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VINÍCIUS RIBAMAR ALENCAR MACEDO

ATRIBUTOS DO SOLO QUE DETERMINAM A PRODUTIVIDADE DAS CULTURAS PARA PREVENIR A DEGRADAÇÃO DE SOLOS ESTRUTURALMENTE FRÁGEIS

São Luís - MA
2018

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Engenheiro Agrônomo

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Orientador: Prof. Dr. Emanoel Gomes de Moura

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RESUMO

Na região centro norte maranhense, os solos têm maior tendência a degradação em função de algumas de suas características, tais como, alto nível de intemperização, decomposição acelerada da matéria orgânica do solo e predisposição a coesão. A coesão impossibilita ou dificulta o preparo do solo com aração e gradagem, uma vez que a aplicação dessas técnicas pode aumentar a compactação destes solos. Estas características dificultam o desenvolvimento da agricultura. Além disso, é predominante o uso do sistema de corte e queima para plantio de culturas agrícolas, um sistema ultrapassado que já não se sustenta, pela ausência de áreas para desbravar e contribuição com a degradação dos recursos naturais. Dada essas circunstâncias e ao aumento da preocupação da sociedade com a forma de produzir alimentos, é necessário a adoção de práticas agrícolas que aumentem a produtividade das culturas, considerando as peculiaridades de cada região, permitindo atender às necessidades do presente sem comprometer a produção alimentícia de futuras gerações. Portanto, a eficiência do uso de nutrientes é o principal fator que influencia o manejo dos agroecossistemas no trópico úmido devido à baixa capacidade de enraizamento das plantas no solo e altas taxas de perda de nutrientes. Alguns estudos desenvolvidos na região, tem sugerido o uso do sistema do plantio direto na palha de leguminosas arbóreas (cultivo em aleias) como prática de manejo. Esse sistema tem se destacado na melhoria de propriedades físicas, químicas e biológicas do solo. Tais vantagens poderiam permitir intensificar a produção pelo aumento da eficiência de uso dos nutrientes e da água com a consequente diminuição da degradação do solo na periferia amazônica. Essas vantagens precisam ser devidamente mensuradas por indicadores de qualidade do solo que antes de tudo devem ser sensíveis às variações do manejo, bem correlacionado com as funções desempenhadas pelo solo, capaz de elucidar os processos do ecossistema, ser compreensível, útil para o agricultor e preferencialmente, de fácil e barata mensuração. Baseado nestas experiências, buscou-se aprofundar o entendimento sobre os indicadores que afetam a produção do milho em solo tropical coeso.

Palavras chaves: Cultivo em aleias, Sustentabilidade, Intensificação

ABSTRACT

In the north central region of Maranhao, soils are more prone to degradation due to some of their characteristics, such as high level of weathering, accelerated decomposition of soil organic matter and predisposition to cohesion. The cohesion makes it difficult or difficult to prepare the soil with plowing and harvesting, since the application of this technique can increase the compaction of these soils. These characteristics hamper the development of agriculture. In addition, it is predominant to use the slash and burning system for planting agricultural crops, an outdated system that is no longer supported by the absence of areas to clear and contribution to the degradation of natural resources. Given these circumstances and the increasing concern of society with the way of producing food, it is necessary to adopt agricultural practices that increase crop productivity, taking into account the peculiarities of each region, allowing to meet the needs of the present without compromising the food production of future generations. Therefore, the efficiency of nutrient use is the main factor that influences the management of agro-systems in the humid tropics due to the low capacity of planting in the soil and high rates of nutrient loss. Some studies developed in the region have suggested the use of no-tillage system in tree legume straw (alley cropping) as a management practice. This system has excelled in improving the physical, chemical and biological properties of the soil. Such advantages could allow to intensify the production by increasing the efficiency of use of nutrients and water with the consequent reduction of soil degradation in the Amazonian periphery. These advantages need to be properly measured by soil quality indicators that must first be sensitive to management variations, well correlated with soil functions, able to elucidate ecosystem processes, be understandable, useful to the farmer and preferably, easy and inexpensive measurement. Based on these experiments, we sought to deepen the understanding of the indicators that affect maize production in cohesive tropical soil.

Key words: Alley cropping, sustainability, Intensification

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CAPÍTULO I

1 Introdução Geral

O aumento da pressão demográfica e a constante necessidade de produzir mais alimentos, tem gerado uma crescente conscientização e busca da sociedade por sistemas agrícolas que sejam sustentáveis. Há certa urgência em intensificar a agricultura e, ao mesmo tempo, conservar os recursos naturais como água e solo, bens essenciais à sobrevivência global.

Na região do trópico úmido, especificamente no centro norte maranhense, os solos têm maior tendência a degradação em função de algumas de suas características, tais como alto nível de intemperização, decomposição acelerada da matéria orgânica do solo, baixa capacidade de reter cátions e predisposição a coesão (MOURA *et al.,* 2008a). Essas características dificultam o desenvolvimento da agricultura na região.

O processo de degradação do solo é acelerado pelo sistema de corte e queima, que é baseado no uso do fogo para derrubada de florestas para implantação de pastos e culturas alimentícias. O fogo pode influenciar diretamente as propriedades do solo através de processos de aquecimento e combustão e, indiretamente, através das mudanças na sua cobertura vegetal e redistribuição do solo através da erosão acelerada pós-queimada (SANTIN e DOERR 2016).

A grande adesão ao sistema de corte e queima pela maioria dos pequenos produtores agrícolas se explicava pela rápida limpeza da área e pelo baixo custo, ou ainda porque no ano da implantação, por haver uma grande quantidade de biomassa, ocorre a disponibilização de alguns nutrientes pela cinza (FERRAZ JR, 2004). Além disso, não há um suporte de políticas públicas para fornecer a estes pequenos produtores fertilizantes químicos e implementos agrícolas.

A ausência de grandes extensões de terra, diminuição da produtividade das culturas e o tempo de pousio das áreas agrícolas insuficiente para permitir a recuperação das áreas (VARMA, 2003) gerou a necessidade de se buscar sistemas de manejo do solo mais sustentáveis e determinar quais destes sistemas e quais culturas são mais rentáveis e ocasionam menos degradação aos solos, considerando as características de cada região.

É difícil a recomendação de tecnologias no centro norte do Maranhão que permitam a sustentabilidade dos agroecossistemas em solos originados de rochas sedimentares clásticas, intemperizados e de fertilidade natural baixa (AGUIAR *et al.*, 2010, MOURA *et al.,* 2008 a). Estes solos possuem características de coesão, ou seja, estruturalmente frágeis e possuem um a tendência a perder a maioria dos poros estruturais durante o umedecimento e endurecer durante a secagem, impedindo o desenvolvimento radicular e dificultando os cultivos agrícolas (LEY *et al*., 1995).

Além disso, a presença de altas quantidades de ferro livre e areia fina dificulta a utilização de práticas comuns em outras regiões do Brasil, a exemplo da aração e gradagem para preparo do solo, uma vez que, solos coesos, podem resultar em áreas degradadas onde a camada arável pode ser recompactada pela ação das chuvas intensas, comum no trópico úmido (MOURA *et al*., 2009 e BUSSCHER *et al.,* 2002).

Nestas condições, a eficiência do uso de nutrientes, que é o rendimento por unidade de fertilizante aplicado é o principal fator que influencia o manejo dos agro-sistemas no trópico úmido, devido à baixa capacidade de enraizamento das plantas no solo e altas taxas de perda de nutrientes (MOURA *et al*., 2008b).

Alguns estudos desenvolvidos na região, tem sugerido o uso do sistema do plantio direto na palha de leguminosas arbóreas (cultivo em aleias) como prática de manejo. Esse sistema pode contribuir com sustentabilidade das áreas de plantio e aumento da produtividade das culturas, pois possibilita a reciclagem de nutrientes, melhora a qualidade dos indicadores físicos do solo, aumenta a capacidade de aeração, reduz o impacto causado pelas gotas de chuva e fornece moderadas quantidades de nutrientes (ADEKALU *et al*., 2006; MOURA *et al*., 2013; MOURA *et al*., 2016). Tais vantagens poderiam permitir intensificar a produção e amenizar a degradação do solo na periferia amazônica.

Baseado nestas experiências, buscou-se aprofundar o entendimento sobre os indicadores que afetam a produção do milho em solo tropical estruturalmente frágil.

2 Referencial Teórico

2.1 A Agricultura na Região do Trópico Úmido

A sustentabilidade da agricultura em ambientes tropicais perpassa por inúmeras restrições decorrentes do baixo teor de nutrientes e da rápida mineralização da matéria orgânica do solo (TIESSEN *et al.,* 1994; ZECH *et al.,* 1997). Ademais, a maioria dos solos tropicais atingiu um estágio avançado de intemperismo, o que evidencia que o desgaste químico nos trópicos é bastante acelerado em comparação com a zona temperada (PASRICHA e FOX, 1993). Assim, muitos solos tropicais dependem da reciclagem de nutrientes da matéria orgânica do solo para manter a fertilidade.

No trópico úmido maranhense, região centro norte, a maioria dos solos é predominantemente arenoso na textura da superfície e predisposto a coesão, o que o torna estruturalmente instável logo após a remoção da floresta ou da pastagem para implantação dos cultivos agrícolas (MOURA *et al*., 2008).

Entende-se como coesão uma forma particular de comportamento de solo em que este se torna muito duro quando seco, a ponto de dificultar ou mesmo impossibilitar o desenvolvimento dos vegetais, e friável quando úmido diminuindo a coesão (NORTHCOTE, 1975; EMBRAPA, 2013).

Os solos coesos têm estrutura frágil porque são constituídos basicamente por areia fina e silte (BUSSCHER *et al*., 2002). Mullins *et al* (1987) relataram uma explicação física para o termo coeso e estabeleceram uma série de problemas agronômicos associados, incluindo o tempo restrito de cultivos e o aumento da resistência física para o crescimento das raízes. Logo, a coesão impossibilita ou dificulta o preparo do solo com aração e gradagem, uma vez que a aplicação dessa técnica pode aumentar ainda mais a compactação destes solos.

Nessas circunstâncias, no centro norte maranhense, o método mais frequente usado na conversão dos ecossistemas naturais em áreas agrícolas é o corte seguido de queima, o qual ocasiona quebra dos ciclos biogeoquímicos, com liberação de nutrientes imobilizados na biomassa florestal e emissão de partículas e gases para a atmosfera (BONILLA, 2005). O uso demasiado desse sistema ocorre em função de custos reduzidos para preparo das áreas de plantio e pelo incremento temporário de nutrientes oriundos das cinzas, que não se mantem nos anos seguintes obrigando o agricultor a mudar de área.

Para aumentar a produtividade das culturas alimentícias e intensificar o uso agrícola dos solos sem abrir novas áreas, é preciso focar na melhoria da qualidade do solo e no aumento da eficiência do uso de nutrientes. Desse modo, a eficiência do uso dos nutrientes é o principal fator que afeta a produtividade no manejo de agroecossistemas do trópico úmido devido a menor absorção e altas perdas de nutrientes (MOURA *et al.,* 2012).

Vale ressaltar que as altas temperaturas e as precipitações intensas dificultam ainda mais o manejo do solo tropical coeso, uma vez que contribuem com os processos de intemperização dos solos tropicais.

Portanto, diferentes estratégias de manejo do solo devem ser adotadas com a finalidade de aumentar a produtividade das culturas por unidade de área e diminuir o impacto da produção de alimentos ao meio ambiente. Isso se explica pela insuficiência de terras aptas para expandir as fronteiras agrícolas e pela necessidade de redução do uso de fontes não renováveis. Espera-se também manter a fertilidade e biodiversidade dos solos, reduzir efeitos da erosão e aumentar a eficiência do uso de nutrientes (HOCHMAN *et al*., 2011, GEHRING *et al*., 2013).

A partir disso, alguns trabalhos desenvolvidos no trópico úmido têm demonstrado que o uso das leguminosas arbóreas, como por exemplo: *Leucaena leucocephala, Gliricidia sepium, Acacia mangium e Clitoria farchildiana* como cobertura do solo podem proporcionar significativas melhorias nas propriedades físicas, químicas e biológica do solo (FERRAZ, 2004; MOURA, 2013; AGUIAR *et al*., 2010).

Moura *et al* (2015) estudaram a relação entre as exigências ecológicas da macrofauna do solo e seus impactos sobre os principais indicadores físicos e químicos na região do trópico úmido. Este estudo relatou que a aplicação de resíduos de leguminosas com alta relação C/N (*Gliricidia sepium e Acacia mangium*) aumentaram as funções ecossistêmicas em um sistema de plantio direto, pois favoreceu a abundância de grupos funcionais do solo, predadores e transformadores de liteira. A liteira transformada associada com o efeito da cobertura melhora vários atributos, tais como infiltração da água, porosidade do solo, densidade do solo, estoque de carbono da liteira, fração leve livre da matéria orgânica do solo (MOS) e carbono orgânico total.

Somente o uso de cobertura com biomassa de leguminosas arbóreas não garante altos níveis de nutrientes na zona radicular, o que sugere a adoção de estratégias que incluam fertilizantes minerais para aumentar a quantidade de nutrientes durante os estágios críticos da cultura (AGUIAR *et al*., 2010). Há que se identificar, reduzir o uso ineficiente dos nutrientes e simultaneamente intensificar a produção, manter a fertilidade do solo, a biodiversidade e reduzir os impactos ambientais da agricultura (AGUIAR *et al*., 2014).

Moura *et al*., (2016) sugerem o uso da gessagem associada ao uso de leguminosas para solos coesos, pois melhora o enraizamento das culturas, aumenta a porosidade do solo e diminui a resistência a penetração. Este estudo avaliou a aplicação de 6 e 12 toneladas/ha de gesso, no qual se observou pequenas diferenças no conteúdo de cálcio quando se aplicou a menor dose de gesso combinado com leguminosas em comparação ao tratamento que recebeu apenas gesso, o que permite a recomendação dessa dosagem para solos tropicais arenosos com baixa capacidade de retenção de cátions.

Deste modo, é imprescindível estimular o desenvolvimento de práticas e sistemas sustentáveis de uso do solo e conservação da água por causa da degradação generalizada dos recursos ambientais (MOTAVALLI *et al.*, 2013).

Portanto, há que se considerar o impacto das mudanças de uso do solo, para poder enfim garantir que determinada prática seja viável, eficiente e sustentável. Essa avaliação é feita por meio de indicadores de qualidade do solo, que antes de tudo deve ser responsivo às variações do manejo, bem correlacionado com as funções desempenhadas pelo solo, capaz de elucidar os processos do ecossistema, ser compreensível e útil para o agricultor e, preferencialmente, de fácil e barata mensuração (DORAN e ZEISS, 2000).

2.2 Qualidade do Solo

A qualidade do solo é cada vez mais recomendada como integradora e avaliadora da qualidade ambiental (MONREAL *et al*., 1998), segurança alimentar (LAL, 1999) e viabilidade econômica (HILLEL, 1991). As avaliações de qualidade do solo têm o potencial para refletir o status do solo como um recurso essencial (DORAN e ZEISS, 2000). Muitas práticas agrícolas aumentam a vulnerabilidade do solo a processos de degradação, como erosão, acidificação, salinização e declínio estrutural do solo (CARTER *et al*., 1997; SLAVICH, 2001).

É crescente a conscientização da sociedade sobre o impacto das práticas agrícolas na qualidade do solo, o que levou a um interesse na mensuração dos efeitos de tais práticas para auxiliar no manejo e garantir o uso de práticas sustentáveis. O conceito de qualidade e saúde do solo se disseminou na década de 1990 e foi definido por vários pesquisadores (LARSON e PIERCE 1991; DORAN e PARKIN 1994; KARLEN *et al.,* 1997).

Doran e Parkin (1994) definiram a qualidade do solo como: a capacidade de um solo funcionar dentro dos limites do ecossistema, sustentar a produtividade biológica, manter a qualidade ambiental e promover a saúde de plantas e animais, enquanto outros definiram como a capacidade do solo ou aptidão para sustentar o crescimento das culturas sem resultar em degradação do solo ou prejudicar o meio ambiente (GREGORICH e ACTON, 1995).

A fim de avaliar e monitorar se as práticas agrícolas têm impacto na qualidade do solo, é necessário mensurar propriedades do solo ao longo do tempo a partir daquelas escolhidas como indicadoras e responsivas da função do solo avaliado. Logo, uma avaliação adequada da qualidade do solo deve incluir propriedades biológicas, químicas, físicas e suas interações (KARLEN *et al*., 2003).

Há que se considerar substancialmente o papel do carbono orgânico (CO), dada a sua importância para uma variedade de propriedades do solo e processos químicos, físicos e biológicos, tais como estrutura do solo, reciclagem de nutrientes e seu papel como substrato para microorganismos do solo.

Carter *et al.,* (1997) delineou uma sequência para avaliar a qualidade do solo compreendendo funções, processos, propriedades, indicadores e metodologia. Andrews *et al.* (2004) afirmou que os indicadores apropriados para a avaliação indireta da função do solo são determinados por suas funções fundamentais em atingir os objetivos do manejo.

Essa abordagem inicialmente requer a definição de metas de manejo. Para a maioria das atividades agrícolas, a produtividade, geralmente definida pelo rendimento é um dos objetivos estabelecidos. Larson e Pierce (1991) argumentam que a qualidade do solo não deve ser limitada à produtividade, mas também ter foco na sustentabilidade, no entanto, para a continuidade das atividades agrícolas é importante que a produtividade seja um componente.

Escolha de Indicadores de Qualidade do Solo

As propriedades do solo são classificadas como inertes ou dinâmicas. As propriedades inertes, como tipo de solo e textura, pouco mudam com uso do solo ou práticas de manejo. Portanto, tem valor para a caracterização inicial do solo, mas não para monitorar mudanças ao longo do tempo. As propriedades dinâmicas, no entanto, como o pH do solo ou o teor de C no solo, mudam em resposta às práticas de manejo.

MacEwan (2007) definiu que um indicador do solo que pode representar a condição do sistema ou sua capacidade de executar as funções do sistema. Ele definiu os atributos de um bom indicador como sensibilidade para mudança, facilidade de medição e interpretação, metodologia repetível e reversibilidade, para que tanto a melhoria como a decadência possa ser monitorada.

Tal abordagem depende de um banco de dados adequado e/ou base de conhecimento (opinião de especialistas) da faixa ideal ou limite dos indicadores escolhidos. O valor crítico de um indicador é definido como o valor acima ou abaixo do qual um determinado sistema de manejo do solo não seja mais sustentável (SYERS *et al.,* 1994). Para certas propriedades do solo os valores críticos podem estar bem definidos, como pH do solo, salinidade e toxicidade de metais, mas para outras propriedades do solo, como carbono orgânico do solo, números de minhoca e outros indicadores biológicos do solo, podem não ser bem conhecidos ou quantificados. O limite dos indicadores para o solo selecionado pode variar regionalmente e com a cultura adotada, também espacialmente e temporalmente dentro de um mesmo campo agrícola.

2.3 Indicadores Físicos

As modificações dos atributos físicos são mais pronunciadas quando ocorre a transição do ambiente natural para um sistema agrícola ou surge durante a implantação de sistemas conservacionistas em substituição ao sistema de preparo convencional. (ROSSETTI, *et al.,* 2013)

Um solo que fornece um meio ideal para as necessidades de produção agrícola tem forma estrutural bem desenvolvida, estabilidade a estresses de água e mecânicos e capacidade de recuperar a sua estrutura após perturbação (KAY, 1990; DEXTER, 2002). O conceito de estrutura do solo envolve a distribuição, faixa de tamanho e conectividade dos espaços porosos entre partículas e agregados no solo (OADES, 1993), que afetam o armazenamento e fornecimento de água, nutrientes e oxigênio (HAMBLIN, 1985; CASS *et al.* 2002).

CASS *et al* (2002) listaram seis propriedades que são consideradas como substitutas a condição estrutural do solo e resistência à degradação estrutural, nomeadamente taxa de infiltração de água, capacidade de água disponível, capacidade de aeração, resistência à penetração nas mesmas condições e estabilidade de agregados. Ademais, pode ser adicionada textura, consistência do solo, densidade aparente e porosidade (LARSON e PIERCE 1991; CARTER *et al.,* 1997, GLOVER *et al.* 2000, SPARLING *et al.,* 2004; PATTISON *et al.,* 2008).

Existem alguns problemas com o uso das propriedades físicas como indicadores da qualidade do solo. Estes incluem o fato de que a medida de algumas propriedades físicas do solo seja intrinsecamente mais custosa do que a medida de atributos químicos, pois não é realizada rotineiramente por laboratórios, e geralmente requer equipamentos especializados e treinamento que tornaria difícil para os produtores realizarem as medições.

Além disso, a limitação ao crescimento das raízes pode ser devido às restrições do subsolo que podem levar considerável tempo de mudança, exigindo monitoramento durante muitos anos antes de serem detectadas as alterações. No entanto, para a medição das propriedades físicas e químicas do solo, é necessário minimizar o efeito da variabilidade espacial e temporal na ordem que os dados são interpretáveis. Assim, é necessário conduzir a medida sempre no mesmo local e sob a mesmas condições ou mais próximo possível. Apesar dessas limitações, consideramos a medição das propriedades físicas do solo listadas anteriormente em termos de adequação como indicadores da qualidade do solo.

Textura do Solo

A determinação da proporção mineral de partículas de diferentes categorias de tamanho em um solo (análise do tamanho da partícula) é convencionalmente usada para quantificar a propriedade textural do solo (FAO, 1999)

A textura foi escolhida como indicador em vários estudos (LARSON e PIERCE 1991; CARTER *et al*., 1997; GRACE e WEIER 2007; PATTISON *et al.,* 2008) e é uma importante propriedade física para caracterizar solos. Não é uma propriedade dinâmica, pois é improvável que as práticas de manejo mudem a textura do solo ao longo do tempo.

Estabilidade de Agregados

Uma estrutura de superfície de solo estável é importante para promover infiltração da água e resistência à erosão (WHITE, 2010). Para que um agregado seja estável, as forças entre as partículas devem ser suficientemente fortes para evitar que a partícula se separe como resultado de forças disruptivas, como: impacto de gotas de chuva, maquinário pesado ou expansão da argila (WHITE, 2003).

A estabilidade de agregados é determinada pela reação do solo quando imerso em água e pode ser medido por peneiração úmida em laboratório ou por um teste de dispersão em campo (HAMBLIN, 1985; EMERSON, 2002). A estabilidade dos agregados é uma propriedade que é sensível às mudanças de manejo e afeta a porosidade, infiltração de água e capacidade de água disponível.

Consistência do solo

A consistência do solo ou a força do solo relaciona-se com a capacidade do solo para resistir à perda de estrutura por meio da compactação, induzida por chuvas ou irrigação, etc., e para resistir à penetração por raízes de plantas e fauna de solo. Um solo com boa qualidade física deve ser forte o suficiente para manter sua estrutura e manter as plantas verticais, mas também fraco o suficiente para permitir a penetração extensiva por raízes de plantas, flora e fauna do solo (TOPP *et al.,* 1997).

A consistência do solo ou a resistência do solo através do perfil do solo é dependente do teor de umidade no momento da medição, e para uma interpretação significativa e comparação temporal de dados, deve ser medido com o mesmo teor de umidade. A força do solo pode ser medida qualitativamente pela força necessária para acrescentar agregados secos ao ar tipicamente em laboratório ou quantitativamente por um penetrômetro no campo (OLIVER *et al*., 2013).

Densidade Global e Porosidade

A densidade aparente tem sido sugerida como medida da qualidade do solo em vários estudos (LARSON e PIERCE 1991; CARTER *et al*., 1997; GLOVER *et al*., 2000, SPARLING *et al.,* 2004, PATTISON *et al.,* 2008). A densidade aparente, no entanto, é uma medida insensível de como o crescimento da raiz e o movimento do ar e da água responde à estrutura do solo (KIRCHHOF e DANIELLS 2001).

A porosidade total (Pt) é a porção do solo em volume, não ocupada por sólidos. Embora a Pt determine o volume do solo que pode ser ocupado por raízes e água (PAGLIAI e VIGNOZZI, 2002), não dá uma medida do número, tamanho ou forma dos poros dentro do solo. Geralmente, os solos com maior porosidade têm maior capacidade para armazenar água, solutos, gases e calor (TOPP *et al*., 1997, DEXTER, 2002).

Em um solo com alto conteúdo de argilas expansivas, como a montmorilonita, o volume total do solo e a porosidade mudam consideravelmente com as mudanças no teor de água (WHITE, 2003). A porosidade cheia de ar na capacidade de campo é o volume mínimo de ar disponível no estado drenado mais úmido, é sugerido um valor crítico de 10-15% do volume do solo (DEXTER, 1988; CASS *et al.,* 2002).

Infiltração e Água disponível

A Infiltração de água é um bom indicador do grau de penetração de água através de um perfil de solo. A infiltração, no entanto, é afetada por quão rapidamente a água (por chuva ou irrigação) é aplicada para o solo e o teor de água do solo na época em que a água é aplicada. A sucção matricial é o desenho da força dominante da água no solo quando estiver seca, mas a gravidade torna-se a força dominante quando o solo está molhado. A infiltração de água em solos argilosos, que se quebram quando seco, geralmente ocorre preferencialmente pelas rachaduras para que o solo se alimente dos lados dos agregados bem como da superfície (WHITE, 2009).

A distribuição da água no solo tem uma forte influência sobre distribuição das raízes no solo (LANYON *et al*., 2004). A capacidade de água disponível (CAD) é o volume de água por unidade de profundidade do solo que está nominalmente disponível para absorção pelas plantas. Seu limite superior é definido pela capacidade de campo, e o limite inferior é o ponto de murcha permanente.

Embora a água disponível tenha sido usada por alguns autores como um indicador de qualidade do solo (LARSON e PIERCE 1991; CARTER *et al.* 1997; GUGINO *et al.* 2009; WHERRET e MURPHY 2012), um dos problemas com o uso da CAD é que a quantidade de água disponível mudará com a profundidade de enraizamento (WHITE, 2009).

Em resumo, a estabilidade de agregados e a consistência do solo (ou força) são consideradas propriedades físicas do solo potencialmente úteis a serem monitoradas ao longo do tempo como indicadoras do efeito de práticas de manejo na qualidade do solo.

2.4 Indicadores Químicos

A principal função do solo em relação à sua qualidade química para a produção agrícola é fornecer nutrientes para o crescimento das culturas (HEIL e SPOSITO 1997; WHITE, 2010). As principais propriedades químicas utilizadas como indicadores em sistemas agrícolas são pH, capacidade de tamponamento de pH, matéria orgânica do solo, soma de bases (SB), capacidade de troca catiônica (CTC), nitrogênio total, fósforo, potássio e vários micronutrientes.

pH do Solo

O pH do solo é um dos determinantes mais importantes da fertilidade do solo através da sua influência na solubilidade de íons metálicos, como Al, Mn, Fe, Cu, Zn e Mo, seu efeito no fornecimento de nutrientes cátions e aníons, e sua influência sobre a presença e atividade de microrganismos no solo. Os solos ácidos são frequentemente associados a deficiências de nutrientes, cátions, como Ca, Mg e K, e deficiências de P (HEIL e SPOSITO, 1997). À medida que o pH do solo aumenta, os cátions Fe^{3+}, Mn^{2+}, Zn^{2+} e Cu^{2+}, formam hidróxidos insolúveis e ficam menos disponíveis para as plantas (WHITE, 2003).

Matéria Orgânica do Solo (MOS)

A matéria orgânica do solo (MOS) não é adquirida pelas plantas como um nutriente do solo, mas o seu ciclismo é importante por causa da associação com nutrientes (N, P e S) e as interações benéficas com as propriedades químicas, físicas e biológicas do solo (HOYLE *et al*., 2011). Os nutrientes podem ser liberados no solo em formas disponíveis às plantas após a decomposição dos compostos orgânicos por microrganismos.

A proporção de cada elemento que é liberado em forma mineral varia de acordo com a composição dos compostos orgânicos decompostos (tais como C:N, C:P e os índices C:S) e as demandas da população microbiana para cada elemento (HEIL e SPOSITO 1997; WHITE, 2010). A MOS também contribui para a capacidade de troca catiônica de um solo devido à presença de grupos carboxílicos e outros grupos funcionais. A magnitude desta contribuição dependerá do pH do solo e aumentará conforme o pH do solo aumenta e dos grupos funcionais ácidos presentes.

Embora Hazelton e Murphy (2007) recomendem um mínimo 2% de MOS para manter a estrutura adequada do solo, a MOS executa uma gama de funções nos solos e o grau de importância da MOS para funções específicas difere a cada tipo de solo.

O conteúdo de MOS pode variar amplamente dentro e entre os tipos de solo devido a numerosos fatores, incluindo manejo, clima, composição mineral do solo, biota e topografia (BALDOCK e SKJEMSTAD 2001). Apesar dos problemas relacionados a variabilidade espacial e temporal das medidas e ausência de limites críticos para MOS, consideramos ser um componente essencial da avaliação da qualidade do solo por sua importância para uma ampla gama de funções do solo e medições recomendadas ao longo do tempo para monitorar o impacto das práticas de manejo na MOS.

Capacidade de Troca Catiônica (CTC)

A CTC indica a carga negativa por unidade de massa do solo e é medido como o número total de moles de carga (como Ca^{2+}, Mg^{2+}, Na^{+} e K^{+}) que podem ser deslocados por unidade de massa de solo por um solução de extração (HEIL e SPOSITO 1997; RENGASAMY e CHURCHMAN 2001; WHITE, 2003). Em solos ácidos, é necessário incluir também Al^{3+} e as vezes Mn^{2+} (RENGASAMY e CHURCHMAN 2001).

A CTC é um importante agente de controle da estabilidade da estrutura do solo, disponibilidade de nutrientes para o crescimento da planta, pH do solo e reação a fertilizantes e outros melhoradores (HAZELTON e MURPHY 2007).

2.5 Relação Cálcio/Matéria Orgânica do Solo

É largamente reconhecido que a MOS é o componente chave para sustentar a fertilidade do solo e conservar a qualidade ambiental (SCHNITZER, 1991; TRUMBORE, 1997). As associações de MOS com minerais, óxidos e agregados do solo foram determinadas como os principais mecanismos pelos quais a MOS está protegida da decomposição microbiana na maioria dos solos do mundo (WIESMEIER *et al*., 2014; SIX e PAUSTIAN 2014).

Como a interação com os minerais do solo via cátions polivalentes é um dos principais meios para a estabilidade do carbono orgânico do solo (COS) e os principais cátions polivalentes são Ca^{2+} e Mg^{2+}, acredita-se que o Ca e Mg trocáveis exercem um forte controle sobre o acúmulo de COS (YANG *et al*., 2016).

No entanto, pouca atenção tem sido dada à dinâmicas do acumulo da MOS em relação as quantidades de cálcio (Ca). O cálcio é um nutriente essencial para as plantas, como é um cátion divalente (Ca^{2+}) que participa de papéis estruturais na parede celular e membranas (MARSCHNER, 1995).

A deficiência de cálcio é rara na natureza, mas o excesso de cálcio restringe as comunidades vegetais em solos corrigidos com calcário (calagem). A calagem do solo e as doses de fertilizantes à base de cal são consideradas medidas tomadas para ajustar a acidez do solo e atender às necessidades de cálcio das plantas. (KOLAR *et al*., 2007).

A interação entre as mudanças na carga de matéria orgânica com alterações no pH e aumento da ligação de cátions polivalentes a altas concentrações de Ca, pode possibilitar as menores taxas de processamento de MOS em solos manejados a altas concentrações de Ca e pH (WHITTINGHILL e HOBBIE 2012).

As variações do pH influenciam a atividade microbiana do solo e o acumulo de MOS, e variação no Ca trocável entre as idades da paisagem pode explicar melhor os padrões locais da atividade microbiana do que a variação do pH. Desse modo espera-se menos atividade microbiana em solos manejados com maiores concentrações de Ca devido à estabilização da matéria orgânica por ponte de cátions polivalentes, reduzindo o acesso à matéria orgânica por microorganismos (WHITTINGHILL e HOBBIE 2012).

2.6 Degradação do Solo

O solo está sob crescente ameaça de uma ampla gama de atividades antrópicas que contribuem com a degradação e prejuízo a longo prazo à sua disponibilidade e viabilidade de uso. Durante as últimas cinco décadas, as atividades agrícolas foram diretamente afetadas por crescimento populacional e distribuição espacial das pessoas. Mudanças no uso da terra e atividades agrícolas intensivas têm efeitos negativos sobre o valor da produção e capacidade produtiva dos solos agrícolas (ZINCK *et al.* 2004; EMADODIN *et al.* 2009; EMADODIN e BORK 2011).

A agricultura intensiva tende a acentuar a erosão do solo e a perda de matéria orgânica do solo, o que representa uma ameaça para a sustentabilidade da agricultura a longo prazo, sobretudo em eventos climáticos extremos, como a seca. É imperativo a urgência em melhorar a eficiência geral dos sistemas agrícolas e reduzir a pressão exercida sobre o meio ambiente e sobre o solo (GOMIERO, 2013).

No passado, o aumento da demanda mundial de alimentos foi atingido pelo aumento das áreas agrícolas, melhoria genética das plantas e intensificação do uso de insumos (por exemplo, fertilizantes e pesticidas), porém no futuro, o aumento da intensificação agrícola pode resultar em mais degradação ambiental, caso práticas agrícolas mais sustentáveis não forem amplamente adotadas (TILMAN *et al*., 2002).

As práticas agrícolas tradicionais diminuíram a produtividade do solo, na medida em que muitos solos agrícolas são esgotados de nutrientes e incapazes de sustentar naturalmente a produtividade das culturas. Nas próximas décadas, um desafio crucial para a agricultura será atender às demandas de alimentos sem prejudicar ainda mais o meio ambiente. Aumentar a produtividade e os retornos econômicos para a agricultura de forma sustentável é um desafio central para atingir os objetivos globais de redução da pobreza e manejo ambiental (FAO, 2012).

Um terço dos solos agrícolas do mundo, ou aproximadamente 2 bilhões de hectares de terra são afetados pela degradação do solo. No sentido geral, a degradação do solo pode ser descrita como a deterioração da qualidade do solo, ou seja, perda parcial ou total de uma ou mais funções do solo (RITSEMA *et al*., 2005).

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Identifying indicators in a structurally fragile tropical soil to recommend management practices and prevent land degradation in the Amazonian periphery

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CAPÍTULO II

Identifying indicators in a structurally fragile tropical soil to recommend management practices and prevent land degradation in the Amazonian periphery

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ABSTRACT

In the Amazonian periphery, farmers need to intensify their productivity and be assured of the sustainability of the areas designated for crops, to prevent illegal deforestation of new areas. The aim of this study was to identify the main indicators that affect crop productivity in a structurally fragile Amazonian soil, and to determine the importance of maize yield indicator and their relationships with promising management practices to intensify crop production in agricultural areas in a sustainable way. The experiment was established with three leguminous species, *Clitoria fairchildiana*, *Acacia mangium* and *Leucaena leucocephala*, and an area without leguminous plants. Maize was sown between the rows of leguminous plants. Chemical and physical soil properties and maize grain yield were determined. Multiple linear regression, hierarchical partitioning analysis and spatial variability were used. Our results suggest the possibility of intensifying crop production in tropical soil prone to hardsetting through soil management practices, because Calcium (Ca) and soil organic matter (SOM) contents were highly correlated and exerted strong influence on maize grain yield (accounted for 30 up to 50 % of maize yield in two years). Other indicators like macroporosity, soil density and resistance to penetration, which also influenced the yield, were correlated with Ca and SOM, both of which can be increased or improved by agronomic practices. It is worth highlighting that due to negative influence of pH on total independent contributions to increased organic matter, higher calcium contents must be achieved by gypsum application rather than using liming material.

KEY WORDS**:** calcium; organic matter; grain yield; alley cropping; gypsum

INTRODUCTION

Land degradation implies long-term decline in soil productivity and reduction in soil capacity to perform specific environmental functions of values to human welfare (Aweke *et al*., 2015). The growing public interest in environmental sustainability has been identified as one of the most important drivers for modern soil science. Consequently, there is an increased demand to determine effects of soil management practices on land degradation and for the sustainability of agroecosystems (Schoenholtz *et al*., 2000). This demand has led to a greater need to understand and evaluate soil quality indicators that can support the prevention, recognition, monitoring and rehabilitation of degraded terrestrial environments (Viana *et* al., 2014). However, as environments differ, as well as soil functions of interest, there is no methodology to characterize soil quality based on a universal set of indicators (Bouma, 2002), as there is also no universal list of indicator properties suitable for all regions and ecosystem functions (Oliver *et al*., 2013). However, a comprehensive analysis of soil will not accurately describe soil quality unless the indicators are chosen with a specific soil function in mind, within a defined ecosystem (Viana *et al*., 2014).

In tropical regions, soil derived from clastic sedimentary rocks with low content of aggregator elements, like calcium, elemental iron and organic carbon, are widespread (Daniells, 2012). Unsuitable management of this soil, which is structurally fragile and prone to hardsetting results in unfavourable conditions for sustainable agrosystems because it affects soil rootability, water and nutrient use efficiency (Moura *et al*., 2016a). Together these factors decrease biomass productivity, soil organic matter, and increase land degradation risks. In addition, under tropical meteorological conditions, due to the high atmospheric evaporative demand, plants can lose turgidity, stop growing and decrease productivity of biomass even when soil moisture supply might be considered suitable for other regions (Denmead & Shaw, 1962). In these circumstances, due to negative interactions between the reduced soil rootability and atmospheric conditions the depth and fertility of the rootable layer, as well as, the soil physical indicators are crucial for plants to reach their full productivity potential, as well as for avoiding land degradation and achieving sustainable agrosystems (Moura *et al*., 2013). Given the environmental condition of the humid tropics some authors (Aguiar *et al*., 2010; Moura *et al*., 2016b) have recommended taking advantage of the rapid growth of leguminous trees in alley cropping systems. In the selection of hedgerow species for alley cropping must be consider nitrogen-fixing capacity and biomass production, in order to ensure maximum crop benefit of the nutrients added through the tree prunings. These qualities are linked to relative potential of three leguminous shrubs to changes on some soil properties, through increased soil organic matter and nutrients availability.

In the Amazon, including periphery regions, it is estimated that there is around 170 thousand km^2 of deforested and underutilized land, often in a state of degradation (Galvão *et al*., 2016). In these circumstances, unsuitable soil use is one of the greatest threats to natural reserve areas and to maintaining a healthy ecosystem, mainly because rainforest areas are almost always considered by farmers to be favourable to support future pasture or cropping, when the depleted area in use can no longer do so (Moura *et al*., 2016b). Yet, this process is now increasingly recognized as a fundamental cause of deforestation, land degradation and increased greenhouse gas emissions in the Amazon region and its surroundings (Aguiar *et al*., 2011). Thus, is now becoming increasingly understood that linkages exist between land degradation, biodiversity and climate change. This leads to justifying land degradation control through local suitable practices as a legitimate global change topic rather than a solely local or domestic topic (Gisladottir & Stocking, 2005).

Therefore, to preserve the rainforest and maintain a healthy Amazonian ecosystem it is essential to provide information for understanding and managing land according to soil resilience and performance through indicators that reflect ecosystem processes and integrate physical, chemical, and biological properties.

Taking this into account, the aim of study was to identify the main indicators that affect maize productivity in a structurally fragile tropical soil from the Amazonian periphery. After this, we seek to determine the importance of each indicator and their relationships with promising management practices to maintain crop production and avoid degradation in agricultural areas.

MATERIALS AND METHODS

Area description

The experiment was conducted in Maranhão state, Brazil (3º 38′ S, 42º 58′W), in a plain with an almost flat landform, with great homogeneity and preferred by the farmers for cultivating maize and soybean. Climatologically, the region has a hot and semi-humid equatorial climate with two well-defined seasons: a rainy season that extends from January to June and a dry season with a marked water deficit from July to December. The annual average temperature is approximately 27 ºC; the maximum temperature is 37 ºC, and the minimum temperature is 23 ºC. The annual mean rainfall during the experimental period was 1,439 mm year^{-1}.

The local soils display hardsetting characteristics determined by relationship between penetration strength and volumetric water contents (Moura et al., 2012) and were classified as Arenic Hapludults (Soil Survey Staff, 2010). Before establishing the experimental area in December, 2010, chemical and physical properties of soil were determined, and are given as follows: pH 4.0 (in $CaCl_2$); 20 g kg^{-1} of organic-C; 15 mg dm^{-3} of P; 25 mmol$_c$ dm^{-3} of (Al + H); 15 mmol$_c$ dm^{-3} of Ca; 9 mmol$_c$ dm^{-3} of Mg; 1 mmol$_c$ dm^{-3} of K; 50 mmol$_c$ dm^{-3} of CEC; 50.0% of percentage base saturation; 300 g kg^{-1} of coarse sand, 545 g kg^{-1} of fine sand, 61 g kg^{-1} of silt; 90 g kg^{-1} of clay. In January 2011, the area *of 11,900 m^2, (which was fallow since 2008 after rice cultivation)* was limed with 2 Mg ha^{-1} of surface-applied lime, corresponding to 780 and 260 kg ha^{-1} of Ca and Mg, respectively. The experiment was established in 2011 using an alley cropping system. The *area was divided* into four equal lots of 42.5 x 70 m and leguminous trees were planted at a spacing of 0.5 m between plants and 2.5 m between rows. Three species were used: sombrero (*Clitoria fairchildiana*), acacia (*Acacia mangium*), and leucaena (*Leucaena leucocephala*). One-fourth of the area was maintained without leguminous plants. In order to measure soil physical parameters and maize productivity, 160 sampling points were delimited in a uniform grid of 10 x 7 m. The coordinates of each sample point were recorded using a GPS device (Figure 1).

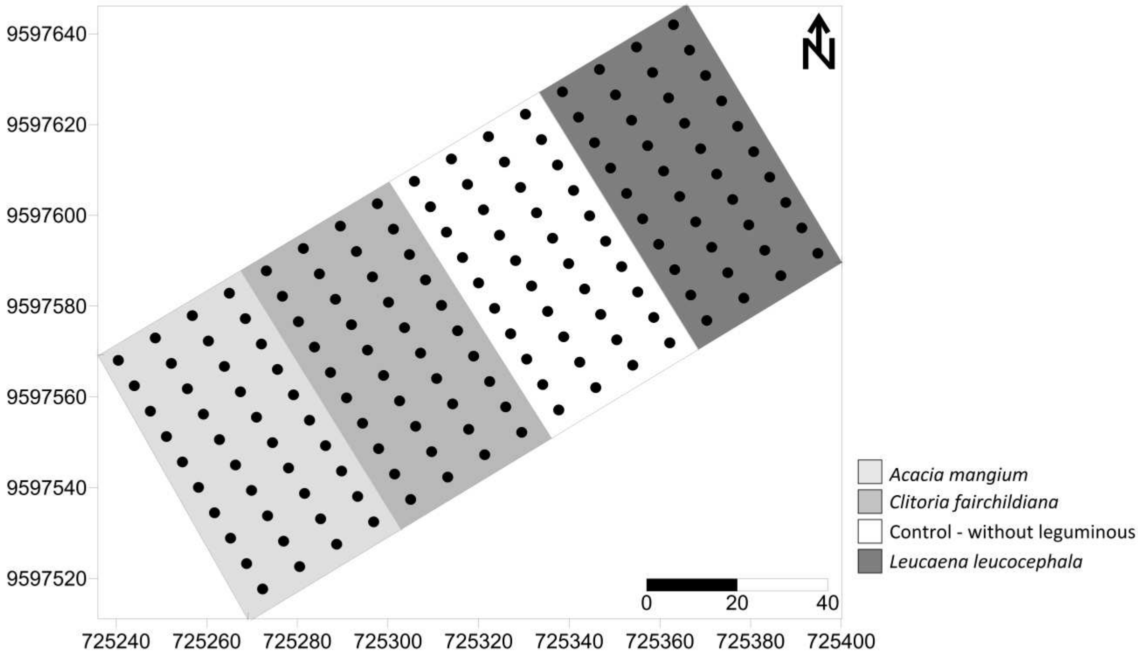

Figure 1. Experimental field design.

In 2011 and 2012, maize (*Zea mays* L.) was grown during the rainy season between the rows of leguminous plants and in the control area with a spacing of

90 cm between the rows and 33 cm between the plants. Aiming at this experiment, in February of 2013 and 2014, at the beginning of the rainy season, three rows of maize (*Zea mays L.*) cultivar AG 7088 spaced 80 cm apart were sown between the rows of leguminous. In all the years the soil was fertilized with 50 kg ha^{-1} N, 120 kg ha^{-1} P_2O_5, 100 kg ha^{-1} K_2O and 5 kg ha^{-1} Zn. A total of kg ha^{-1} of N, supplied as urea, was *applied at the V3 maize growth stage, in all years.* The maize was fertilized using 300 kg ha^{-1} of formula 10-25-15 + 0.05 Zn. A total of 50 kg ha^{-1} of N.

The first pruning of leguminous plants was performed in 2012 and continued in the following years. The annual pruning was 0.5 m above ground level and the green biomass of the leguminous was evenly distributed between the maize rows, just after planting. The amount of residues applied after implementing the alley cropping system is shown in Table I.

Table I. Applied dry matter of legumes in the experimental field.

Legumes	Dry matter (Mg ha^{-1})		
	2012	2013	2014
Leucaena leucocephala	0.73	0.85	3.15
Clitoria fairchildiana	3.81	5.23	7.94
Acacia mangium	2.90	3.69	5.21

Soil physical analyses

The soil was sampled using 100 cm^3 rings in May 2013 in order to determine, soil dry bulk density, total porosity (φt), macro-porosity (non capillary porous) and microporosity (capillary porous). Two replicates were collected per point from a depth of 8-12 cm (in the middle of the 0 -20 cm layer). Samples were saturated, weighed, placed on a tension table and equilibrated at -6 kPa. After weighing, each sample was oven dried at 105 °C. Soil dry bulk density (ϱb) was calculated as m/v, where m is the dry collection soil mass at 105 °C and v is the ring volume. Total porosity (φt) was calculated as [1 – (ϱb / ϱp)], where ϱb is the soil density (Mg m^3) and ϱp is the particle density (Mg m^3), which was determined according to EMBRAPA (1997). We calculated the macroporosity corresponding to the volume of pores with equivalent diameter larger than 50 μm as the mass difference between saturated sample and equilibrated sample at -6 kPa (Thomasson, 1978). Microporosity was determined by the difference between the macroporosity and total porosity.

The soil penetration strength (SPS) was measured with 5-cm gradations, at depths of 0-5 cm, 6-10 cm, 11-15 cm, and 16-20 cm, using a digital penetrometer (Falker, Porto Alegre, Brazil) with three replicates per point. Furthermore, the soil moisture was measured at depths 0 to 20 cm, with two replicates per point using a TDR - TRIME-FM instrument (IMKO, Ettlingen, Germany). Soil particle size distribution was measured in the same soil samples taken for chemical analyses.

Soil chemical analyses and maize grain yield

Soil samples were taken for chemical analysis in May 2013 at depths of 0-20cm; six replicates were collected using a Dutch auger. The samples from each point were passed through a 2-mm sieve and then air-dried prior to the analyses. Soil samples were analysed for C, pH, P and exchangeable K^+, Ca^{2+}, Mg^{2+} and (H^+ + Al^{3+}). At physiological maturity, the maize yield was determined in two 10-m^2 areas, within each 70-m^2 grid. Table II shows the analytical method for each chemical and physical variable in this study.

Table II. Analytical method for each physical and chemical variable.

Variable	Unit	Method	References
SOM	g dm^{-3}	Dichromate oxidation	Walkley & Black, 1934
P, Ca, Mg, K	$mmol_c$ dm^{-3}	Ion-exchange resin procedure	Raij *et al*., 1986
H+AL	$mmol_c$ dm^{-3}	Solution SMP	Quaggio *et al*., 1985
pH	-	pH in $CaCl_2$	Peech, 1965
ϱs	Mg m^{-3}	Rings of 100 cm^3	Thomasson, 1978
φ_t	m^3 m^{-3}	From the values of dry bulk density	Aikins & Afuakwa, 2012
Clay	g kg^{-1}	Pipette method	Gee & Bauder, 1986
Sand	g kg^{-1}	Pipette method	Gee & Bauder, 1986
Silt	g kg^{-1}	Pipette method	Gee & Bauder, 1986
SPS	MPa	By manual action	ASAE, 1999
MPS	MPa	By manual action	ASAE, 1999
Mac	m^3 m^{-3}	non capillary porous	Danielson & Sutherland, 1986
Mic	m^3 m^{-3}	capillary porous	Danielson & Sutherland, 1986
Soil moisture	%	Time domain reflectometry (TDR)	Topp *et al*., 1980

SOM – Soil organic matter, ϱs – Bulk density; φt - Total porosity; SPS – Soil penetration strength; MPS - Maximum penetration strength; Mac - Macroporosity; Mic – Microporosity

Statistical Analysis

The data were subjected to the homogeneity of variance (Levene's test) and normality (Shapiro-Wilk) (Table III). Multiple linear regression (MLR) was used to identify the best predictors (physical and chemical soil properties) for yield of maize ("MASS" package version 7.3-45, (Venables & Ripley, 2002), implemented in the R statistical program (R Development Core Team, 2009). The selection of predictors was carried out by a stepwise backward selection including all of the variables, except to those eliminated by test of multicollinearity. The stepping criteria employed for entry and removal was based on the Akaike information criterion, AIC (Akaike, 1973). A standard regression coefficient (β) was used to represent the amount of the response variable changed (yield of maize) when the explanatory variable (physical and chemical soil properties) changes 1 unit. MLR was also used to identify the best predictors for the soil organic matter (SOM).

Table III. Descriptive statistics of physical and chemical soil properties, and two years of yield of maize.

Variables	Mean	Min	Max	SD	CV
SOM, g dm^{-3}	26.91	16.45	37.10	4.39	16.31
Ca, $mmol_c$ dm^{-3}	16.07	7.50	33.50	5.27	32.82
K, $mmol_c$ dm^{-3}	0.88	0.53	1.33	0.16	17.64
pH ($CaCl_2$)	4.43	4.04	4.90	0.19	4.26
ϱ_s, g cm^{-3}	1.40	1.31	1.52	0.05	3.26
Clay, g $100g^{-1}$	17.38	11.50	23.50	2.60	14.96
Silt, g $100g^{-1}$	8.33	4.90	17.00	2.18	26.13
PS (6-10cm), Mpa	1.01	0.41	1.98	0.34	34.00
PS (16-20cm), MPa	1.54	0.90	2.40	0.31	19.85
MPS, Mpa	1.74	1.11	2.94	0.38	21.85
Mac, $m^3 m^{-3}$	0.21	0.17	0.27	0.02	9.90
Mic, $m^3 m^{-3}$	0.20	0.15	0.27	0.02	11.64
Yield[1], Mg ha^{-1}	4.35	2.40	6.49	0.71	16.40
Yield[2], Mg ha^{-1}	4.33	2.95	5.95	0.58	13.47

Min – Minimum value; Max – Maximum value; SD – Standard Deviation; CV – Coefficient of Variation in %.
SOM – Soil organic matter; ϱs – Bulk Density; PS – Penetration Strength; MPS – Maximum penetration strength; Mac – Macroporosity; Mic – Microporosity; 1Yield from 2013; 2Yield from 2014.

Next, a Hierarchical Partitioning analysis (HP) was performed ("hier.part" packge version 1.0-4 (Walsh & Mac Nally, 2015), done in the R statistical program (R Development Core Team, 2009), to estimate the percentage of total variation in a specified variable, yield of maize or SOM, explained by a given independent variable (Mac Nally, 2000; Mac Nally & Wash, 2004). Only the variables selected by MLR were used in the HP. The HP considers all the possible models in an MLR to determine the independent contribution of each predictor variable to the total variability of the response variable (Mac Nally, 2000). Statistical significance of the independent contributions of each independent variable was determined using a randomization approach with 1,000 interactions (95% confidence limit) (Mac Nally, 2000).

The spatial variability was analyzed by constructing adjusted semivariograms in a mathematical model according to the following parameters: nugget effect (C_0), sill ($C_0 + C_1$), and range (a). The fit of the semivariogram models to the experimental data was based on the Root Mean Square Error (RMSE) between estimated and experimental values. The ratio between nugget semi-variance and total semi-variance or sill was used to define different classes of spatial dependence. If the ratio was 25%, the variable was considered to be strongly spatially dependent, or strongly distributed in patches. The semivariograms and the maps were generated using kriging with a GS + geostatistical package Software (Gamma Design de Software, 2004).

RESULTS

The multiple regression model showed that there were differences as for the more significant indicators to changes in maize production, between 2013 and 2014. However, there was a prevalence of indicators related to physical soil conditions in both years (Table IV). In 2013, SOM and soil density ($p < 0.001$) was highly significant, while the clay content ($p < 0.016$) and SPS in the 16 – 20 cm layer ($p < 0.046$) were less significant. In 2014, macroporosity ($p < 0.001$), calcium ($p < 0.002$), SOM ($p < 0.008$) and microporosity ($p < 0.034$) were the most significant indicators for grain yield. The proportion of variability accounted for by a statistical model, or *coefficient of determination* (R^2) was 0.30 in 2013 and 0.31 in 2014.

Table IV. Multiple regression with maize yield as dependent variable, in 2013 and 2014.

	B	SE	β	*p*
		2013		
SOM	0.132	0.024	0.470	<0.001
ϱs	-5.362	1.268	-0.346	<0.001
Clay	-0.052	0.022	-0.191	0.016
SPS (16-20cm)	-0.734	0.333	-0.314	0.029
SPS (6-10cm)	0.405	0.201	0.195	0.046
MPS	0.466	0.266	0.248	0.082
Mac	-4.792	2.843	-0.140	0.094
		2014		
Mac	-9.054	1.907	-0.324	<0.001
Ca	0.041	0.013	0.372	0.002
SOM	0.067	0.025	0.295	0.008
Mic	-5.427	2.539	-0.219	0.034

B – Regression coefficient; SE – Standard error; β – Standardised beta coefficient; p – value.
SOM – Soil organic matter, ϱs – Bulk density; φt - Total porosity; SPS – Soil penetration strength; MPS - Maximum penetration strength; Mac - Macroporosity; Mic – Microporosity.

For complementing multiple regression analysis and identifying the most likely causal factors while alleviating multicollinearity problems, HP, an analytical method of multiple regression was used. In 2013, estimates of total contribution by HP showed that the highest total contributions to grain yield were provided by SOM (50%), bulk density (22%) and SPS in the 16 – 20 cm layer (11 %) (Figure 2a, 2b), while in 2014 calcium, SOM and macroporosity, all around 30%, were indicators with the highest total independent contribution. Microporosity appears with 10% of total independent contribution to grain yield.

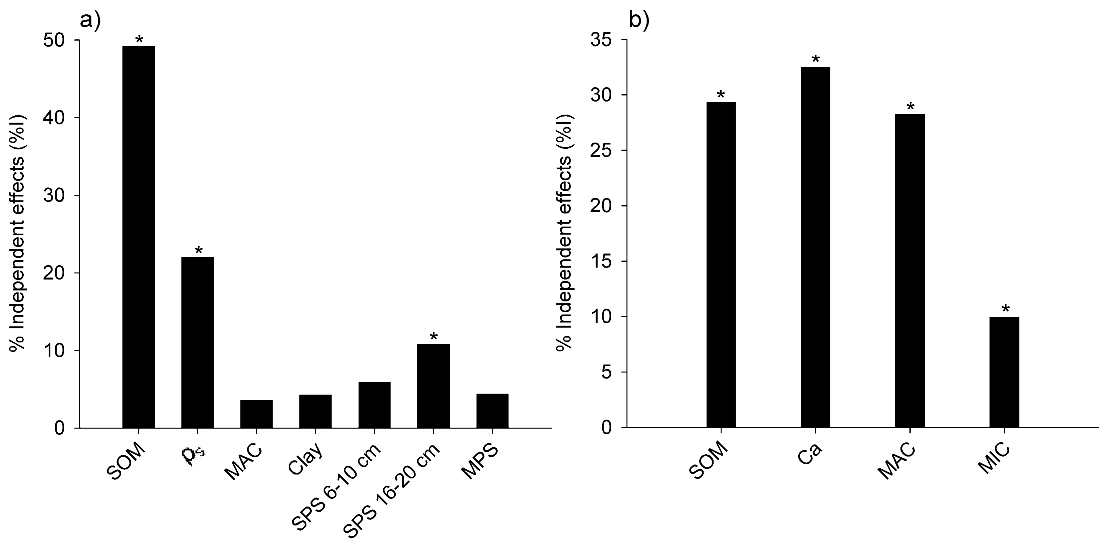

Figure 2. Distribution of the percentage of independent effect (%I) of each variable (physical and chemical soil properties) on the maize grain yield in 2013 (a) and 2014 (b). Significant predictors are indicated by asterisks ($p<0.05$). SOM – Soil organic matter, ϱs – Bulk density; φt - Total porosity; SPS – Soil penetration strength; MPS - Maximum penetration strength; Mac - Macroporosity; Mic – Microporosity

Results of both 2013 and 2014 showed that SOM contents might be even more important to explain the variation in maize grain yields. In addition, due to its relation with other physical soil properties, a multiple regression model was used to select predictor variables for SOM. The model showed that calcium (*p* <

0.001), clay ($p < 0.001$), silt ($p < 0.002$), K ($p < 0.008$) and pH ($p < 0.014$) were significant (Table V).

Table V. Multiple regression of physical and chemical soil properties with soil organic matter.

	B	SE	β	*p*
Ca	0.521	0.048	0.626	<0.001
Clay	0.385	0.102	0.228	<0.001
Silt	0.383	0.121	0.190	0.002
K	3.488	1.307	0.123	0.008
pH	-2.973	1.191	-0.128	0.014

B – Regression coefficient; SE - Standard Error; β - Standardised beta coefficient; p - value.

The proportion of variability accounted for by a statistical model, or *coefficient of determination* (R^2) was 0.69. Meanwhile, estimates of total independent contribution by HP showed that the highest total independent contributions to SOM variation were given by calcium (63 %), clay (16 %), silt (12 %), and pH (7 %) (Figure 3).

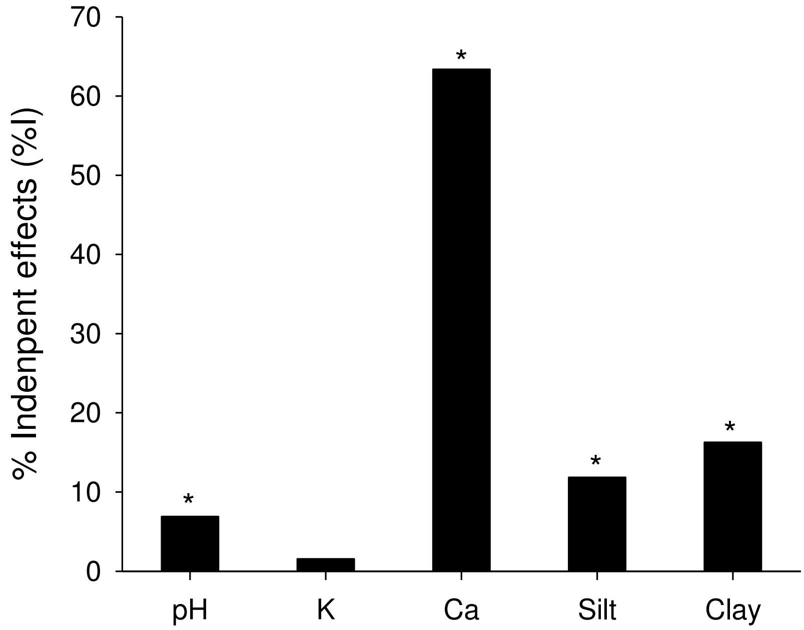

Figure 3. Distribution of the percentage of independent effect (%I) of each variable (physical and chemical soil properties) on the soil organic matter. Significant predictors are indicated by asterisks ($p<0.05$).

Spatial analysis of data showed that the fields had significant spatial variability in their indicators, which exhibit some degree of positive spatial auto-correlation. Geostatistical methods are often suitable for analysis of properties that show spatially correlated behaviour. Semivariograms were computed for calcium, SOM and yield, and parameters for the best fitting spherical models were estimated (Table VI). The semivariogram for SOM contents showed a higher nugget effect and sill than calcium contents and yields. The nugget parameter of the semivariogram is a measure of unexplained variability. The percentage of unexplained variability can be estimated from the ratio of the nugget to the sill. Approximately 18% and 23% of the variation in measured calcium and SOM, respectively, at the field site was unexplained. This unexplained variability could be due to variability at scales of sampling less than the 7 m interval used for this study or to variability resulting from measurement errors. The range of influence for calcium and SOM measured was 70 m and 69 m, respectively. The range (A) is a measure of the maximum distance over which properties remain spatially correlated. At distances shorter than the range the pairwise sample variation depends upon the distance of separation between them. The values of DSD indicate the degree of spatial dependence. DSD of 0 to 25% indicate a strong spatial dependence, 25 to 75% indicate a moderate spatial dependence, and 75 to 100% corresponds to a weak spatial dependence (Cambardella et al., 1994).

Table VI. Parameters of semivariogram adjusted for Ca, SOM, maize grain yield in 2013 and 2014.

Variable	Model	C_0	C_0+ C	a (m)	DSD(%)	r^2	CV
Ca	Spherical	4.82	26.2	70	18	0.94	0.97
SOM	Spherical	1.54	6.70	69	23	0.93	0.95
Yield 2013	Spherical	0.25	0.65	67	38	0.89	0.95
Yield 2014	Spherical	0.12	0.40	48	31	0.81	0.87

C_0 – nugget effect; C_0+ C – sill; a – range; DSD - Degree of spatial dependence [C_0*100/(C + C_0)]; CV – Cross validation; SOM – Soil organic matter.

A positive spatial auto-correlation, as shown by semivariograms here, indicates that similar attributes are grouped together spatially. Thus, if spatial dependence is detected, the modelled semivariograms can then be used to map the interested variable by kriging, an interpolation method that produces unbiased estimates with minimal estimation variance. The maps obtained through kriging showed significant predictor variables for yield that could be influenced by management practice as SOM and calcium are spatially associated and present low values in most of the area (Figure 4a, 4b). Thus, around 98% of the area showed low or very low calcium contents (<26 $mmol_c$ dm^{-3}), while SOM was very low (< 20 g dm^{-3}) in almost 99% of the sampled area.

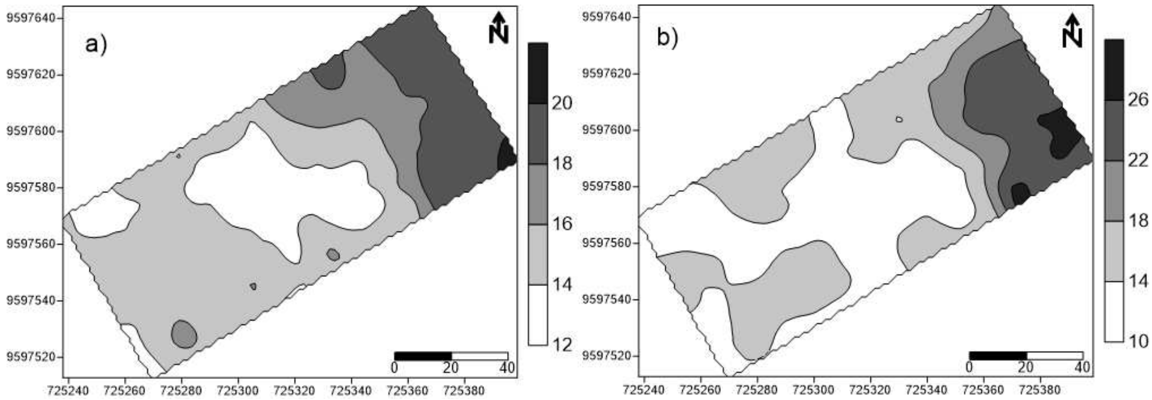

Figure 4. Spatial distribution of (a) Soil organic matter and (b) calcium in the experimental field.

In the same way, the range of maize grain yield variation in 2013 (2.40 to 6.49 Mg ha^{-1}) and 2014 (2.95 to 5.95 Mg ha^{-1}) also showed low productivity values (Figure 5a, 5b). Thus, in around 96% of the area, the productivity was lower than 5 Mg ha^{-1} in 2013. In 2014 the area with productivity lower than 5 Mg ha^{-1} increased to 98%.

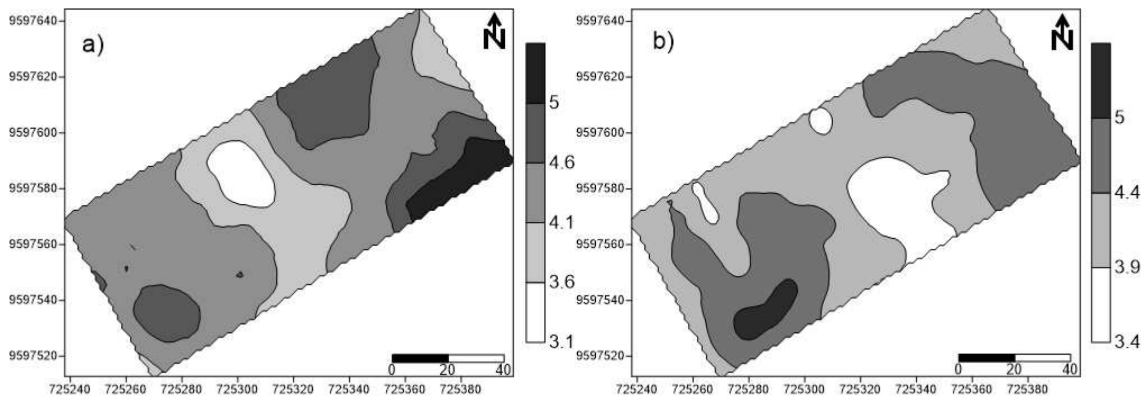

Figure 5. Spatial distribution of maize grain yield 2013 (a) and 2014 (b) in the experimental field.

DISCUSSION

There was a clear prevalence of the indicators related to physical soil conditions to maize production. Indeed, in structurally fragile tropical soil, physical properties exert a dominant influence on soil management and plant productivity because hardsetting during soil drying has serious implications for root growth due to increasing penetration resistance, and decreasing water and nutrient uptake (Fabiola *et al*., 2003). Furthermore, differences for significant indicators between yields from 2013 and 2014 can be explained by the way in which the physical properties affect plant growth. In tropical soils, physical factors in the root zone that directly affects root growth and function are water availability and soil strength (Letey, 1985). Each of these factors is closely related to the soil water content, which unfortunately, changes constantly through the growing season making it difficult to explain plant growth and yield responses to physical soil conditions in a given season (Jayawardane & Chan, 1994).

The SOM substantially influenced the maize yield in 2013 and 2014. SOM increases resistance to structural breakdown by wetting, which is a characteristic behaviour of structurally fragile tropical soil. Therefore, only soils with less than a critical concentration of SOM are likely to breakdown (Nciizah & Wakindiki, 2012). Mullins (1999) suggested a threshold of 2% SOM, below of which the soil would be vulnerable to hardsetting. The maps from the field showed that the area with SOM higher than the critical level of 2% was less than 1%. This finding suggests enormous risks for land degradation when SOM content is highly reliant on soil management practices. Indeed, environmental factors, such as high temperature, water, oxygen, and nutrient availability in humid tropical environments can accelerate residue decomposition and impair the possibility of increasing SOM contents (Christensen, 2000). Therefore, Moura *et al*. (2009) has suggested a constant addition of residues allowed by alley cropping in a no till system for maintaining the dynamic equilibrium between C inputs and high decomposition rates in humid tropical regions. Furthermore, in these circumstances, tillage can decrease SOM content increasing bulk density and water-suspendable solids, which can lead to a decline in structural and soil physical properties associated with an increase in penetration strength as observed by Ley *et al*. (1995). The negative correlation between grain yield and SPS in the 16 – 20 cm layer in this experiment may be explained by the generally decreasing SOM in soil depths.

Influence of calcium over yield can be accounted for by physical improvements caused by increasing flocculation and aggregation in the subsoil enhancing root activity, which leads to greater soil aggregation (Sumner, 2009). The positive effect of calcium on soil physical and chemical properties due to flocculation of soil particles, thereby creating supportive conditions in degraded tropical soil, was also reported by Anikwe *et al*. (2016). Less than 2% of the mapped area had a calcium content level higher than 26 $mmol_c\ dm^{-3}$, which shows great potential to improve soil fertility of this soil.

In addition, an association between calcium and SOM has been reported by some authors who describe the formation of cation bridges with products derived from decomposition of the applied biomass (Moore & Turunen, 2004; Whittinghill & Hobbie, 2012). The major cation involved in the formation of bridges is Ca^{2+}, whose concentrations can affect fluxes of dissolved organic matter by stabilizing negatively charged organic matter through sorption to positively charged cations. The bond between polyvalent cations and negatively charged organic matter functional groups is not easily reversed and surfaces of organic materials will be less accessible for microbial activity. This flocculation prevented biological, chemical, or physical breakdown, which explains the spatial association between calcium and SOM (Figure 3) (Oste *et al*., 2002). On the other hand, a correlation between SOM and contents of clay and silt was reported by Azlan *et al*. (2012). SOM tends to increase as the clay content increases due to bonds between the surface of clay particles and SOM, which retard the decomposition process. In addition, soils with higher clay content increase the potential for aggregate formation. Macro-aggregates physically protect organic matter molecules from further mineralization caused by microbial attack (Rice, 2002). Influence of increased pH on SOM content through stimulation of microbial activity was reported by Whittinghill & Hobbie (2012). These findings suggest that in soil prone to hardsetting, suitable calcium content could be achieved by gypsum application rather than lime material with carbonate or bicarbonate associated with the Ca^{2+}. According to Moura *et al*., (2016), the application of gypsum plus leguminous residues can enhance the soil rootability when used on tropical soils prone to hardsetting. These effects facilitate greater root growth into deeper soil layers and greater nutrient uptake. In contrast, in tropical soil with low pH buffering capacity large quantity of lime application can raise pH to level, which favour the fast organic matter decomposition (Aye *et al*., 2016).

In 2013 and 2014, around 4 % of the mapped field showed grain yield higher than 5 Mg ha^{-1}, which is less than half the potential of the sown maize hybrid. Inadequate soil physical conditions and high atmospheric evaporative demand prevent crops from reaching their full productivity potential when intervals without rainfall greater than four days occur during the growing season (Moura *et al*., 2016a). Low water use capacity in conditions with a narrow depth of the rootable layer may be crucial for crop growth (Atta et al., 2013). Therefore, in soil tropical conditions of the upper soil layer must be improved by increasing the volume in the soil available for root growth and water and nutrients uptake. Thus, to reduce soil hardening because of cohesion, plant residues may be applied in soil surface to preserve soil moisture by reducing evaporative losses and to increase organic matter and nutrients availability. Therefore, legume cover increases maize yield by a steady release of N and K during crop cycle, better distribution and maintenance of adequate levels of base in the root zone as well as enhanced water and nutrients uptake.

It is worth highlighting that a higher grain yield was achieved in the areas with three years of biomass application of leguminous cover, compared to the control area. Our experience in soil management of the region has shown that the paradigm of soil management established for other regions is not adequate for the conditions of a tropical environment. In the periphery of Brazilian Amazonia, agricultural practices that are recommended for the Brazilian savannah, such as improvements in the tilled topsoil cannot be maintained if deterioration of the porous soil structure is not prevented. Ripping cohesive soil without removing the causes of compaction might not improve yield. Each time the soil is tilled, it is aerated, which reduces the organic matter contents and accelerates the process of re-compaction, increasing strength after a year or less.

According to results from Moura *et al*. (2016a) in the same soil, positive interaction between applied calcium and leguminous biomass can increase nitrogen uptaken and maize grain yield. On the other hand, the low *coefficients of determination* (0.30 and 0.31) suggest that other predictors that were not measured, such as the available nitrogen, may have affected the grain yields, which can help explain higher grain yield in leguminous areas.

CONCLUSION

Our results suggest the possibility of intensifying the production and mitigating land degradation in the Amazonian periphery. For this must be recommended biomass and gypsum application to increasing soil organic matter and calcium contents to improve fertility and enhance crop productivity in farmland; thus, preventing deforestation of new areas. The main findings that support this conclusion are: i) high correlation of grain yield with the contents of soil organic matter and calcium, which can be increased by agronomic practices; ii) very low contents of these soil components in already cultivated soil; iii) a spatial association and high correlation between calcium and SOM and: iv) their influence on other significant indicators like macroporosity, bulk density and soil penetration strength. It is worth highlighting that due to the negative influence of pH on total independent contributions to increased soil organic matter, higher calcium contents must be achieved by gypsum application rather than using liming material.

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Soil physical changes and maize growth in a structurally fragile tropical soil due to mulching and duration between irrigation intervals

CAPÍTULO III

Soil physical changes and maize growth in a structurally fragile tropical soil due to mulching and duration between irrigation intervals

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Running title: Soil physical changes and maize growth

Abstract

Under tropical meteorological conditions, the volume of soil explored by plant roots is crucial for crop growth as it allows increased water and nutrient use efficiency. We hypothesized that, under different irrigation intervals, leguminous mulch can extend the duration between irrigation events but maintain crop performance, because decreased evaporative fluxes also reduce constraints to root exploration imposed by mechanical stress. We evaluated the combined effects of leguminous mulch and irrigation intervals on soil physical properties to determine whether the growth and productivity of maize were modified in a structurally fragile tropical soil. The experiment involved following treatments: 4-day irrigation intervals with soil mulched (4C) or bare (4S), 6-day irrigation intervals with soil mulched (6C) or bare (6S), 8-day irrigation intervals with soil mulched (8C) or bare (8S), 10-day irrigation intervals with soil mulched (10C) or bare (10S). Mulch decreased soil penetration resistance and increased to four days the favourable time for root development in drying soil. Relative to bare soil, mulch with a 6-day irrigation interval almost doubled nitrogen uptake post-tasseling, which decreased nitrogen remobilization and increased the crop growth rate during this stage. These conditions had a positive effect on the transpiration rate and stomatal conductance as well as on the growth and yield of maize. A 6-day irrigation interval with mulch compared to 4-days with bare soil resulted in similar conditions for root development, but greater uptake of nitrogen (102.73 to 78.70 kg/ha) and better yield (6.2 to 5.3 t/ha), which means greater efficiency in nitrogen and water use.

Keywords: Water use efficiency, soil physical attributes, nitrogen uptake, physiological parameters, crop growth

Introduction

Under tropical meteorological conditions, due to the high evaporative demand, the depth of soil that roots can explore is crucial for water uptake, crop growth and nutrient use efficiency (Atta *et al*., 2013). As water and nutrient availability are major requirements for crops, they greatly affect the volume of soil explored by plant roots (Wong & Asseng, 2007). In tropical sandy loam soils, both, available water capacity and nutrient availability are often limited. In addition, due to the generally small contents of free-iron and organic carbon, combined with large proportions of fine sand and silt, most of this soil tends to harden during drying, which adversely affects root development (Daniells, 2012). Therefore, due to negative interactions between unsuitable soil conditions and the large evaporative demand, crops do not always reach their full productivity potential even though the availability of water and nutrients would be considered adequate in other regions (Moura *et al*., 2013).

In soil that tends to harden with drying, effects on root growth are common when the water potential approaches -100 kPa (Becher *et al*., 1997), which, according to Moura *et al*. (2009), may occur around the fourth day without rain or irrigation in tropical conditions. In addition, root systems are unable to completely exploit available nitrogen, required in large amounts by the crops. The restriction of root growth limits exploration to gain access to soil nitrogen, further suppressing crop productivity. This is especially true for annual crops that require time to develop extensive root systems because N may be lost gaseously by volatilization or denitrification, by leaching or by uptake by competing organisms during root development (Lynch, 2013).

Thus, mulching the soil surface with plant residues has been recommended by some researchers because it has the combined effect of protecting surface soil from erosion, as well as decreasing the rate of soil drying and hence hardening (Mulumba & Lal, 2008; Moura *et al*., 2010).

However, understanding the relation between improved soil physical conditions, such as its rootability, and crop productivity may be challenging in rainfed crop conditions due to uncontrolled variations in soil moisture and the poor correlation between static physical properties (quantitatively not related to changes in soil moisture) and plant growth (Häkansson & Lipiec, 2000). Benjamin *et al.* (2003) suggested a soil physical indicator expressed as 'water stress day' to determine the total number of days when soil moisture contents are sufficiently reduced to cause crop water stress. In cohesive sandy loam soil in tropical regions, a water stress day might begin to be observed on the fourth day without rain or irrigation (Moura *et al.*, 2012).

We hypothesized that, under different irrigation intervals, leguminous mulch can extend the duration between irrigation events but maintain crop performance, because decreased evaporative fluxes also reduce constraints to root exploration imposed by mechanical stress. Thus, the objective of this work was to evaluate the effects of leguminous mulch and irrigation intervals on soil physical properties and how the growth and productivity of maize were modified in a structurally fragile tropical soil from the humid tropics. Increased uptake of water and nutrients is crucial for agricultural production in a tropical climate with a high potential evapotranspiration and soils with little available nutrient content, particularly with precipitation changes under global warming.

Material and Methods

Experimental site and background information

The experiment was conducted at Maranhão State University, Brazil (2°30'4" S, 44°18'33" W), which had a hot, semi humid, equatorial climate with a mean precipitation of 2,100 mm year^{-1} and two well-defined seasons, a rainy season extending from January to June and a dry season without rain and with a pronounced water deficit extending from July to December. The evapotranspiration during the experimental period was 622.2 mm. The average temperature is approximately 27°C, with a maximum temperature of 37°C, and a minimum temperature of 23°C. The average potential evapotranspiration rate of the experimental period was 6.5 mm per day.

The soil showed cohesive characteristics (determined by relationship between penetration resistance and volumetric water content of soil) (Moura et al., 2009) and was classified as Arenic Hapludults (Soil Survey Staff, 2014). The A horizon had the following properties: pH 4.0 (in $CaCl_2$); organic-C 20 g/kg (Walkley–Black); P 15 mg/dm^3; (Al + H) 25 $mmol_c/dm^3$; Ca 15, Mg 9, K 1 $mmol_c/dm^3$ (resin), respectively; CEC 50 $mmol_c/dm^3$; base saturation 46.2 %; coarse sand 300, fine sand 545, silt 61, clay 90 g/kg, respectively. The soil properties were measured using standard methods (Carter & Gregorich, 2008).

The area had been fallow since 1990 and supported a native species of grass, which was killed using glyphosate. Lime and gypsum were broadcast by hand in December 2012 at rate of 1 t/ha and 6 t/ha, respectively. These application rates were calculated to raise base saturation to 55% and calcium to 45 $mmol_c/dm^3$. Maize (cultivar AG 1051) was sown in the beginning of the rainy season in 2012, 2013, and 2014, with a between-row spacing of 80 cm and 25 cm between plants. The fertilizer application consisted of 50 kg/ha N as urea, 35 kg/ha of P as triple superphosphate, 100 kg/ha of K as potassium chloride and 5 kg/ha of Zn in the form of zinc sulphate.

Trial set up

The experiment was conducted under no-tillage conditions, and the experimental layout was established in October 2015 with 4, 6, 8, and 10-day irrigation intervals, with soil mulched or bare. Four replicates of the treatments were arranged in a completely randomized block design. Irrigation water was conveyed to the experimental plots through a CPVC plastic pipe and applied in closed-ended furrows through a windowed tube. A water outlet port controlled the volume of water applied on each occasion and the total applied to treatments 4C, 4S was 440mm; 300 mm to treatments 6C, 6S; 220 mm to treatments 8C, 8S; 180 mm to treatments 10C, 10S. No rain-fell during the experimental period and the average daily evapotranspiration was 6.6 mm (October), 6.8 mm (November) and 7.1 mm (December).

Plot size was 8 x 5 m and the sampling area was 10 m^2. The same maize cultivar was sown on October 10, 2015, with a density of four plants per square meter. The soil received the same rates of nutrients at planting as in preview years. Five days after emergence of the maize a total of 12 t/ha of dry biomass (branches and leaves) of *Acacia mangium* legume was applied between the rows. Biomass of *Acacia mangium* had been applied in the years 2012, 2013, and 2014 in the same plots and at the same rate (typical for alley cropping systems), according to Aguiar *et al*. (2010). The quality parameters of the acacia residue was as follows: a C/N ratio of 23.5; 22.2 g/kg of N; 3.1 g/kg of P; 5.1 g/kg of K; 16.4 g/kg of Ca; 3.2 g/kg of Mg. The amount of nitrogen applied via legume was 216 kg/ha. In addition, 50 kg/ha N was applied as side dressing, when the fourth pair of corn leaves appeared.

In September 2015 the soil showed the following chemical properties: pH 5.1 (in $CaCl_2$); organic-C 25 g/kg (Walkley–Black); P 25 mg/dm^3; (Al + H) 18 $mmol_c/dm^3$; Ca 45, Mg 11, K 1,2 $mmol_c/dm^3$ (resin), respectively; CEC 75.2 $mmol_c/dm^3$; base saturation 76.1 %.

Soil and plant measurements

The soil penetration resistance (SPR) was measured with 5-cm gradations, at depths of 0-5 cm, 6-10 cm, 11-15 cm and 16-20 cm, using a digital penetrometer (Falker, Porto Alegre, Brazil) with three replicates per plot at stages: V8, tasseling and maturity of the maize. The table of critical level defined by Hazelton and Murphy (2007) was used to construct a graph of soil penetration resistance.

We sampled soil in volumetric rings with a 100-cm^3 capacity. We collected three replicates per plot from a depth of 5 to 12 cm. Samples were saturated, weighed, placed on a tension table and equilibrated at a potential of -6 kPa to drain pores >50 μm. After weighing, each replicate was oven-dried at 105ºC. Soil dry bulk density (ρ_b) was calculated as m/v, where: m = dry soil mass at 105ºC and v = ring volume. Total porosity (φt) was calculated as $[1 – (\rho_b/\rho_p)]$, where: ρ_b = soil density (Mg/m^3); ρ_p = particle density (Mg/m^3), which was determined according to Embrapa (1997). We divided the total porosity into macroporosity and microporosity. We calculated the macroporosity, corresponding to the volume of pores with equivalent diameter larger than 50 μm as the mass difference between the samples at saturation and after equilibration at -6 kPa, and we calculated the microporosity, corresponding to the volume of pores with equivalent diameter narrower than 50 μm as the mass difference between the sample equilibrated at -6 kPa and the oven-dry sample (Thomasson 1978)**.** All measurements were done immediately before irrigation of each treatment.

We determined the volumetric water content of soil at V8, tasseling, and maturity for the maize, on a daily basis for the 0-10cm and 10-20cm layers. Measurements were always made between 0700 and 0900 hours, with three replicates per plot. A TRIME-FM instrument (IMKO, Ettlingen, Germany) was used to collect time domain reflectometry

(TDR) data. All soil physical measurements were done immediately before irrigation of each treatment.

In the evaluation of the stomatal conductance (g_S) and transpiration rate (E), a Portable Measurement System for Gaseous Exchanges, an Infrared Gas Analyzer (IRGA) was used, LI-6400® model, LI-COR, (Lincoln, NE, USA). These physiological parameters were measured in two new fully expanded leaves, for three plants chosen at random in each plot, in the upper part of the canopy exposed to full sunlight, between 0800 to 1000 hours. Three measurements were recorded automatically every 2 min for each leaf to ensure a steady-state condition for the gas exchange flow. The light units (the diode array contained blue and red LEDs), with the upper jaw enclosing the leaf, were used to ensure constant irradiance to replicate sunlight (1600 μmol/m/s). The measurements were carried out in the tasseling stage immediately before irrigation.

Crop growth dynamics were monitored by weekly evaluations of crop growth rates (CGR) using leaf area (LA) and dry matter (DM) variations with time (t). To accomplish this, five plants were collected per plot at seven-day intervals, from the 25th day after emergence. Seven collections were performed; the last collection coincided with the corn milky grain stage. Leaf area was measured with a Licor device; dry matter was determined after drying the plants in a forced-air circulation oven at $70^{o}C$.

Nitrogen content was measured on two occasions: at tasseling (or approximately one week before anthesis) and at the physiological maturity stage. At each sampling, five plants from each plot were randomly selected and separated into leaves, stalks and, at the second sampling, reproductive components. All of these plant materials were dried at $60^{o}C$ for 3-4 days to obtain a constant weight. Three subsamples were collected and ground to pass through a 1-mm screen. Total N concentration was determined in the maize following H_2O_4 - H_2O_2 digestion according to the standard distillation method described by Cottenie (1980). Based on the measurements of plant dry matter (DM) and N uptake, we calculated the N remobilization: [Vegetative DM (N content) at silking - vegetative DM (N content) at maturity]. At the final harvest or at physiological maturity, the grain yield components were separately assessed in a 10-m^2 area and the values were adjusted according to moisture level of 145 g/kg.

Statistical analyses

The data were analysed via analysis of variance (ANOVA), and the means were compared using Duncan post hoc test at a $P = 0.05$ significance level. The data were analysed using InfoStat software (InfoStat Group, College of Agricultural Sciences, National University of Córdoba, Argentina). Except for the crop growth rate that was estimated and modeled with the ANACRES software (Portes & Castro Júnior 1991).

Results

Changes in soil physical attributes and nitrogen uptake

Physical measurements, with less variation in the time scale, such as soil density, and macroporosity were not affected by mulching or by irrigation intervals. However, microporosity was lower in the treatments 4S, 8S and 10S than in the treatments with mulching. However, total porosity was only statistically less in the bare soil treatments 4S and 10S than in their mulched comparisons (Table 1).

Table 1 Soil dry bulk density (ρ_b), microporosity, macroporosity and total porosity (Φt) in the experimental treatments in 5-12 cm layer.

Treatments	ρ_b	Microporosity	Macroporosity	Φt
	g/cm³	-------------------- cm³/cm³	----------------------	
4S	1.44 a	0.15 c	0.29 a	0.44 b
4C	1.39 a	0.17 b	0.30 a	0.47 a
6S	1.44 a	0.16 bc	0.29 a	0.46 a
6C	1.40 a	0.18 ab	0.30 a	0.47 a
8S	1.45 a	0.15 c	0.30 a	0.46 a
8C	1.39 a	0.19 a	0.29 a	0.48 a
10S	1.43 a	0.14 c	0.30 a	0.44 b
10C	1.40 a	0.17 b	0.32 a	0.47 a

4S= 4 days irrigation intervals in bare soil; 4C= 4 days irrigation intervals with soil covered; 6S= 6 days irrigation intervals in bare soil; 6C= 6 days irrigation intervals with soil covered; 8S= 8 days irrigation intervals in bare soil; 8C= 8 days irrigation intervals with soil covered; 10C= 10 days irrigation intervals with soil covered, 10S= 10 days irrigation intervals in bare soil. Different letters in the same column indicate differences at the 5% level by Duncan's test.

In the 0–10cm layer, mulching significantly increased water volumetric contents only when the interval of irrigation was 4 days, at V8 and at the tasseling stage. In the 10–20cm layer, volumetric water content was increased by mulching at V8 (8 leaves produced) and at the tasseling stage in the 4- and 6-day irrigation intervals (Table 2).

Table 2 Volumetric water content (m^3/m^3) in the experimental treatments in V8 stage, at tasseling and at maturity, in 0 – 10 cm and 10 to 20 cm layer.

	V8	At tasseling	At maturity
0 – 10 cm		---------- m^3/m^3 ----------	
4S	0.11 b	0.15 b	0.11 a
4C	0.16 a	0.18 a	0.13 a
6S	0.07 c	0.06 c	0.08 b
6C	0.06 c	0.07 c	0.09 ab
8S	0.06 c	0.05 c	0.07 bc
8C	0.06 c	0.08 c	0.09 ab
10S	0.04 c	0.05 c	0.05 c
10C	0.04 c	0.07 c	0.06 bc
10 – 20 cm			
4S	0.06 ab	0.06 b	0.07 b
4C	0.07 a	0.08 a	0.11 a
6S	0.06 ab	0.04 c	0.04 c
6C	0.06 ab	0.06 b	0.06 b
8S	0.04 bc	0.04 c	0.04 c
8C	0.06 ab	0.04 c	0.07 b
10S	0.03 c	0.04 c	0.03 c
10C	0.03 c	0.04 c	0.04 c

4S= 4 days irrigation intervals in bare soil; 4C= 4 days irrigation intervals with soil covered; 6S= 6 days irrigation intervals in bare soil; 6C= 6 days irrigation intervals with soil covered; 8S= 8 days irrigation intervals in bare soil; 8C= 8 days irrigation intervals with soil covered; 10C= 10 days irrigation intervals with soil covered, 10S= 10 days irrigation intervals in bare soil. Different letters in the same column indicate differences at the 5% level by Duncan's test.

In contrast, penetration resistance (SPR) was strongly influenced by soil water content, varied considerably over time and was significantly affected by mulching (Figure

1). However, effects were significantly only in the 0-5 cm layer. In the 5–15 cm layers, the effects of mulch on decreasing SPR was significant, when comparing treatments with and without mulch for the same irrigation intervals ($P < 0.05$). Furthermore, in the 5 – 10cm layer, SPR was smaller for treatment 10C than in 6S at all stages. In 10 – 15 cm layer SPR was greater in 8S than in 10C during the entire cycle of the maize, while in the 15 – 20cm layer there was no difference between 4S to 6C, 6S to 8C and 8S to 10C ($P >$ 0.05). In the treatments without mulch, although the effect of irrigation was always more significant when the intervals were more than four days, SPR was greater in 8S than in 6S in the 5 – 20 cm layer at first and third stage, and in the 10 – 20 cm layer at the second stage ($P < 0.05$). In the plots with mulch, differences were only observed below the 10–15cm layer, where SPR was greater in 10C and 8C than in 4C in all stages ($P < 0.05$). According to Hazelton and Murphy (2007), in the treatments 8S and 10S, the SPR indicated that the soil was hard in the 5-10cm layer and very hard in the 10–20cm layer in all stages. Below 10cm, SPR was hard in 4S, 6C, 6S and 8C. In the treatments 4C and 6C, SPR was moderate in 10–15 cm layer and hard of 15–20cm layer. There were no interactions between irrigation intervals and mulching regarding variation in SPR.

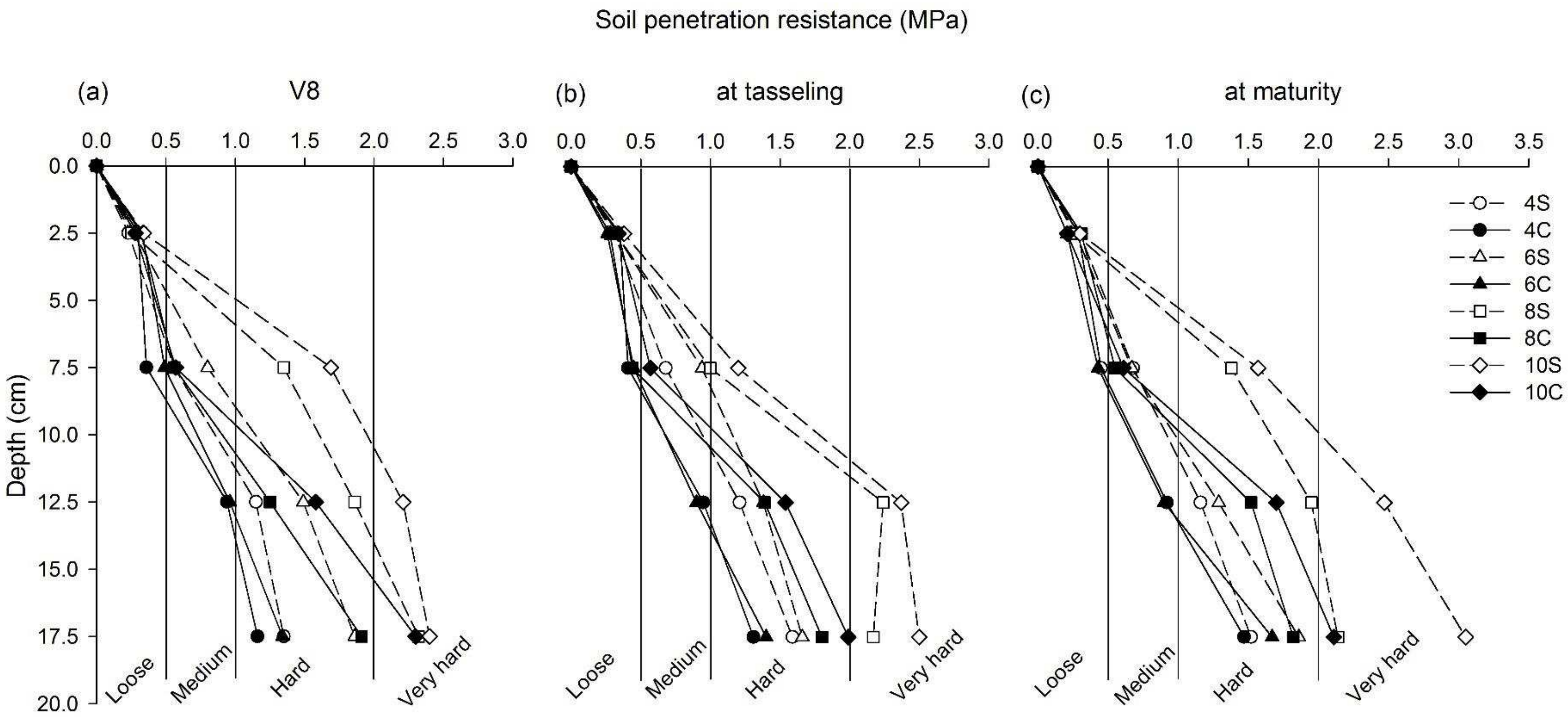

Figure 1 Soil penetration resistance at three stage of maize: (a) V8, (b) at tasseling and (c) at maturity, in the experimental area in 2015. 4S= 4 days irrigation intervals in bare soil; 4C= 4 days irrigation intervals with soil covered; 6S= 6 days irrigation intervals in bare soil; 6C= 6 days irrigation intervals with soil covered; 8S= 8 days irrigation intervals in bare soil; 8C= 8 days irrigation intervals with soil covered; 10C= 10 days irrigation intervals with soil covered, 10S= 10 days irrigation intervals in bare soil. Vertical bars mean the critical levels by Hazelton and Murphy (2007).

Uptake of nitrogen was affected by mulching and irrigation intervals, with different intensities in the stages evaluated (Table 3). At the pre-tasseling stage, the differences were small and just 4C, and 10S treatments showed significant differences in nitrogen content. In 4C it was enhanced, while in 10S it was less than in all the other treatments ($P < 0.05$). Nitrogen uptake post tasseling widely varied. At all irrigation intervals, it was always greater in plots with residue. The largest nitrogen content at post-tasseling was observed in the 6C treatment, where it was almost 50% greater than in 6S and was larger than in the 4C treatment ($P < 0.05$). In 10S the nitrogen uptake post tasseling was less than for all other treatments. There was no significant difference between 8C and 4S treatments ($P < 0.05$). The most nitrogen remobilized occurred in 8S, whereas in 6C the amount was similar to that in 10S but in both it was less than in all other treatments ($P < 0.05$). The total uptake of nitrogen was small, even in treatments with a greater nitrogen content. The greatest amount of nitrogen accumulated was in treatments 4C and 6C, and was more than twice that in 10S, where accumulation was least. In 4S, 6S, 8S, 8C and 10C the total nitrogen was less than in 4C and 6C ($P < 0.05$). In 4C, 6C, 6S and 8C more than half of nitrogen was accumulated post – tasseling, whereas in 8S and 10S it was less than 40%.

Table 3 Amount of nitrogen at tasseling (NT), amount of nitrogen remobilized (NR), amount of nitrogen uptake post-tasseling (NPT), total nitrogen accumulated (TN), percentage of nitrogen uptake post-tasseling (NPT%), in the experimental area in 2015.

Treatments	NT	NR	NPT	TN	NPT%
			(kg/ha)		
4C	49.5 a	13.8 bc	51.1 b	100.6 a	50.3 b
4S	45.4 ab	18.0 ab	33.2 cd	78.7 b	42.1 bc
6C	40.8 ab	5.6 d	61.9 a	102.7 a	60.3 a
6S	39.8 ab	10.6 c	42.5 bc	82.3 b	51.0 b
8C	38.1 b	11.0 c	38.2 c	76.4 b	50.2 bc
8S	49.2 ab	20.1 a	24.9 d	74.1 b	33.6 d
10C	39.7 ab	15.9 ab	30.2 d	69.9 b	44.1 bc
10S	25.4 c	7.0 cd	14.8 e	40.1 c	37.7 cd

4S= 4 days irrigation intervals in bare soil; 4C= 4 days irrigation intervals with soil covered; 6S= 6 days irrigation intervals in bare soil; 6C= 6 days irrigation intervals with soil covered; 8S= 8 days irrigation intervals in bare soil; 8C= 8 days irrigation intervals with soil covered; 10C= 10 days irrigation intervals with soil covered, 10S= 10 days irrigation intervals in bare soil. Different letters in the same column indicate differences at the 5% level by Duncan's test.

Changes in physiological parameters and crop growth

The transpiration rate was not affected by mulching when comparing the same irrigation intervals (Figure 2). However, when comparing different intervals 6C = 4S, 8C = 6S and 10C = 8S ($P < 0.05$). The stomatal conductance was smaller in 10S than in 6S and also smaller than in all plots with mulch. Conductance in treatment 4C was greater than in all other treatments and was double that in 10S, which was similar to that for 8S. There were significant differences between 4S, 6S, 6C, and 8C ($P < 0.05$). There were no interactions between irrigation intervals and mulching regarding variation in transpiration rate.

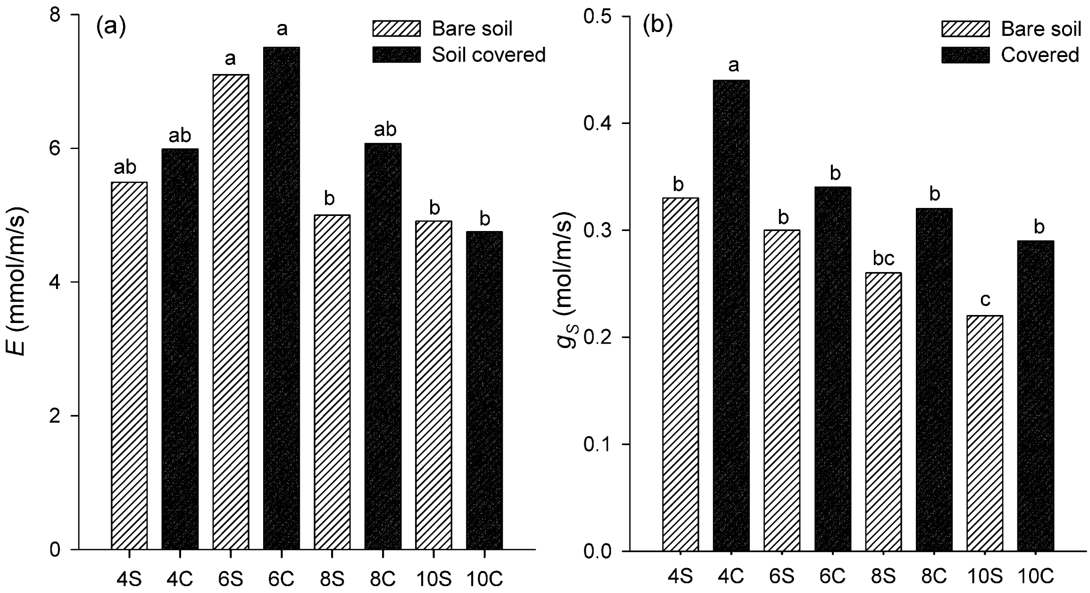

Figure 2 (a) Transpiration rate (*E*) and (b) stomatal conductance (g_s) of maize in the experimental area in 2015. 4S= 4 days irrigation intervals in bare soil; 4C= 4 days irrigation intervals with soil covered; 6S= 6 days irrigation intervals in bare soil; 6C= 6 days irrigation intervals with soil covered; 8S= 8 days irrigation intervals in bare soil; 8C= 8 days irrigation intervals with soil covered; 10C= 10 days irrigation intervals with soil covered, 10S= 10 days irrigation intervals in bare soil. Different letters indicate differences at the 5% level by Duncan's test.

The crop growth rate (CGR) was affected by mulching in different intensities dependent on the irrigation interval or stage of the maize (Figure 3). From 44 days after emergence until at tasseling stage (65 days after emergence) CGR was greater in 4C and 4S ($P < 0.05$). CGR continued to increase after tasseling only in the plants from plots with residue. 10S had the lowest CGR during the entire evaluated period ($P < 0.05$).

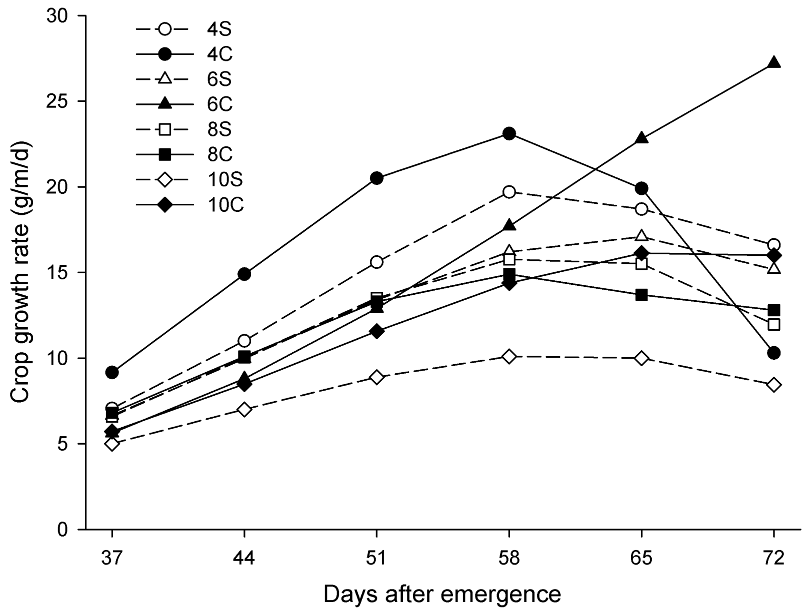

Figure 3 Crop growth rate of maize in the experimental area in 2015. 4S= 4 days irrigation intervals in bare soil; 4C= 4 days irrigation intervals with soil covered; 6S= 6 days irrigation intervals in bare soil; 6C= 6 days irrigation intervals with soil covered; 8S= 8 days irrigation intervals in bare soil; 8C= 8 days irrigation intervals with soil covered; 10C= 10 days irrigation intervals with soil covered, 10S= 10 days irrigation intervals in bare soil.

The mulch significantly increased the dry matter production in 4-, 8-, and 10-day irrigation intervals (Figure 4). In plots without residue the dry matter production was as follows: 4S = 6S > 8S > 10S, whereas in plots with residues was 4C = 6C > 8C > 10C. ($P < 0.05$). Mulching increased yield at all irrigation intervals. There was no significant difference between 4 and 6 days of irrigation intervals when they are compared with or without mulch. In contrast, the grain yield was higher in 8S than in 10S as well as in 8C than in 10C ($P < 0.05$). There were no interactions between irrigation intervals and mulching to variation in grain yield.

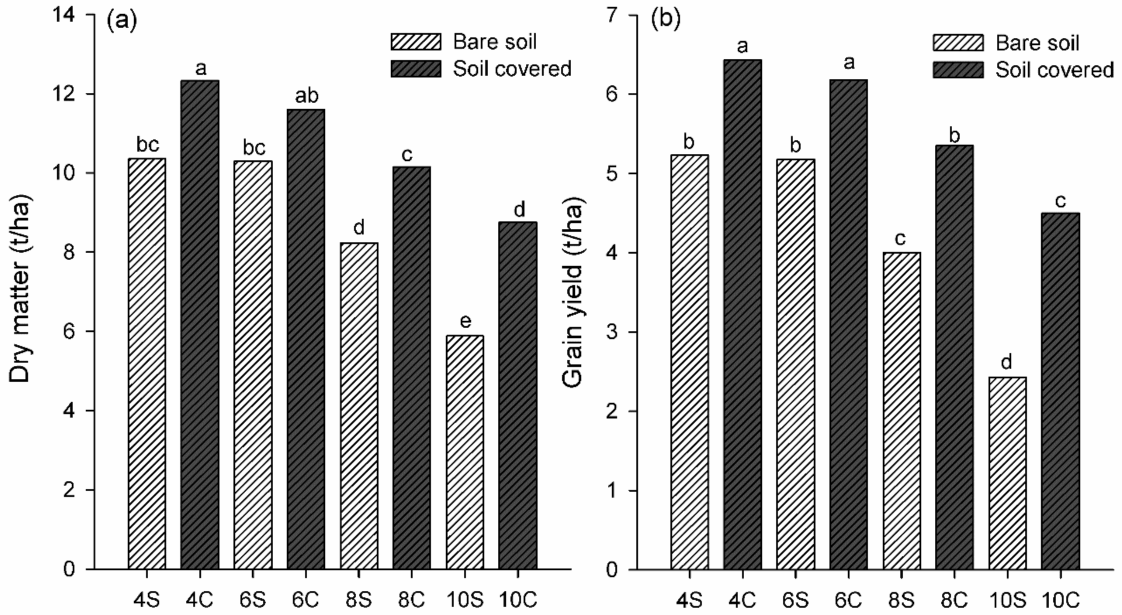

Figure 4 (a) Dry matter and (b) grain yield of maize in the experimental area in 2015. 4S= 4 days irrigation intervals in bare soil; 4C= 4 days irrigation intervals with soil covered; 6S= 6 days irrigation intervals in bare soil; 6C= 6 days irrigation intervals with soil covered; 8S= 8 days irrigation intervals in bare soil; 8C= 8 days irrigation intervals with soil covered; 10C= 10 days irrigation intervals with soil covered, 10S= 10 days irrigation intervals in bare soil. Different letters indicate differences at the 5% level by Duncan's test.

Discussion

Although the effect of mulching on soil penetrometer resistance (SPR) decreased with depth, comparing 4S to 6C, 6S to 8C and 8S to 10C, our results showed that the damaging effect on SPR in drying soil could be delayed for two days by use of mulch. In the 0 – 10cm layer the delay may be up to four days if comparing 6S to 10C. Lack of differences in the transpiration rate between treatments 6C/4S, 8C/6S and 10C/8S also confirms a physiological effect of the mulch in decreasing the number of water stress days by two. This delay was also observed in the stomatal conductance in the irrigation intervals of four and 10 days. This can also be important for rainfed crops in tropical conditions when intervals larger than four days without rain can significantly impair the crop root growth, water uptake and crop yield (Moura *et al.*, 2016).

According to Mulumba & Lal (2008), residues on the soil surface shade the soil, serve as a vapour barrier against moisture losses from the soil and therefore more water is conserved in the soil profile during the early growth period with mulch than without it. However, in this experiment the small differences in volumetric water contents cannot explain the differences in the maize crop. Furthermore, residue application in previous years may have contributed to an environment favourable to root growth and water uptake promoting the formation of 'ephemeral structures' in the structurally fragile soil by increasing the free light fraction of soil organic matter (Shepherd *et al*., 2002). It is worth highlighting that even in plots with mulch, the 15 – 20 cm layer was hard four days after irrigation, which shows importance of this practice in enhancing rootability in this soil.

Several critical conditions may explain the differences in nitrogen uptake in this experiment. First, the application of nitrogen in sidedressing at the V8 maize stage decreased differences in nitrogen content among treatments, at the pre-tasseling stage. Second, post tasseling, the nitrogen uptake was greater in plots with mulch due to enhanced soil rootability with lower penetration strength, as well as, due to increased availability of nitrogen released by leguminous residue.

Absorption of N is highly dependent on root development and therefore on soil rootability, while increased root system growth results in greater uptake and less N loss (Garnett *et al*., 2009). In addition, a steady nitrogen release by leguminous biomass during the entire crop cycle is more important in humid tropical conditions compared to the rapid early availability of nitrogen that results from application of synthetic fertilizers (Aguiar *et al*., 2010). Lastly, the greater water application rate in 4C may have impaired the nitrogen uptake, by leaching induction, compared to 6C. Some authors (Bronson, 2008; Wang *et al*., 2012) report that loss of nitrogen by leaching increases with water infiltration rates and amount of water applied by irrigation. According to Moura *et al*. (2009) the water infiltration rate may achieve up to 70 mm/h in the same soil with residue. These results may be very important to water use efficiency and nitrogen, since greater water application rates can result in a wasted water and nitrogen. On the other hand, for rainfed crops the humid tropics, which receive large amounts of rainfall, this means that the fragmentation of the fertilizer application can lead to greater efficiency than a single application at the V8 stage.

The smallest nitrogen remobilization in 6C is related to the greatest post tasseling nitrogen uptake under this treatment. Remobilization in different plant organs is needed to route nitrogen to grains during the period of grain-fill, when nitrogen uptake is generally insufficient for the high demand of the seeds (Borrel *et al*., 2000). In contrast, the relative flow and remobilization of nitrogen to the grain during grain-fill period can also be analysed in terms of the source of nitrogen to redistribution and sites for reutilization and storage. Therefore in 10S, without N from legumes and with small cobs, remobilization was less than in other treatments. On the other hand, N depletion, due to remobilization, tends to accelerate the senescence in the leaves, reducing the photosynthesis decreasing the dry matter and yield (Masclaux-Daubresse *et al.*, 2010).

The increase in growth rate of the plants after tasselling, on the plots with mulch, reflected the greater availability and uptake of nitrogen promoted by the leguminous residue. However, greater dry matter and grain yield was obtained in treatments with larger amounts of total nitrogen uptake. For yield, the results 10C = 8S, 8C = 6S suggest that the effect of mulch on decreasing water stress days and on nitrogen uptake increased maize production. In addition, the results of 6C = 4C > 4S indicated that this effect was influenced by nitrogen uptake post tasseling when the irrigation interval was not harmful to maize growth. Thus, the greater growth and yield of the maize in plots with mulch can be accounted for most likely by its effect on water stress and nitrogen uptake.

In the Amazonian periphery with soil that is difficult to manage, small intervals without rain can decrease maize grain yield due to water stress and poor nutrient uptake. From a practical point of view, our results mean that, the use of mulch in a quantity similar to that commonly produced in alley cropping system can increase the viability of a crop even in cultivated and cohesive soils predominant in the region. From an environmental point of view, this may reduce expansion of farming into forested or in fallow areas, and it may prevent more deforestation, which is a critical issue in this region.

Conclusion

Mulch used on tropical soil surfaces may decrease soil penetration resistance, thereby expanding the time that root systems can develop in drying soil, which has a positive effect on the physiological parameters as well as on the growth and yield of maize. Furthermore, mulch of leguminous residue increased nitrogen uptake at the post tasseling stage, which decreased the remobilization and increased total uptake nitrogen. The use of 6-day irrigation intervals with mulch compared to 4 days without mulch resulted in the same conditions for root development, greater amounts of nitrogen uptake and larger yields, which means greater water use efficiency.

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