root contact, which may hinder uptake of water and nutrients by crops. LV has naturally high porosity due to its very small and stable granular structure. These properties, intrinsic to this soil class, were enhanced by the DM tillage system. In contrast, at depths 0.2-0.4 and 0.4-0.6 m, both CX and PV had RFC above 0.7 in all the treatments, indicating possible limitations regarding deficient aeration.

AC and Pmac, the main indicators of aeration, behaved differently depending on soil classes and tillage systems (Figure 4), especially at depth 0.2-0.4 m. Their values were higher for deep tillage methods (SB and DM at 0.2-0.4 m) and for LV at all depths. At depth 0-0.2 m, no tillage method had results lower than the minimum limit of AC and Pmac.

According to the classification of Pagliai [69], a soil is considered dense or compacted when the total macroporosity (pores larger than 50 μm) is < 10%, moderately porous when the total macroporosity ranges from 10% to 25%, porous when it ranges from 25% to 40%, and extremely porous when above 40%. Thus, it should be emphasized that no soil class was considered dense, independently of tillage system. Even in tillage systems that did not reach deeper soil layers, the lowest value of Pmac was 14.6% in CX at depth 0.2-0.4 m using the CT tillage system, similar to MT.

Comparing MT and DM, for example, at all depths of CX a mean increase of 51% was observed in Pmac. At 0-0.2 and 0.4-0.6 m in PV there was a mean increase of 31%; at 0.2-0.4 m, an increase of 100%. For LV, at depths 0-0.2 and 0.4-0.6 m, increases of 6% and 15% were observed, respectively; while at 0.2-0.4 m, there was an increase of 79% in Pmac.

The tillage systems did not change Bd at depths 0-0.2 and 0.4-0.6 m, and no tillage system reached Bdc at 0-0.2 m (Figure 3 D). Bd varied according to soil class; its lowest values were observed in LV. In contrast, tillage systems affected Bd at 0.2-0.4 m (Figure 3 I). The lowest values of Bd were observed for the DM system (1.21g cm^{-3}), and highest values, for MT (1.47 g cm^{-3}). It is noteworthy that the MT, CT, and SB systems exceeded Bdc in LV, presenting values greater than 1.32 g cm^{-3}. This corroborates other indicators that evaluate aeration and soil structure (AC and Pmac). No tillage system exceeded the Bdc value for CX. Conversely, Bdc was exceeded for all systems in PV (values > 1.31 g cm^{-3}) at depth 0.4-0.6 m, except for DM.

The mean values of S_{gi} per soil class were higher than the limit of 0.045 at 0-0.2 m for all soil classes (Figure 3 E, J and O). S_{gi} was significantly higher for LV, showing that the tillage systems at this depth provided an excellent physical environment for the plants. However, the deeper layers show a big reduction in S_{gi} values and a discrepancy in results of the DM treatment at 0.2-0.4 m and 0.4-0.6 m for CX and PV. No tillage system affected the soil structure of LV at 0.4-0.6 m. In the deeper layers of studied soil classes, only deep tillage systems (DM and SB) led to improvements in soil structure, as indicated by S_{gi} values (Figure 3 E, J and O).

3.3. Correlations and principal component analysis (PCA)

Pearson's correlation coefficients are presented in Figure 4; only significant correlations are shown ($p < 0.05$). Positive correlations were observed between plant height and root collar diameter (r = 0.55 for CX and LV; 0.74 for PV). Only in PV there was significant correlation between plants measurements and soil physical quality indicators. PAW had positive correlation with plant height (r = 0.34) and root collar diameter (r = 0.46) (Figure 4), indicating the importance of soil water availability for plant growth in the initial phase.

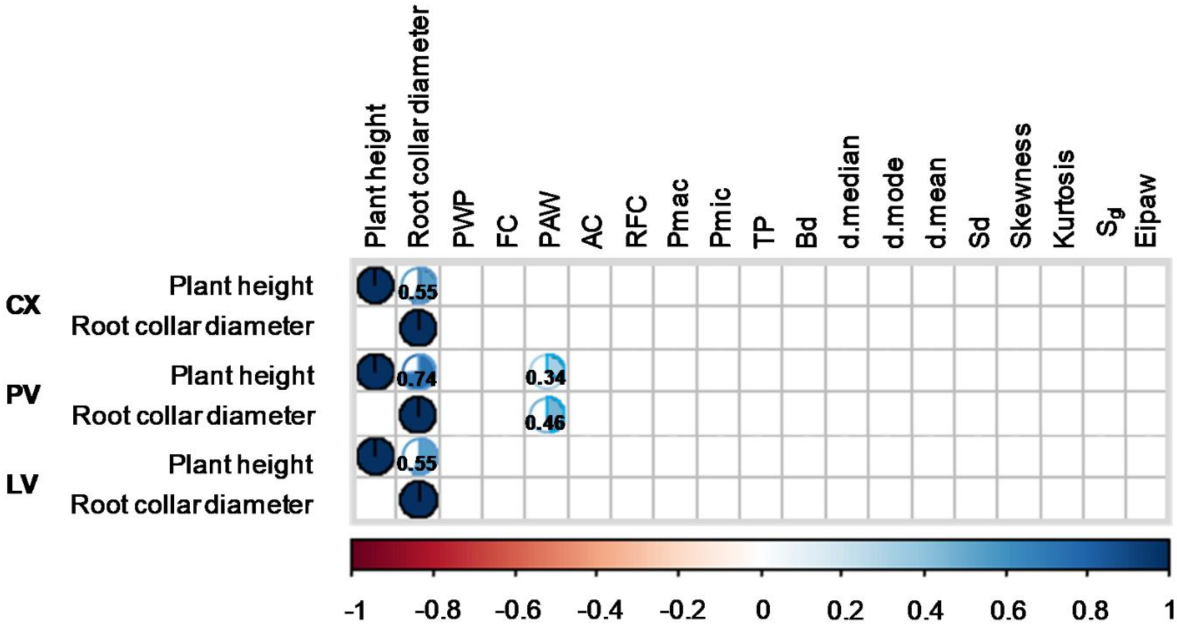

Figure 4. Pearson's correlation coefficients between plant measurements and soil quality indicators. Only correlations significant at $p < 0.05$ are shown.

Tillage systems did not present differing tendencies at depth 0-0.2 m. Comparing soil classes, LV showed different behavior. It was affected mainly by TP, S_{gi}, and skewness (Figure 5 B and C). At 0.2-0.4 m of depth, DM showed clear differences compared to other treatments, except for SB. Dm was positively correlated with the d.mode, d.mean, d.median, Pmac, AC, and S_{gi}. Other treatments showed positive correlation mainly with Pmic, Bd, and RFC (Figure 5 E and F). At depth 0.4-0.6 m, the tillage systems did not differ from each other. LV, however, again presented distinct trend, correlated with TP, S_{gi}, skewness, PAW, Pmac, and AC.

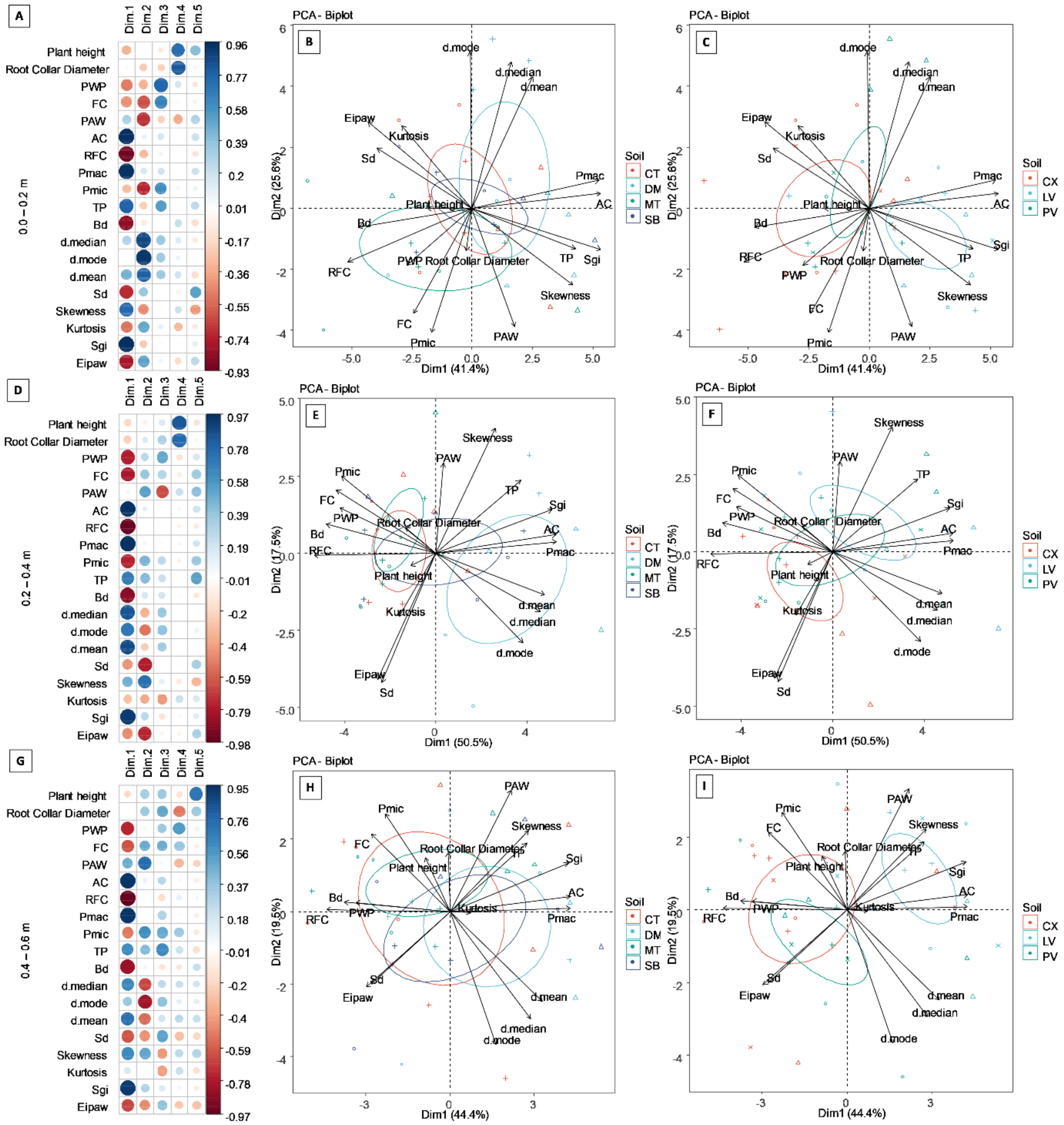

Figure 5. Principal Component Analysis (PCA) of soil physical quality indicators for three soil classes: Typic Dystrustepts (**CX**), Rhodic Hapludults (**PV**) and Rhodic Hapludoxes (**LV**). PCA used soil properties and results of the treatments. A, D, and G (plots on the left): variables and their contributions for each dimension. The ellipses delimit the mean values of the groups: treatments in B, E, and H; and soil classes in C, F, and I, with a confidence interval of 95%.

In general, the LV stood out at all the depths compared to other soil classes, and was affected mostly by Pmac, AC, S_{gi}, and skewness. CX and PV were grouped and showed better correlation with Eipaw, Sd, and RFC (Figure 5).

4. Discussion

4.1.The effect of tillage practices on pore size distribution

Deep tillage promotes the reorganization of the soil structure [20,70,71], which changes porosity and water retention capacity of soils [70,72]. The effect of tillage systems on the pore distribution curves (S*(h)) at depth 0-0.2 m showed similarities between the soil classes (Figure 1 A, B, and C). This was expected, since most tillage systems mobilized this layer, except MT (ridger to mark off the plant row, reaching 0.1 m). An important aspect is that the surface was permanently covered with *Brachiaria Ruziziensis*, hence there was direct influence of plant roots. The beneficial effects of this grass between the rows of perennial crops, such as coffee, have been reported by many studies [8,22,73], especially on bulk density and soil porosity.

The displacement of the S*(h) curves to the right observed in the DM tillage system (Figure 1), especially at 0.2-0.4 m, indicated an increase in the frequency of pores with greater diameter. This suggests a structural improvement caused by rupturing restrictive layers in CX and PV (Table 1). The DM soil tillage system is very aggressive and is able to turn over/mix the entire 0-0.6 m layer. The main effect of deep tillage is observed in the macropores (> 50 µm) [74], also known as structural pores [75]. This was observed herein by the mentioned displacement of the curves to the right. This is beneficial, both agronomically and environmentally [55], as it improves soil drainage and aeration, positively affecting root growth while making soils more resilient to erosional processes [8,22,72,76].

At 0.4-0.6 m, the displacement of the curve in CX by the DM system is directly linked to the depth of tillage. DM, which presented most frequent pore diameter of 231 µm, reached 0.6 m depth; whereas SB only reached 0.45 m, resulting in a value of 216 µm. It appears that the performance of SB and DM did not cause sufficient change of pore diameter in PV. This soil class presented natural densification at 0.12 m (Table 1), which increased with depth. This must have hampered the performance of management systems at 0.4-0.6 m. The natural densification found in the subsurface in Ultisols is a prominent property of this soil class [42,77,78]. The consequences are the increase in Bd and the mechanical resistance of soils.

Values of Sd lower or equal to 1 mean that the pores have similar size, whereas values greater than 1 indicate variation in the size of the pores [45]. In CX, higher Sd values for the DM system at 0.2-0.4 m indicated an increase in the variation of pore diameter, improving their distribution and increasing pore diameter compared to MT. In contrast, PV presented a reduction in Sd values at this same depth for the DM system compared to MT. That is, the variation of pore diameter decreased, showing that DM homogenized porosity and increased the diameter of pores, corroborating the values of d.mode, d.mean, and d.median. In LV, no tillage system was able to change pore distribution, confirming the high stability of granular structure [17,71]. Although treatments showed differences in d.mean and pore size for LV, the Sd value did not change (Figure 2 L).

Predominant pore sizes can be measured by skewness. Positive values indicate the predominance of large pores; while negative values, predominance of small pores; and zero indicates a log normal distribution [45]. Here, all studied soil classes showed predominance of very small pores, with skewness < -3 [79]. Differences between treatments were observed only at depth 0.2-0.4 m, which was most affected by tillage systems, especially DM. It is known that tillage tends to increase the number of large pores [8,14,80]. However, in tilled soils, the reduction of pore size between aggregates is not uncommon [81]. Especially in clayey soils such as those studied herein, which may explain the negative values of skewness.

4.2.Deep tillage and limitations of soil classes

As mentioned, CX and PV are soil classes that exhibit natural densification of subsurface horizons (Bw and Bt, respectively) (Table 1), physical conditions that are unfavorable to plant development, particularly for perennial crops, since soils are only tilled once when crops are established. If the dense soil barrier is not properly ruptured, plants will permanently suffer the consequences. This is often neglected when devising tillage strategies, but results showed that these soil classes indeed respond differently to tillage practices (Figure 3).

Soil thickness, silt content and clay accumulation are the main limiting factors for Ultisols and Inceptisols in Brazil. In CX, the greater silt content and block structure in the Bw horizon favor natural densification [41,82], resulting in low soil porosity. These physical restrictions could be observed in the studied CX: its silt content almost doubled at the 0-0.05 m layer, favoring the packing of particles and increasing Bd (Table 1). Its reduced *solum* thickness was also noteworthy (Table 1).

In Ultisols (PV), clay accumulates in the subsurface (Bt horizon). This class usually has blocky structure and therefore is also prone to natural densification, although with a moderately thick *solum* (Table 1). Values above the Bdc restrict root growth and, therefore, decrease plant yield [65]. This is commonly a problem for Ultisols in Brazil (PV), due to the natural densification caused by the accumulation of clay and their block structure. This could be observed in PV at depths 0.2-0.4 and 0.4-0.6 m, where Bd was near the critical value.

Contrasting with CX and PV, LV has very small and stable granular structure throughout its profile, favoring high porosity [43] and lower bulk density compared to CX and

PV, explaining higher values of AC, Pmac, and Sgi, and lower values of RFC and Bd (Figure 3). However, similar to PV, Bd values were close to the critical value at 0.4-0.6 m, despite its granular structure. In this case, the rearrangement of the very small structure outweighed the beneficial effect of having homogeneous soil texture (not having clay accumulation). This clearly indicates the need to consider the soil class when choosing a tillage system. Additionally, França et al. [83] emphasize that these critical values come from investigations on annual crops (such as wheat, maize, soybean, etc.), and there is little information about perennial crops, such as atemoya.

Furthermore, LV has large pores and very small pores, in which water is both rapidly drained (large pores) and very strongly retained (small pores), greatly reducing water availability to plants [78,84,85]. There are practically no mesopores [86]. The resulting low water availability to plants explains the low RFC values for LV observed in this study [17,87]. At the surface of LV (0-0.2 m), tillage systems led to a large increase in structural pores, due to its granular structure, hindering water retaining capacity (Figure 3 B and C). Water deficit for plants in these soils should be more pronounced. However, the great effective depth of perennial plant roots and their accentuated development in the dry winter season partly compensate the water retention deficit [86,88]. Therefore, the hypothesis of this study was confirmed, considering that LV responded differently to management systems compared to the other studied soils.

Results confirmed the effectiveness of the DM system in breaking the naturally dense soil layers of PV and CX, leading to benefits in structural arrangement, favoring water infiltration and plant rooting. Deep soil tillage loosens this densified layer, improving soil physical quality for crops [8]. This could be observed in studied soils by the increase in Pmac and reduction in Bd, especially in the SB and DM treatments (deep tillage systems) (Figure 2). Similar results were also found by Cai et al. [89], Querejeta et al. [90], Serafim et al. [16], and Silva et al. [17]. Schneider et al. [14] reported that in the presence of soil layers that restricted root growth, especially compacted layers, deep tillage increased crop yield by 20% compared to other tested tillage methods.

The positive correlation between PAW and plant height (r = 0.34), and between PAW and root collar diameter (r = 0.46) indicated that water availability positively affected the development of atemoya plants (Figure 4). The increase in available water favors transpiration and water flow in plants, and also improve nutrient uptake, especially by mass flow.

The DM tillage system greatly affected Pmac values. Macroporosity controls the flow of water and air (AC) and influences root growth [17,73]. Studies performed by Lipiec et al.

[91] showed that, in intensive tillage (plowing), structural pores predominated (pores > 200 µm), whereas in the no-tillage system, there was predominance of textural porosity (pores < 12 µm). Deep tillage reduces the mechanical impedance of soils [92], thereby increasing the density, diameter, and length of plant roots [10].

The increase in Pmac caused by DM enhances soil AC [93], since these pores are directly related to oxygen supply to roots [94]. Increasing Pmac also improves drainage, reducing the risks of water erosion [95], especially for PV and CX, which in the study region occur on slopes from 12% to 45% and on slopes > 45%, respectively [96].

As aforementioned, the depth 0-0.2 m was highly affected by tillage systems and plant cover. However, some systems did not improve soil conditions at 0.2-0.4 m and 0.4-0.6 m. For instance, at 0.2-0.4 m, little or no effect was observed for MT and CT. At 0.4-0.6 m, MT, CT, and SB did not improve AC significantly, as it presented values lower than 0.1 $cm^3.cm^{-3}$, which may compromise plant yield [55,97]. Yet, in terms of Pmac values, no-tillage system indicated compaction or consolidation, regardless of soil class [63,64]. Pmac values were all within the optimal range, which suggests that the critical limits of AC are not adequate to evaluate the effect of tillage systems in the studied soil classes, especially of deep tillage. Both AC and Pmac are capacity properties that define a potential or generalized condition, not defining the entire aeration process, which has a spatial-temporal dynamic [2,98]. This implies accuracy limitations of the capacity indicators.

4.3.Deep tillage applied to sustainable and productive crop management

Prolonged high productivity in intense agricultural systems is deeply connected with sustainable practices. Intense agriculture without the due care negatively impacts long-term productivity. Naturally, following what was exposed in former sections, choosing the adequate tillage system is essential guarantee a sustainable and productive crop system.

For instance, the structural loosening driven by management practices is crucial for CX and PV, as they are very common classes in Brazil. Their high-density layer of pedogenetic origin behaves similar to a compacted layer (from human activity) and increase the risk of water erosion [99,100], water infiltration restrictions [78], and limit the development of crops by restricting root growth [101].

Especially in the initial stages of crop development, it is of utmost importance to have sufficient available water. The lack of water utterly compromises plant establishment. In this stage, adequate development of the aboveground part and of the root system is important. Deep soil tillage in pre-planting, associated with other management practices, such brachiaria grass between rows, makes it possible for a larger volume of soil to be explored by roots in soils that have compacted or densified layers, or soils that are shallow or have low permeability [14,19,20]. Consequently, deep tillage improves root development at depth and reduces water stress [89,90,102].

Subsoiling was performed by Medeiros et al. [103] between the rows of a 14-years-old orange orchard and found a reduction in bulk density and resistance to penetration, along with an increase in microporosity. These improvements in soil physical quality resulted in an increase of 31% in the weight of fruit produced. In this study, since there were no differences between the tillage systems in the surface layer (Figure 3), it was not possible to identify correlations that could act as robust indicators of the initial growth of atemoya plants.

Thus, as observed by Barbosa et al. [8] and Silva et al. [22], deep tillage increased the number of large pores, i.e., increased empty spaces in soil. More empty spaces led to better water and air flows, favoring the development of the root system in coffee plants [17,87], a very common perennial crop in Brazil. This dynamic may bring mid- to long-term benefits to atemoya and other perennial plants (orchards and eucalyptus, for example), which encourages future studies.

Studies on the duration of the effects of physical-hydraulic changes stemming from deep tillage (greater than 0.3 m depth) and their implications on the longevity and yield of perennial crops are rare, but should be encouraged. Barbosa et al. [8] and Silva et al. [22] reported improvements in soil physical quality at depth one year after establishment of coffee plants, and highlighted significant increase in aeration capacity and water availability. The authors used tillage systems similar to those studied here in a Typic Dystrustept, also similar to the CX of this study.

Therefore, the effectiveness of tillage systems was highly dependent on inherent properties of the studied soil classes. Taking soil class into account is needed to achieve a mor productive and sustainable system. The most noteworthy factor that effected tillage results was the subsurface horizon of CX and PV. These had denser underlying layers due to their block structure and natural densification, which could be perceived even at 0-0.2 m. These two classes benefited more from deep tillage than LV. The main point was that CX and PV did not respond equally to tillage treatments. Although most of quality indicators did not show differences, PCA and Sgi clearly showed that the granular structure of LV responded differently to tillage systems compared to CX and PV, corroborating the main hypothesis of this study (Figure 3 E, J, and O; Figure 5).

5. Conclusions

Soil classes responded differently to tillage systems. Deep tillage was the system that most improved soil physical quality, providing greater structural relief. The studied Inceptisol and Ultisol, which presented natural physical restrictions (densified layers), showed better response to deep tillage. The effect of the treatments was less expressive in the studied Oxisol, due its small size granular structure and high stability.

The physical indicators of soil quality that showed that better explained data variability were: aeration capacity (AC), relative field capacity (RFC), macroporosity (Pmac), bulk density (Bd), and the S index (S_{gi}). The results showed that the soil class has important implications for the effect of the management system, especially when assessing the effect of management in greater depths. Therefore, deciding the optimal tillage strategies must involve the soil class properties, especially in greater depths, in order to guarantee a more sustainable and productive agricultural system.

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ARTIGO 3 – USO DO INTERVALO HÍDRICO ÓTIMO COMO APOIO À RECOMENDAÇÃO DO TIPO DE PREPARO DO SOLO PARA CULTURA PERENE EM FUNÇÃO DA CLASSE DE SOLO

Destaques

- Inserir a umidade crítica melhora a exatidão do intervalo hídrico ótimo crítico;
- O preparo profundo proporcionou melhor ambiente físico para as plantas;
- A profundidade mais afetada pelo preparo é a 0,2 – 0,4 m;
- O efeito do preparo de solo é influenciado pela classe de solo e suas propriedades intrínsecas.
- Foi sugerido um tipo de preparo de solo específico para cada classe de solo.

Resumo

Limitações relacionadas a atributos físicos do solo podem afetar negativamente o desenvolvimento das culturas. Neste sentido, o preparo de solo tem essencial importância em proporcionar um ambiente adequado para o desenvolvimentodas plantas, favorecido pela atividade biológica e ao fornecimento de água, oxigênio, calor e nutrientes. O objetivo deste estudo foi avaliar o efeito de métodos de preparo profundo do solo para implantação de culturas perenes em diferentes classes de solo por meio da modelagem do intervalo hídrico ótimo ou Least Limiting Water Range (LLWR). A área experimental está localizada no estado de Minas Gerais, Brasil. As práticas de preparo foram avaliadas em Typic Dystrustept, Rhodic Hapludult e Rhodic Hapludox, e incluem: MT: sulcamento superficial + coveamento; CT: aração seguida de duas gradagens + sulcamento; SB: aração seguida de duas gradagens + subsolagem; e DM: aração seguida de duas gradagens + enxada rotativa. O intervalo hídrico ótimo (LLWR) foi calculado em função da densidade do solo (Bd), e é definido como a faixa de água menos limitante. O LLWR considera, dentro da variação da Bd, o conteúdo de umidade no ponto de murcha permanente, a resistência do solo à penetração, capacidade de campo e porosidade de aeração. Foi também testada uma adaptação do LLWR, na qual o ponto de murcha foi substituído pelo conteúdo crítico de água (θ*) (LLWR*). O delineamento experimental foi inteiramente casualizado, com 4 tratamentos e 5 repetições. Os dados de Bd foram avaliados por análise de variância e teste de Tukey (p> 0,05). Os preparos de solo afetaram de maneira diferente a Bd em função da classe de solo e profundidade. O preparo do solo causou alívio estrutural reduzindo a Bd média e proporcionando um ambiente físico menos restritivo, principalmente com os preparos SB e DM. Não foram encontradas limitações em nenhuma classe de solo dentro da faixa de Bd da profundidade de 0 - 0,2 m. Nas profundidades de 0,2 - 0,4 e 0,4 - 0,6 m foram observadas limitações físicas através dos valores de PR e AP. A inserção da umidade crítica do solo (θ*) como limite inferior do intervalo hídrico ótimo crítico (LLWR*) possibilitou maior exatidão na definição da faixa de conteúdo de água no solo. Foi possível sugerir um preparo específico de solo, a partir dos efeitos observados de cada preparo, em cada classe de solo, assim: Deep Mixing till (DM) para o Cambissolo (CX), Subsoiling (SB) ou Deep Mixing till (DM) para Argissolo (PV) e Conventional till (CT) para o Latossolo (LV).

Palavras-chave: Manejo do solo; estrutura do solo; qualidade física do solo; capacidade de água disponível; preparo profundo do solo.

Abstract

Limitations related to the physical attributes of the soil can negatively affect crop development. In this sense, the soil preparation is essential in providing a favorable environment for biological activity and the supply of water, oxygen, heat and nutrients to plants. The aim of this study was to evaluate the effect of deep tillage methods for planting perennial crops in different soil classes by modeling the optimum water range. The experimental area is located in the state of Minas Gerais, Brazil. Tillage practices were evaluated in Typic Dystrustept, Rhodic Hapludult and Rhodic Hapludox, and include: MT: surface furrowing + pitting; CT: plowing followed by two harrowing + furrowing; SB: plowing followed by two harrowing + subsoiling; and DM: plowing followed by two harrowing + rotary hoe. The Least Limiting Water Range (LLWR) was calculated as a function of the soil density (Bd), and is defined as the least limiting range of water. The LLWR considers within the Bd range the moisture content at permanent wilting point, soil resistance to penetration, field capacity and aeration porosity. An adaptation of the LLWR was also tested, in which we replaced the wilting point by the critical water content (θ*)

(LLWR*). The experimental design was completely randomized, with 4 treatments and 5 replications. Bd data were evaluated by analysis of variance and Tukey's test (p> 0.05). Soil tillage affected Bd differently depending on soil class and depth. Soil tillage caused structural relief by reducing the average Bd and providing a less restrictive physical environment, especially with SB and DM tillages. No limitations were found in any soil class within the 0 - 0.2 m depth Bd range. At depths of 0.2 - 0.4 and 0.4 - 0.6 m, physical limitations caused by PR and AP were observed. Insertion of the critical soil moisture (θ*) as the lower limit of the critical optimum water range (LLWR*) enabled greater accuracy in defining the soil water content range. It was possible to suggest a specific soil tillage, based on its performance, for each soil class, thus: Deep Mixing till (DM) for Typic Dystrustept (CX), Subsoiling (SB) or Deep Mixing till (DM) for Rhodic Hapludult (PV) and Conventional till (CT) for Rhodic Hapludox (LV).

Keywords: soil tillage; soil structure; soil physical quality; available water capacity; deep soil preparation.

1. Introdução

O Brasil tem atualmente cerca de 7.755.817 ha utilizados com cultivo de culturas perenes (IBGE, 2017). O preparo do solo para esse tipo de cultura forma a base para instalação de culturas que permanecerão no solo por muitos anos. É possível encontrar lavouras de café produtivas, por exemplo, com 10 a 15 anos de idade no Brasil (Silva et al., 2021). Nesse sentido, o preparo do solo é parte essencial do manejo para possibilitar uma vida útil prolongada e produtiva para a cultura, sobretudo ao considerar o custo expressivo para implantação das culturas perenes.

Visando o desenvolvimento adequado e produtivo das culturas, o solo, como meio de crescimento das plantas, deve fornecer um ambiente favorável à atividade biológica e ao fornecimento de água, oxigênio, calor e nutrientes (Carter, 1986; Hamilton et al., 2019). Assim, a estrutura do solo e os atributos físico-hídricos, correlatos, influenciam a profundidade efetiva, o fluxo e armazenamento de calor, a quantidade de água armazenada, o movimento do ar, da água e da fauna do solo (Hermavan & Cameron, 1993) que afeta a produtividade agrícola (Blanco-Canqui & Ruis, 2018). Por conseguinte, limitações físicas do solo podem afetar negativamente o rendimento das culturas (Moura et al., 2021).

O manejo do solo pode alterar positivamente as propriedades relacionadas à dinâmicas da água no solo (Silva et al., 2021). As estratégias de preparo profundo mostraram-se importantes por impactar positivamente a porosidade (Schneider et al., 2017; Peixoto et al., 2019; 2020) e a resistência do solo a penetração (Azevedo et al., 2022), visando sempre a melhoria do ambiente de crescimento das raízes (Secco et al., 2009). Czyz et al. (2001) observaram relação linear entre a massa de raízes de cevada no perfil e a produtividade, o que enfatiza a importância das condições físico-hídricas para o ótimo crescimento e rendimento das culturas.

A densidade do solo (Bd) é uma propriedade muito importante para avaliação da qualidade física do solo, porém fornece pouca informação sobre o ambiente do solo que afeta o crescimento das raízes e das plantas (Benjamin et al. 2003). A densidade do solo influencia o crescimento das raízes e das plantas apenas indiretamente, por meio de seu efeito na resistência mecânica, estresse hídrico e estresse pela falta oxigênio. A Bd pode afetar negativamente o crescimento das plantas, no entanto depende também de muitos outros fatores, incluindo a textura e estrutura do solo, o material de origem, as condições climáticas, o conteúdo de matéria orgânica (MO), a presença e posição de uma camada restritiva (Logsdon & Karlen, 2004). Portanto, a densidade do solo sozinha não é um indicador apropriado para descrever a qualidade física de um solo para o crescimento das plantas

Nesse sentido o Intervalo hídrico ótimo (LLWR) ou faixa de água menos limitante, proposto por Silva et al. (1994), é um índice de qualidade estrutural do solo, que vai além da capacidade de água disponível. Esse indicador considera dentro da variação da Bd o conteúdo de umidade no ponto de murcha permanente, resistência do solo à penetração, capacidade de campo e porosidade de aeração (Lima et al., 2012; 2019). Em busca de melhores correlações desse indicador com o rendimento das culturas adaptações dessa modelagem já foram testadas (Asgarzadeh et al., 2011; Mohammadi et al., 2010; Silva et al., 2015). Silva et al. (2015) por exemplo inseriram a umidade crítica (θ^*) em substituição ao ponto de murcha permanente (θ_{PWP}), um fator fisiológico relacionado ao estresse hídrico, para calcular o LLWR*. Apesar do conteúdo de água no LLWR* ser menor que o LLWR tradicional, essa adaptação tem maior coerência, pois o valor de θ^* representa o teor onde a transpiração da planta é reduzida, no entanto, seu impacto no crescimento e na produtividade da cultura devido ao estresse hídrico não é significativo.

Estudos que buscam entender o efeito do preparo, sobretudo em preparo profundo relacionados a culturas perenes, sobre os atributos físicos no solo são encontrados na literatura (Serafim et al., 2011; Medeiros et al., 2013; Serafim 2013a, 2013b, 2013c, Silva et al., 2015;

Barbosa et al., 2020, Silva et al., 2021; Azevedo et al., 2022). No entanto, a maioria dos trabalhos com preparo profundo são realizados em culturas anuais/cereais (Schneider et al., 2017) e ou não apresentam contraste na estrutura das classes de solo avaliadas (Coulouma et al., 2006; Bordoni et al., 2019). Além disso, a maioria deles se limita a avaliação em uma única classe de solo, ou quando em mais de uma classe simplesmente desprezam as características pedogenéticas dos horizontes e passam a tratar apenas de camadas de profundidade e classificação textural (Kaufmann et al., 2010; Pöhlitz et al.,2020).

Trabalhos já realizados pelo grupo de pesquisa vinculado a este estudo têm encontrado resultados positivos com uso de preparo profundo, principalmente na cultura do café. A melhoria do ambiente radicular provocada por esse manejo possibilita maior volume de solo explorado, consequentemente maior uso da água armazenada, trazendo como resultado altos rendimentos e longevidade dos cafeeiros cultivados em áreas de Cambissolos e Latossolos (Serafim et al., 2013a; 2013b; 2013c; Santos et al., 2014; Silva et al., 2015a; Silva et al., 2016b; Silva et al., 2017; Oliveira et al., 2019; Silva et al., 2019a; 2019b; Barbosa et al., 2020).

Guimarães et al. (2013b) verificaram redução do LLWR mais acentuada em Latossolo cultivado com citros em relação a área de mata nativa, revelando maior degradação da qualidade física do solo sob esse uso e manejo. Já Kahlon & Chawla (2017) avaliando o efeito de práticas de manejo do solo no noroeste da Índia verificaram que o preparo profundo do solo foi o que proporcionou maiores valores de LLWR dentre os manejos analisados. No Brasil, Pacheco & Cantalice (2011) avaliaram o efeito do cultivo com cana-de-açúcar sobre o LLWR de um Argissolo Amarelo distrocoeso dos Tabuleiros Costeiros de Alagoas. Esses autores verificaram que a subsolagem realizada na área para implantação dos canaviais promoveu aumento do LLWR do horizonte superficial do solo em relação a área de mata nativa. Vários estudos realizados em diferentes solos, culturas agrícolas e sistemas de manejo comprovam a utilidade do LLWR como indicador de qualidade física do solo (Silva et al., 1994; Tormena et al., 1999; Lapen et al., 2004; Tormena et al., 2007; Kaiser et al., 2009). O LLWR é um indicador sensível à compactação do solo (Silva et al., 1994; Silva et al., 1997; Gubiani et al., 2013; Chen et al., 2014).

Com base nas ideias apresentadas, a hipótese deste trabalho é que a qualidade física do solo para as plantas depende não só do tipo de preparo, mas também dos atributos intrínsecos da classe de solo. Nesse sentido, o objetivo com este estudo foi avaliar o efeito de métodos de preparo profundo do solo para implantação de culturas perenes em diferentes classes de solo por meio da modelagem do intervalo hídrico ótimo.

2. Material e Metodos

2.1.Caracterização da área de estudo

O estudo foi conduzido na área experimental do setor de Fruticultura da Universidade Federal de Lavras (UFLA), localizada na região sudeste do Brasil. O clima da região é classificado como Cwa de acordo com o sistema de classificação climática de Köppen (Alvares et al., 2013), possui verões quentes e úmidos, invernos frios e secos, a temperatura média é de 21,6 °C e a precipitação média é de 1339,5 mm, concentrada nos meses de novembro a março, de acordo com dados obtidos no intervalo de 01/01/1998 a 01/01/2018 (INMET, 2019).

O município de Lavras possui uma grande diversidade de material de origem dos solos, devido à complexidade geológica existente na região (Andrade et al., 1998; Lacerda et al., 2000). O campus da UFLA está localizado na unidade geomorfológica do Planalto Atlântico, sob influência de gnaisses graníticos leucocráticos (GgL) e mesocráticos (GgM), o que permite ampla variedade de classes de solo em pequena extensão de área. Dessa maneira foram selecionadas três classes de solos, classificados por Curi et al. (2017) segundo Santos et al. (2013), como Cambissolo Háplico Tb Eutrófico típico ou Typic Dystrustept (CXbe3 – GgL) – CX; Argissolo Vermelho Distrófico típico ou Rhodic Hapludult (PVd2 – GgM) – PV e Latossolo Vermelho Eutrófico típico ou Rhodic Hapludox (LVe2 – GgL) – LV; sendo estes solos muito representativos em escala nacional (Latossolos – 31.6%; Argissolos – 26.9%, e Cambissolos – 5.26 %, Santos et al., 2011), e mesmo mundial quando se considera correlações com as ordens da Soil Taxonomy (Inceptsol - 15%; Ultisol - 8%, e Oxisol - 8% (Sawe, 2017).

Além da representatividade nacional e mundial a escolha das classes buscou condições contrastantes entre os solos para o crescimento da cultura no que diz respeito ao desenvolvimento de raízes e disponibilidade de água no solo. O adensamento natural encontrado nos Inceptsols (Cambissolos) e Ultisols (Argissolos) é uma característica de destaque nessas classes de solo (Pereira et al., 2010; Busscher et al., 1995), assim como a estrutura granular muito pequena presente nos Oxisols (Latossolos) das regiões tropicais (Ferreira et al. 1999).

Antes da instalação do experimento, amostras indeformadas de solo foram coletadas nos horizontes diagnósticos do solo para a caracterização física (Tabela 1), e amostras deformadas nas profundidades de 0-0.2; 0.2-0.4 e 0.4-0.6 m (Tabela 2) para a caracterização química e de fertilidade, conforme métodos descritos em Teixeira et al. (2017).

Tabela 1. Caracterização física dos solos da área experimental.

Soil		CXbe3			PVd2			LVe2		
Horizon		A	Bi	BC	A	BA	Bt	A	Bw1	Bw2
Depth	m	0-0,05	0,05-0,15	0,15-0,60+	0-0,12	0,12-0,35	0,35-0,55+	0-0,10	0,10-0,60	0,60+
Bd	$g\ cm^{-3}$	1,38	1,41	1,47	1,11	1,42	1,47	1,32	1,06	1,19
Pd		2,55	2,63	2,63	2,53	2,63	2,7	2,64	2,73	2,69
Tp	m^3m^{-3}	0,49	0,45	0,48	0,54	0,46	0,46	0,54	0,57	0,53
FC		0,36	0,37	0,41	0,32	0,33	0,38	0,4	0,33	0,38
Mic		0,38	0,39	0,42	0,33	0,34	0,39	0,41	0,34	0,4
Mac		0,11	0,07	0,06	0,21	0,12	0,08	0,13	0,23	0,13
AC		0,25	0,17	0,15	0,41	0,28	0,18	0,26	0,43	0,28
Clay	%	41,7	35,5	35,5	44,8	46,9	67,3	50,6	65,5	68,6
Sand		41,9	28,4	28,4	40,6	38,9	24	29,6	21,3	20,1
Silt		16,5	36,1	36,1	14,5	14,2	8,64	19,7	13,1	11,3
Soil Texture		Clay	Clay loam	Clay loam	Clay	Clay	Clay	Clay	Clay	Clay

CXbe3: Typic Dystrustept; PVd2: Rhodic Hapludult; LVe2: Rhodic Hapludox. Bd: bulk density; Pd: particle density; Tp: calculated total porosity; FC: field capacity estimated at -10 kPa; Mic: Microporosity estimated at -6 kPa; Mac: Macroporosity; determined according to Teixeira et al. (2017); CA: soil aeration capacity determined according to Reynolds et al. (2009); Textural Class according to the Soil Survey Division Staff (2017). CXbe3: Cambissolo Háplico Tb Eutrófico típico, textura argilosa, horizonte A moderado; LVe2: Latossolo Vermelho Eutrófico típico, textura argilosa, horizonte A fraco; PVd2: Argissolo Vermelho Distrófico típico, textura argilosa, horizonte A fraco; Classe Textural conforme Santos et al., (2018).

Tabela 2. Caracterização química dos solos da área experimental.

Soil		CXbe3			PVd2			LVe2		
Depth	m	0-0,2	0,2-0,4	0,4-0,6	0-0,2	0,2-0,4	0,4-0,6	0-0,2	0,2-0,4	0,4-0,6
pH	H_2O	6,30	5,70	5,50	6,00	5,70	5,70	6,90	6,50	6,00
	$CaCl_2$	5,70	5,10	4,90	5,40	5,10	5,10	6,30	5,90	5,40
P – Mehlich-1	mg kg^{-1}	14,2	3,38	2,50	2,55	2,27	0,71	11,1	10,8	1,90
P – resin		25,4	5,73	1,18	10,9	5,25	3,41	10,4	4,76	3,45
K – Mehlich-1		94,0	45,4	32,5	133	103,0	71,7	66,5	38,9	23,4
Ca	$cmol_c$ kg^{-1}	5,42	3,38	2,50	4,22	3,12	2,41	4,76	2,86	2,14
Mg		1,25	0,59	0,44	1,11	0,85	0,57	1,19	0,95	0,60
Al		0,00	0,06	0,15	0,00	0,00	0,00	0,00	0,00	0,00
H+Al		3,06	4,12	3,68	2,55	3,41	3,55	1,79	2,14	2,86
CEC_7		10,1	8,38	6,62	8,21	7,67	3,12	7,85	3,93	2,86
OC	%	1,40	0,90	0,90	1,80	1,10	0,80	1,10	1,10	0,60
SOM		2,41	1,55	1,55	3,10	1,90	1,38	1,90	1,90	1,03
BS		9,40	50,8	46,0	69,1	55,3	46,6	77,4	64,6	49,5
Al_{sat}		0,00	1,30	3,50	0,00	0,00	0,00	0,00	0,00	0,00
Ki		1,24	1,50	-	1,84	-	1,69	1,35	-	1,29
Kr		1,10	1,37	-	1,47	-	1,51	1,05	-	0,99

CXbe3: Typic Dystrustept; PVd2: Rhodic Hapludult; LVe2: Rhodic Hapludox. (Soil Survey Division Staff, 2017); P e K – Mehlich-1 = fósforo e potássio disponível; P – resina = fósforo trocável; OC = carbono orgânico; SOM = matéria orgânica do solo; Al_{sat} = saturação de alumínio; BS = saturação de bases; Ki = $\%SiO_2/\%Al_2O_3$ x 1,7; Kr = $(\%SiO_2/0.6)$ / $[(\%Al_2O_3/1.02)+(\%Fe_2O_3/1.6)]$ (Teixeira et al., 2017).
CXbe3: Cambissolo Háplico Tb Eutrófico típico, textura argilosa, horizonte A moderado; LVe2: Latossolo Vermelho Eutrófico típico, textura argilosa, horizonte A fraco; PVd2: Argissolo Vermelho Distrófico típico, textura argilosa, horizonte A fraco (Santos et al., 2018).

2.2.Delineamento experimental e Tratamentos

Nas três classes de solo foi instalado o mesmo experimento com quatro tratamentos e cinco repetições em delineamento inteiramente casualizado, totalizando 60 parcelas experimentais em campo. Cada parcela foi composta por uma linha de plantio contendo 6 plantas ocupando uma área de 40.5 m^2. A escolha dos tratamentos baseou-se nos principais preparos de solos utilizados para implantação de culturas perenes no Brasil e trabalhos desenvolvidos por nosso grupo de pesquisa. A natureza dos tratamentos foi o preparo do solo para implantação de cultura perene utilizando diferentes equipamentos, assim descritos: **MT** – preparo mínimo: sulco superficial (0.10 m de profundidade) para marcação da linha de plantio utilizando sulcador + cova (0.40 m de diâmetro por 0.70 m de profundidade) utilizando perfuratriz; **CT** – preparo convencional: aração com discos (0.25 m), duas gradagens (0.20 m) + sulco (0.25 m) utilizando sulcador; **SB** - subsolador: aração (0.25 m), duas gradagens (0.20 m) + subsolador de ponta cuneiforme de duas hastes espaçadas de 0.50 m (0.45m); **DM** – preparo profundo: aração com discos (0.25 m), duas gradagens (0.20 m) + preparador de solo (0.50 largura por 0.60 m de profundidade). O preparador de solo é um tipo de enxada rotativa modificada com largura de ação de 0.5 m conduzido em faixas, composta por uma roda de corte vertical que mistura os horizontes superficial e subsuperficial, modelo BigMix® AS-2, fabricado pela Mafes Agromecânica (Mafes, 2017). O preparo da área foi realizado na primavera, em 11/29/2018, após 3 dias do último evento de precipitação com 20 mm.

O plantio de Atemóia (Annona cherimola x Annona squamosa) ocorreu em 12/14/2018 no espaçamento de 4,5 x 1,5 m, com 6 plantas por parcela. A correção do solo foi realizada com calcário, na profundidade de 0 a 0.4 m, para elevação da saturação de Ca e Mg na saturação de bases para 70 e 15%, respectivamente, exceto para o MT, onde a calagem foi realizada na cova. Adicionalmente foi realizada semeadura de Braquiária Ruziziensis (Urochloa ruziziensis) nas entrelinhas, mantidas com roçadas periódicas. A recomendação de calagem e adubação foi realizada conforme necessidade cultura, descrita em Rozane e Natale (2014).

2.3.Determinação do intervalo hídrico ótimo (LLWR)

A avaliação do efeito dos tratamentos sobre o LLWR ocorreu aos sete meses após o preparo do solo. A amostragem do solo foi realizada em cilindros volumétricos (6,5 cm de diâmetro por 2,5 cm de altura) no centro das profundidades de 0 – 0,2; 0,2 – 0,4 e 0,4 – 0,6 m com auxílio do amostrador de Uhland. Vale ressaltar que a coleta dos cilindros no tratamento MT foi realizada no solo entre-plantas e não dentro da cova, pois poderia comprometer a integridade da planta. Portanto pode-se considerar o MT como condição natural ou testemunha.

Em cada solo foram coletadas quatro amostras em três repetições, para cada tratamento e em cada profundidade (3 solos x 4 tratamentos x 3 profundidades x 4 amostras x 3 repetições), totalizando 432 amostras. Após preparadas e saturadas lentamente com água destilada foram submetidas aos potenciais matriciais (h) de -4 kPa, utilizando funis de placa porosa (Funis de Büchner), -33, -100 e -1500 kPa utilizando os extratores de Richards (Klute, 1986), como descrito em Nascimento et al (2019).

Cada amostra foi submetida a apenas uma tensão e após atingirem o equilíbrio hídrico sua massa foi aferida e a resistência à penetração (PR) foi determinada em um penetrógrafo de bancada (Marconi, modelo MA 933) utilizando uma ponteira tipo cone de 45°, 3.66 mm de diâmetro e velocidade constante de 100 mm min^{-1}. Em seguida cada amostra foi seca em estufa 105-110°C até atingirem peso constante para determinação do conteúdo de água (θ) e densidade do solo (Bd) (Silva et al.,1994; 2015; 2019).

A partir dos dados medidos de todas as amostras de cada tratamento em cada solo, obteve-se modelos não lineares para retenção de água (WRC) (eq. 1) e PR (PRC) (eq. 2), conforme afetado pelo Bd (Busscher, 1990; Silva et al., 2015, 2019). Os coeficientes do modelo foram obtidos minimizando os desvios quadrados entre os valores medidos e calculados (Leão e Silva, 2004).

$$WRC = \theta = a\psi^{b}\, Bd^{c} \quad (1)$$

$$PRC = PR = d\theta^{e} Bd^{f} \quad (2)$$

Onde:
θ é o teor de água no solo ($m^3 m^{-3}$);
ψ é o potencial hídrico do solo (kPa);
PR é a resistência à penetração (MPa);
Bd é a densidade aparente (g cm^{-3}); e
“a” , “b” e “c” são parâmetros de ajuste da eq. 1;
“d” , “e” , “f” são parâmetros de ajuste da eq. 2 .

O LLWR foi calculado segundo Silva et al (1994) como sendo o limite superior do LLWR o θ mais seco da FC (θ_{FC}) estimada no potencial de -10 kPa ou valor de θ onde a porosidade de aeração é de 0,10 m^3 m^{-3} (θ_{PA}) (Grable & Siemer, 1968). Enquanto o limite inferior é a θ no ponto de murcha permanente (θ_{PWP}), estimada no potencial de -1500 kPa (Savage et al., 1996) ou a θ na qual a resistência do solo à penetração das raízes limita o crescimento das plantas (θ_{PR}) obtido pela eq. 3. Dada a ausência de estudos que expressem o valor de PR restritivo para a cultura da Atemóia, utilizamos para a criação dos modelos e discussão dos resultados valor de 3 MPa (Sinnett et al., 2008; Serafim et al., 2013; Colombi et al., 2018). A θ na porosidade de 0,1 $m^3 m^{-3}$ foi estimada pela eq. 4.

$$\theta_{PR} = \left(\frac{PR}{dBd^{f}}\right)^{1/e} \quad (3)$$

$$\theta_{AP} = \left(1 - \frac{Bd}{Pd}\right) - 0{,}1 \quad (4)$$

Onde:
Pd é a média ponderada das densidades de partículas de cada horizonte de cada solo em g cm^{-3}, determinados de acordo com Teixeira et al (2017) (CX = 2,62 g cm^{-3}, PV = 2,63 g cm^{-3}, LV = 2,71 g cm^{-3});
“d”, “e” e “f” são os mesmos parâmetros de ajuste que na eq. 2 .

Fundamentado nos conceitos de água prontamente disponível e no fator de depleção de evapotranspiração (p), o que definem a fração média da água total disponível no solo que pode ser esgotada da zona de raiz antes da redução da transpiração, que caracteriza o estresse hídrico (Doorenbos; Kassan, 1979; Allen et al., 1998, van der Berg; Driessen, 2002; Eitzinger et al., 2004) que Silva et al. (2015) adicionaram ao conceito de LLWR a θ*. Ou seja, é o teor de água do solo (m^3 m^{-3}) em que a transpiração da planta é reduzida, no entanto, seu impacto no crescimento e na produtividade da cultura devido ao estresse hídrico não é significativo. Uma vez que a θ* refere-se a água no solo onde não há restrições a transpiração (Silva et al.,2015). Mais detalhes podem ser encontrados em Silva et al. (2015, 2019) e Moura et al. (2021).

Silva et al. (2015; 2019) e Moura et al. (2021) provaram que a θ* é um parâmetro mais preciso que o θ_{PWP} para estimar a água prontamente disponível para as plantas. A θ * é expressa com base no fator p, que pode assumir um valor médio ou variável, dependendo da demanda evapotranspirativa da cultura, condutividade hidráulica do solo e condições climáticas do ambiente. Em função de limitações nas informações sobre evapotranspiração da cultura da Atemoia decidiu-se usar o fator *p* médio de 0,5 (eq. 5), considerando evapotranspiração média de 3 mm dia^{-1} (Allen et al., 1998. Soares et al., 2005, Reichardt et al., 2009), assim como Silva et al. (2015) e Moura et al. (2021) para a cultura do cafeeiro, para calcular θ* (eq. 6).

$$\theta_{FC} - \theta^* = p\,(\theta_{FC} - \theta_{PWP}) \qquad (5)$$

$$\theta^* = a[10^b - p\,(10^b - 1500^b)]Bd^c \qquad (6)$$

Onde:
θ* é a umidade crítica (m^3 m^{-3});
p é o fator de depleção da evapotranspiração;
Bd é a densidade aparente (g cm^{-3});
“a”, “b” e “c” são os mesmos parâmetros de ajuste da eq. 1.

2.4.Análise estatística

Os parâmetros de ajuste do modelo não linear de LLWR (“a”, “b”, “c”, “d”, “e” e “f”) foram calculados utilizando o software R versão 4.2.1 (R Development Core Team, 2022) minimizando a soma dos quadrados das diferenças entre os valores determinados e os estimados pelo modelo. Os dados de Bd foram testados quanto à normalidade, independência e homogeneidade de variância. Atendendo a esses pressupostos, foram realizados testes de análise de variância (ANOVA) e comparação de médias dos tratamentos pelo teste de Tukey ($p > 0,05$) para cada classe de solo em cada profundidade.

Estatísticas descritivas foram realizadas em todo o conjunto de dados referentes ao LLWR e o LLWR foi plotado em função do Bd (Silva et al., 1994; Silva et al., 2015, 2019).

3. Resultados

3.1.Alteração da densidade do solo (Bd)

Na figura 1 são apresentadas as comparações das médias de Bd de cada preparo de solo avaliado (MT, CT, SB e DM) dentro de cada profundidade e classe de solo. Os preparos de solo afetaram de maneira diferente a Bd em função da classe de solo e profundidade. De maneira geral os preparos foram eficientes em reduzir a densidade, haja vista que na maioria dos casos os preparos apresentaram valores menores que em MT (não houve mobilização do solo) especialmente os preparos SB e DM (Figura 1).

Independente do preparo avaliado os menores valores de Bd foram observados no LV enquanto os maiores valores foram registrados no CX. Em todas as classes de solo a profundidade mais influenciada pelo preparo foi 0,2 - 0,4 m onde os preparos profundos (SB e DM) se destacaram apresentando menores valores de Bd em relação aos demais, demostrando como SB e DM foram efetivos no afrouxamento do solo e melhorando fisicamente no ambiente radicular. A camada de 0 – 0,2 m não apresentou diferenças estatísticas sobre a Bd em função dos preparos testados, exceto para o tratamento MT no PV que apresentou a maior média de Bd (1,23 g cm^{-3}) em relação ao DM (1,10 g cm^{-3}).

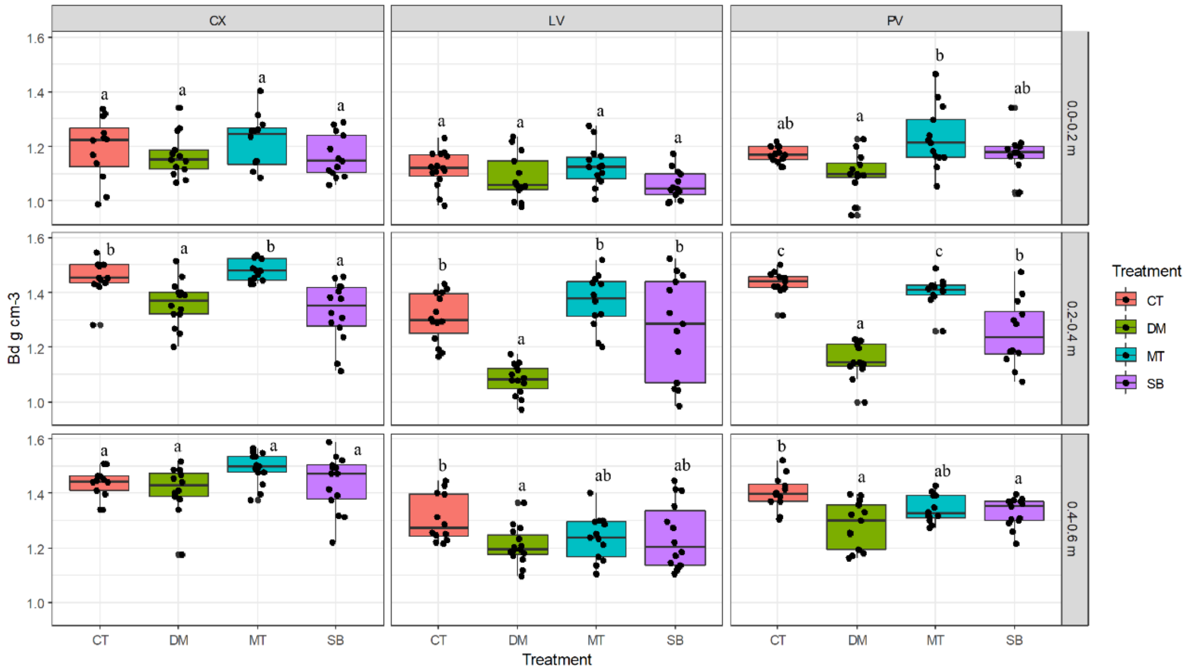

Figura 1. Variação da densidade do solo (Bd – g cm^{-3}) em função dos tipos de preparo de solo (MT, CT, SB e DM) para implantação de cultura perene nas classes de solo Cambissolo Háplico (CX), Argissolo Vermelho (PV) e Latossolo Vermelho (LV).

No CX a Bd não foi alterada pelos sistemas de preparo nas profundidades de 0 – 0,2 e 0,4 – 0,6 m, apenas os preparos profundos (SB e DM) apresentaram efeito sobre a Bd, exclusivamente em 0,2 – 0,4 m. O CX foi considerado como a classe mais resistente ao efeito dos preparos testados. No PV o comportamento da Bd variou e função da profundidade e tipo de preparo. A maior variação entre os preparos ocorreu na profundidade de 0,2 – 0,4 m, na seguinte ordem: DM<SB<MT e CT (1,16< 1,25< 1,40 e 1,43 g cm^{-3}). Onde se destaca o contraste entre MT (1,40 g cm^{-3}) e o DM (1,16 g cm^{-3}), MT expressa a ausência de preparo e DM efeito de um implemento que revolve o solo entre 0 e 0,6 m. De maneira semelhante, porém com menor proeminência, na profundidade de 0.4-0.6 m os preparos profundos se destacaram com menores valores Bd que o CT e MT.

Assim como PV, o LV também apresentou maior variação da Bd na profundidade de 0.2-0.4 m, no entanto em DM observou-se melhor efeito que SB, que não foi diferente dos demais preparos, devido principalmente a grande amplitude de valores de Bd coletados nesse tratamento (SB). Na profundidade de 0,4 – 0,6 m observou-se que houve efeito do preparo profundo DM, mesmo que pouco, mas suficiente para demostrar diferença estatística. Porém cabe ressaltar que os preparos MT e CT apresentam valores coerentes, uma vez que em MT não houve mobilização do solo e em CT o preparo não atingiu essa profundidade, o que traz solidez aos dados e descarta um eventual erro de amostragem.

3.2.Modelos de WRC e PRC

O conjunto de dados para geração dos modelos de WRC e PRC foi composto por classe de solo, preparo de solo e profundidades, de modo que foram gerados 12 modelos de WRC e 12 modelos PRC (tabelas 3 e 4). Todos os coeficientes de ambos os modelos foram significativos, exceto o “d” do modelo PRC. Para o modelo WRC o R^2 variou de 0.61 (CX-MT) a 0.88 (LV-DM) e para o modelo PRC o R^2 apresentou maior variação, de 0.42 (LV-DM) a 0.79 (CX-DM). Enquanto a variação média deRMSE do modelo WRC foi de 0.035 cm^3 cm^{-3} – CX, 0.045 cm^3 cm^{-3} – PV e 0.027 cm^3 cm^{-3} – LV; e para o modelo PRC de 1.017 Mpa – CX, 0.785 MPa – PV e 0.611 MPa – LV. A grande variação entre os coeficientes pode ser explicada pela elevada variabilidade das características intrínsecas de cada solo (Tabela 1), considerando também o efeito do preparo e seus horizontes pedogenéticos.

Tabela 3. Coeficientes ‘a’, ‘b’, e ‘c’ da curva de retenção de água (WRC), coeficiente de determinação (R^2) e raiz do erro quadrático médio (RMSE) para diferentes tratamentos em três classes de solo contrastantes.

Soil	Treatment	a	b	C	R^2	RMSE cm^3 cm^{-3}
CX	MT	-1,629***	0,255**	-0,057***	0,61	0,046
	CT	-1,646***	0,290*	-0,051***	0,65	0,039
	SB	-1,979***	0,471***	-0,068***	0,82	0,031
	DM	-2,167***	0,611***	-0,064***	0,82	0,022
PV	MT	-1,764***	0,390*	-0,056***	0,62	0,042
	CT	-2,431***	0,841***	-0,052***	0,78	0,033
	SB	-2,545***	1,021***	-0,046***	0,70	0,038
	DM	-2,824***	1,192***	-0,065***	0,83	0,066
LV	MT	-2,075***	0,633***	-0,050***	0,70	0,025
	CT	-2,212***	0,699***	-0,057***	0,73	0,024
	SB	-2,119***	0,641***	-0,060***	0,80	0,027
	DM	-2,495***	0,922***	-0,075***	0,88	0,031

CX: Typic Dystrustept; PV: Rhodic Hapludult; LV: Rhodic Hapludox. (Soil Survey Division Staff, 2017); CX: Cambissolo Háplico Tb Eutrófico típico, textura argilosa, horizonte A moderado; LV: Latossolo Vermelho Eutrófico típico, textura argilosa, horizonte A fraco; PV: Argissolo Vermelho Distrófico típico, textura argilosa, horizonte A fraco (Santos et al., 2018). MT: prepare mínimo, CT: prepare convencional, SB: subsolador, DM: preparo profundo.

Tabela 4. Valores dos indicadores da qualidade física do solo em diferentes profundidades e classe de solo em um Cmabissolo (CX), Argissolo (PV) e Latossolo (LV) e limites propostos na literatura. MT: preparo mínimo; CT: preparo convencional; SB: subsolador e DM: preparo profundo.

Solo	Tratamentos	d	e	f	R^2	RMSE $cm^3\ cm^{-3}$
CX	MT	0.008	5.284***	-3.316***	0.76	1.382
	CT	0.026	4.534***	-2.688***	0.56	1.221
	SB	0.015	6.695***	-2.462***	0.66	0.881
	DM	0.007	6.909***	-2.984***	0.79	0.585
PV	MT	0.053	5.289***	-1.848***	0.55	0.748
	CT	0.009	9.309***	-2.145**	0.62	0.998
	SB	0.019	7.407***	-2.402**	0.58	0.866
	DM	0.009	9.025***	-2.601***	0.74	0.528
LV	MT	0.001	9.176***	-4.691***	0.73	0.689
	CT	0.004	7.835***	-3.270***	0.63	0.657
	SB	0.005	7.211***	-3.298***	0.68	0.547
	DM	0.028	7.281***	-2.035**	0.42	0.551

CX: Typic Dystrustept; PV: Rhodic Hapludult; LV: Rhodic Hapludox. (Soil Survey Division Staff, 2017); CX: Cambissolo Háplico Tb Eutrófico típico, textura argilosa, horizonte A moderado; LV: Latossolo Vermelho Eutrófico típico, textura argilosa, horizonte A fraco; PV: Argissolo Vermelho Distrófico típico, textura argilosa, horizonte A fraco (Santos et al., 2018); MT: preparo mínimo; CT: preparo convencional; SB: subsolador e DM: preparo profundo.

3.3. Intervalo hídrico ótimo

A variação da θ em função da Bd para os limites críticos do LLWR e LLWR* em cada solo é apresentada nas Figuras 2, 3 e 4. Em todas as classes de solo e preparos avaliados o aumento da Bd resulta, mesmo que pequeno, em aumento do LLWR e LLWR*, até que esse aumento de Bd resulte em limitação física, mecânica pelo aumento da PR ou restrição de aeração pela redução da AP.

Em nenhuma classe de solo houve limitação dentro da faixa de Bd da profundidade de 0 – 0,2 m. Por outro lado, nas profundidades de 0,2 – 0,4 e 0,4 – 0,6 m são observadas limitações físicas causadas pela PR e AP. Tomando como referência (controle) o preparo MT, podemos perceber nitidamente o efeito do preparo no alívio estrutural do solo reduzindo a Bd média e proporcionando um ambiente físico menos restritivo, principalmente com os preparos SB e DM (Figuras 2, 3 e 4).

No CX até a Bd de 1,36, 1,33, 1,33 e 1,32 g cm^{-3} em MT, CT, SB e DM, respectivamente, não foi observada nenhuma restrição física, seja ela mecânica ou de areação, portanto a θ foi limitado pela θ_{FC} e θ_{PWP}. No entanto a partir desses valores a PR passa a limitar a θ. Com o aumento da Bd a AP passa a limitar também a partir dos valores de 1,40, 1,39, 1,40 e 1,41 g cm^{-3}, reduzindo ainda mais a θ, até atingir a Bd*LLWR em 1,52, 1,47, 1,48, 1,48 g cm^{-3} em MT, CT, SB e DM, respectivamente (Figura 2).

Em PV, no preparo MT, quem limita a θ inicialmente foi a AC, a partir de 1,38 g cm^{-3} e a partir de 1,40 g cm^{-3} a PR até a atingir a Bd*LLWR em 1,47 g cm^{-3}. Ao contrário, no preparo CT primeiramente a limitação da θ ocorreu pela PR (1,37 g cm^{-3}) e depois pela AP (1,40 g cm^{-3}) e Bd*LLWR de 1,45 g cm^{-3}. Em SB e DM tanto a PR como a AP restringem a θ no mesmo momento 1,35 e 1,33 g cm^{-3}, respectivamente, porém SB atinge Bd*LLWR em 1,42 g cm^{-3}, enquanto DM não apresenta esse parâmetro para o intervalo de Bd analisado.

Com o aumento da densidade em LV foi observado limitação na θ, primeiramente pela PR na Bd de 1,30, 1,34, 1,35 e 1,32 g cm^{-3} nos preparos MT, CT, SB e DM, respectivamente. Posteriormente passa a limitar a θ a AP nos preparos MT, CT e SB (1,40, 1,41 e 1,39 g cm^{-3}) enquanto a Bd*LLWR somente foi alcançada nos preparos MT e SB (1,47 e 1.50 g cm^{-3}).

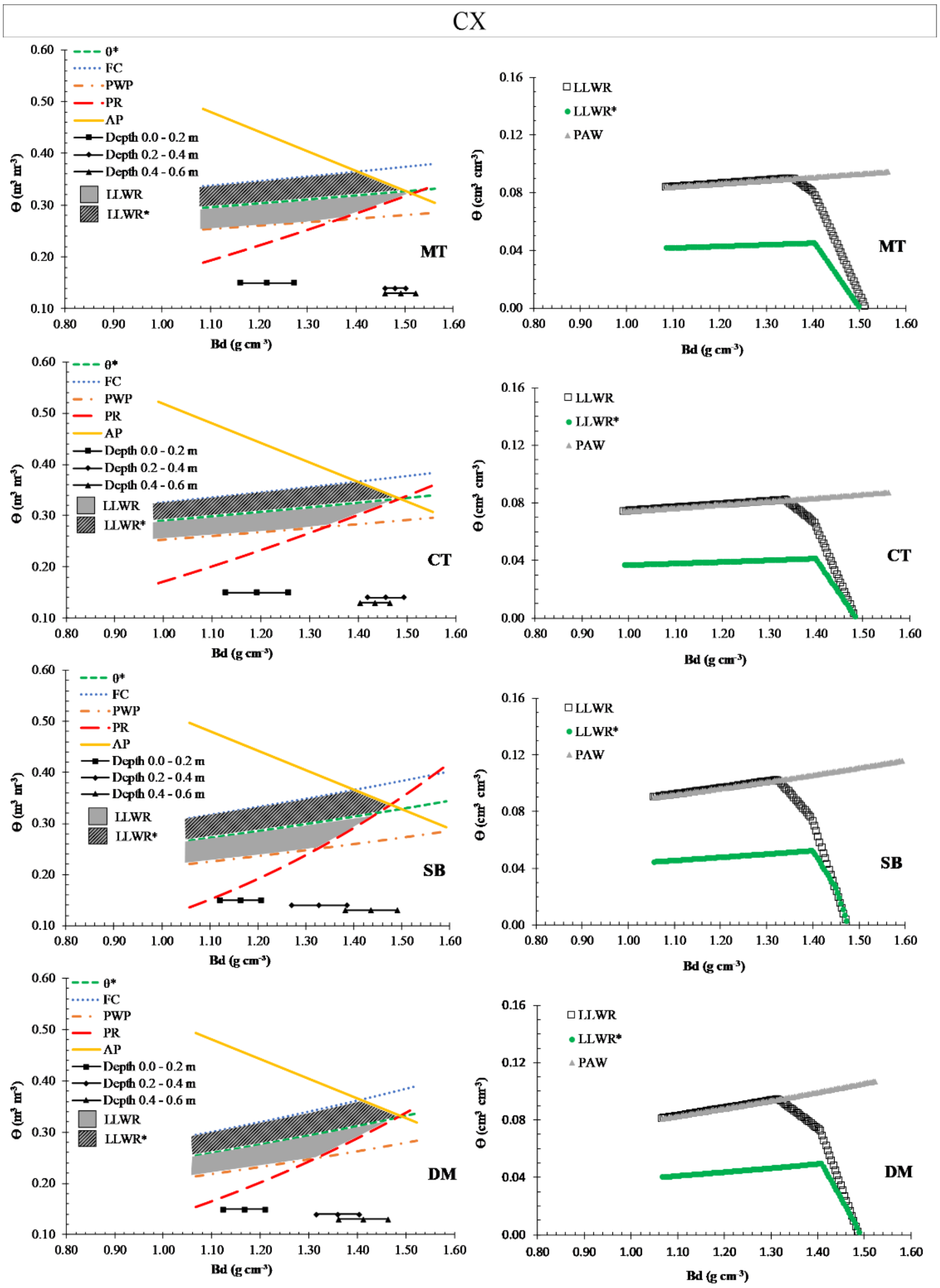

Figura 2. Modelagem da variação do conteúdo de água (θ), capacidade de campo (FC), ponto de murcha permanente (PWP), porosidade de aeração de 0.10 m^3m^{-3} (AP), resistência do solo a penetração de 3 MPa (PR), umidade crítica com fator de depleção de 0,55 (θ*) em função da densidade do solo (Bd). A área colorida representa o intervalo hídrico ótimo (LLWR), a área hachurada representa o intervalo hídrico ótimo crítico (LLWR*), ambas usando todas as amostras coletadas em cada preparo de solo no Cambissolo (CX); linhas horizontais representam o intervalo de confiança da Bd para cada profundidade (lado esquerdo). Representação gráfica do conteúdo de água (θ) em função da Bd para conteúdo de água disponível (PAW), LLWR e LLWR* (lado direito).

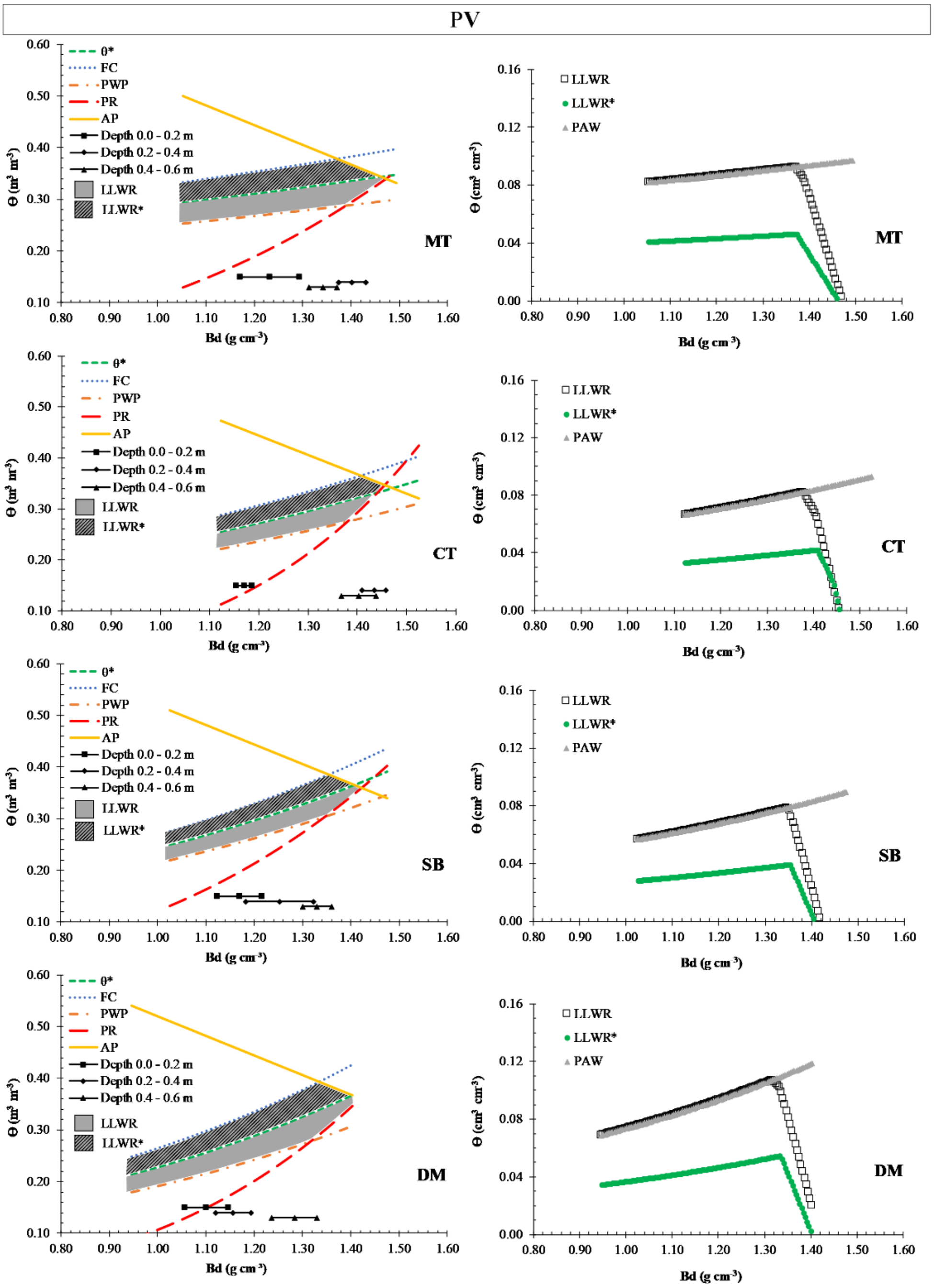

Figura 3. Modelagem da variação do conteúdo de água (θ), capacidade de campo (FC), ponto de murcha permanente (PWP), porosidade de aeração de 0.10 m^3m^{-3} (AP), resistência do solo a penetração de 3 MPa (PR), umidade crítica com fator de depleção de 0,55 (θ*) em função da densidade do solo (Bd). A área colorida representa o intervalo hídrico ótimo (LLWR), a área hachurada representa o intervalo hídrico ótimo crítico (LLWR*), ambas usando todas as amostras coletadas em cada preparo de solo no Argissolo (PV); linhas horizontais representam o intervalo de confiança da Bd para cada profundidade (lado esquerdo). Representação gráfica do conteúdo de água (θ) em função da Bd para conteúdo de água disponível (PAW), LLWR e LLWR* (lado direito).

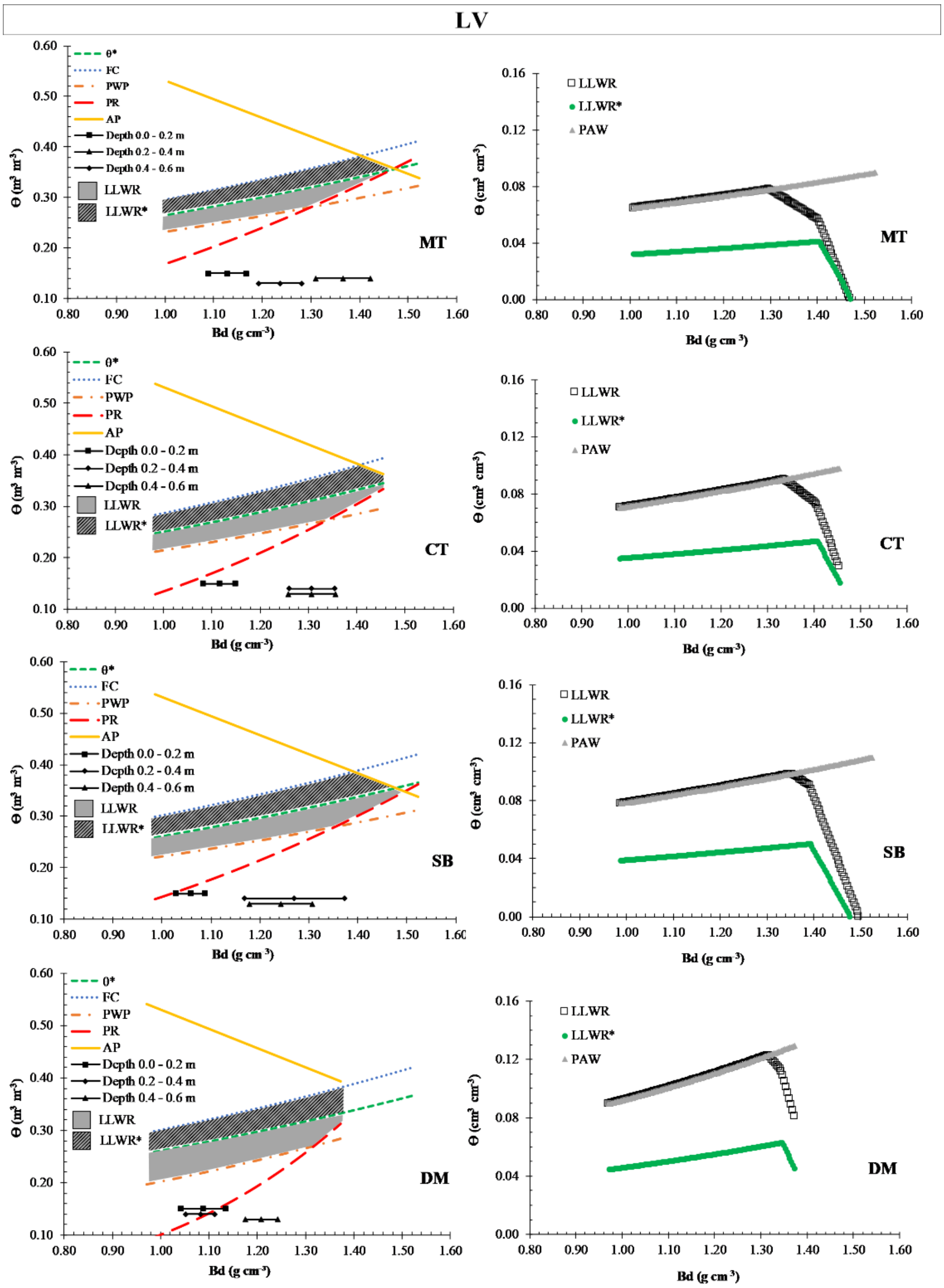

Figura 4. Modelagem da variação do conteúdo de água (θ), capacidade de campo (FC), ponto de murcha permanente (PWP), porosidade de aeração de 0.10 m^3m^{-3} (AP), resistência do solo a penetração de 3 MPa (PR), umidade crítica com fator de depleção de 0,55 (θ*) em função da densidade do solo (Bd). A área colorida representa o intervalo hídrico ótimo (LLWR), a área hachurada representa o intervalo hídrico ótimo crítico (LLWR*), ambas usando todas as amostras coletadas em cada preparo de solo no Latossolo (LV); linhas horizontais representam o intervalo de confiança da Bd para cada profundidade (lado esquerdo). Representação gráfica do conteúdo de água (θ) em função da Bd para conteúdo de água disponível (PAW), LLWR e LLWR* (lado direito).

Por outro lado, quando se observa o intervalo de confiança da Bd de cada profundidade em cada solo e preparo, nota-se que há um desempenho melhor de SB e DM, pois promoveu alívio estrutural em maior profundidade, melhorou a aeração do solo e reduzem a Bd na profundidade de 0,2 – 0,4 m no CX e 0,2 – 0,4 e 0,4 – 0,6 m em PV e LV (Figura 1). De maneira diferente, principalmente em CX, devida a não mobilização do solo pelo MT e reduzida profundidade do preparo CT, o intervalo da Bd das profundidades 0,2 – 0,4 e 0,4 – 0,6 m apresentam valores de Bd acima da Bd*LLWR, assim como o preparo SB em 0,4 – 0,6 m (Figura 2). No PV apenas o preparo CT apresentou Bd superior à Bd*LLWR na profundidade de 0,2 – 0,4 m. Por outro lado no LV essas profundidades experimentam limitações quanto a PR e AP, contudo não atingiu a Bd*LLWR (Figura 2).

3.4.Intervalo hídrico ótimo com umidade crítica (LLWR)*

Com o intiuito de melhorar a acurácia da modelagem do conteúdo de água não limitante para o rendimento das culturas (Silva et al., 2015) utilizou-se a θ* como limite inferior do LLWR em função da Bd (Figuras 2, 3 e 4).

Via de regra, o LLWR* foi menor que o LLWR tradicional para a Bd média observada (Tabela 5). Comparando os modelos pela área hachurada (Figura 2, 3 e 4), diferentemente do modelo tradicional de LLWR, no LLWR* o limite inferior, majoritariamente, foi a θ* tornando a própria como fator mais limitante que outros parâmetros físicos como θ_{PWP} e θ_{PR}. Apenas em duas ocasiões em que a PR apresentou maior limitação ao LLWR*, a partir de 1,45 g cm^{-3} em SB-CX e 1,44 g cm^{-3} CT-PV, no entanto com pouca relevância pois estes valores estão muito próximos da Bd*LLWR*, 1,48 e 1,45 g cm^{-3}, respectivamente.

Analisando os parâmetros de contorno, o limitante superior do LLWR* é o mesmo para LLWR (resultados descritos anteriormente), porém, por ocasião da inserção da θ* houve alteração Bd*LLWR*. Isso ocorreu pois a θ* limitou com maior intensidade que os parâmetros θ_{PWP} e θ_{PR}, de tal maneira que nos preparos-solo MT-CX, MT, SB e DM-PV e SB-LV obtiveram Bd*LLWR* menor que a Bd*LLWR (Tabela 5; Figura 2). Porém, quem provocou maior limitação no LLWR* foi a AP, levando a maioria dos preparos nas três classes de solo a atingirem a Bd*LLWR* (Tabela 5).

Analisando o intervalo de Bd em relação ao LLWR* observa-se que os mesmos preparos que apresentaram valores de Bd maiores que a Bd*LLWR também presentaram para a Bd*LLWR*. Isso indica que nessas profundidades existem severas restrições ao desenvolvimento vegetal, seja pela restrição de θ ou por impedimento físico causado pela alta densidade ou déficit de aeração.

Observando a análise de LLWR para entendermos o efeito do manejo sobre a qualidade física do solo, com foco em cultura de produção, como neste caso a Atemóia, percebe-se que sobre essa ótica a introdução da θ* teve uma melhor leitura da situação. Essa abordagem se concentra na umidade onde o estresse hídrico não prejudica a produção, apesar de já provocar estresse hídrico fisiológico nas plantas, o que é mais útil pois em condições menos úmidas, mesmo corrigindo a situação algum prejuízo na produtividade já foi consumado.

4. Discussão

4.1.Densidade do solo

Trabalhos que relacionam as características morfológicas de classes de solos em relação ao crescimento das plantas ou ao manejo são escassos. Geralmente relacionam as propriedades físicas do solo ao manejo apenas na camada arável, em média 0 – 0,30 m, e não consideram as características morfológicas e pedogenéticas de cada horizonte na discussão, assim como sua influência no crescimento e produção das culturas (Lipiec; Hatano, 2003; Imhoff et al., 2004; Nhantumbo; Cambule, 2006; Keller; Håkansson, 2010; Suzuki et al., 2013; Sato et al., 2015; Pott et al., 2019; Etana et al., 2020).

A ausência de diferenças estatísticas na profundidade de 0 – 0,2 m entre os preparos em cada solo se deve principalmente ao fato de que todos os preparos, exceto MT, foram mobilizados intensamente (1 aração e 2 gradagens no mínimo, vide **2.2.**), promovendo homogeneização dessa profundidade. Aliado a isso, principalmente em CX e LV, a elevada densidade e vigor da vegetação (braquiária semeada + plantas espontâneas) promoveu elevado volume de raízes superficiais que auxiliaram a redução da Bd (Rocha et al., 2016; Barbosa et al., 2020; Silva et al., 2021). Isso não foi observado apenas no preparo MT em PV, pois, além da ausência de aração e gradagens, nesse tratamento foi observado menor vigor da braquiária e menor ocorrência de vegetação expontanea, o que justifica maior Bd em relação aos demais preparos (Figura 1).

Outro ponto importante que explica a diferença de Bd em MT no PV é a reconsolidação, potencializada pelo menor vigor vegetativo, ou seja, menor influência biológica sobre a agregação. O fenômeno de reconsolidação é resultado do rearranjo das partículas do solo, principalmente argila, em novas posições de energia mínima livre e do fortalecimento das ligações de cimentação em novos pontos de contato entre pares de partículas minerais (Bonetti et al., 2017). Logo, em solos com maior teor de argila, maior grau de intemperismo e maior concentração de óxidos, que por sua vez agem como cimentante (Bonetti et al., 2017), favorecem esse fenômeno. A reconsolidação ou age-hardening phenomenon (Dexter et al., 1988; Moraes et al., 2017; Utomo; Dexter, 1981) é um processo natural, que ocorre de forma mais lenta em profundidade do que na superfície e depende principalmente da precipitação acumulada (Busscher et al.; 2002; Simões et al., 2009) e ciclos de umedecimento e secagem (Hillel et al., 2003), mesmo não havendo tráfego de máquinas (Drescher et al., 2011).

CX e PV são classes completamente diferentes, mas com a semelhança de possuírem camadas restritivas naturais em subsuperfície. Restrições físicas são comuns em CX sob condições naturais, sobretudo na região de estudo (Curi et al. 2020). Em CX a restrição é imposta pelo aumento da Bd a partir de 0.05 m, do horizonte Bi em diante, causada principalmente pelo aumento expressivo da fração silte, aproximadamente 2 vezes em relação ao horizonte Ap (Tabela 1). Essa fração tem baixíssima capacidade de agregação, reduz a porosidade do solo, favorece o empacotamento das partículas e aumento da Bd, o que é intrínseco à maioria dos solos incluídos nesta classe. Dada sua mineralogia caulinítica os Cambissolos apresentam no horizonte Bi estrutura em blocos, enquanto os horizontes subjacentes, ausência de estrutura ou estrutura maciça, o que caracteriza o adensamento natural da classe (Pereira et al., 2010; Santos et al., 2013).

O adensamento natural promove aumento da resistência mecânica do solo para o preparo. No entanto, o preparo profundo do solo proporcionou alívio estrutural medido pela redução da Bd, especialmente nos tratamentos SB e DM em 0,20 – 0,40 m (Figura 1), como observado por outros trabalhos, sendo efetivo para melhorar a qualidade física do solo para as culturas em solos naturalmente adensados (Barbosa et al., 2020; Silva et al., 2021). De maneira geral a maior amplitude de variação dos valores de Bd entre amostras ocorreu no preparo com SB. Isso porque, o implemento rompe barreiras de maior resistência, mas não mistura o solo de maneira homogênea, deixando o solo de maneira geral mais solto, mas ainda com torrões. O efeito desse tratamento poderia, talvez, ser melhor visualizado numa escala maior que a de um cilindro de amostra indeformada, como por exemplo perfil cultural (Tavares Filho et al., 1999) e/ou mapa 2D da resistência a penetração (Azevedo et al., 2022; Jonard et al., 2013).

Por outro lado, os Argissolos têm pedogênese avançada (podzolização) que leva ao acúmulo de argila, pela argiluviação, formando o horizonte sub-superficial B textural (Santos et al., 2013). As características dessas classes de solo exercem efeito sobre o preparo de solo, especialmente na profundidade de 0,20 – 0,40 m, onde aumentam a dificuldade de execução da operação, reduzindo a eficiência do preparo, principalmente abaixo dessa profundidade (Figura 1). Na camada de 0,2 – 0,4 m os preparos profundos foram os responsáveis pelas menores Bd, causando diferenças significativas, essencialmente devido ao seu poder de mobilização do solo. A ausência do efeito dos preparos CT e MT abaixo de 0,20 m é explicada pela reduzida profundidade de ação desses implementos, onde MT não houve mobilização e CT mobilizou apenas até 0,25 m.

Tal como CX, PV também apresentou horizonte com restrições físicas a partir de 0,12 m (Tabela 1). No entanto em comparação a CX, o efeito do preparo foi melhor em PV, apresentando maior diferença entre MT e DM, na profundidade de 0,20 – 0,40 m. Isso mostra que os preparos profundos foram mais eficientes em PV do que em CX. Em ambos os solos a camada adensada (origem pedogenética) pode apresentar comportamento semelhante a uma camada compactada, o que pode aumentar o risco de erosão hídrica, diminuir a infiltração e o desenvolvimento radicular (Souza et al. 2008; Bengough et al., 2011; Gao et al. 2016; Oliveira et al., 2019).

Em contrapartida, as pequenas diferenças observadas na profundidade de 0.4-0.6 m podem ser justificadas pela baixa eficiência dos implementos em atingir por completo a profundidade requerida, o que foi de fato observado no momento do preparo dada a dificuldade de execução. Exceto em LV onde o preparo pode não ter tido efeito sobre o ambiente já proporcionado pela estrutura natural do solo. Os Latossolos possuem avançado grau de intemperismo, por predominar no seu desenvolvimento os processos de remoção, transformação e translocação, que levam a formação de um perfil praticamente homogêneo (Santos et al., 2013). Sua mineralogia oxídica proporciona boa agregação, formando estrutura granular muito pequena que promove elevada porosidade (Ferreira et al., 1999), o que justifica as menores médias de Bd em todas as situações.

Peixoto et al. (2019a) ranquearam propriedades do solo mais sensíveis para detectar alterações estruturais devido ao preparo do solo por algoritmo de machine-learning, no qual a RP foi mais importante e a Bd apareceu na sexta posição, concordando com estudo prévio de Abreu et al. (2004), que também mostraram maior sensibilidade da RP em relação Bd. Portanto, tomar a Bd como único critério para avaliar a qualidade física do solo ou eficiência de preparo, pode incorrer em erros.

4.2.Modelagem do intervalo hídrico ótimo

O LLWR foi construído a partir de todas as observações de Bd, definindo a faixa total de variação do modelo. Isso permite que se possa visualizar as alterações ao longo do LLWR e antecipar possíveis efeitos sobre o aumento da Bd média da área (Serafim et al., 2013b). Os modelos gerados para LLWR e LLWR* indicam limitações físicas para o crescimento das plantas nas profundidades de 0,2 – 0,4 m e 0,4 – 0,6 m.

A água disponível do solo para as plantas definida pelo LLWR foi muito semelhante ao PAW (Tabela 5). O PAW, segundo a classificação de Hall et al. (1977) e White (2006) em apenas SB-CX e DM-LV atingiram valores considerados “limitados” (0,15 a 0,10 m^3 m^{-3}) enquanto os demais foram considerados “pobres” (< 0,10 m^3 m^{-3}). Por se tratar de solos de região tropical essa classificação pode não ser adequada, por não considerar nela questões estruturais desses solos. Por exemplo, a classe dos LV utilizada nesse trabalho possui estrutura granular muito pequena e estável praticamente em todo perfil, favorecendo elevada porosidade (Ferreira et al., 1999), podendo este solo apresentar comportamento físico-hídrico de um solo arenoso. Porém, segundo Nascimento et al. (2019) a proximidade dos valores de LLWR e PAW revelam pouco ou nenhum impacto da PR e AP sobre a θ_{LLWR}. Ou seja, os valores de Bd dentro desse intervalo são considerados como o melhor cenário dentro do modelo.

Apesar da semelhança entre os valores de PAW com LLWR, este último como ferramenta para essa aferição do conteúdo de água se mostra muito mais sensível, principalmente devido ao número de fatores envolvendo a definição. Porém, ao inserir a θ* (umidade crítica) o modelo (LLWR*) se torna ainda mais sensível, pois passa a ter um fator mais limitante que considera um parâmetro fisiológico mais restritivo que a θ_{PWP}, onde as plantas já passam por estresse hídrico que compromete a produção (Silva et al., 2015). De maneira geral, considerando todos os limitantes testados, a θ foi melhor estimada utilizando a θ*, pois o estresse hídrico na forma de transpiração reduzida foi mais limitante para as plantas em termos produtivos que o desenvolvimento deficiente das raízes provocado pelo aumento da PR ou pela murcha permanente em condição de θ_{PWP} (Moura et al., 2021).

Considerando as diferenças contrastantes entre as classes de solo escolhidas nota-se que o comportamento dos preparos de solo analisados pelo LLWR e LLWR* também foi diferente. Comparando LLWR e LLWR* (as áreas hachuradas, Figuras 2, 3 e 4) em todas as classes e preparos observa-se que a θ* foi o fator mais limitante. A inserção da θ* na avaliação do LLWR além de reduzir pela metade a faixa de água disponível às plantas, tende a reduzir também a Bd*LLWR* (Tabela 5). Porém o ambiente delimitado pelo LLWR* foi mais úmido, sendo reduzido o intervalo entre o limite superior (θ_{FC}) e o limite inferior (θ*). LLWR* passou a ser mais restrito que o θ_{PWP} e na maior parte dos casos que a θ_{PR}. Como as condições limitantes da θ* possuem maior conteúdo água no solo a θ_{PWP} se torna irrelevante, como observado por Moura et al. (2021), além disso, limitações do LLWR* pela θ_{PR} foram observadas apenas em duas situações SB-CX e CT-PV, no entanto como pouca importância dada a proximidade do valor de Bd da limitação à Bd*LLWR*. Isso se deve ao fato de que o aumento da θ compensa a fricção ou coesão entre as partículas, justificando a razão que para se manter a PR a 3MPa a Bd aumenta (Tormena et al., 2007).

O intervalo de confiança da Bd permitiu visualizar a condição atual do LLWR, sem deixar de expor os valores extremos de Bd (modelo) (Serafim et al. 2013b). A amplitude dos valores permite avaliar o LLWR atual em 95% das amostras analisadas. A profundidade de 0 –

0,2 m apresentou a melhor qualidade física, sem restrições quanto a disponibilidade de água para as plantas, independente do tratamento e da classe de solo.

As condições ótimas de LLWR foram encontradas para os menores valores de Bd, enquanto o LLWR nulo, nos maiores valores de Bd (Bd*LLWR e Bd*LLWR*), isso pode corresponder a valores isolados (outlies) dentro da área amostrada (Serafim et al., 2013b). Vários fatores unidos culminam para a melhor qualidade física da profundidade de 0 – 0,2 m. O principal fato é que os preparos CT, SB e DM mobilizam intensamente essa camada. Somado a isso temos que nessa profundidade não existem restrições físicas naturais ou antrópicas e em MT, cujo preparo não mobilizou o solo, pode ser entendido como estado que antecede o preparo ou testemunha e seu comportamento físico está diretamente associado às características intrínsecas da classe de solo (Tabela 1).

Por outro lado, em todos os casos, exceto MT-CX (mencionado anteriormente, vide **4.1.**), a cobertura vegetal, tanto nas entrelinhas como entre plantas favoreceu a melhora da qualidade estrutural. Vale ressaltar que, mesmo havendo valor elevado da Bd média para o preparo MT-PV, em 0,2 – 0,4 m não houve limitação hídrica indicada pelo LLWR para essa profundidade. Os efeitos benéficos da implantação de gramínea nas entrelinhas de culturas perenes, como o cafeeiro, têm sido relatados por vários autores na literatura (Rocha et al., 2016; Barbosa et al., 2020; Silva et al., 2021), o que provoca além da redução da densidade do solo, incorporação de matéria orgânica, aumento da infiltração de água.

Em todas as classes de solo o LLWR apresentou restrições físicas nas profundidades de 0,2 – 0,4 m e 0,4 – 0,6 m para o intervalo de confiança da Bd. Os preparos MT, CT e SB no CX, atingiram o valor de densidade crítica do modelo (LLWR*) ora na profundidade de 0,2 – 0,4 m (CT) ora na de0,4 – 0,6 m (MT e SB) (Figura 2). Tal fato leva a crer que mesmo os preparos profundos que pretendem atingir maiores profundidades (SB – 0,45 m; DM – 0,6 m), estes não foram eficientes no CX e apresentando nesses casos restrições severas ao crescimento radicular, principalmente na profundidade 0,4 – 0,6 m. Porém, esses preparos apresentaram o melhor desempenho no CX, com maior redução de Bd ao longo do perfil. Como citado anteriormente a restrição física natural de CX, imposta pela estrutura em blocos e elevada concentração de silte, reduz a efetividade do preparo, inclusive de atingir a profundidade esperada, observada no preparo DM. Preparos semelhantes foram testados por Barbosa et al., (2020) e Silva et al. (2021) em Inceptsol que perceberam melhora das propriedades físico-hídricas.

No PV é importante mencionar que, apesar de haver diferenças estatísticas entre as médias das Bd entre MT e CT, a Bd*LLWR em MT foi maior do que no CT, assim o intervalo de confiança de CT atingiu a Bd*LLWR. Aqui pode-se observar como a faixa de variação de Bd para criação do modelo geral influenciou na interpretação do intervalo de confiança da Bd. Por outro lado, os preparos profundos foram eficazes em reduzir a Bd nas profundidades de 0,2 – 0,4 e 0,4 – 0,6 m, não apresentando nessa classe restrições físicas dignas de menção. Comparando aqui as áreas coloridas do gráfico de DM (Figura 2) observa-se que a maior limitação imposta pela θ* leva o LLWR* a zero o que não ocorre para o LLWR, devido a maior faixa de umidade. Nessa classe, ocorreu adensamento natural a partir de 0,12 m (Tabela 1) que foi pouco influenciado pelos preparos. CT por exemplo, preconizou mobilizar até 0,25 m obtendo resultados positivos na camada superficial de 0 – 0,2 m, assim como SB e DM que reduziram a Bd das profundidades de 0,2 – 0,4 e 0,4 – 0,6 m em comparação ao MT, deslocando o intervalo de confiança para esquerda, onde não ocorrem restrições físicas à disponibilidade de água, ambos apresentando o melhor desempenho nessa classe.

No LV a primeira restrição ao LLWR, resultado do aumento de Bd, foi causada pela θ_{PR} e em seguida a θ_{AP}, exceto no preparo DM onde, dentro do intervalo de Bd do modelo, a θ_{AP} não reduz ao ponto de causar limitação. LV A Bd*LLWR foi atingida apenas em dois tratamentos MT (1.47 cm^3 cm^{-3}) e SB (1.42 cm^3 cm^{-3}), em CT e DM, para o intervalo de Bd observado, o modelo não converge para a Bd*LLWR. Observando o intervalo de confiança da Bd nenhuma profundidade atingiu o Bd*LLWR*, por essa ótica, tão pouco apresentam restrições físicas. As melhores condições físicas foram observadas no LV em grande parte graças às propriedades naturais, como já mencionado anteriormente (vide **4.1.**), onde devido boa agregação elevada porosidade, derivadas de sua estrutura granular muito pequena de alta estabilidade (Ferreira et al., 1999; Silva et al., 2015; Silva et al., 2016). O preparo de melhor desempenho no LV foi sem dúvidas o DM, no entanto, CT pode ser uma opção viável por se tratar de uma operação menos onerosa e de maior facilidade de execução.

O DM demostrou efeito superior aos demais preparos, levando os modelos de LLWR nos solos a não atingirem a Bd*LLWR em PV e LV, reduzindo a Bd_{max} em comparação aos demais preparos em todo os solos. O preparo profundo usando misturador de solo – DM rompe e mistura as camadas restritivas, diferentemente do SB que rompe sem misturar, porém, ambos têm a capacidade de aumentar a porosidade do solo (Schneider et al., 2017; Peixoto et al., 2019; 2020) aumentando a infiltração do solo (Singh et al., 2019; Silva et al., 2021).

5. Conclusões

A qualidade física do solo para o crescimento de plantas perenes foi modelada por meio do intervalo hídrico ótimo (LLWR), considerando o efeito de métodos de preparo do solo. O tipo de preparo do solo, assim como as características intrínsecas da classe de solo impactaram nos atributos físicos do solo. A inserção da umidade crítica do solo (θ*) como limite inferior do intervalo hídrico ótimo crítico (LLWR*) substituindo a umidade no ponto de murcha permanente (θ_{PWP}) possibilitou maior exatidão na definição da faixa de conteúdo de água no solo com condições adequadas às plantas, indicando em que condição a planta poderá sofrer déficit hídrico no solo sem que seu potencial produtivo seja comprometido.

Comparando os métodos de preparo do solo, o melhor efeito na qualidade física do solo avaliado por Bd e LLWR* foi promovido pelo preparo profundo DM, o qual tem a premissa de misturar a camada de 0-0.60 m do solo, proporcionando maior alívio estrutural no perfil. Considerando as condições de estrutura do solo em cada classe, e baseado nos resultados obtidos nesse estudo, foi possível sugerir um preparo de solo, a partir do seu desemprenho, para cada classe de solo, assim: Deep Mixing till (DM) para o Cambissolo (CX), Subsoiling (SB) ou Deep Mixing till (DM) para Argissolo (PV) e Conventional till (CT) para o Latossolo (LV).

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THIRD PART - CONCLUDING REMARKS

CONCLUDING REMARKS

O objetivo desta tese foi avaliar o efeito de métodos de preparo do solo na implantação de culturas perenes sobre a qualidade física do solo e disponibilidade de água para a planta, considerando como esses efeitos se diferenciam em três classes de solo morfogeneticamente contrastantes em termos de textura, estrutura, profundidade efetiva e mineralogia - Cambissolo/Dystrustept, Argissolo/Hapludult e Latossolo/Haplustox.

O fechamento desse trabalho indica que as hipóteses foram atendidas, assim como os objetivos foram alcançados. Nossos resultados mostraram que as classes de solo responderam de forma diferente aos preparos de solo aplicados. O maior efeito sobre estrutura do solo, que proporcionou melhor qualidade física, foi alcançado pelos preparos profundo, os quais garantiram maior alívio estrutural. O efeito dos preparos foi melhor visualizado no Cambissolo/Dystrustept e Argissolo/Hapludult, que apresentavam restrições físicas naturais (camadas adensadas). No Latossolo/Hapludox devido a sua elevada estabilidade e qualidade estrutural, promovida por sua estrutura granular, o efeito dos tratamentos foi menos expressivo, não superando o controle genético do solo.

Portanto, a classe do solo tem implicações importantes para o efeito do sistema de preparo, especialmente quando se avalia o efeito do preparo em maiores profundidades. Assim, a decisão da melhor estratégia de preparo do solo deve envolver as condições morfogenéticas / propriedades da classe do solo, especialmente em maiores profundidades, a fim de garantir um sistema agrícola mais sustentável e produtivo, evitando operações de preparo desnecessárias.

Do ponto de vista instrumental utilizado para as avaliaçãoes podemos concluir que o VESS não demonstrou sensibilidade para apontar as diferenças entre os preparos de solo e que a densidade do solo sozinha não é um bom indicador da qualidade física e das mudanças estruturais causadas pelas práticas de preparo. Por outro lado, a resistividade apresentou-se como uma ferramenta com potencial para identificação das mudanças estruturais do solo, necessitando ainda de mais estudo para confirmação dessa técnica para avaliações nos moldes desse trabalho.

Os indicadores que apresentaram maior variação dos dados e consequentemente possuem maior poder explicativo foram capacidade de aeração (AC), capacidade de campo relativa (RFC), macroporosidade (Pmac), densidade do solo (Bd) e índice S (Sgi). A partir desses indicadores foi possível observar que tanto o preparo como a classe de solo impactaram os atributos físicos do solo. Além disso, a inserção da umidade crítica do solo (θ^*) na determinação do intervalo hídrico ótimo crítico (LLWR*) possibilitou maior exatidão na definição da faixa de conteúdo de água no solo.

Finalmente, considerando as condições de estrutura do solo em cada classe e baseado nos resultados obtidos nessa tese, foi possível sugerir um preparo de solo para cada classe de solo, assim sendo: Deep Mixing till (DM) para o Cambissolo/Dystrustept (CX), Subsoiling (SB) ou Deep Mixing till (DM) para Argissolo/Haplusdult (PV) e Conventional till (CT) para o Latossolo/Haplustox (LV).