UNIVERSIDADE ESTADUAL DO MARANHÃO
CENTRO DE CIÊNCIAS AGRÁRIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM AGROECOLOGIA
CURSO DE MESTRADO EM AGROECOLOGIA

JÉSSICA DE FREITAS NUNES PIRES

CONTRIBUIÇÃO DA COBERTURA MORTA EM CURTO E LONGO PRAZO PARA MELHORIA DO SOLO, ABSORÇÃO DE NITROGÊNIO E PRODUTIVIDADE DO MILHO

São Luís-MA
2020

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Orientador: Prof. Dr. Emanoel Gomes de Moura.

JÉSSICA DE FREITAS NUNES PIRES

Engenheira Agrônoma

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Dissertação apresentada ao Programa de Pós-Graduação em Agroecologia da Universidade Estadual do Maranhão como parte das exigências para obtenção do título de Mestre em Agroecologia.

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A minha família que sempre me incentivou e nunca deixou que eu desistisse

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A absorção de nutrientes pelas plantas está estreitamente relacionada às condições de enraizabilidade do solo. Uma estratégia para aumentar a eficiência do uso dos nutrientes em solos coesos deve incluir a manutenção de camada de resíduos vegetais na superfície do solo para, consequentemente, diminuir a evaporação mantendo o solo mais úmido e assim diminuindo a coesão. Este estudo tem como objetivo avaliar os efeitos de curto e longo prazo da cobertura morta no acúmulo de MOS, retenção de SBC e melhoramento físico de um solo tropical coeso enriquecido com cálcio. Também avaliamos a contribuição da cobertura morta e do N sintético (Ns) para a absorção de N e produtividade de grãos do milho. Este experimento foi conduzido usando um delineamento de blocos ao acaso com os seguintes tratamentos: cobertura morta de longo prazo (LTM), cobertura vegetal de longo prazo mais nitrogênio (LTM + N), cobertura vegetal de curto prazo (STM), cobertura vegetal de curto prazo mais nitrogênio (STM + N), mulching de longo prazo mais cobertura de curto prazo (LTM + STM), cobertura de longo prazo mais cobertura de curto prazo mais nitrogênio (LTM + STM + N), plantio com nitrogênio (N) e um controle. Palha composta por biomassa seca (galhos e folhas) de Gliricidia sepium aplicada na proporção de 12 Mg ha^{-1} em solo enriquecido com cálcio. A interação entre Ns e cálcio (Ca) foi mais intensa em áreas LTM, resultando em maior teor de carbono, cátions básicos, melhor enraizamento do solo e maior absorção de nitrogênio. STM manteve a umidade do solo, diminuindo a resistência à penetração e, quando emparelhado com LTM, fornecendo nitrogênio biológico suficiente para substituir o Ns. Os efeitos do STM e do LTM isoladamente foram cumulativos, com absorção de N 54% maior, N acumulado 163% maior e rendimento de grãos de milho 125% maior (4,77 a 10,78 Mg ha^{-1}). O uso contínuo de cobertura morta, portanto, traz benefícios tanto para a sustentabilidade quanto para a viabilidade dos agroecossistemas tropicais, prevenindo a degradação do solo e evitando o desmatamento.

Palavras-chave: frações da matéria orgânica, retenção de cátions base, agrossistema tropical, sustentabilidade.

1 INTRODUÇÃO GERAL

Nos últimos anos, houve uma aceleração no crescimento demográfico e, por conseguinte, mudanças nos hábitos alimentares, o que resultou na produção de mais alimentos e ao mesmo tempo tem gerado conscientização da sociedade quanto às relações da agricultura, meio ambiente e recursos naturais, ou seja, sistemas agrícolas sustentáveis (FOLEY *et al*., 2011*)*.

O sistema agrícola deve modificar suas práticas tradicionais, com uso intensivo do solo e alto uso de insumos agroquímicos, que constantemente provocam impactos ambientais negativos; e evidenciar na ciclagem de nutrientes para suprir as necessidades nutricionais das plantas cultivadas. Certas técnicas que são recomendadas para o manejo do solo no Cerrado brasileiro como aração, gradagem e adição de fertilizantes solúveis são insustentáveis para a manutenção dos agroecossistemas por não se moldarem às características edafoclimáticas do local (MOURA *et al.,* 2013).

Dessa forma, a agricultura sustentável busca reverter tais métodos tradicionais e, portanto, faz-se necessário aumentar a produtividade e concomitantemente a eficiência dos recursos naturais e também atender a demanda de alimentos no presente sem comprometer futuras gerações.

As regiões central e norte do Maranhão são caracterizadas por fazer parte da Formação Itapecuru, tomando 60% do território maranhense, caracterizando-se pela predominância de arenitos finos argilosos. Essa composição confere aos solos do estado propriedades agronômicas distintas, a baixa resposta das culturas aos adubos minerais como Nitrogênio, Fósforo e Potássio, a taxa de infiltração de água no solo muito baixa, decomposição acelerada da matéria orgânica do solo, baixa capacidade de reter cátions e predisposição à coesão (MOURA; ALBUQUERQUE; AGUIAR, 2008).

Por essas características, na região centro norte maranhense, ainda predomina entre a maioria dos pequenos agricultores a agricultura itinerante ou corte e queima, processo esse que aumenta a degradação do solo e que consiste no corte da vegetação primária para posteriormente realizar a queima e utilizar as cinzas para o plantio. Logo após a colheita, a área permanece em pousio por um período, o agricultor muda novamente de área e recomeça um novo ciclo com a conversão de novas superfícies de floresta primária. O uso do sistema de corte e queima se explica pela rápida limpeza da área, pelo baixo custo e disponibilização de nutrientes pelas cinzas (FERRAZ JÚNIOR, 2004).

Desse modo, torna-se inevitável levar em conta que grande parte dos solos do trópico úmido possui baixa fertilidade natural, pois sua mineralogia de argila é comumente denominada por caulinitas e na maioria das vezes são pobres em matéria orgânica. Portanto, diante dessas características, esses solos desprovidos de matéria orgânica e compostos de ferros são geralmente propensos à coesão. A propensão à coesão tem uma influência no desenvolvimento do sistema radicular, no que diz respeito à enraizabilidade do solo, assim, diminuindo a eficiência no uso da água e dos nutrientes (LEY *et al*., 1995).

Nesse contexto, a absorção de nutrientes pelas plantas está estreitamente relacionada às condições de enraizabilidade do solo. Uma estratégia para aumentar a eficiência do uso dos nutrientes em solos coesos deve incluir a manutenção de camada de resíduos vegetais na superfície do solo para, consequentemente, diminuir a evaporação mantendo o solo mais úmido e assim diminuindo a coesão. Ademais, a adição continuada de resíduos pode favorecer o aumento do conteúdo da fração mais lábil da matéria orgânica, o que contribui para formação de uma estrutura do solo efêmera e para melhorar a enraizabilidade do solo (MOURA *et al*., 2010).

A combinação dos resíduos de leguminosas arbóreas de alta qualidade com outra de baixa qualidade proporciona uma liberação de nutrientes sincronizada com as necessidades nutricionais da cultura (MOURA *et al*., 2010; AGUIAR *et al*., 2010). Isso porque esse sistema apresenta algumas vantagens que são: aumento da capacidade de aeração do solo; liberação lenta nos valores de nitrogênio (N) adicional; e o aumento dos níveis de cálcio (Ca) na zona radicular (AGUIAR *et al*., 2010). Além disso, essa prática aumenta os estoques de carbono orgânico do solo e as quantidades de agregados estáveis em água.

Embasado nessas experiências, espera-se que o uso da biomassa de leguminosas arbóreas aplicada sobre a superfície do solo, em condições do trópico úmido, possa proporcionar melhorias nas propriedades físicas e químicas do solo; aumentar a absorção dos nutrientes; aumentar as frações mais estáveis da matéria orgânica; estimular o aumento da produtividade das culturas e possibilitar a sustentabilidade dos agroecossistemas.

2 REFERENCIAL TEÓRICO

2.1 Solos Tropicais propensos à coesão

A expressão coesão tem sido aplicada para caracterizar solos que possuem horizontes superficiais e subsuperficiais, isto é, apresentam consistência dura quando secos, e friável quando úmidos (JACOMINE, 1996; GIAROLA; SILVA, 2002). Solos com essa característica, quando secos, são resistentes à penetração, têm baixa saturação por bases ($V < 50\%$), e o teor de Fe_2O_3 (pelo H_2SO_4) é menor que 8 g kg^{-1} e o Ki (indicador de idade do solo) é 1,7 ou maior, ou seja, são cauliníticos. (GIAROLA; SILVA, 2002).

Solos coesos variam no que tange a esse caráter, sendo assim mais ou menos limitante ao crescimento das culturas. Em solos mais arenosos com o aumento da umidade a resistência à penetração torna-se menor, já em solos com característica argilosa ou areno-argilosa, a enraizabilidade do solo torna-se maior, impedindo que o sistema radicular se desenvolva, pois o solo apresenta-se seco e quando úmido o crescimento da planta também é afetado com a falta de aeração no solo (GIAROLA; SILVA, 2002).

Quanto à gênese dos horizontes coesos, um dos principais processos envolvidos para explicar esse fenômeno refere-se à deposição de argila dispersa em poros, ou seja, o processo chamado de argiluviação e compactação natural promovida pela secagem e dessecação do solo (BEZERRA *et al*., 2015).

No Brasil, solos com caráter coeso têm ocorrência basicamente relacionada a regiões de climas que apresentam estações secas e úmidas definidas. Também ocorre nas classes do Latossolos e Podzólicos Amarelos desenvolvidos dos sedimentos da formação Barreiras (FONSECA, 1986; JACOMINE, 1996; REZENDE, 2000; GIAROLA; SILVA, 2002).

Os solos da Formação Itapecuru possuem características coesas, por serem derivados de rochas sedimentares clásticas, com baixo teor de elementos de agregação como ferro e cálcio, e propendem a sofrer o comportamento *hardsetting*. (DANIELLS, 2012). Esse comportamento foi descrito pela primeira vez por McDonald *et al.* (1984) devido esses solos *hardsetting* apresentarem consistência dura e compacta, condição aparentemente apedal (não apresentam agregados naturais), formada durante o secamento (GIAROLA; SILVA, 2002). A ocorrência de solos que apresentam comportamento *hardsetting* são de climas com alternância entre períodos secos e úmidos (CHARTRES *et al.,* 1990; MULLINS *et al.,* 1990; YOUNG et al., 1991; GIAROLA; SILVA, 2002).

Os elementos químicos como a sílica, ferro e alumínio são agentes que possuem ação cimentante e consistem em um papel efetivo na gênese de um solo com caraterísticas *hardsetting* (MOREAU *et al*., 2006). Semelhantemente, solos duros também são encontrados na Austrália (MULLINS *et al.,* 1990) por terem a sílica como um dos agentes que promove a cimentação e o endurecimento dos horizontes desses solos (GIAROLA; SILVA, 2002).

2.2 Estratégias para melhorar a Eficiência do Uso de Nitrogênio (EUN)

O nitrogênio (N) é conhecido como um nutriente essencial para o crescimento e desenvolvimento das plantas, é aplicado aos campos agrícolas para aumentar o rendimento das culturas, sua disponibilidade é o principal fator restritivo da produtividade dos agroecossistemas, tornando-se um desafio para a agricultura, pois equilibrar as condições de nutrientes das culturas e minimizar as perdas para conservar um ambiente sustentável e manter os benefícios econômicos para os agricultores ainda não é tarefa fácil (MOSIER *et al*., 2001, SHARMA; SUKHWINDER, 2017).

O uso ponderado da adubação nitrogenada é indispensável, não somente para aumentar a eficiência de recuperação, como também para aumentar a produtividade e reduzir o custo de produção (FAGERIA *et al*., 2007).

Apresentada a sua importância, o N tem sido intensamente estudado, na perspectiva de melhorar a eficiência do seu uso. Nesse sentido, tem-se procurado reduzir as perdas de nitrogênio no solo, assim como melhorar a absorção e assimilação do N pela planta (BREDEMEIER; MUNDSTOCK, 2000).

Para Sharma e Sukhwinder (2017), a Eficiência do Uso do Nitrogênio (EUN) tem duas definições: a primeira diz que é a eficiência com que as plantas usam e retêm o nitrogênio no solo. As leguminosas têm EUN alta porque coletam e armazenam nitrogênio em seus corpos, em vez de liberá-los na atmosfera. Portanto, a EUN mede a eficiência com que as plantas usam e retêm o nitrogênio; a segunda definição diz que a EUN é a eficiência com que o nitrogênio aplicado nos solos, tanto por meios naturais ou artificiais, é absorvido pelas plantas e não usado para outros fins como alimentar bactérias anaeróbicas que causam desnitrificação.

Já para Fageria (1998) e Moura *et al*. (2012), a EUN pode ser definida como a produtividade obtida por unidade de fertilizante aplicado. Essa ideia baseia-se no ideal de produzir mais em uma menor área, aumentando a eficiência do sistema. Assim, nas condições tropicais, é indispensável manejar o solo de modo a aumentar a disponibilidade de nutrientes por meio de retenção de cátions e da redução das perdas por lixiviação, escorrimento superficial e erosão (MUSYOKA *et al*., 2017).

O emprego de estratégias de manejos apropriados de N é determinante para melhorar a EUN e a produção eficiente de culturas. Essas estratégias de manejo abrangeriam a manipulação de variáveis de solo, planta, clima e fertilizantes (FAGERIA, 1998). Em solos tropicais propensos à coesão, a baixa enraizabilidade da planta no solo, por exemplo, torna-se um dos principais problemas enfrentados na agricultura, visto que, causa diminuição na absorção de nutrientes, sendo acentuados por altas temperaturas e altos índices pluviométricos.

Sendo assim, estratégias para aumentar a EUN são cruciais, dentre elas, o uso de biomassas de leguminosas, já que algumas têm potencial para converter N em formas utilizáveis pelas plantas. Além de cobrir o solo, podem colaborar com quantidades significativas de N, porém não o suficiente para satisfazer a necessidade da cultura, havendo necessidade de aplicação de nitrogênio adicional via adubação (LADHA *et al*., 2003).

Indubitavelmente, promover estratégias para aumentar a EUN depende também do conhecimento sobre o manejo do solo e os processos envolvidos na degradação do solo tropical (MOURA *et al*., 2016). As estratégias devem englobar: aumento da fertilidade do solo, uso eficiente da água, disponibilidade dos nutrientes, adoção de plantio direto, agricultura conservacionista e adaptação às mudanças climáticas (LAL, 2009).

2.3 Matéria Orgânica do solo

Garantir a sustentabilidade da agricultura tem sido um assunto de recorrentes debates, sobretudo, em que a Agricultura Sustentável apresente produtividade que acompanhe as necessidades de uma demanda grande e crescente. Nesse cenário, torna-se importante evidenciar que a conservação da qualidade dos solos agrícolas é elementar, que se relaciona com a minimização de impactos ambientais e a um melhor crescimento e desenvolvimento das plantas, e, por conseguinte, a produtividade das culturas (RICHARDSON *et al.,* 2001).

Desse modo, ressalta-se a importância da matéria orgânica do solo (MOS), que nas principais funções do solo é bem conhecida (JOHNSTON *et al*., 2009) e, consequentemente, sua perda é considerada uma grande ameaça às funções sustentáveis do solo (AMUNDSON *et al*., 2015). A MOS constitui uma fonte importante de nutrientes inorgânicos para a produção de plantas em ecossistemas naturais e manejados.

A dinâmica da matéria orgânica do solo é influenciada por diversas atividades de manejo, como:

a) Manipulação do solo por meio do plantio direto, cobertura morta e aplicação de fertilizantes orgânicos ou inorgânicos. A formação de cobertura morta favorece a manutenção e o aumento do conteúdo de matéria orgânica do solo (BAYER; SCHNEIDER, 1999; BALESDENT *et al*., 2000; COSTA *et al*., 2004);

b) Variando não somente na quantidade e qualidade dos insumos, mas também na distribuição e no tempo de aplicação;

c) Manejo da fauna do solo (BUSATO *et al*., 2012).

Os constituintes da matéria orgânica do solo ainda são extremamente complexos devido à natureza dos seus diversos compostos e seus diferentes estágios de decomposição (CHENU *et al*., 2014). A variação do grau de decomposição da MOS depende do sistema de manejo do solo adotado. A deposição de grandes quantidades de resíduos e o não revolvimento têm como resultado o acúmulo de palhada na superfície do solo e na taxa reduzida de decomposição, o que contribui para diminuir as perdas de C na forma de CO_2, favorecendo assim o acúmulo de MOS (BAYER *et al*., 2000; COSTA *et al*., 2008). Logo, em sistemas de manejos agrícolas que são capazes de aumentar as reservas de C no solo poderiam contribuir para manter a produtividade do solo e, ao mesmo tempo, mitigar o aquecimento global (CAMPOS *et al*., 2011).

Deste modo, visto a grande diversidade de plantas cultivadas, seria interessante o conhecimento, em cada ambiente de produção, a contribuição das culturas ou sistemas que mais favoreçam em seu equilíbrio dinâmico, o acúmulo da MOS, representando uma ferramenta de manejo agrícola para que se tenha no solo um reservatório estável e menos sujeito à decomposição e à emissão de CO_2 para a atmosfera (COLLINS *et al*., 2001).

A melhor estratégia para evitar perda da matéria orgânica do solo é o manejo conservacionista do solo. No trópico úmido, estratégias que devem ser amplamente utilizadas para aumentar o teor de matéria orgânica no perfil do solo envolvem a manutenção contínua de biomassas de leguminosas e aplicação de cálcio. Ademais, a adição continuada de resíduos pode favorecer o aumento do conteúdo da fração mais lábil da matéria orgânica, o que contribui para formação de uma estrutura efêmera e para melhorar a enrazabilidade do solo.

2.4 Frações da Matéria Orgânica do Solo

A matéria orgânica do solo (MOS) é um elemento fundamental dos agroecossistemas cuja dinâmica é afetada pelas práticas de manejo do solo. O papel da MOS na melhoria das condições do solo para o crescimento das plantas por meio da disponibilidade de água e nutrientes é conhecido durante muito tempo (DIEKOW *et al*., 2005).

O solo possui característica de ser um ambiente ativo, isto é, funciona como um catalizador das transformações dos resíduos da biomassa vegetal, que resulta em produtos com peculiaridades diferentes. A heterogeneidade dos produtos que são decompostos torna-se de difícil entendimento a sua dinâmica e função no solo. A MOS possui múltiplos estágios de decomposição, uma vez que apresentam características específicas quanto a sua decomposição, liberação de nutrientes e estabilidade (CORREIA; ANDRADE, 2008).

A possibilidade de avaliar quantitativamente frações de MOS torna-se especialmente importante para compreender a sua dinâmica em sistemas manejados intensivamente, ao passo que, avança-se na adoção de práticas mais sustentáveis e ambientalmente mais saudáveis (CAMBARDELLA; ELLIOTT, 1992).

O desenvolvimento de metodologias de fracionamento da matéria orgânica, com o intuito de dividir o carbono orgânico total em grupos com características similares, tem ocorrido desde o século passado. Existem dois métodos de fracionamentos: químico e físico. O fracionamento químico baseia-se na solubilidade das substâncias húmicas em soluções ácidas e alcalinas que permite a separação da matéria orgânica do solo em três frações: ácidos fúlvicos, ácidos húmicos e humina (ROSCOE; MACHADO, 2002). Porém, a utilização do fracionamento químico dificulta no entendimento da dinâmica da matéria orgânica do solo em curto espaço de tempo, haja vista que a taxa de ciclagem dos ácidos fúlvicos e húmicos é muito lenta.

Por outro lado, o fracionamento físico permite estratificar e caracterizar a matéria orgânica do solo por intermédio da quantificação do carbono em compartimentos funcionais. A separação das frações da matéria orgânica é baseada no tamanho dos constituintes em nível das partículas do solo (areia, silte e argila) devido à formação de complexos organo-minerais e em tamanhos maiores (>53 μm) pela associação da matéria orgânica com macro e microagregados estáveis do solo (ROSCOE; MACHADO, 2002). Esses compartimentos estão relacionados com propriedades físicas e estruturais do solo e podem indicar o efeito de um sistema de uso da terra na acumulação de carbono.

O fracionamento físico é o mais indicado para estudo qualitativo da MOS em comparação a métodos químicos (BAYER *et al*., 2003), assim resultando em frações mais associadas à estrutura e função da MOS do que aquelas obtidas pelos métodos químicos, tendo-se em vista sua relação com a textura do solo (FELLER *et al*., 2000). Auxilia, também, na avaliação das modificações resultantes do uso do solo em relação a maior sensibilidade dessas frações em função do manejo (CAMBARDELLA; ELLIOTT, 1992; BAYER *et al*., 2004).

O fracionamento físico da MOS consiste na separação de duas frações orgânicas: carbono orgânico particulado (COP) e o carbono orgânico associado aos minerais (COM) (CAMBARDELLA; ELLIOTT, 1992).

O COP é a fração da MOS separada por dispersão e peneiramento do solo associada à fração areia (COP>53 µm), que representa fragmentos de plantas, fungos e animais. É sensível em identificar variações em práticas agrícolas e, por isso, é apontada como indicador para controlar alterações na qualidade do solo dos sistemas de manejo (BAYER *et al*., 2001; BAYER *et al*., 2004; CONCEIÇÃO *et al*., 2005; DIEKOW *et al*., 2005).

O COM é a fração da MOS associada às frações silte e argila do solo (COM <53 µm), é dependente da quantidade de material orgânico que é transferido do COP e da proteção coloidal exercida pelas superfícies minerais sendo definida como fração da MOS que interage com as superfícies de partículas minerais, formando os complexos organominerais (BALDOCK; SKJEMSTAD, 2000; CHRISTENSEN, 1996). Certas práticas viabilizam a melhoria nos sistemas de cultivo, como por exemplo, o manejo para aumentar a cobertura vegetal e o uso eficiente de insumos na produção como nutrientes e água podem ajudar a restaurar a MOS (FOLLETT, 2001).

A cobertura do solo proporciona efeitos benéficos por aumentar a enraizabilidade dos solos propensos à coesão, uma vez que essa cobertura cobre a superfície do solo, conserva a umidade do solo, diminuindo as perdas por evaporação retardando a coesão, promovendo a formação de agregados instáveis por meio da aplicação contínua de resíduos sólidos que melhoram o ambiente para o desenvolvimento das raízes e através do aumento da fração livre da matéria orgânica (SHEPHERD *et al*., 2002).

2.5 Interação cálcio e matéria orgânica

A matéria orgânica (MO) é um componente importante do solo, tem uma função nutricional, servindo como um reservatório de N, P e S. Promove à estruturação do solo, uma alta capacidade e ligação de cátions (SCHNITZER, 1991; TRUMBORE, 1997).

Um dos principais meios para a estabilidade do carbono orgânico do solo (COS) é a interação com os nutrientes do solo via cátions polivalentes que são Ca e Mg. Acredita-se que o Ca e Mg trocáveis exercem um forte controle sobre o acúmulo de COS (YANG *et al*., 2016).

De acordo com Oades (1988), há uma correlação positiva entre os teores de argila e carbono orgânico, desde que os agregados de argila protejam a matéria orgânica da decomposição. Um mecanismo importante para a estabilização da matéria orgânica são pontes de cátions por meio do Ca^{2+} que juntamente com a argila solúvel atuam nos compostos do Ca^{2+} como fontes em equilíbrio com a solução do solo.

Estudos enfatizam que a interação entre o cálcio e os compostos de matéria orgânica derivados da decomposição da biomassa pode melhorar a estrutura na zona radicular e aumentar a eficiência do uso dos nutrientes (WUDDIVIRA; CAMPS-ROACH, 2007; WHITTINGHILL; HOBBIE, 2012; RANJBAR; JALALI, 2012; ROWLEY *et al*., 2018).

Pesquisas realizadas por Ziglio, Miyazawa e Pavan (1999) concluíram que, com a presença de ligantes orgânicos provenientes de vegetais, ocorre ação na diminuição da mobilidade do Ca no solo e o efeito negativo da remoção de Ca por compostos orgânicos pode ser diminuído por meio de rotação de culturas que proporcionam diferentes capacidades de produção de ânions orgânicos solúveis.

Desse modo, o uso do gesso ($CaSO_4$. $2H_2O$*)* além da disponibilidade de Ca^{2+} pode aumentar também a estabilidade dos agregados, melhorar o desempenho das raízes em camadas mais profundas, e como resultado, aumentar a eficiência do uso da água e de nutrientes (SUMNER *et al*., 1990; CAIRES *et al*.,2011). O gesso também possui a peculiaridade de liberar eletrólitos, fazendo com que haja o aumento na agregação das frações orgânicas do solo (FLANAGAN *et al*., 1997; NORTON e DONTSOVA, 1998; VÁZQUEZ *et al*., 2009).

Portanto, para que ocorra a proteção da biomassa e outros materiais orgânicos de mineralização rápida em solos ligeiramente lixiviados é indispensável a aplicação de Ca^{2+} nesses solos com essas caraterísticas OADES, 1988; WHITTINGHILL; HOBBIE, 2012).

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CAPÍTULO II

CONTRIBUTION OF THE MULCHING IN SHORT-AND LONG-TERM FOR SOIL IMPROVEMENT, NITROGEN UPTAKE AND MAIZE PRODUCTIVITY

Contribution of the mulching in short-and long-term for soil improvement, nitrogen uptake and maize productivity

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Abstract

The dynamics and long-term responses to mulching management processes in tropical agroecosystems remain poorly understood. This study aims to evaluate the short-and long-term effects of mulching on SOM accumulation, SBC retention, and physical improvement of a cohesive tropical soil enriched with calcium. We also assess the contribution of mulching and synthetic N (Ns) to the uptake of N and maize grain yield. This experiment was conducted using a randomized block design with the following treatments: Long-term mulching (LTM), long-term mulching plus nitrogen (LTM+N), short-term mulching (STM), short-term mulching plus nitrogen (STM+N), long-term mulching plus short-term mulching (LTM+STM), long-term mulching plus short-term mulching plus nitrogen (LTM+STM+N), planting with nitrogen (N), and a control. Mulch consisting of dry biomass (branches and leaves) of *Gliricidia sepium* applied at a rate of 12 Mg ha^{-1} in soil enriched with calcium. The interaction between Ns and calcium (Ca) was more intense in LTM areas, resulting in higher carbon content, base cations, enhanced soil rootability, and increased nitrogen uptake. STM maintained soil moisture, decreasing penetration resistance, and, when paired with LTM, providing enough biological nitrogen to replace Ns. The effects of STM and LTM on their own were cumulative, with N uptake 54% higher, accumulated N 163% higher, and maize grain yield 125% higher (4.77 to 10.78 Mg ha^{-1}). The continuous use of mulch, therefore, has benefits for both the sustainability and feasibility of tropical agro-ecosystems, preventing land degradation and avoiding deforestation.

KEYWORDS

organic matter fractions, base cations retention, tropical agrosystem, sustainability

1 INTRODUCTION

In many regions of the humid tropics, such as the Amazonian periphery, the sustainability and feasibility of agroecosystems are predominantly dependent on a balance between soil organic matter (SOM) input/output and the maintenance of an adequate sum of base cations (SBC) in the root zone (Quesada et al., 2020). In this region, land degradations occur when soil management cannot overcome the natural forces that decrease the SOM content due to fast decomposition and reduce the SBC due to rapid leaching (Ramos et al., 2018). Furthermore, most soils in this region have a low intrinsic resilience against physical degradation, due to the low content of aggregator elements like carbon, calcium, and elemental iron in the soil (Moura et al., 2018). In the natural conditions of the Amazonian periphery, the soil-vegetation system is resilient against degradation, as a consequence of complete soil surface cover combined with the high activity of the soil fauna (Ciemer et al., 2019).

Unfortunately, the continuous use of soil in the humid tropics without fertility depletion is a hard task since it relies heavily on soil organic matter accumulation/stabilization, increased retention of base cations in the root zone, and improvements to the soil structure (Kannan et al., 2020). Furthermore, the short-term effects of mulching, although leading to a positive impact on crop performance, have not contributed to overcoming the main challenges to replace shifting cultivation in the humid tropics (Moura et al., 2018). Therefore, to meet the expectation of soil sustainability and to replace the shifting cultivation in the humid tropics, the strategies adopted must go beyond the annual effect on crop productivity; they must include management proceedings that could enhance and maintain soil fertility over time.

Of the mechanisms that can contribute to SOM stabilization, the interactions with mineral surfaces and polyvalent cations are the most effective (von Lützow et al., 2006). Indeed, numerous studies have focused on organomineral interactions that slow SOM turnover due to physicochemical protection by mineral association (von Lützow et al., 2006; Ellerbrock, & Gerke, 2018). Furthermore, in soil enriched with calcium, the accumulation of stabilized SOM through mineral association increases the capacity of the soil to retain cations, by enhancing the soil rootability and avoiding the adverse effects of acidic cation concentration in the root zone (Ramos et al., 2018). Application of N fertilizer associated to mulch has also been reported as another mechanism for SOC stabilization or accumulation (Sarker et al., 2017). However, although, carbon and nitrogen allocation and assimilation are coupled processes that likely have mutualistic effects on SOM stabilization, there is no consensus concerning the effect of N fertilization on SOC accumulation in tropical soils (Poffenbarger et al., 2017).

Indeed, the dynamic interactions with soil nutrients and long-term responses from mulching in tropical agroecosystems are poorly understood (Prescott, 2010). According to Six et al., (2004) long-term cropping substantially decreases the magnitude of the mineral-stabilizing SOM process, which means that SOM associated with the mineral phases is not entirely resistant to degradation. On the other side, though positive mulching effects on crop yields have been verified in structurally fragile tropical sandy loam soils, these effects have been often variable under irregular rainfall conditions (Moura et al., 2017). Therefore, to take full advantage of the use of mulching to the incumbency of replacing shifting cultivation in the humid tropics, it is essential to identify the mechanisms by which mulching affects yields and soil quality improvements differently, when used in the short-term or long-term. We hypothesized that, in a tropical soil enriched with calcium, the short-and long-term positive effects on maize yield and soil improvements are different and can be cumulative if mulch is continuously used. Therefore, this study aims to evaluate the short-term and long-term effects of mulching on SOM accumulation, SBC retention, and physical improvement of a cohesive tropical soil enriched with calcium. We also assess the contribution of mulching and synthetic N (Ns) to the N uptake and maize grain yield.

2 MATERIALS AND METHODS

2.1 Experimental area and setup

The experimental work was conducted in the municipality of São Luís, Maranhão, Brazil, (2°30’S, 44°18′W)). The soil of the study area was classified as an Arenic Hapludult with hard-setting characteristics, due to the relationship between penetration resistance and volumetric water content (Moura et al., 2009). The climate of the region, according to Köppen, is Aw type, equatorial, hot and humid with a mean precipitation of 2100 mm/year and two well-defined seasons, a first rainy season extending from January to June and a second from July to December a dry season almost without rain.

2.2 History and layout of the experimental area

The experimental area had been in fallow since 2008. At the beginning of the experiment in 2012 we used a randomized block design with the treatments divided into two groups of plots with 4 x 10 m with and without mulch. Both groups were treated with the same four irrigation intervals, for a total of eight treatments. Mulch was applied at a rate of 12 Mg

ha^{-1} of dry biomass (branches and leaves) of *Gliricidia sepium*, a leguminous tree that was applied between 2012 and 2016 in the same plots and at the same rate, following Aguiar et al., (2010). The total organic Ca including Gliricidia applied residues in 2017, was 1,188 kg ha^{-1}. Following mowing in September 2014, lime was surface applied to the site at a rate of 1 Mg ha^{-1}, corresponding to 390 kg ha^{-1} of Mg and 130 kg ha^{-1} of Ca. During this period, natural gypsum was applied manually at a rate of 6 Mg ha^{-1}, which corresponds to 1,020 kg ha^{-1} of Ca.

Throughout the full experiment, 2,598 kg ha^{-1} of Ca was applied. Maize (cultivar AG 1051) was sown in October of each year between 2012 and 2016, with a between-row spacing of 80 cm and 25 cm between plants.

2.3 Experimental design this experiment

This experiment was conducted under no-tillage system using a randomized block design with two groups of 4 × 10 m plots used in previous years (2012 to 2016). The total area of the experiment was 640 m^2. Mulch had been applied to the first group of plots for five years; here, the following treatments were established: Long-term mulching in uncovered soil (LTM), long-term mulching plus nitrogen (LTM+N), long-term mulching plus short-term mulching (LTM+STM), and long-term mulching plus short-term mulching plus nitrogen (LTM+STM+N). In the second group of plots, which had not been mulched in previous years, the treatments were: short-term mulching (STM), short-term mulching plus nitrogen (STM+N), planting with nitrogen alone (N) and a control with neither added N nor mulching. In plots with short-term mulching, 12 Mg ha^{-1} dry branches and leaves of *Gliricidia sepium* was applied as mulch.

Maize (cultivar 30F35) was planted on October 2, 2017, with a between-row spacing of 80 cm and 25 cm between plants. At the time of planting, fertilizer at a rate of 55 kg ha^{-1} of P as triple superphosphate, 83 kg ha^{-1} of K as potassium chloride, and 5 kg ha^{-1} of Zn in the form of zinc sulfate was applied. In treatments with N, 50 kg ha^{-1} N was applied as urea. In addition, the latter plots were fertilized at 25 and 44 days after emergence of the maize plants using 50 kg ha^{-1} of N as urea in each fertilization.

The plants were irrigated every seven days, for a total application of 350 mm over the entire growing period. Water was supplied by drip tape irrigation using one tape per row with emitters spaced 25 cm apart. Throughout 5 h each drip emitter delivered 1.25 L h^{-1}, which was equivalent to 25 mm of water per irrigation.

2.4 Soil chemical and organic matter analyses

Soil samples for chemical and SOM analyses were collected in January 2018 at depths of 0–20 cm. Using a Dutch auger with a 3-inch diameter three replicates per plots were collected. SOM was physically fractionated following Cambardella & Elliott (1992). Soil mineral-associated carbon (MOC) was calculated as the difference between TOC and POC. The TOC stock (TOCS) of the 0–20 cm layer was calculated using expression by the following expression (Veldkamp 1994): TOCS = (TOC x ρs x E) /10, where TOCS = organic C stock at a given depth (Mg ha^{-1}); TOC = total organic C content at the sampled depth (g kg^{-1}); ρs = soil bulk density (kg dm^{-3}); and E = thickness of the layer (20 cm).

As for the soil chemical analysis, samples were analyzed for exchangeable K^{+}, Ca^{2+}, and Mg^{2+} using an exchangeable ion resin with a Varian 720-ES ICP Optical Emission Matter Analysis Spectrometer. The accumulations of Ca, in kg ha^{-1}, in the 0–20 cm layer of the soil profile, were calculated according to the equation of Ellert and Bettany (1995) : SCaA = SEC × ρs × E × 10, where SCaA = Soil Ca accumulated in the 0–20 cm layer (kg ha^{-1}); SEC = soil element content (mg kg^{-1}); ρs = soil bulk density (Mg m^{-3}); and E = thickness of the layer (m).

2.5 Soil physical properties

Soil penetration resistance and soil moisture content were measured at depths of 0–0.20 m with three replicates per plot, in April of 2015, after seven days without irrigation. The soil penetration resistance was measured using a digital penetrometer (Falker, Porto Alegre, Brazil) with 5 cm graduations. Soil moisture content was determined using the gravimetric method with samples obtained at three points along a given line. Undisturbed soil samples, collected in May 2017 in volumetric rings with a 100 cm^3 volume, were used to determine soil bulk density (ρs). The bulk density was calculated as a ratio of the dry soil mass at 105°C, and v is the ring volume.

2.6 Plant analysis

Total nitrogen content was measured of maize at two physiological periods: at tasseling and at the physiological maturity stage. Five plants were randomly selected from each plot during each stage. All plant materials were dried to obtain a constant weight at 60°C for 3–4 days and were then ground for analysis. The amount of nitrogen in each sample was determined from the mass of dried plant matter by digestion in sulfuric acid (H_2SO_4–H_2O_2), according to the standard distillation method described by Cottenie (1980).

The various parameters related to nitrogen translocation in the maize plant were calculated according to the following formulas 1, 2, 3, 4, 5, and 6 according to Fageria and Baligar (2005):

(1) Accumulated nitrogen at tasseling (NT) = dry matter (kg ha^{-1}) × N at tasseling (g kg^{-1}) 1000.

(2) Accumulated nitrogen post-tasseling (NPT) = total nitrogen (kg ha^{-1}) − N at tasseling (kg ha^{-1}).

(3) Nitrogen remobilized (NR) = NT – N in stalks and leaves at maturity.

(4) Total accumulated nitrogen (TN) = total dry matter (kg ha^{-1}) at maturity × N at maturity (g kg^{-1}) 1000.

(5) Contribution to nitrogen uptake $(CNU)_1$ = uptaken N in the treatment - uptaken N in the treatment with N/total uptaken N (for treatments with applied synthetic N),

(6) CNU_2 = uptaken N in the treatment - uptaken N in the control treatment /total uptaken N (for treatments without applied synthetic N).

The harvest was carried out manually in early January 2018, when the plants were at physiological maturity. Kernel weight (100 kernel), kernel number and maize grain yield (MGY) were assessed in a $10m^2$ area. MGY was determined and standardized using a moisture level of 145 g kg^{-1}.

2.7 Statistical analyses

The data were analyzed using the ESTATISTIX program (version 9). An analysis of variance (ANOVA) was undertaken on all data, after which the means were compared using Fisher's LSD test at a level of 5% probability of error**.** The software SIGMAPLOT (version 11.0) was used to plot the graphs. Correlations between the soil organic carbon fractions, basic cations, maize grain yield, and soil penetration resistance were investigated through canonical redundancy analysis (RDA).

3 RESULTS

3.1 Soil improvements by mulching treatments, Ca, and synthetic N (Ns)

Both short-and long-term mulching (STM) (LTM) had higher total organic carbon (TOC) than the control, though the increase in STM was 15% higher than in LTM (Table 1). There was a positive effect of Ns on TOC, but only when it was used in areas that had received LTM. In the latter areas, TOC was 50% higher than plots with only LTM alone and 18% higher than STM+N. There was no significant difference between LTM+N and LTM+STM. Meanwhile, the amount of TOC accumulated in LTM+ STM+N was 22% higher than in LTM+N. Mineral associated carbon (MOC) contributed more to differences in TOC. Interactions between mulches, Ca, and Ns in the 0–20 cm layer doubled total carbon stock (TOCS) in LTM+STM+N compared to the control (57.70 Mg ha^{-1} vs. 28.20 Mg ha^{-1}, respectively).

In general, the sum of base cations (SBC) followed the same tendency of the TOC, with SBC 33% higher in STM compared to LTM. Again, the effect of Ns was only significant in the LTM plots. SBC was higher in LTM+N than in all other treatments except for LTM+STM+N, where it was 33% higher than the former treatment. There was no difference in SBC between STM+N and LTM+STM. Meanwhile, soil Ca accumulated (SCaA) in LTM+STM+N after six years was approximately half of the applied Ca (2,598 kg ha^{-1} to 1,240 kg ha^{-1}). In contrast, the control area lost 80% of the applied Ca (1,410 kg ha^{-1} to 292 kg ha^{-1}).

Table 1. Soil Organic Carbon (SOC) fractions: Particulate Organic Carbon (POC), Mineral Associated-Organic Carbon (MOC), Total Organic Carbon in the soil (TOCS) , cations content, sum of base cation (SBC) and soil accumulated calcium (SACa) at a depth of 0-20 cm in the experimental area 2017.

Treatments[a]	SOC fractions				Cations content				
	POC	MOC	TOC	TOCS	Ca	Mg	K	SBC	SACa
	g Kg $^{-1}$			Mg ha^{-1}	mmolc m^{-3}				Kg ha^{-1}
LTM+STM+N	10.27 a	13.76 a	24.04 a	57.70 a	31.4 a	14.6 a	5.1 a	51.0 a	1.240 a
LTM+STM	7.47 b	11.42 b	18.90 b	49,14 b	18.3 c	7.0 c	3.3 b	28.6 c	723 c
LTM+N	6.57 b	13.12 a	19.70 b	51.22 b	23.5 b	10.5 b	4.3 ab	38.3 b	928 b
STM+N	7.22 b	9.49 b	16.71 c	43.44 c	19.4 c	5.7 cd	2.3 b	27.4 c	776 c
STM	6.17 bc	8.87 b	15.06 c	40.56 c	18.8 c	4.0 d	3.9 c	26.7 c	742 c
LTM	5.96 c	7.12 bc	13.08 d	34.00 d	12.2 d	2.8 d	0.4 c	17.9 e	482 d
N	3.33 d	6.53 cd	9.86 e	29.58 e	10.2 d	2.3 d	0.4 c	12.9 f	403 d
CONTROL	3.13 d	5.92 d	9.40 e	28.20 e	7.4 e	0.7 e	0.5 c	8.5 g	292 c
CV%	5.22	7.08	3.11	3.12	9.27	8.46	4.77	4.76	9.11

Abbreviations: [a]LTM+STM+N = soil with long-term mulching and covered by mulch and with nitrogen; LTM+STM = soil with long-term mulching and covered by mulch; LTM+N = soil with long-term mulching and with nitrogen; STM+N = soil covered by mulch and with nitrogen; STM = soil covered by mulch; LTM = soil with long-term mulching; N = soil with nitrogen and control. Values in the same column with the same letter are not statistically different at the 5% level by LSD test.

3.2 Soil humidity and soil penetration resistance

The soil humidity results showed that different mulching and nitrogen treatments affected water maintenance in the root zone (Figure 1). After seven days without irrigation, soil humidity was higher than 5% base mass in the 0–12.5 cm layer in the LTM+STM and LTM+STM+N treatments and was lower than 3% in the N and control treatments.

The effect of Ns additions on water content is apparent in the soil moisture results, with LTM+N and STM+N always having higher moisture values than LTM and STM. Both mulching treatments decreased soil penetration resistance (SPR), but this positive effect was more accentuated in STM than in LTM. After seven days without irrigation, the soil was very dense in the 6-20 cm layer in the N and control plots, while SPR did not achieve the threshold of 2 MPa in the 0–20 cm layer in the STM, STM+N and LTM+STM+N treatments. In LTM and LTM+N, only the 11–20 cm layer was very dense.

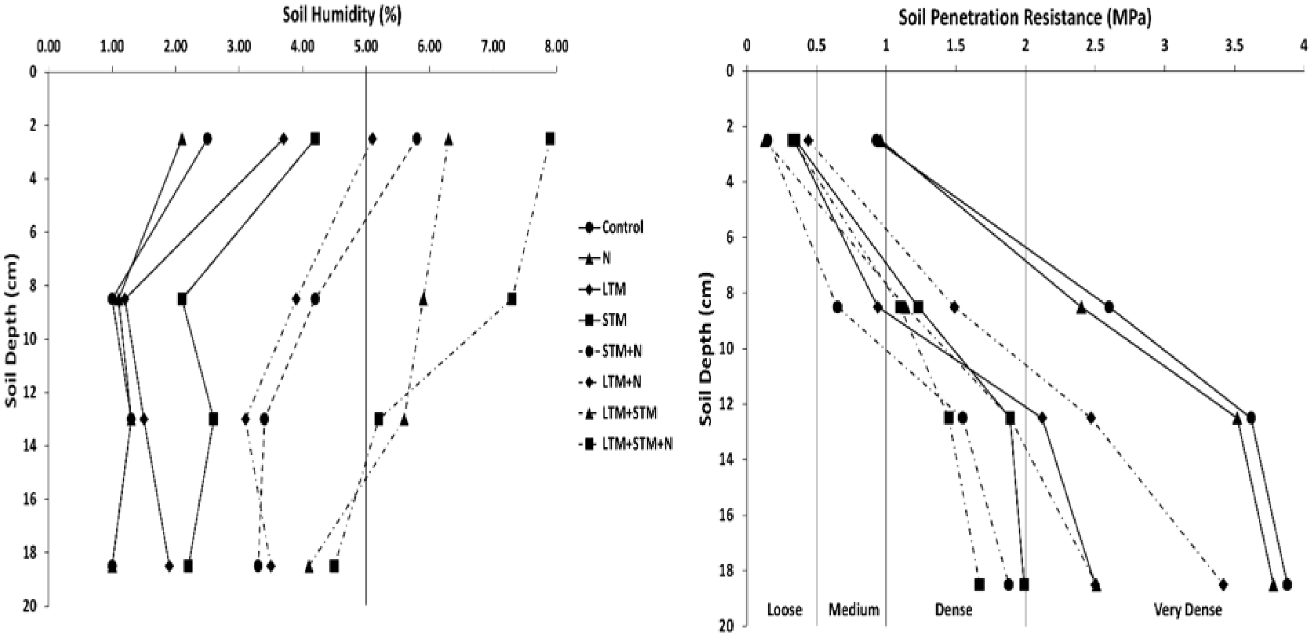

Figure 1 Soil humidity (a) and soil penetration resistance (b) seven days after irrigation. LTM+STM+N = soil with long-term mulching and covered by mulch and with nitrogen; LTM+STM = soil with long-term mulching and covered by mulch; LTM+N = soil with long-term mulching and with nitrogen; STM+N = soil covered by mulch and with nitrogen; LTM = soil with long-term mulching; STM = soil covered by mulch; N = soil with nitrogen and control. Vertical bars show the critical levels of Moura et al (2009) and Hazelton & Murphy (2007).

3.3 Amount of nitrogen accumulated, maize yield and principal components analysis

Total N accumulated (TN) in STM was 18% higher than in LTM, though additions of Ns in the post-tasseling stage increased this difference to 47% between the STM+N and LTM+N (Table 2). TN in LTM+STM was higher than in LTM+N and was not significantly different from STM+N. The TN in LTM+STM+N was 38% higher than even STM+N. The results of the contribution for N uptake (CNU) showed very low values for urea when used alone (8%), as opposed to 62% for LTM+STM+N, which was the highest of all treatments. The contribution of LTM also was low (25%), compared to 45% for STM. There was no significant difference between LTM+STM, LTM+N, and STM for this variable.

Table 2. Amount of nitrogen at tasselling (NT), amount of nitrogen remobilized (RN), amount of nitrogen uptake post-tasselling (NPT), total nitrogen accumulated (TN) and contribution for nitrogen accumulation (CNA) in Maize (cultivar 30F35) in the experimental area 2017.

	NT	RN	NPT	TN	CNA
Treatments[a]	Kg ha^{-1}				(%)
LTM+STM+N	107.60 a	36.01 a	51.75 a	159.35 a	62.00 a
LTM+STM	64.96 c	17.36 cd	47.21 b	112.17 b	50.00 b
LTM+N	76.17 b	30.46 b	28.21 d	104.38 c	42.00 c
STM+N	74.12 b	22.61 c	41.48 c	115.60 b	48.00 b
STM	57.12 d	21.06 c	37.74 c	94.86 d	45.00 bc
LTM	47.44 e	15.10 de	33.17 d	80.61 e	25.00 d
N	57.32 d	12.62 de	3.26 f	60.58 f	8.00 e
CONTROL	33.38 f	11.33 e	22.21 e	55.59 g	--

Abbreviations: [a]LTM+STM+N = soil with long-term mulching and covered by mulch and with nitrogen; LTM+STM = soil with long-term mulching and covered by mulch; LTM+N = soil with long-term mulching and with nitrogen; STM+N = soil covered by mulch and with nitrogen; STM = soil covered by mulch; LTM = soil with long-term mulching; N = soil with nitrogen and control. Values in the same column with the same letter are not statistically different at the 5% level by LSD test.

Ns also had a significant effect on kernel number, which increased when Ns was used with mulch (Figure 2). Nitrogen accumulated at tasseling (NT) followed much the same trend. There was no significant difference between treatments in which mulches or Ns were used alone. The differences between treatments with and without Ns were small, around 5%, except between LTM+STM+N and N, where there was a 36% difference between treatments. Meanwhile, kernel weight was significant in treatments with mulches or Ns alone, in the following order: STM > LTM > N > control. The difference was most pronounced between LTM+STM+N and N, with the former 109% higher. The effects of long-and short-term mulching on maize grain yield (MGY) were positive, and the size of the effect was dependent on Ns. When urea was used, there was no difference in MGY between the two mulching types (LTM+N = STM+N), though MGY was higher in STM than in LTM without urea. The application of urea alone increased MGY by 22%. There was no significant difference between LTM+STM and LTM+N. In LTM+STM+N, MGY was 20% higher than in LTM+N.

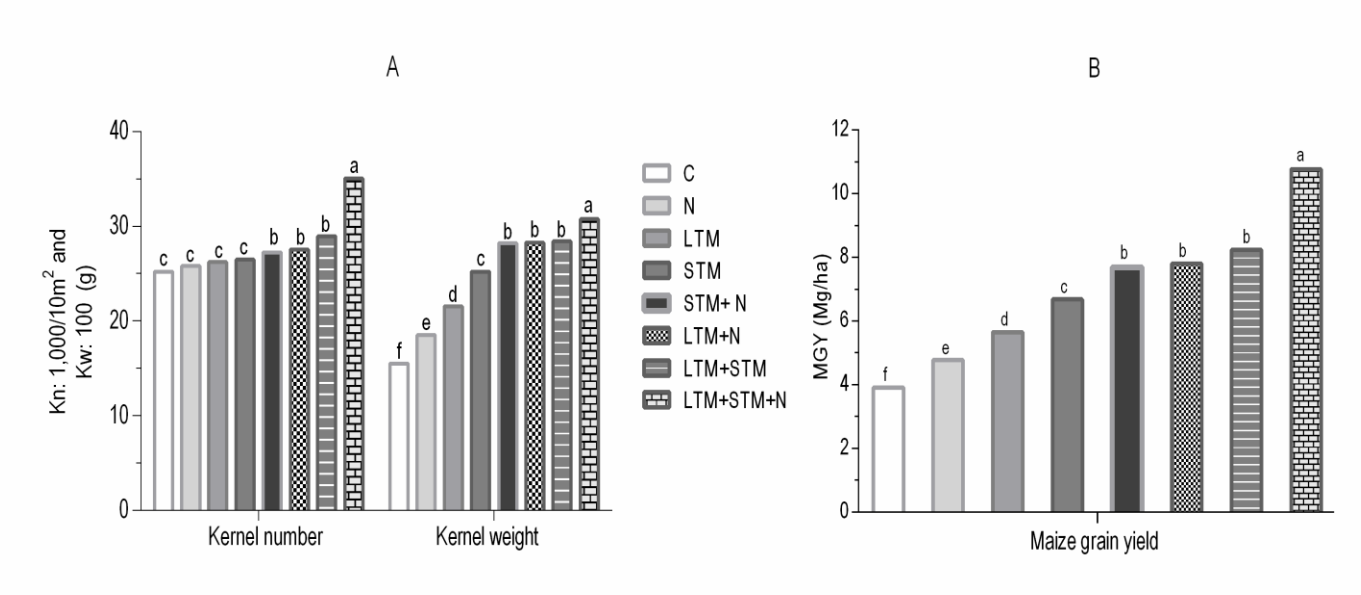

Figure 2 (a) Kernel number (a), kernel weight (b), and grain yield (c) of maize in the experimental area in 2017. LTM+STM+N = soil with long-term mulching, covered by mulch and with added nitrogen; LTM+STM = soil with long-term mulching and covered by mulch; LTM+N = soil with long-term mulching and with nitrogen; STM+N = soil covered by mulch and with nitrogen; LTM = soil with long-term mulching; STM = soil covered by mulch; N = soil with nitrogen and control. Different letters indicate differences at the 5% level per LSD test.

The principal components analysis showed a cluster with Ca, POC, MOC, and MGY (Figure 3) in the treatments with mulches and Ns, mainly in LTM + N. On the other hand, POC was more associated with STM + N.

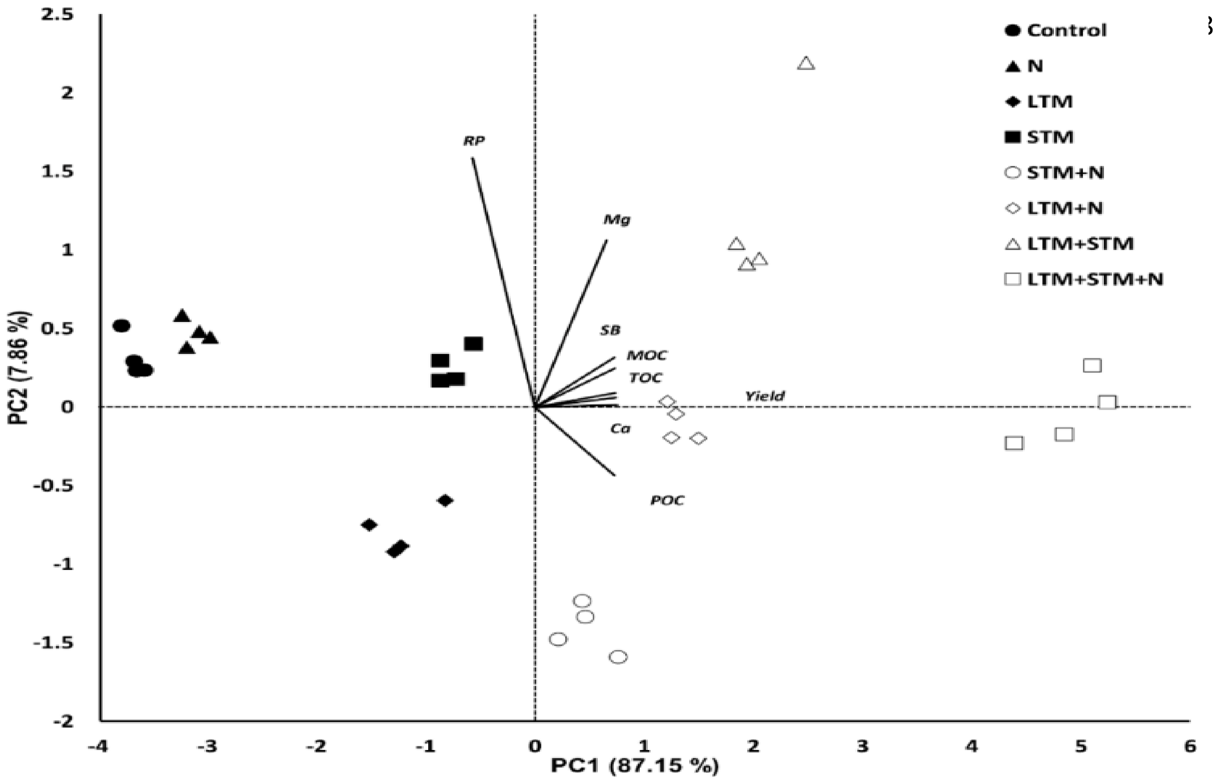

Figure 3. Principal components analyses of calcium, magnesium, sum of base, resistance penetration grain yield and organic carbon fractions. POC, particulate organic carbon; MOC, mineral organic carbon; TOC, total organic carbon; Ca, calcium; Mg, magnesium; SB, sum of bases; RP, resistance penetration**.**

4 DISCUSSION

SOM dynamics involving mulch and Ns, as well as their multiple interactions in a tropical environment, are complex (Poffenbarger et al., 2017). We have shown clear evidence that the interactions between mulching treatments (short-and long-term) with Ns and Ca were responsible for the largest increase in TOC. First, TOC was not different in the N and control treatments, but in treatments combining Ns with STM or LTM, TOC was 82% and 109% higher than control, respectively.

The increase of TOC in mulching treatments without Ns was lower (60% and 39%). There is strong evidence that most stable soil organic matter has been microbiologically transformed, (Prescott, 2010). In a sandy loam soil without the physical protection mechanisms provided by clay, it is more likely that the stable compounds that comprise MOC have been largely transformed through biological activities that Ns speeds up.

In soils with an exchange complex dominated by Ca^{2+}, von Lützow et al., (2006) stated mechanisms that promote microbial transformations that lead to the creation of recalcitrant organic products through the formation of polyvalent cation bridges due to interaction with SOM. Indeed, a 93% in Ca content between LTM+N and LTM (23.5 $mmol_c$ m^{-3} vs. 12.2 $mmol_c$ m^{-3}, respectively) could be explained by retention of Ca during SOM transformation in the presence of Ns (Table 1).

Moreover, as a result of this process, the POC:MOC ratio decreased from 1:1.2 in LTM to 1:2 in LTM+N, which reflects a proportional increase in mineral associated organic carbon. In the same way, when N was added in LTM+STM, Ca was increased by 72% (18.3 $mmol_c$ cm^{-3} to 31.4 $mmol_c$ cm^{-3}) (Table 1). These results suggest that increased TOC and Ca maintenance in the root zone were a consequence of the interaction between transformed compounds, Ca, and Ns, which occurs in the soil environment created by long-term mulching. Furthermore, the principal components analysis showed Ca and organic carbon accumulation are significantly associated in treatments with mulch and Ns. Indeed, control treatment lost 80% of applied Ca, while LTM+STM+N retained 50% of applied Ca.

Lower SPR and increased moisture in treatments with LTM compared to the control can be explained by changes in pore size distribution promoted by SOM, while the higher relative number of small pores due to lower bulk density increases water holding capacity (Robin et al., 2018). In turn, higher levels of SOM increase aggregation, the stability of soil aggregates, and total pore space, which generally lead to reduced SPR (Tarkiewicz & Nosalewicz, 2005). It is important to highlight that the increases in soil rootability were higher when short-term mulching was used because of the ability of mulch to reduce soil evaporation (Jimenez et al., 2017).

Improvements in soil rootability were reflected in total N uptake by maize in LTM+N, which was 72% higher than in the treatment with added N and without mulch. Meanwhile, the positive effect of short-term mulch on N uptake can also be partially explained by the N released by mulch decomposition and increased N availability during the entire maize cycle, which was also verified by Moura et al. (2009). Indeed, N uptake post-tasseling (NPT) in STM+N represented 56% of total N uptake and was 47% higher than in LTM+N, where NPT represented just 37% of total N uptake (Table 2). These effects of short- and long-term mulching on N uptake led to an even higher increase in LTM+STM+N, where N uptake was 163% higher than in the compared to the treatment with added N and no mulching.

The differences in N use between treatments can be clearly seen in the contribution to N uptake (CNU) results. First, the meager contribution of urea used without mulch (8%) showed that using Ns is inviable on uncovered, cohesive tropical soil. Second, as was also reported by Senna et al. (2020), the great contribution of legume mulch (almost 50%) to N uptake showed that its short-term effect is essential to increase N uptake. Finally, combining short- and long-term mulch usage with Ns inputs leads to benefits from both inputs, boosting CNU up to 62%.

Both long- and short-term mulching had a positive effect on MGY. However, the size of the effect of the mulches on MGY was heavily reliant on Ns. The effect of Ns was higher when it was used with LTM (36%) than with STM (15%) (Figure 2). In maize, the yield is determined by the harvested kernel number (KN) per unit land area and the average kernel weight (KW) (Wei et al., 2019). KN is a function of the physiological condition of the crop during the period before flowering (Borrás & Vitantonio-Mazzini, 2018). Thus, nitrogen deficiency-induced effects on KN could be related to photosynthesis or plant growth rate at flowering, which can be roughly evaluated from NT values. Once the number of kernels is established, the final KW becomes a main factor determining maize yield (Wang et al., 2014). KW varies with the rate of kernel growth and the duration of grain-filling. Therefore, a high N supply post-tasseling is beneficial for optimizing grain-filling parameters and improving the KW of maize kernels (Sadras & Egli, 2008). The effect of mulches on KN and KW varied due to differences in their capacity to provide N during the maize growing cycle. Indeed, the fact that KW was higher in STM than in LTM treatments was due to the higher N remobilization and N accumulated at NPT stage, which resulted in higher MGY.

5 CONCLUSIONS

Our results showed a clear difference between the effects of short- and long-term legume tree mulching. Short-term mulching maintains soil moisture, which decreases penetration resistance and provides biological nitrogen that can replace Ns if combined with long-term mulching. While in areas with long-term mulching the interactions between Ns and Ca in the soil are more intense, which results in improved soil with a higher content of carbon and base cations. These changes are reflected in enhanced soil rootability and increased uptake of nitrogen compared to areas with urea and without mulching.

Finally, it is worth highlighting that the effects of short- and long-term mulching are cumulative. We observe that the two mulching practices, when used together, increase accumulated N by 163%, and maize grain yield by 125% (4.77 to 10.78 Mg ha^{-1}) compared to cultivation with added Ns and no mulching. Therefore, to prevent degradation of agricultural land, which in turn reduces the risk of deforestation, the continuously use of legume tree mulching must be recommended.

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ANEXO

(Normas da Revista Soil Use and Manegement)

Soil Use and Management

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iii. The full names of authors;
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