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PRÁTICAS DE MANEJO PARA A SUSTENTABILIDADE DA PRODUÇÃO AGRÍCOLA EM SOLO TROPICAL COESO

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Engenheira Agrônoma

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Tese apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Agroecologia da Universidade Estadual do Maranhão, para a obtenção do título de Doutora em Agroecologia.

Orientador: Prof. Dr. Emanoel Gomes de Moura

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2021

DEDICO

A Deus, pai todo poderoso.

A meus pais pelo amor, educação e dedicação.

Aos meus irmãos pela atenção e carinho.

Ao meu companheiro pelo incentivo e força.

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John Quincy Adams

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CAPÍTULO II

RESUMO

No trópico úmido, os solos estruturalmente frágeis e coesos são amplamente distribuídos, em virtude da combinação do material de origem sedimentar, aliado a alta intemperização e baixos teores de matéria orgânica no solo. Nesta região, as plantas exploram água e nutrientes apenas em uma fina camada superficial, o que prejudica o acúmulo de biomassa e a produtividade das culturas. A cobertura do solo aliado ao uso de gesso, têm sido indicado como uma estratégia eficiente para a melhoria da estrutura física, acúmulo de carbono orgânico do solo e aumento na produtividade das culturas no trópico úmido. A biomassa de leguminosas é capaz de fornecer cobertura do solo, reter a umidade, favorecer a atividade microbiana e fornecer nutrientes, incluindo o nitrogênio. Enquanto, o gesso por sua alta solubilidade e altos teores de cálcio, têm sido indicado como uma excelente alternativa para reter carbono orgânico no solo e melhorar agregação e enraizabilidade. Neste sentido, nosso objetivo foi acompanhar a dinâmica do carbono orgânico e cátions na zona radicular de um solo frágil tropical arenoso após a aplicação de gesso e resíduo de leguminosas, para verificar seu período de permanência em nível crítico e avaliar como essa dinâmica afeta a produtividade do milho. Nossos resultados sugerem que cobertura morta e gesso, usados com ureia, podem aumentar a capacidade de enraizamento do solo, melhorar a retenção da umidade, fornecer carbono orgânico, reter cálcio no perfil do solo e aumentar a produtividade do milho. Portanto, em solos coesos de estrutura frágil, a combinação de biomassa de leguminosas e gesso permite a manutenção de níveis adequados de carbono orgânico e cálcio na zona radicular, o que consiste em uma estratégia simples e vantajosa a ser explorada pelos agricultores, para aumentar a capacidade de enraizamento do solo e a produtividade das culturas.

Palavras-chave: cálcio, carbono orgânico do solo, resistência à penetração do solo, solo arenoso.

ABSTRACT

In the humid tropics, structurally fragile and cohesive soils are widely distributed, due to the combination of sedimentary material, high weathering and low levels of soil organic matter. In this region, plants explore water and nutrients only from a thin surface layer, which impairs biomass accumulation and crop productivity. Soil coverage combined with gypsum application has been indicated as an efficient strategy for improving soil physical structure, organic carbon accumulation and also increasing crop productivity in the humid tropics. Legume biomass can provide soil cover, retain moisture, favor microbial activity and provide nutrients, including nitrogen. While gypsum, due to its high solubility and high calcium content, has been indicated as an excellent alternative to retain organic carbon in the soil and improve aggregation and rooting. In this sense, our aim was to monitor the dynamics of organic carbon and cations in the radicular zone of a cohesion tropical sandy soil after the application of gypsum and legume residue to verify its period of stay at a critical level and to evaluate how this dynamics affects maize productivity. Our results suggest that mulch and gypsum, applied with urea, can increase soil rooting capacity, improve moisture retention, provide organic carbon, retain calcium in the soil profile and increase maize productivity. Therefore, in cohesive soils with a fragile structure, the combination of legume biomass and gypsum allows the maintenance of adequate levels of organic carbon and calcium in the root zone, which consists of a simple and advantageous strategy to be explored by farmers to increase the soil rooting capacity and crop productivity.

Key words: calcium, soil organic carbon, soil penetration strength, sandy soil.

Práticas de manejo para a sustentabilidade da produção agrícola em solo tropical coeso

CAPÍTULO I

1. INTRODUÇÃO GERAL

Os níveis de produtividade das culturas agrícolas no trópico úmido são menores que a média global, em grande parte devido a estrutura frágil dos solos da região, ao menor uso de fertilizantes, ao esgotamento de nutrientes do solo e a baixa eficiência de uso de nutrientes (AGEGNEHU e AMEDE, 2017). Nessa região, a fertilidade do solo é gerenciada por meio do deslocamento e da expansão da área de cultivo por grande parte dos pequenos produtores familiares que ainda se fundamentam na substituição da cobertura florestal e das matas nativas por práticas de agricultura itinerante, principalmente o corte e queima.

Entretanto, esse sistema de agricultura itinerante está relacionado com impactos ambientais como desmatamento, depleção de nutrientes do solo, aumento da emissão de gases do efeito estufa e perda da biodiversidade, além de não ser mais capaz de promover benefícios econômicos e sociais aos agricultores que adotam essa prática (POWER, 2010; MOURA et al., 2020). Logo, esse método de manejo é considerado insustentável, principalmente devido ao aumento da pressão populacional. Como há pouca área disponível para expansão agrícola, a fertilidade do solo deve ser gerenciada por meio da intensificação sustentável da agricultura e da eficiência de uso dos nutrientes, o que pode ser obtido com a combinação de fertilizantes orgânicos e inorgânicos, e com práticas que estabeleçam balanço positivo de carbono orgânico no solo (COS).

O fertilizante inorgânico é um insumo importante para atender as necessidades de nutrientes do solo, contudo, os produtores de pequena escala da região do trópico úmido maranhense geralmente não possuem acesso ou condições financeiras para comprar quantidades suficientes, devido infraestrutura e acesso limitado a financiamentos (IBGE, 2017). Além disso, um suprimento excedente de nitrogênio reativo (N) e fósforo (P) pode resultar em emissões de amônia e óxido nitroso no ar, além de contaminação da água subterrânea com nitrato e fósforo (SUTTON et al., 2017). Uma das principais causas do declínio da produtividade é a depleção contínua de nutrientes dos solos (particularmente P, K, nutrientes secundários e micronutrientes) resultantes da aplicação desequilibrada de fertilizantes (IFAD, 2012). A aplicação equilibrada de NPK e enxofre (S) pode aumentar substancialmente a produção de biomassa e o sequestro de C, uma vez que a formação e a rotatividade da matéria orgânica do solo dependem amplamente dos processos biogeoquímicos que envolvem C, N, P e S (NATH et al., 2018).

Adicionalmente, a aplicação de fertilizantes orgânicos, como resíduos de leguminosas arbóreas, potencialmente fornecem nitrogênio e aumentam a quantidade de componentes orgânicos necessários para atender às demandas de nutrientes das culturas a um nível bem maior do que os produtores dessa região geralmente podem obter. Associar insumos orgânicos e inorgânicos é a melhor maneira para os pequenos produtores atenderem às necessidades das culturas e, assim, maximizar a eficiência no uso de nutrientes (VANLAUWE et al., 2010). Adoção em larga escala de práticas agroflorestais com leguminosas arbóreas pode fortalecer os serviços ecossistêmicos nesta região, com aumento dos microrganismos benéficos no solo e melhoria expressiva na produtividade agrícola e, ao mesmo tempo, aumento do sequestro de COS (LAYEK et al., 2018; BARRIOS et al., 2018; MOURA et al., 2020).

Os potenciais de adaptação e mitigação de gases do efeito estufa da agrossilvicultura também atraem um interesse significativo em créditos de carbono sob os programas Padrões de Carbono Verificados e Emissões Reduzidas do Desmatamento e Degradação Florestal (REDD +). Os títulos verdes emitidos pelo Banco Mundial também oferecem oportunidades para intervenções agroflorestais em benefício da população local para contribuir com a mitigação e a adaptação às mudanças climáticas.

Quando usado em rotação com culturas, as leguminosas podem restaurar os estoques de carbono orgânico do solo, e minimizar incidência de doenças e pragas (DEAKIN e BROUGHTON, 2009). Além disso, as leguminosas arbóreas (*Acacia mangium* e *Gliricídia sepium*) realizam fixação biológica de N (FBN) o que promove melhorias na "saúde" do solo e menor degradação ao meio ambiente através da redução no uso de fertilizantes e perdas de N nos campos agrícolas (DHAKAL et al., 2015; MEENA e LAL, 2018; MOURA et al., 2020). No entanto, os ganhos potenciais nos estoques de carbono orgânico do solo (COS) provavelmente serão mais lentos no trópico úmido do que em outras regiões, porque as condições climáticas locais aceleram a taxa de decomposição da matéria orgânica. Nessa abordagem, técnicas que aumentam a permanência do carbono orgânico do solo podem representar um caminho a seguir, tais como não revolvimento do solo, plantio direto na palha de leguminosas, adubação balanceada com macro e micronutrientes associada a prática da gessagem.

Essas técnicas conjugadas podem aumentar os mecanismos de proteção físico-químico do COS, pois a presença de íons Ca^{2+} formam uma ponte iônica entre a matéria orgânica do solo e as partículas de argila, aumentando a agregação do solo e fornecendo proteção (INAGAKI et al., 2017). Segundo os autores, a melhoria da fertilidade do solo em camadas mais profundas pode promover um melhor desenvolvimento das raízes das culturas, consequentemente, uma maior eficiência no uso de nitrogênio. O aumento da entrada de COS devido a integração do plantio na palha de leguminosas arbóreas com a prática da gessagem associados à adubação mineral podem melhorar de maneira sustentável a produtividade do solo e a segurança alimentar no trópico úmido (Figura 1). Logo, o papel deste estudo é esclarecer a melhoria de indicadores físcos e químicos do solo, na retenção de COS e cátions no perfil do solo, e na produtividade agrícola na região do trópico úmido.

Figura 1 – Alternativa ao sistema de corte e queima no Maranhão. Área com plantio direto na palhada de leguminosas arbóreas (*Acácia mangium* e *Gliricídia sepium*) em solo coeso tratado com gesso no trópico úmido.

2. REFERENCIAL TEÓRICO

2.1 Atual cenário da expansão agrícola no trópico úmido maranhense

A zona tropical apresenta fatores abióticos que aceleram a suscetibilidade dos solos a degradação (MOURA et al., 2018). Além disso, 91% dos 219.765 estabelecimentos agrícolas do Maranhão, não realizam adubação (IBGE, 2017). O que caracteriza o predomínio de agricultura familiar de baixo *input* no Estado, com alta suscetibilidade a degradação. Um dos exemplos desse cenário é a Amazônia Legal maranhense, que consiste numa região problemática em relação as questões sociais, agrárias e ecológicas, perante as questões legais, apresenta reduzida área disponível para o plantio. Em área de cerrado, o produtor está habilitado a explorar 65% da área total do imóvel, em caso de floresta somente 20% (LEI FEDERAL 12.651, 2012) (Figura 2).

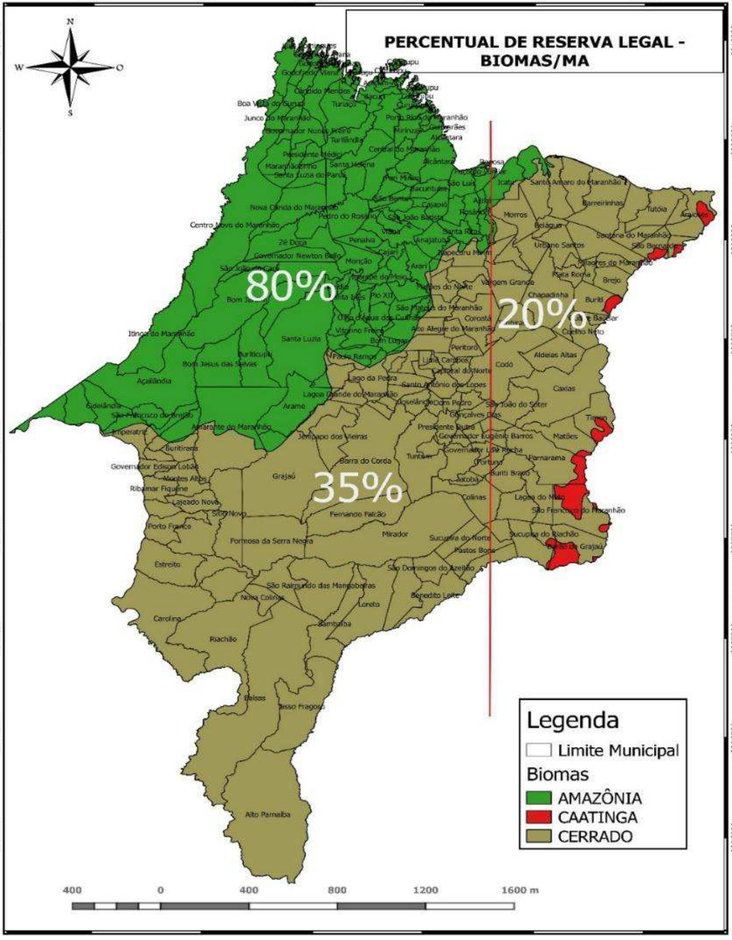


Figura 2 – Representação geográfica dos percentuais de reserva legal no Estado do Maranhão, segundo a lei Federal 12.651, de 25 de maio de 2012.

Neste cenário é comum a conversão das áreas de vegetação nativa em agricultura de corte e queima (Figura 3). Somente em 2020, foram detectados 16.817 focos de calor no Maranhão (INPE, 2021).

Figura 3 – Conversão de área de vegetação nativa para agricultura de corte e queima no Maranhão. (Fonte: GEHRING, 2006.)

As cinzas são fortemente alcalinas e, portanto, aumentam o pH do solo, favorecendo a atividade microbiana e, portanto, a disponibilidade de nutrientes no solo (DEMEYER et al., 2001). Isso é particularmente útil em solos ácidos tropicais, onde a disponibilidade de nutrientes é baixa devido à lixiviação, translocação ou ligação com metais (FROSSARD et al., 1995). No entanto, grandes quantidades de cinzas podem afetar a estequiometria dos macronutrientes do solo, pois as cinzas geralmente são pobres em N, principalmente devido à volatilização durante a combustão (DEMEYER et al., 2001), o que é problemático para o crescimento das culturas.

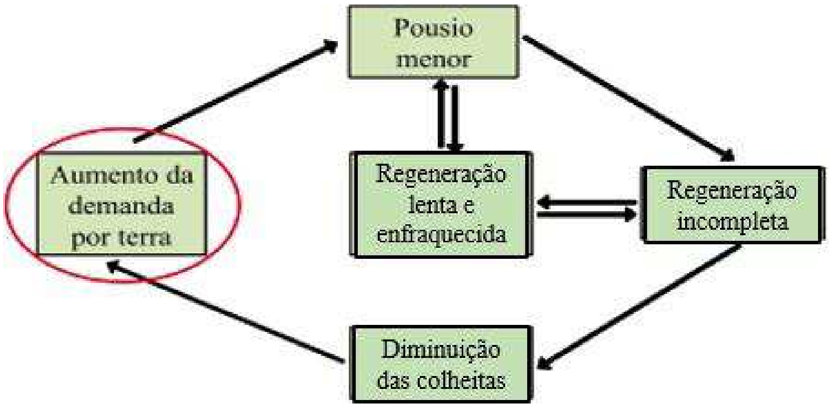
Após três anos de cultivo nesse sistema, e total depleção dos nutrientes do solo (RAHARIMALALA et al., 2010), a área é revolvida e convertida em pecuária extensiva. Segundo o IBGE (2017) 47% da área em uso no Estado do Maranhão é caraterizada como pastagem. Apenas 9% dos empreendimentos agrícolas no Estado realizam plantio de *commodities* e somente 25% realizam plantio direto na palha (IBGE, 2017). O revolvimento dessas áreas provoca a degradação física do solo e acelera a mineralização do carbono orgânico, pois a quebra dos macroagregados expõem o carbono protegido no seu interior aos processos microbianos (CAMBARDELLA e ELLIOTT, 1992). A cada revolvimento estima se a perda de 10 t ha^{-1} ano^{-1} de solo (ANACHE et al., 2018). Essas partículas são carreadas pelo vento e pela chuva e causam o assoreamento e contaminação dos rios e mananciais (TAPIA-VARGAS et al., 2001).

A ampla zona de desmatamento no Maranhão, principalmente na Amazônia Legal, associada a práticas inadequadas de cultivo aceleram as mudanças climáticas e modificam o regime pluviométrico da região (JUNIOR et al., 2020). Segundo o INMET (2016) as taxas de precipitação diminuíram no Maranhão, especialmente na região de floresta, onde os modelos climáticos preveem aumento da temperatura e diminuição da precipitação (IPCC, 2014; ALMEIDA et al., 2016). Segundo Lal (2016), o declínio efetivo dos serviços ecossistêmicos e da qualidade do solo afetam direta e indiretamente a qualidade de vida de sua população e economia, via regulação hidrológica e climática. A combinação desses fatores, levam os agricultores a migrarem para novas áreas, geralmente regiões de floresta, em busca de uma regularidade nas chuvas associada a médios teores de carbono no solo. Isso alimenta um ciclo vicioso de desmatamento e degradação (STYGER et al., 2007). Em escala global essas ações provocam modificação no clima, perda de biodiversidade e aumento dos gases de efeito estufa. Em escala local, este cenário reduz os estoques de carbono orgânico do solo, aumentam a depleção de nutrientes e promovem a coesão e compactação da camada arável.

Esse modelo de agricultura praticada no trópico úmido maranhense precisa ser reformulado para garantir segurança alimentar, proteger os recursos naturais e os serviços ambientais com intuito de mitigar as mudanças climáticas, melhorar a qualidade do solo e a produtividade das culturas agrícolas e garantir a renda dos agricultores, principalmente aqueles com menos poder aquisitivo. No entanto, é preciso atentar que modelos fundamentados na implementação de irrigação, cultivo intensivo, mecanização e aplicação somente de fertilizantes, corretivos e pesticidas (MATSON et al., 1997; CASSMAN, 1999) aumentaram drasticamente a produção de alimentos em todo o mundo, mas resultaram em amplas consequências ambientais negativas (TILMAN et al., 2002; GODFRAY et al., 2010).

O novo modelo deve se fundamentar na redução da dependência de recursos não renováveis com o intuito de manter a fertilidade do solo e a biodiversidade e, assim, minimizar as consequências externas ao local da agricultura, tais como a erosão do solo, a poluição das águas subterrâneas, a eutrofização dos rios e lagos e a redução das emissões de gases do efeito estufa. Com esse intuito, se faz necessário adoção de algumas práticas, como: (I) plantio direto, com rotação de culturas que garantam a cobertura do solo durante o período de estiagem para assegurar a permanência de estoques de carbono orgânico no solo (COS) e melhorar as propriedades físicas do solo, (II) consórcio de gramínea com leguminosa no período de safra para aumentar a eficiência de uso da água e nutrientes e aumentar o COS, (III) aplicação balanceada de nutrientes para as plantas, isso inclui redução da dosagem de fertilizante nitrogenado e adição de cátions, como cálcio e magnésio que melhoram agregação do solo, estimulam o crescimento radicular e tornam as culturas mais resistentes aos períodos de estiagem, (IV) estabelecimento de equilíbrio iônico adequado do solo, assim como seu monitoramento ao longo da camada arável (SENA et al., 2020) e (V) recuperar pastagens degradas com pousio do solo (um período chuvoso) seguido de estabelecimento de lavoura com base nos passos anteriores; após a lavoura, diversificar área com gramíneas para aumentar a resistência a pragas e doenças.

O solo é um recurso natural não renovável na escala humana; estima se que são necessários 300 anos para formar 25 mm de solo superficial (LAL, 2016). Para agricultura de corte e queima, o Estado deve fomentar o estabelecimento de sistemas agroflorestais de baixo *input* visando autonomia e melhoria dos serviços ecossistêmicos, pois o atual modelo não garante segurança alimentar e nutricional (Figura 4). Segundo o IBGE (2017), o rendimento médio de grãos do milho alcançado no Maranhão é de 1,28 t ha^{-1}, um pouco superior ao alcançado pela África Central, que é cerca de 0,9 t ha^{-1} (TUECHE e HAUSER, 2011). Várias pesquisas locais abordam essa temática com aumento expressivo de produção e melhoria da qualidade do solo, com rendimento médio de grãos do milho entre 6-8 t ha^{-1} (MOURA et al., 2016; AGUIAR et al., 2018; MOURA et al., 2018; SENA et al., 2020). No entanto, as agências de extensão agrícola do Estado precisam acelerar a transferência destas tecnologias para os produtores da região.



Fonte: GEHRING, 2006.

Figura 4 – Ciclo da agricultura itinerante praticada no trópico úmido.

2.2 Importância do Carbono orgânico para agricultura tropical

A maioria dos agroecossistemas contém reservatórios de carbono orgânico do solo (COS) mais baixos do que suas contrapartes naturais, devido o uso indevido da terra, práticas de manejo, como o revolvimento, que expõe a matéria orgânica aos fatores ambientais e mineração dos nutrientes do solo (CAMBARDELLA e ELLIOTT, 1992; LAL, 2004a). A restauração do COS acima do nível crítico é essencial para melhorar a qualidade do solo e a produtividade agronômica, especialmente na agricultura com baixo uso de insumos (LAL, 2006). Um nível ideal de COS é determinante para a qualidade do solo devido ao seu impacto positivo na (I) estrutura e agregação do solo, (II) retenção de nutrientes, (III) atividade biótica, incluindo a biomassa microbiana, (IV) sequestro de C, (V) aumento da eficiência de uso dos insumos e (VI) aumento da produção de biomassa.

Além disso, existe uma forte relação entre o reservatório de COS e a capacidade de água disponível do solo e a tolerância das culturas de resistir à seca (GUPTA e LARSON, 1979; EMERSON, 1995; FISCHER e GLASER, 2012). Em geral, o teor de umidade disponível no solo aumenta de 1 a 10 g para cada aumento de 1 g no conteúdo de matéria orgânica do solo (MOS) (EMERSON, 1995). Esses valores podem ser suficientes para manter o crescimento da cultura entre períodos de estiagem de 5 a 10 dias. Acumulação de COS é um processo biótico lento a longo prazo influenciado por fatores abióticos (JERANYAMA et al.,

2000) e geralmente não é detectável em 1 ou 2 anos, mesmo com uma considerável quantidade de entrada de biomassa no solo (LAL, 2004b).

O limite crítico do conteúdo total de COS, abaixo do qual o rendimento das culturas diminui em cerca de 20%, é de 1% para a maioria dos solos dos trópicos (AUNE e LAL, 1997) e de 2% para os solos das regiões temperadas (KEMPER e KOCH, 1966; LOVELAND e WEBB, 2003). Lal (1987) sugere adição de 6 a 8 t ha^{-1} de matéria seca sobre o solo, para melhorar as propriedades físicas e controlar a erosão do solo. Aguiar et al. (2010) sugere aplicação de 12 t ha^{-1} de matéria seca de leguminosas arbóreas para melhorar a estrutura efêmera do solo e aumentar o rendimento de grãos no trópico úmido.

Os ganhos de produtividade com um aumento no *pool* de COS são grandes, especialmente quando combinados com a entrada criteriosa de fertilizantes e irrigação (LIU et al*.,* 2020*)*. O *pool* do COS compreende dois componentes predominantes: (1) o componente inerte ou recalcitrante, que não está envolvido no processo de mineralização e depende do tipo de solo, clima, histórico de uso da terra e posição da paisagem; e (2) a fração lábil ou ativa, que depende do manejo. A mudança no reservatório de COS devido alteração no uso e gerenciamento da terra é principalmente devido a mudança na fração lábil (LAL, 2006). Existe também uma forte ligação entre a concentração da fração lábil do COS e a qualidade do solo, especialmente em solos empobrecidos dos trópicos e subtrópicos, que perderam de 60 a 80% do seu reservatório de COS devido às práticas extrativistas da agricultura de subsistência (LAL, 2017).

A reversão da degradação e desertificação através do aprimoramento e preservação do carbono orgânico do solo aumentaria a capacidade de troca catiônica (CTC), melhoraria a atividade biótica de microrganismos e o suprimento de nutrientes (LAVELLE et al., 1997). O reservatório de COS é a força motriz da atividade biológica e é a principal fonte de energia e nutrientes para a biota do solo (POWLSON et al., 2001). O aumento no *pool* de COS também aumenta a CTC (JOHNSTON, 1986). O declínio em 1 g kg^{-1} de COS reduziu a CTC efetiva em até 4 mmol kg^{-1} em solos de argila de baixa atividade, reduzindo a capacidade do solo de reter nutrientes (BATIONO e MOKWUNYE, 1991). Portanto, um aumento na concentração de COS produziria o mesmo nível de rendimento das culturas com um nível reduzido de fertilizantes (VALLIS et al., 1996; AGGARWAL et al., 1997) devido a um aumento na eficiência do uso de fertilizantes e uma diminuição na lixiviação do nitrato (VALLIS et al., 1996). Ampliação do reservatório de COS também melhora a estrutura e agregação do solo

(TISDALL e OATES, 1982; FELLER e BEARE, 1997; HAYNES e NAIDU, 1998), tornando os solos menos propensos a crostas e compactação (DIAZ-ZORITA e GROSSO, 2000) e erosão do solo.

Pequenas mudanças no estoque de COS podem ter impactos consideráveis nas concentrações atmosféricas globais de CO_2, além de desempenhar um papel crucial na consecução do objetivo de longo prazo de limitar o aquecimento global a 1,5 ° C (PAUSTIAN et al., 2016). Entre as opções de mitigação agrícola, o seqüestro de C do solo é uma das poucas estratégias que podem ser aplicadas em larga escala e com menor custo (SMITH, 2002). Dessa forma, é importante monitorar a concentração de carbono ao longo do perfil do solo, pois a profundidade é o principal preditor do conteúdo de COS em todo o mundo (RASMUSSEN et al., 2018). Embora os subsolos (> 20 cm) possuam baixas concentrações de C e N, eles contribuem para mais da metade dos estoques globais de COS e N (JOBBÁGY e JACKSON, 2000).

A estratégia de sequestro de carbono nos solos ocorre com o aprimoramento da formação de microagregados estáveis, translocação de COS para o subsolo e formação de substâncias recalcitrantes através do aprimoramento de mecanismos de proteção (por exemplo, físico, químico e biológico). Com a projeção da população mundial para atingir 9,2 bilhões em 2050, não basta minimizar o impacto ambiental, produção agronômica também deve ser aumentada, para a qual a melhoria do *pool* de COS é um determinante importante e pode ser aprimorado através da adoção de sistemas de cultivo que observem as leis básicas do manejo sustentável do solo (LAL, 2009) e aqueles que criam balanços positivos de carbono e nutrientes na zona radicular (SENA et al*., 2020).*

2.3 O gesso como fonte de cálcio e seus efeitos na matéria orgânica do solo

O aumento da agregação do solo consiste em uma das principais estratégias para aumentar/estabilizar o carbono orgânico em solos altamente intemperizados (BLANCO-CANQUI E LAL, 2004). Para tanto, adição de íons de cálcio na superfície desses solos pode desempenhar um importante papel, pois funciona como agente de agregação através da formação de pontes catiônicas entre partículas de argila e matéria orgânica (CLOUGH E SKJEMSTAD, 2000). Essas ligações conferem proteção física contra processos de oxidação, e melhorias efêmeras na estrutura do solo (SIX et al., 2002). Briedis et al. (2012) demonstram que, através de técnicas de microscopia eletrônica há estreitas relações entre átomos de carbono e cálcio nos solos. Chan e Heenan (1999) também relataram que a adição de Ca aos solos aumentou o nível de agregação em aproximadamente 10%.

O gesso, por ser uma das principais fontes de Ca em sistemas agrícolas, pode contribuir significativamente para o aumento da agregação do solo e assim acumulação/estabilização de matéria orgânica, sua solubilidade (2,5 g L^{-1}) é cerca de 170 vezes maior que a do calcário (BENNETT et al., 2014; CRUSCIOL et al., 2016), aumenta eficientemente a mobilidade de cátions alcalinos, como Ca^{2+}, Mg^{2+} e K^{+} trocáveis (PAULETTI et al., 2014; CRUSCIOL et al., 2016; DALLA NORA et al., 2017; ZOCCA E PENN, 2017). Apesar desse potencial, a maior parte dos estudos relatando a influência da gessagem sobre a dinâmica da matéria orgânica, são desenvolvidos em solos sódicos e/ou alcalinos. Carter (1986) e Batra et al. (1997) observaram aumento da atividade biológica do solo em parcelas tratadas com aplicação de gesso em solos sódicos alcalinos. Segundo os autores, a melhoria das propriedades químicas devido à aplicação do gesso como redução dos teores de sódio e decréscimo do pH criariam condições mais propícias para o desenvolvimento da microbiota do solo. Estas modificações químicas, no entanto, não se aplicariam para solos ácidos e intemperizados, uma vez que estes apresentam níveis de pH naturalmente baixos que não são influenciados pela aplicação de gesso (CAIRES et al., 1998; OLIVEIRA et al., 1994).

Um experimento de incubação observou que, apesar de melhorar as propriedades químicas, a adição de gesso não influenciou significativamente nos atributos biológicos do solo quando foi aplicado de forma isolada (WONG et al., 2009). A sua adição em conjunto com a incorporação de resíduos orgânicos, resultou em aumentos da respiração basal e biomassa microbiana. A influência do gesso sobre a dinâmica da matéria orgânica estaria, portanto, dependente da presença de resíduos no sistema, e suas mudanças dos atributos químicos por si não influenciariam significativamente os teores de C do solo (INAGAKI et al., 2017).

Em um sistema de plantio direto em solo ácido e intemperizado, MOURA et al. (2018) observaram incrementos significativos na produção de milho, devido a aplicação de gesso e biomassa de leguminosas arbóreas. Segundo os autores, o aumento dos teores de Ca em profundidade contribui para uma melhora na enraizabilidade do solo, obtendo-se dessa forma maior absorção de água e nutrientes melhorando o desenvolvimento da cultura. Diversos autores têm citado a importância do sistema radicular no aporte de biomassa em sistemas agrícolas (JACKSON et al., 1997; PIETOLA e ALAKUKKU, 2005). Tal melhoria do sistema radicular pela gessagem consistiu em uma das principais influências da prática nos níveis de carbono de sistemas agrícolas em solos ácidos e intemperizados.

A utilização do gesso têm sido benéfica principalmente em regiões com ocorrências de veranicos, uma vez que a melhoria da fertilidade do solo na subsuperfície permite um desenvolvimento radicular mais profundo, aumentando dessa forma a produtividade das culturas (CAIRES et al., 2011; SOUSA et al., 2007; RITCHEY, 2015). Aumentos de produtividade de culturas em resposta à aplicação de gesso tem sido observados principalmente em milho, enquanto a soja não costuma apresentar as mesmas respostas à gessagem (CAIRES et al., 2003; CAIRES et al., 1999; OLIVEIRA et al., 1994). Segundo CAIRES et al. (2011), este fato se deve à capacidade de troca catiônica de gramíneas ser menor que a de leguminosas, fato que confere à soja uma capacidade maior de absorver nutrientes como o Ca^{+2}, resultando em menores respostas da cultura à adição do elemento pelo gesso.

Apesar de Tisdall e Oades (1982) terem enfatizado a relação dos agentes persistentes de agregação com frações do solo associada aos minerais, relações mais estreitas dos íons de cálcio foram encontradas com os compartimentos mais lábeis do carbono (INAGAKI et al., 2017; ROWLEY et al., 2018). Essa íntima relação entre as variáveis pode ser um indício de que o cálcio atua como um protetor dessas frações mais lábeis. Em geral, os materiais que se decompõem rapidamente, como a glicose, exercem um efeito de estabilização rápido, mas que é transitório (WALIAA e DICK, 2018).

Dessa forma, as aplicações de gesso em plantio direto contribuem no aumento das frações mais lábeis do carbono do solo, porém não possui efeito em frações mais recalcitrantes (INAGAKI et al., 2016). O uso mais intenso de milho na rotação de culturas, cuja produtividade é mais afetada pela gessagem, pode proporcionar maiores aumentos nos estoques (CAIRES et al., 2011), o maior aporte de biomassa, tanto da parte aérea quanto das raízes, aliado ao não revolvimento do solo melhora os níveis de agregação do solo e proteção do carbono orgânico, contribuindo assim para o aumento dos estoques (DE MORAES SÁ et al., 2014; HOK et al., 2015).

2.4 Manejo de solos coesos

Os solos coesos são aqueles que se tornam duros quando secos, dificultando seu cultivo, e suscetíveis a deterioração e dispersão quando úmidos (CHARTRES, KIRBY e RAUPACH,1990; MULLINS, 1999). A coesão reduz o volume de solo que as plantas conseguem explorar e a enraizabilidade do solo, prejudicando a absorção de nutrientes, o acúmulo de biomassa e a produtividade das culturas, além de reduzir a eficiência de uso da água (MOURA et al., 2010).

Pesquisadores atribuem esse efeito à dispersão da argila e do silte, principalmente nos solos que apresentam baixas concentrações de matéria orgânica (ECK e UNGER, 1985; MULLINS et al., 1990; YOUNG et al., 1991). Churchman et al. (1994) observaram também que solos dominados pela mica hidratada (ilita) ou caulinita apresentavam endurecimento na camada superficial. Para alguns autores a coesão é característica de solos com predomínio de silício (Si), pois as partículas de óxido de ferro são atraídas para a superfície da sílica por forças eletrostáticas, formando fortes ligações Fe-O-Si que endurecem o solo (SCHEIDEGGER, BORKOVEC e STICHER, 1993).

Íons de sódio e magnésio promovem condutividade hidráulica reduzida e argila altamente dispersa em água, resultando também em endurecimento do solo (FRANZMEIER, CHARTRES e WOOD, 1996). Os solos que não apresentam endurecimento em seu estado natural, podem se tornar compactados como resultado de um sistema inadequado de manejo e uso de práticas como excesso de revolvimento do solo e do uso de maquinário agrícola ou pisoteio animal (MULLINS et al., 1990).

A medição da coesão inclui métodos como resistência à penetração (RP), dispersão da argila, frações da matéria orgânica do solo e um uso específico da curva de retenção de água no solo. No entanto, a presença de argila dispersa não é uma condição necessária para o endurecimento do solo, já a resistência do solo à penetração é considerada a propriedade mais adequada para expressar o grau de compactação do solo e sua enraizabilidade (YOUNG et al., 1991; SILVEIRA et al., 2010). A coesão é predominantemente observada em solos com baixas concentrações de matéria orgânica (STOCK e DOWNES, 2008), tipicamente <2% (MULLINS et al., 1990).

A resistência à penetração do solo (RP) é controlada pela umidade do solo, densidade aparente e o teor de argila (MULUMBA e LAL, 2008; DEXTER et al., 2007), Ley (1988) e

YOUNG et al. (1991) recomendam que as medições ocorram em condição de campo para evitar subestimação de valores. A resistência a penetração permite acompanhar em tempo real se o solo está apto ao desenvolvimento radicular. Em solos suscetíveis à coesão, um curto período de estiagem (≥ 6 dias) é suficiente para exceder o valor considerado como nível crítico para a resistência à penetração do solo na camada de 0-20 cm (≥ 2 Mpa) (WEAICH et al., 1992), em solos tropicais, onde a evapotranspiração é elevada, esse valor pode ser menor.

Nesse caso, adição de substrato orgânico pode atenuar esses efeitos sobre a RP (MULUMBA e LAL, 2008). Pois a cobertura orgânica conserva a água *in situ*, reduz a drenagem profunda e o escoamento superficial (MOURA et al., 2012). O aprimoramento do carbono orgânico do solo através do cultivo de cobertura pode melhorar a umidade do solo (LAL, 2016). De fato, parece provável que todos os solos com uma distribuição de tamanho de partícula apropriada e mineralogia de argila sejam potencialmente difíceis na ausência de uma boa concentração de matéria orgânica (MULLINS et al., 1990).

Em um experimento de campo com solo coeso, no Instituto Waite-Austrália, para cada aumento de 0,1% no carbono orgânico, havia um aumento de 2% nos macroagregados instáveis (> 250 µm de diâmetro); a atividade de raízes e hifas estabilizou esses macroagregados (TISDALL e OADES, 1980). Taboada-Castro (2009) mostrou que além da matéria orgânica do solo, o cálcio também é um importante agente agregador. Segundo Giovannini e Sequi (1976), o Ca forma complexos com matéria orgânica e argila no solo, formando agregados fortes. Para Moura et al. (2018), ação do cálcio com o carbono orgânico melhora a estrutura efêmera do solo no trópico úmido. Alguns autores recomendam o uso de gesso para aumentar o cálcio em profundidade, pois é um condicionador de solo de baixo custo e mais solúvel que o calcário (BENNETT et al., 2014; ZOCCA e PENN, 2017).

O gesso quando aplicado nos solos suscetíveis a coesão promove a diminuição da forte dispersão do solo na superfície assim como retarda seu processo de secagem. Esses fatores aumentam a porosidade e a capacidade de água disponível no solo e diminuem a resistência à penetração, e essa melhora nas propriedades físicas do solo refletem em maior absorção de água e nutrientes pelas culturas (GRIERSON, 1978; SUMNER, 1999; MOURA et al., 2018). Vários autores relatam que o gesso também aumenta estabilidade de agregados, a macroporosidade e a condutividade hidráulica no solo (SCOTTER e LOVEDAY, 1966; LOVEDAY, 1974; CHARTRES et al., 1985). No entanto, os efeitos diretos do gesso não persistem quando o cálcio é lixiviado das camadas da superfície (GREENE e FORD, 1985; CHARTRES et al., 1985).

O gesso aplicado nos solos coesos no norte da Austrália, na dosagem de 5 e 15 t ha^{-1}, diminuíram a dispersão da argila e a formação de crostas e impediram o colapso dos macroporos formados pelo preparo do solo. À medida que a chuva lixiviou o gesso das camadas superficiais (cerca de 1 t ha^{-1} por 125 mm a 360 mm de chuva, dependendo da taxa de gesso aplicada), a macroporosidade diminuiu e as crostas se formaram (GREENE e FORD, 1985; CHARTRES et al., 1985). Dessa forma, é necessário que a aplicação de gesso ocorra periodicamente. Em um experimento irrigado no norte da Austrália, após três anos da aplicação superficial de gesso, observou-se que o cálcio foi lixiviado da profundidade superficial a 0,3 m, e a água penetrava mais profundamente no subsolo do que no solo sem adição de gesso. Isso foi atribuído à estabilização dos poros do solo por raízes e organismos do solo, possivelmente auxiliados pelo gesso (TAYLOR e OLSSON, 1987).

No entanto, altas concentrações de matéria orgânica, bom volume de palhada sobre o solo, pH neutro e carbonato de cálcio podem reduzir a resposta de um solo ao gesso (EMERSON, 1983; RENGASAMY et al., 1984; FONTOURA et al., 2019). A vantagem do gesso também pode depender da estação do ano. Nos anos em que a precipitação é menor que a média, o gesso pode aumentar a taxa de infiltração de água disponível no solo e por um período mais longo (MULLINS et al., 1990).

O principal problema dos solos coesos não é como obter, mas como manter porosidade suficiente (Figura 5; Figura 6). Nessa abordagem, mesmo quando os resíduos orgânicos são escassos, eles podem representar um caminho a seguir. Lal (1987) sugere que 6 a 8 t ha^{-1} por ano de matéria orgânica seria suficiente para melhorar as propriedades físicas do solo e controlar a erosão. Mullins et al. (1990) sugere aplicação inicial de 5 a 7,5 t ha^{-1} de gesso para solos coesos com baixo teor de bases. Mas devido ao efeito de lixiviação, aplicação de gesso deve ocorrer periodicamente para manter uma concentração alta de eletrólitos suficiente para estabilizar solos arenosos (LOVEDAY, 1974).

Para regiões que apresentam alto índice pluviométrico é necessário o monitoramento anual do teor de cálcio no solo para que não seja inferior ao nível crítico estabelecido por Heckman (2006) de 25 mmolc Ca^{2+} dm^{-3} na camada de 0-20 cm. Segundo Moura et al. (2018), a aplicação de gesso com resíduos de leguminosas aumentou o nível de cálcio e matéria orgânica do solo e reduziu a resistência a penetração em um solo coeso, demonstrando ser uma estratégia adequada para aumentar a produtividade e sustentabilidade em sistemas agrícolas tropicais.

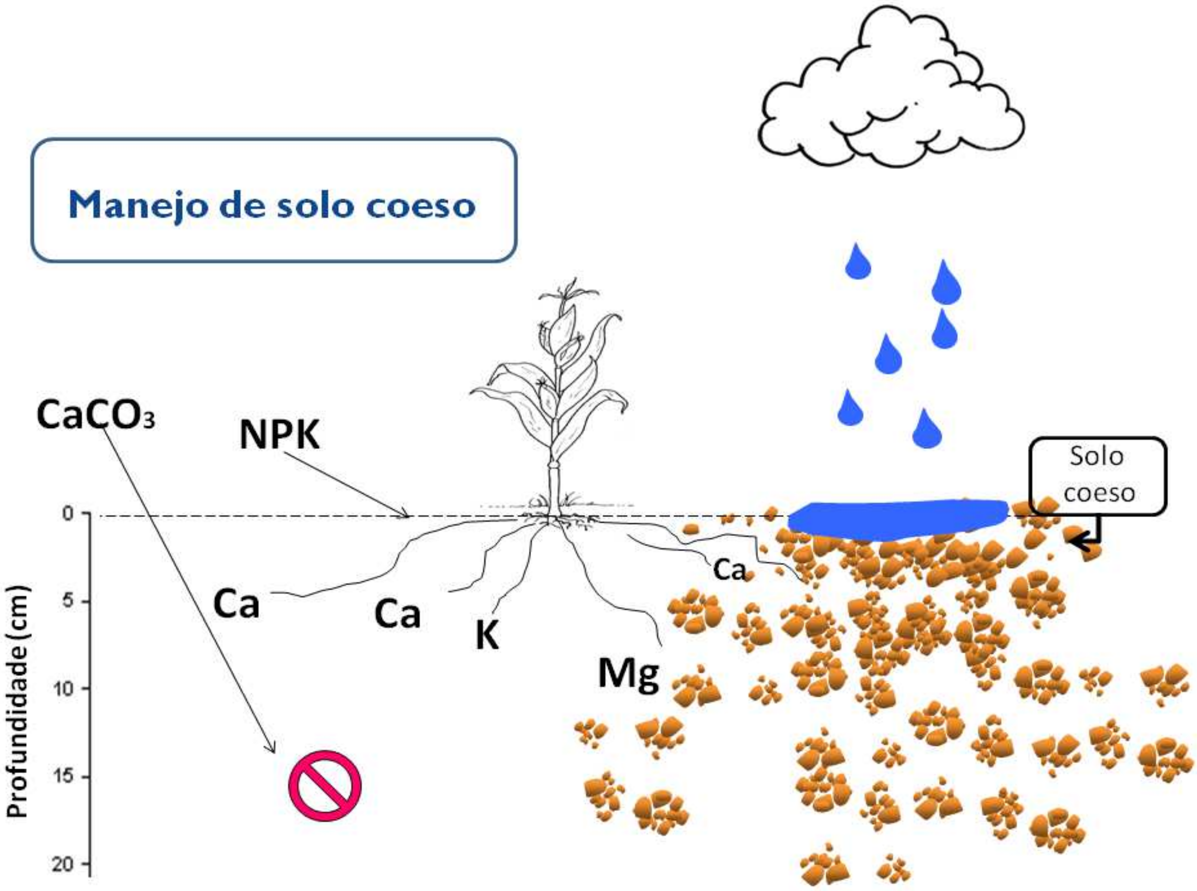


Figura 5. Representação didática em que práticas convencionais de manejo do solo, como a recomendação da calagem ($CaCO_3$) e a saturação do solo com nutrientes solúveis (NPK) não garantem aumento da produção agrícola assim como, a viabilidade dos sistemas de cultivo na região do trópico úmido. NPK: adubação sintética com nitrogênio, fósforo e potássio.

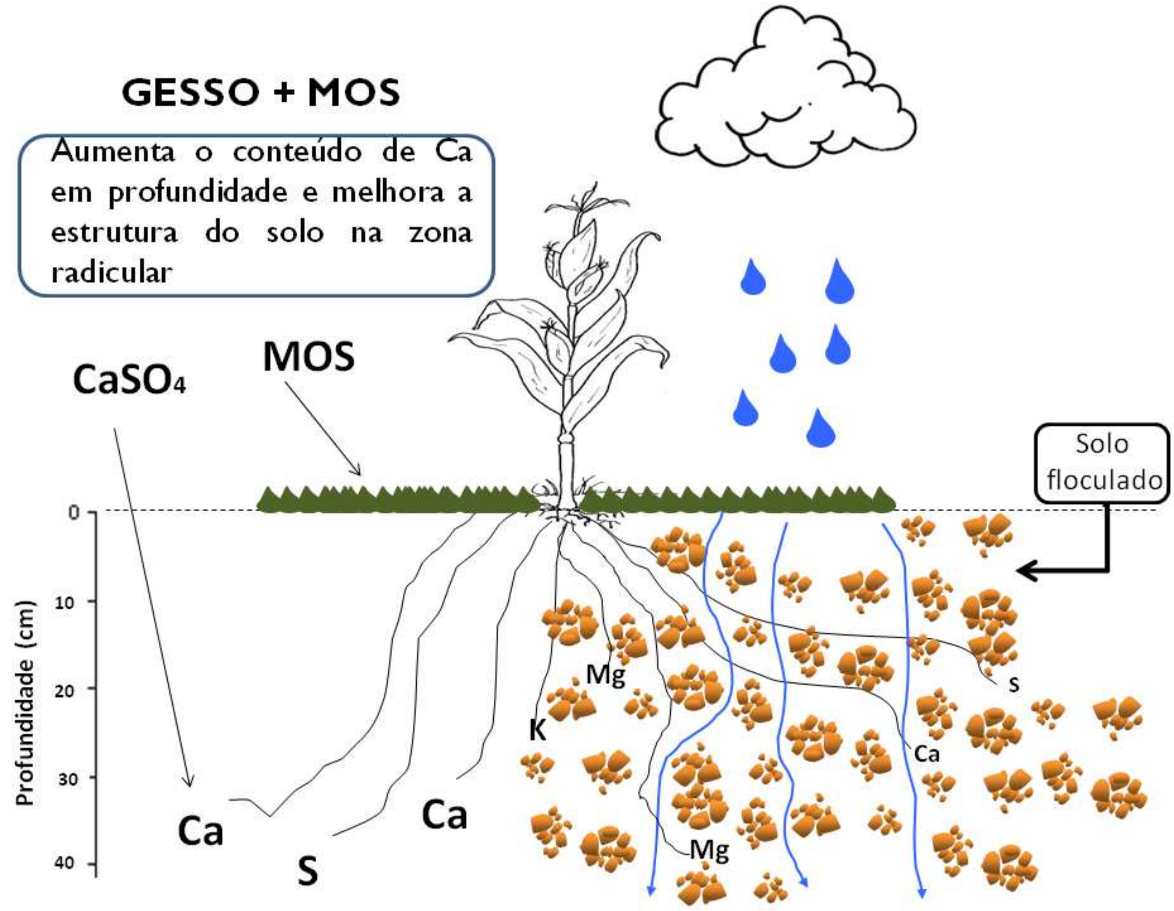


Figura 6. Representação didática em que práticas de manejo do solo, como adição de gesso ($CaSO_4$) e matéria orgânica do solo (MOS) reduzem os efeitos da coesão do solo e ampliam a espessura da camada hábil ao desenvolvimento radicular.

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Management practices for crop production sustainability in cohesion tropical soil

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CAPÍTULO II

Management practices for crop production sustainability in cohesion tropical soil

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Abstract

This study aimed to follow the dynamic of organic carbon and base cations in the root zone of a sandy loam cohesion tropical soil after gypsum and legume residue application to determine their permanence period in critical level and assess how this dynamic affects maize productivity. Assessements started in January 2011, testing the following treatments: Legumes + Urea + Gypsum (LUG); Legumes + Gypsum (LG); Legumes (L); Urea + Gypsum (UG); Urea (U); Gypsum (G); Control (C). Experimental design was in randomized blocks with four replications for each treatment. Our results suggest that legume residue and gypsum, applied with urea, can increase soil rootability, improve soil moisture, provide soil organic carbon, retain calcium in the soil profile and increase maize productivity. Therefore, in cohesive soils with cohesion structure from the humid tropics, the combination of legume and gypsum biomass allows the maintenance of adequate levels of calcium in the soil, water retention and improves soil ephemeral structure. Thus, this combination is recommended to growers as a simple and profitable strategy to increase soil rootability and crop productivity.

Keywords: calcium, organic carbon, soil penetration strength, sandy soil.

Resumo

O objetivo deste estudo foi acompanhar a dinâmica do carbono orgânico e cátions na zona radicular de um solo tropical coeso de textura arenosa após aplicação de gesso e resíduo de leguminosa para verificar seu período de permanência em nível crítico e avaliar como essa dinâmica afeta a produtividade do milho. O experimento foi iniciado em janeiro de 2011, testando os seguintes tratamentos: Leguminosas + Ureia + Gesso (LUG); Leguminosas + Gesso (LG); Leguminosas (L); Ureia + Gesso (UG); Ureia (U); Gesso (G); Controle (C). O desenho expeimental foi em blocos ao acaso, com quatro repetições para cada tratamento. Nossos resultados sugerem que cobertura morta e gesso, usados com ureia, podem aumentar a capacidade de enraizamento do solo, melhorar a retenção da umidade, fornecer carbono orgânico, reter cálcio no perfil do solo e aumentar a produtividade do milho. Portanto, em solos coesos de estrutura frágil nos trópicos úmidos a combinação biomassa de leguminosas e gesso permite a manutenção de níveis adequados de cálcio no solo e melhora sua estrutura efêmera. Assim, essa combinação é recomendada aos produtores, como uma estratégia simples e vantajosa para aumentar a capacidade de enraizamento do solo e a produtividade das culturas.

Palavras-chave: cálcio, carbono orgânico, resistência à penetração do solo, solo arenoso.

Introduction

A large proportion of rural poor in the tropics lives in regions with marginal land, naturally inadequate to carry out a long-term sustainable agriculture, which is one of the ultimate FAO's goals to alleviate poverty and reduce threats to human and ecosystem health (Shah and Wu 2019). Most of the poor farmers from this region continue to practice shifting cultivation agriculture, mainly due to several economic difficulties to adopt innovative producing systems, which could allow them to change to sustainable agricultural intensification and avoid deforestation (Ragasa *et al.* 2016). Therefore, agricultural innovation using sustainable and accessible practices are the key determinants and essential to address incompatibilities among the social, environmental and agricultural dimensions of agriculture activity (Sayer and Cassman 2013).

In the humid tropics, the loss of soil quality damages tradicional agroecosystems, by reducing productivity and reducing job and subsistence opportunities, which constitute a clear cause for poverty (Naylor 1993). In these circumstances, a significant challenge to researchers is how to maintain soil fertility in a sustainable and accessible manner to farmers (Souza *et al.* 2018). Indeed, in order to avoid the unsustainability of the land use in the humid tropic, the main challenge is to overcome the harmful association between high soil organic matter decomposition and increased base cations which is rapidly leached from the soil profile, (Moura *et al.* 2016). Both processes are accelerated by intense climate forces and by inadequate agricultural practices, leading to agricultural soil degradation, which difficults the continuous use of the land, encouraging shifting cultivation.

Moreover, in tropical soil, which exhibits low-activity clay and low concentration of other aggregating elements such as iron, decreasing in organic carbon has a double effect on root growth and nutrient use efficiency, which are crucial to tropical agrosystems viability (Tarkiewicz and Nosalewicz 2005). First, when soil organic matter reaches a low and inappropriate level, damage in soil chemical properties causes a considerable decrease in its capacity to sustain base cations. Reduction in base cations along soil profile by leaching may lead to a concentration of acid cations, resulting in a level of percentage base saturation inadequate to root growth. Second, in tropical cohesive soil, crop plants can exploit only a thin surface layer to uptake water and nutrients, due to an increased fine particle content and reduced organic carbon at lower depth layers, which makes it inhospitable to root growth (Moura *et al*. 2020a).

Indeed, beyond the improvement in chemical attributes, improvement in physical properties to enhance soil rootability is also crucial to increase root growth and, consequently, nutrient and water uptake, even under an irregular rainfall regime (Sena *et al*. 2020). Fortunately, although many humid tropic soils are acidic, with low essential nutrient reserves and sometimes prone to cohesion, constant warm temperatures, plentiful rainfall, and even allocation of sunlight throughout the year might allow abundant plant growth producing biomass that can be converted in soil organic matter and improve soil quality (Berenguer *et al*. 2018).

Therefore, if managed wisely, these tropical advantages could contribute to overcome the main challenge for sustainable soil management, that is enhance biomass production to increase soil organic matter and nutrient recycling to maintain basic cations in the root zone (Moura *et al*. 2016).

Furthermore, it is possible to use a positive interaction between soil organic matter and calcium as an essential mechanism to prevente biological, chemical, or physical organic matter breakdown, increasing its stability and retaining base cation along the soil profile (Whittinghill and Hobbie 2012). According to Rowley *et al.* (2018), there is evidence of a potential role of Ca in the stabilisation of SOC. Contrary to the common view of base cation the chemistry in soils, chemical modelling indicates that Ca^{2+} can readily exchange its hydration shell and create inner sphere complexes with organic functional groups.

The bond between polyvalent cations as Ca and negatively charged organic matter functional groups is not easily reversible, and surfaces of organic materials will be less accessible for microbial activity, according to Moore and Turunen (2004). Some authors have confirmed the positive effects of this process on soil rootability, nutrient uptake and crop productivity (Sena *et al.* 2020; Moura *et al.* 2020a). Thus, a good strategy to match sustainability and viability in tropical agrosystems may to combine the advantages of the tropical environment to leguminous tree growth to produce biomass with the use of the interactions between polyvalent cations and compounds derived from biomass decomposition.

In this work, we hypothesized that this process may increase soil organic matter stabilization/accumulation and contribute to hold base cation along soil profile, improving soil rootability and increasing nutrients uptake and crop productivity. Thus, our aim was to follow the dynamic of organic carbon and base cations in the root zone of a sandy loam cohesion tropical soil after gypsum and legume residue application to assess its permanence period in critical level and evaluate how this dynamic affects maize productivity.

Methodology

Experimental Design

This study was conducted during eight growing seasons (2011 up to 2018) at Maranhão State University, Brazil (2°30′ S, 44°18′ W). The region has a hot and semi-humid equatorial climate with two well-defined seasons: (I) a rainy season that extends from January to June; and (II) a dry season with a marked water deficit from July to December. The annual average temperature is approximately 27 °C, the maximum temperature is 37 °C, and the minimum temperature is 23 °C. The mean rainfall (mm) during the experimental period was 1756 mm year^{-1}, from 2011 to 2015, and 2547 mm year^{-1} , from 2016 to 2018 (Fig. 1). General average rainfall for the region is 2200 mm ano $^{-1}$ (CPTEC 2020).

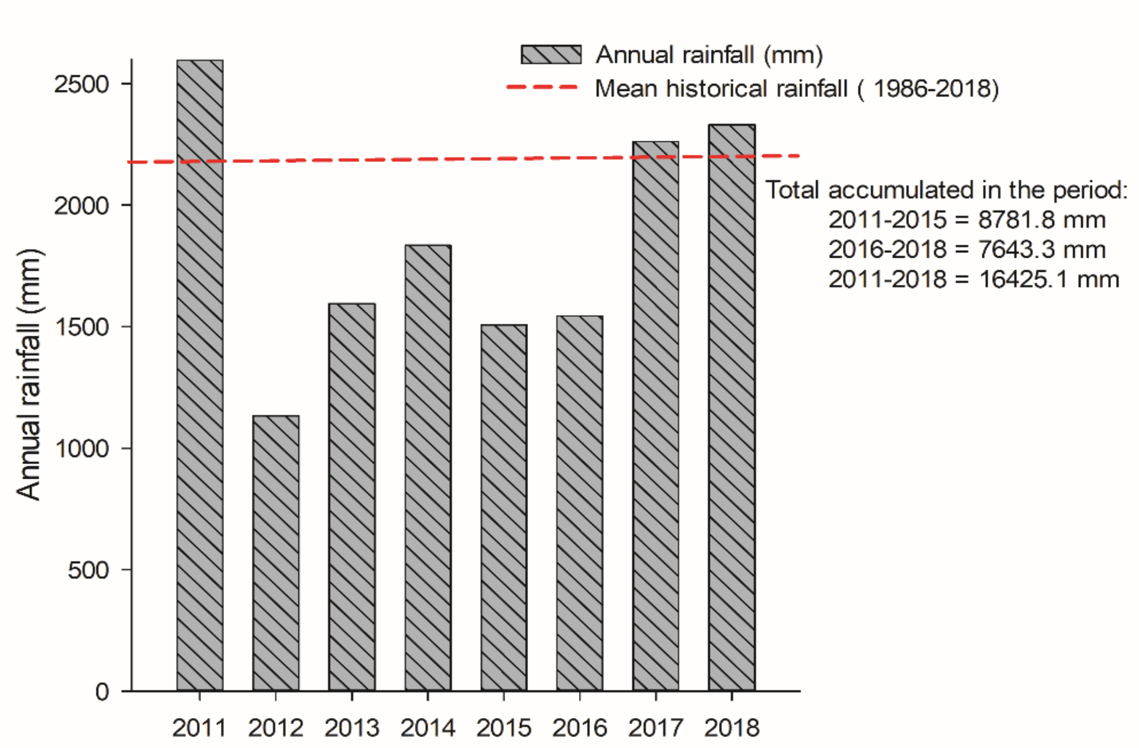

Fig. 1. Annual rainfall during the experimental period (2011–2018) (São Luís-MA, Brazil - 2°30′ S, 44°18′ W).

Local soils displayed cohesive characteristics (determined by the relationship between penetration strength and soil volumetric water content) (Moura *et al*. 2012; Moussadek *et al*. 2014) and they were classified as Arenic Hapludults (SOIL SURVEY STAFF, 2014). Before the first sowing on the experimental area in December of 2010, soil chemical and physical properties were determined as follow, in the 0-20 cm layer: pH 4.0 (in $CaCl_2$); 20 g kg^{-1} of organic carbon (C); 15 mg dm^{-1} of phosphorus (P); 25 mmol$_c$ dm^{-1} of potential acidity (Al + H); 15 mmol$_c$ dm^{-1} of calcium (Ca); 9 mmol$_c$ dm^{-1} of magnesium (Mg); 1 mmol$_c$ dm^{-1} of potassium (K); 50 mmol$_c$ dm^{-1} of cation exchange capacity (CEC); 50.0% of percentage base saturation; 300 g kg^{-1} of coarse sand, 529 g kg^{-1} of fine sand, 61 g kg^{-1} of silt; 110 g kg^{-1} of clay. In

January 2011, the area was limed with 1 t ha^{-1} of surface-applied lime, corresponding to 390 and 130 kg ha^{-1} of Ca and Mg, respectively. In that same period, natural gypsum was applied at a rate of 6 t ha^{-1} in the plots predetermined to receive this treatment, which corresponds to 1.002 kg ha^{-1} of Ca. In January of 2016, 4 t ha^{-1} of gypsum and 1 t ha^{-1} of lime were reaplied on soil surface supply the Ca that was leached after five years of experimentation, which corresponds to 390 and 130 kg ha^{-1} of Ca and Mg, respectively for lime application and 680 kg ha^{-1} of Ca for gypsum application. Considering the pluviometric index of 2200 mm per year, the gypsum recommendation took into account the maintenance of the calcium content above 25 mmol dm^{-3} in the 0-20 cm layer. The gypsum grain size was such that 95% by weight passed through a 0.25-mm screen mesh.

The experimental area had been fallowing since 1990 and supported a native species of grass, which was removed using a glyphosate application. Some remaining weed was removed manually. The experiment was conducted under no-tillage mulch system, with planting maize seed by hand, and the experimental plot size was 4 × 8 m. The study followed a randomized block design with four replications for each of the following treatments: leguminous + urea + gypsum (LUG); leguminous + gypsum (LG); leguminous (L); urea + gypsum (UG); urea (U); gypsum (G); control (C). Soil samples were analyzed in 2012 up to 2018. Maize yield was determined in 2011, 2012, 2013, 2015, 2016, 2017 and 2018. In 2018, soil penetration strength and soil moisture were mesuared.

Maize (cv AG 7088) was sown at the beginning of the rainy season in 2011 up to 2013 and 2015 up to 2017, with 80 cm spacing between rows and 25 cm between plants. Only in the 2018, irrigated maize was planted with an irrigation interval of 8 days for all treatments. Water was supplied by drip tape irrigation, using one tape by row with emitters spaced 25 cm apart, each delivering 1.25 L h^{-1} over 4h to deliver a total of 40 mm of water per irrigation. In January of 2014, soybean was sown as crop rotation (data not shown). Fertilization (commonly recommended for the region) on maize and soybean consisted of applying 80 kg ha^{-1} of phosphate (P_2O_5) from triple superphosphate, 180 kg ha^{-1} of K_2O from potassium chloride and 5 kg ha^{-1} of zinc (Zn) in the form of zinc sulphate. Inorganic nitrogen was applied in the form of urea at a dosage of 180 kg ha^{-1} of N, only in the plots that received this treatment.

Residues from *Gliricidia sepium* (gliricidia) and *Acacia mangium* (acacia) were applied at 6 t ha^{-1} for each legume (a total of 12 t ha^{-1} per year), a rate that is commonly applied in alley cropping systems according to Aguiar *et al.* (2010). The legume residues were applied in the years 2011 up to 2018, in the form of fresh branches. The quantities of nutrients added per year, calculated based on quality parameters of leguminous residues was: 342 kg ha^{-1} of N, 27.2 kg ha^{-1} of P, 60.6 kg ha^{-1} of K, 177.6 kg ha^{-1} of Ca, 33.0 kg ha^{-1} of Mg. The total amount of urea and leguminous residues were divided and applied at the time of sowing, 30 and 45 days after sowing.

Soil Sampling and Analyses

Soil samples were collected at maize physiological maturity in 2012 up to 2018 at depths of 0–10 cm, 10–20 cm, 20–30 cm and 30-40 cm. Nine replicates for each depth were collected using a Dutch auger 3-inch diameter. Samples from each point were passed through a 2 mm sieve and then air dried before determining the exchangeable Ca^{2+} with an extractor of potassium chloride 1.0 mol L^{-1}, measured by an inductively coupled plasma (WALNUT CREEK, CA, USA), model ES-720, with ICP Expert II Software, based on Raij *et al.* (2001). The table of critical level defined by Heckman (2006) was used to construct the estimated soil calcium graph. Portions of the samples collected at a depth of 0–10 and 10-20 cm were separated to determine organic carbon following wet oxidation followed by titration with the ferrous ammonium sulphate method described by Tiessen and Moir (1993). The table of critical level defined by Prout *et al.* (2020) was used to construct the estimated soil carbon content graph. Prout and collaborators established that SOC / clay threshold values can indicate degraded and good soil structural condition. The scale obtained consists of a soil organic matter index with threshold SOC / clay ratios of 1/8, 1/10 and 1/13 which separates the soils into very good, good, moderate (medium) and degraded (bad) classes of SOC content and physical structure condition. For the ratio calculation, we used a clay content value of 110 g kg^{-1}, which was estimated from the physical analysis of the soil.

Soil penetration strength and soil moisture were measured at depths of 0–10, 10–20, 20-30 and 30-40 cm with three replicates per plot, in september of 2018, after 4, 6 and 8 days after irrigation. Soil penetration strength was measured using a digital penetrometer (Falker, Porto Alegre, Brazil) with 1 cm gradations. The table of critical level defined by Hazelton and Murphy (2016) was used to construct the soil penetration strength graph. Soil moisture was determined by gravimetric method, using samples obtained in the same period of soil penetration strength assessment, at three points along the given line. The table of critical level defined by Moura *et al* (2009) was used to construct the soil moisture graph. In 2018, soil physical analysis determined ephemeral improvements in soil aggregation, mainly due to effects of calcium from gypsum and legumes and their interactions with soil organic carbon. Therefore, only treatments LG, L, G and C were sampled for soil penetration strength and soil moisture.

Correlations between calcium and soil organic carbon (SOC) were investigated through regression analysis with the use of all treatments for Ca and COS in all evaluated years. These analyzes were performed using R software (R Development Core Team 2009).

Maize Grain Yield

Maize grain yield was determined at the final harvest or at physiological maturity in 2011 up to 2013 and 2015 up to 2018, which was assessed in a 12 m^{-2} area. Values were adjusted according to moisture level of 145 g kg^{-1}. Results were subjected to analysis of variance (ANOVA). Means were compared by Duncan’s test at 5% probability using InfoStat software (InfoStat Group, College of Agricultural Sciences, National University of Córdoba, Córdoba, Argentina).

Results

Results from calcium contents showed the positive effect of leguminous biomass combined with gypsum to maintain the adequate level of this nutrient in the root zone. Indeed, in 0-20 cm layer, just in the treatments with biomass and gypsum (LUG and LG), calcium was in the high critical level from the second year (Fig. 2). In the treatments with urea and gypsum (UG) and gypsum (G) in the fourth year, calcium content was below of the high critical level. In contrast, in the treatments with urea (U) and control (C), calcium was low in the last year. Leguminous biomass (L) was able to maintain calcium in medium critical level, close to the high critical level, even in the last four years (Fig. 2).

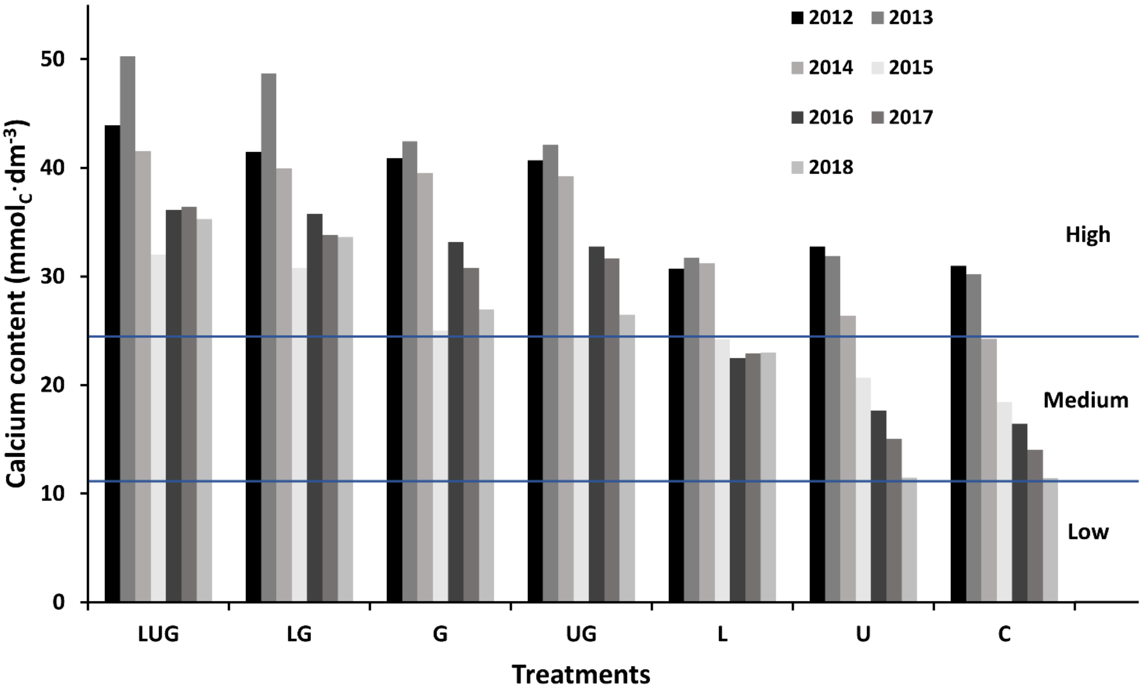

Fig. 2. Soil calcium content at a soil depth of 0 to 20 cm. Study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with cohesive characteristics. Leguminous trees used to supply biomass: *Gliricidia sepium* + *Acacia mangium*. LUG = leguminous, urea and gypsum; LG = leguminous and gypsum; G = gypsum; UG = urea and gypsum; L = leguminous; U = urea; C = control. Horizontal bars represent the critical levels by Hechman (2006).

There was a wider variation in calcium content from year to year in the 20-40 cm layer compared to 0-20 cm layer. In this layer calcium was high only in treatments with gypsum in the third year (Fig. 3). Furthermore, after gypsum and biomass application, calcium contents never been below the medium critical level.

Leguminous biomass alone was able to maintain calcium into or close to medium critical level during all cultivation period. In contrast, in the treatments without biomass or gypsum, calcium content was always low (Fig. 3).

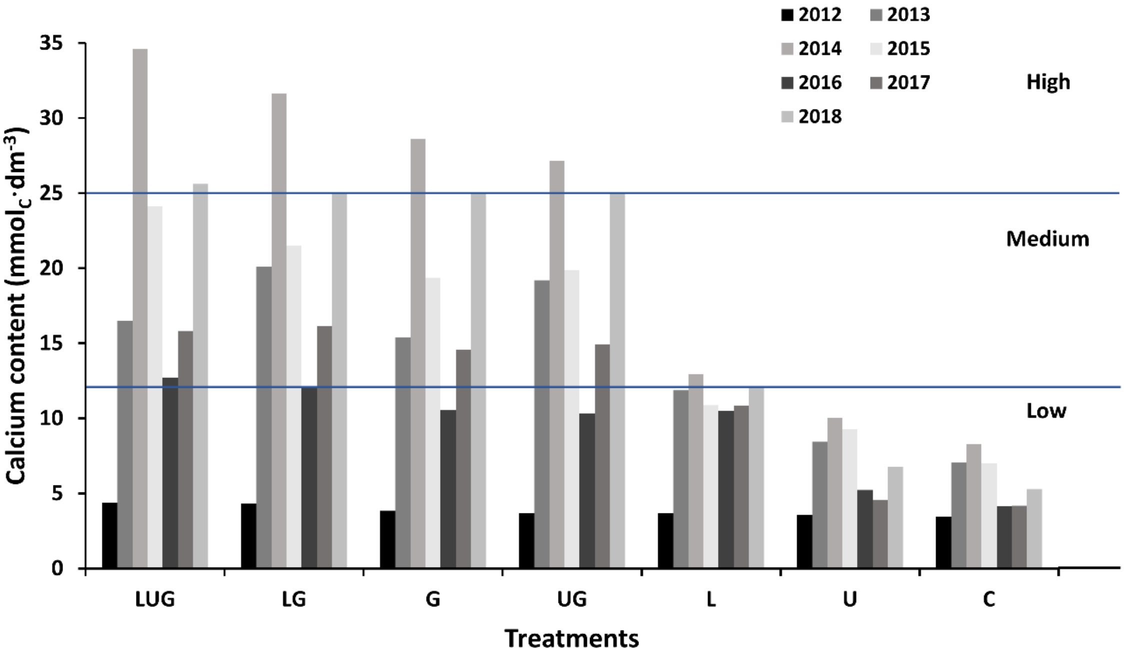

Fig. 3. Soil calcium content at a soil depth of 20 to 40 cm. Study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with cohesive characteristics. Leguminous trees used to supply biomass: Gliricidia sepium + *Acacia mangium*. LUG = leguminous, urea and gypsum; LG = leguminous and gypsum; G = gypsum; UG = urea and gypsum; L = leguminous; U = urea; C = control. Horizontal bars represent the critical levels by Hechman (2006).

According to Prout *et al*. (2020) criteria, combination biomass and gypsum (LUG and LG) improved the 0-10 cm layer by maintaining soil structure in the very good or good level during all years of cultivation (Fig. 4). The biomass effect was greater than the gypsum effect when they are compared isolated. Indeed, soil structure from the biomass treatment (L) was classified in the good level in all evaltuated years, except from 2016, when it was classified in the medium critical level. Soil from gypsum treatment (G) was considered good during the first three years of evaluations, while in the flowing four years it was classified as medium, bad, medium, and bad. Urea application affected positively the soil structure compared to control treatment only in the first year, when it enhanced soil to a particularly good critical level. However, in the last years the soil structure was bad for this treatment. In the control treatment, soil structure was classified in the good critical level for the first three years, while it was consired in the bad critical level for the following years (Fig. 4).

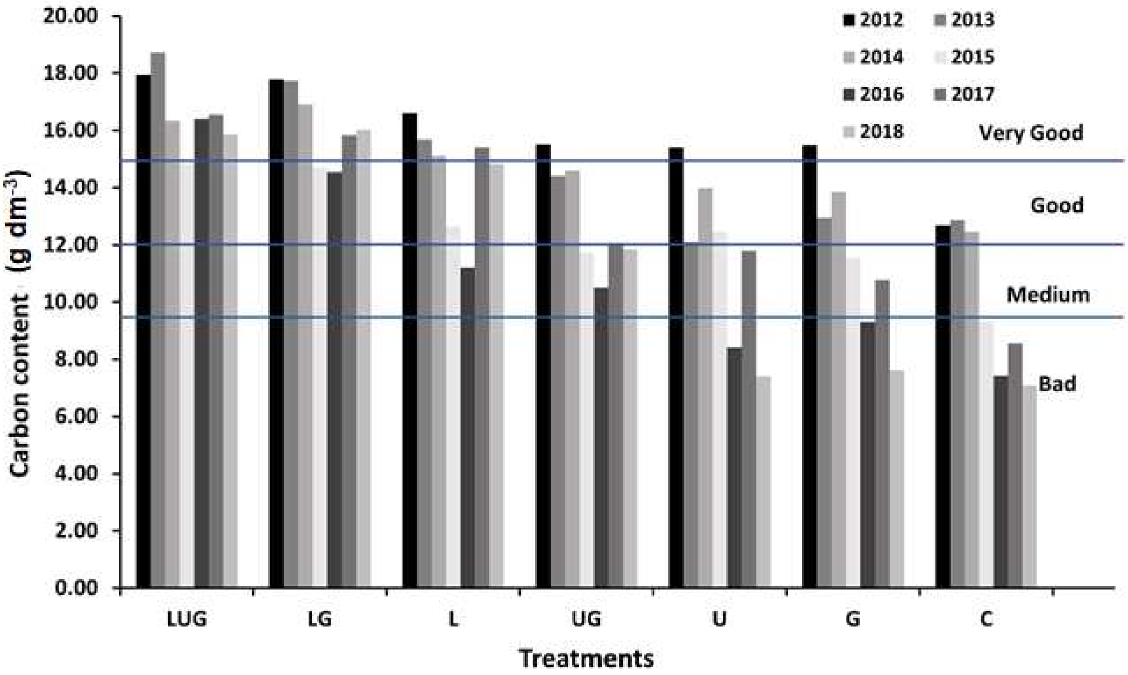

Fig. 4. Soil carbon content at a soil depth of 0 to 10 cm. Study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with

cohesive characteristics. Leguminous trees used to supply biomass: *Gliricidia sepium* + *Acacia mangium*. LUG = leguminous, urea and gypsum; LG = leguminous and gypsum; L = leguminous; UG = urea and gypsum; U = urea; G = gypsum; C = control. Horizontal bars represent the critical levels by Prout et al. (2020).

In the 10-20 cm layer, just in the treatments that combined biomass and gypsum, soil structure was lightly improved (Fig. 5). Thus, in the treatment with biomass, gypsum, and urea (LUG) soil was classified in the medium critical level for the first three, in the fifth and sixth year. In all other years and treatments that did not combine gypsum with biomass, the soil structure was at a bad critical level for that layer (Fig. 5).

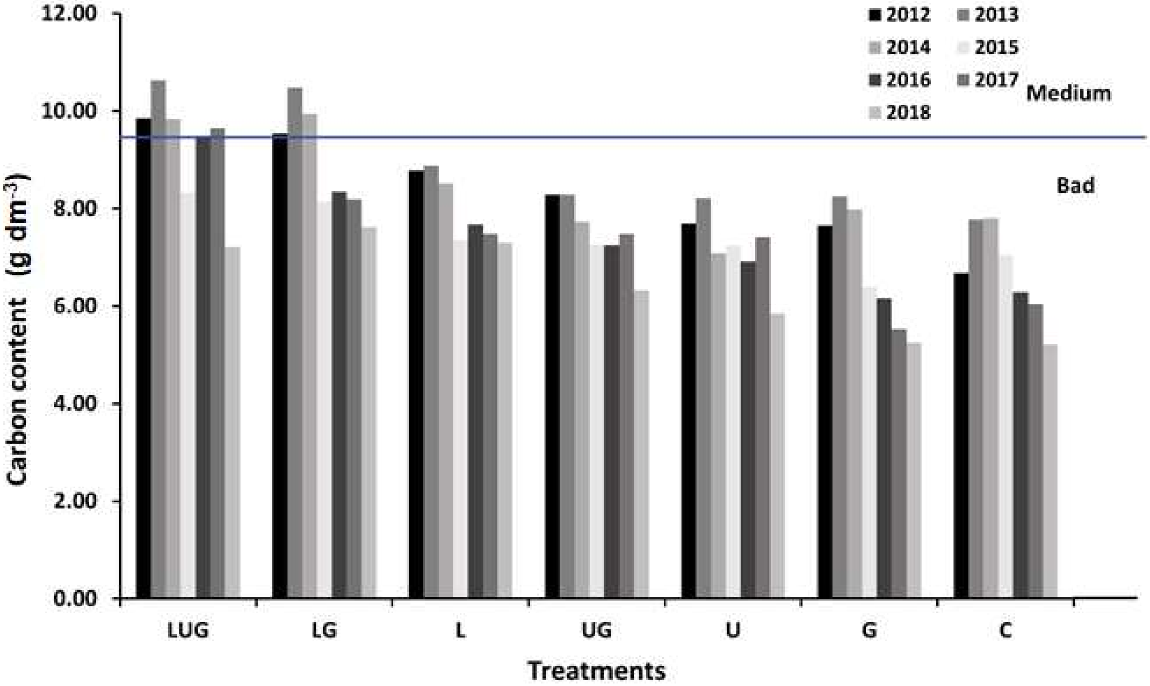

Fig. 5. Soil carbon content at a soil depth of 10 to 20 cm. Study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with

cohesive characteristics. Leguminous trees used to supply biomass: *Gliricidia sepium* + *Acacia mangium*. LUG = leguminous, urea and gypsum; LG = leguminous and gypsum; L = leguminous; UG = urea and gypsum; U = urea; G = gypsum; C = control. Horizontal bars represent the critical levels by Prout et al. (2020).

Regression analysis showed that soil organic carbon was significantly correlated with calcium content ($P < 0.001$, $R^2 = 0.57$), with higher calcium content leading to higher SOC levels (Fig. 6). Most of the data points for calcium are concentrated in low level below of 20 $\text{mmol}_c\ \text{dm}^{-3}$ (Fig. 6).

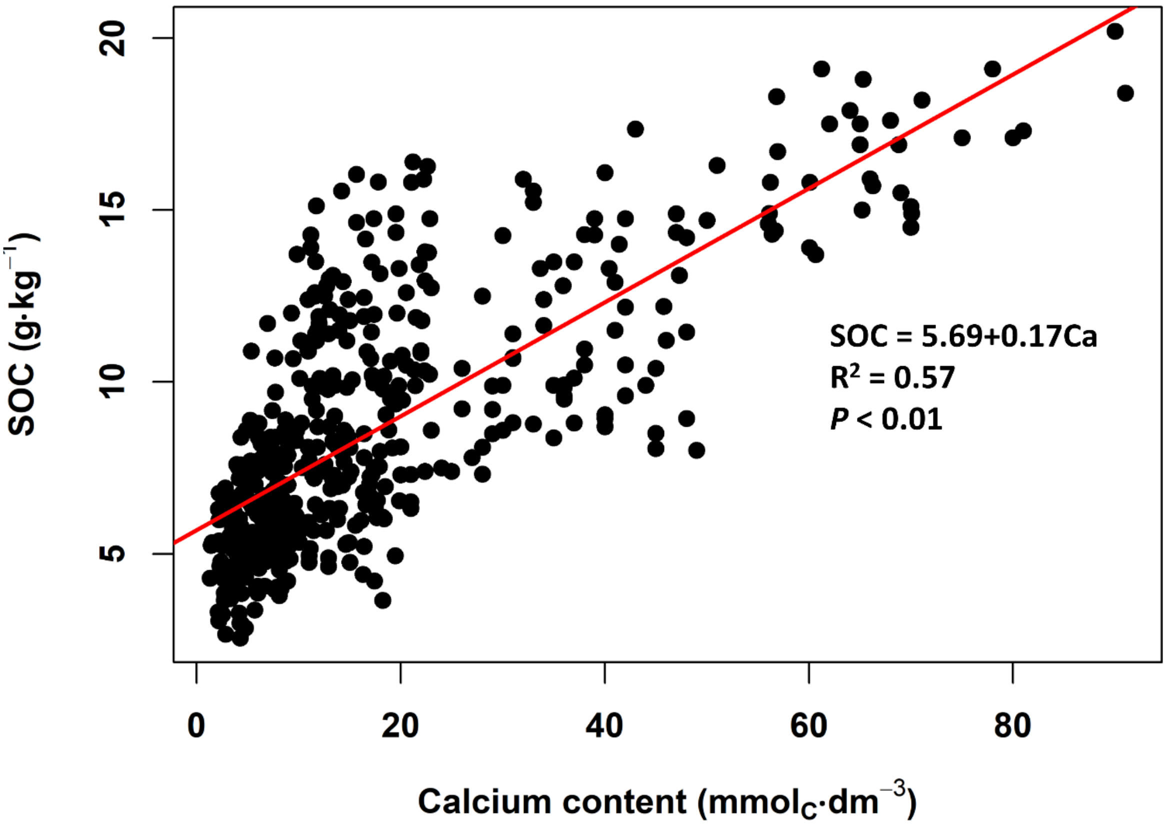

Fig. 6. Soil Organic Carbon (SOC) as a function of Calcium content in a study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with cohesive characteristics. Treatments are derived from the

combination of mulch application (*Gliricida sepium* + *Acacia mangium*) and gypsum: LUG = leguminous, urea and gypsum; LG = leguminous and gypsum; L = leguminous; UG = urea and gypsum; U = urea; G = gypsum; C = control.

Both biomass and gypsum increased soil water retention compared to control. However, soil moisture profile was different between these treatments. Thus, eight days after irrigation, it was possible to verify that biomass effect was greater on the surface layer, while gypsum increased water retention in the 20-40 cm layer (Fig. 7A). When applied together, biomass and gypsum (LG) kept the soil humidity above the critical level of 5% up to 40cm depth. In contrast, the control treatment was not able to conserve humidity above critical level in any layer up to 40 cm depth (Fig. 7A). Six days after irrigation, the soil moisture profile was similar to eight days for all treatments, except to the control. Nervertheless, in any treatment, humidity was higher than the critical level, though it hits the 5% critical level in the control treatment at 40 cm depth (Fig. 7B). The results for soil moisture at four days after irrigation were similar to those obtained at six days after irrigation.

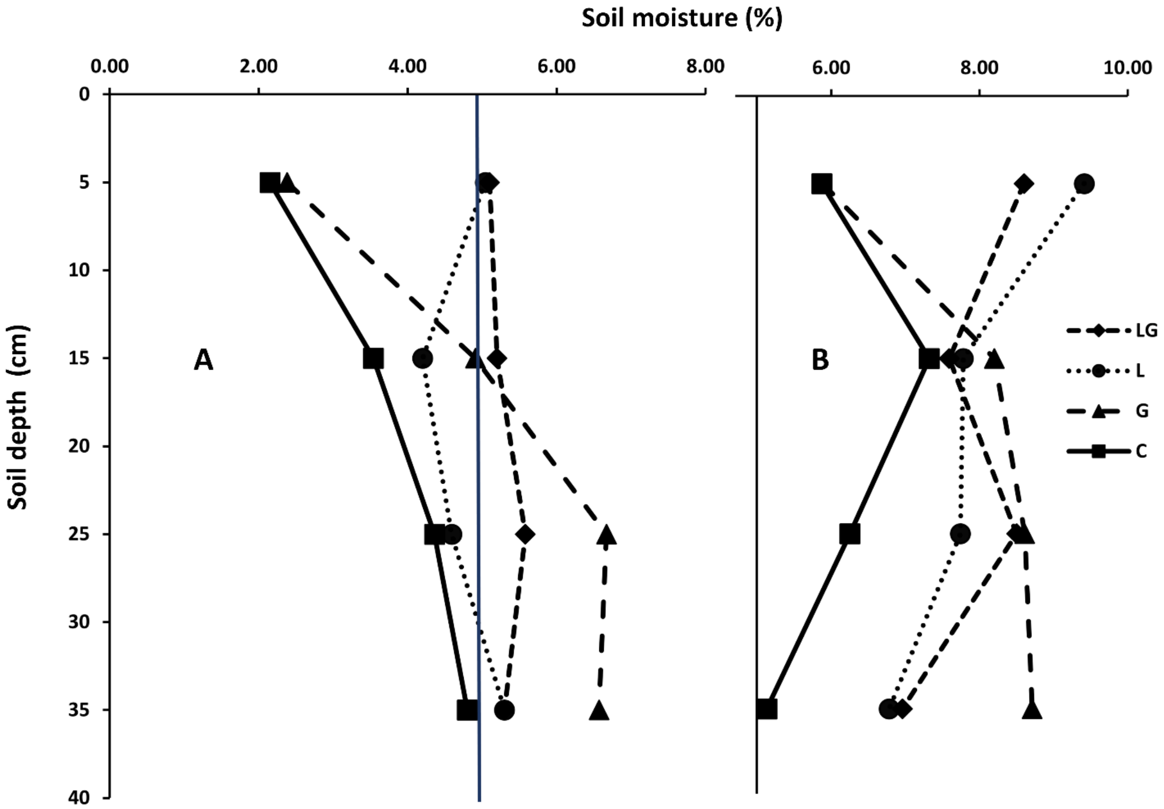

Fig. 7. Soil moisture in 8 days after irrigation (A) and 6 days after irrigation (B) in the 0-40 cm soil deph. Study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with cohesive characteristics. Leguminous trees used to supply biomass: *Gliricidia sepium* + *Acacia mangium*. LG = leguminous and gypsum; L = leguminous; G = gypsum; C = control. Vertical bars represent the critical levels by Moura *et al.* (2009).

Soil penetration strength (SPS) also was reduced by biomass and gypsum applications however, biomass effect was effective just up to 15 cm while gypsum reduced SPS up to 25 cm (Fig. 8). Therefore, in the 10-20 cm layer, eight days after irrigation SPS was above the critical level of 2 Mpa in the treatment with biomass, but in the treatment with gypsum it was below this level up to 30 cm. Four days after irrigation, the 20-30 cm layer was dense in treatment with gypsum and very dense in treatment with biomass.

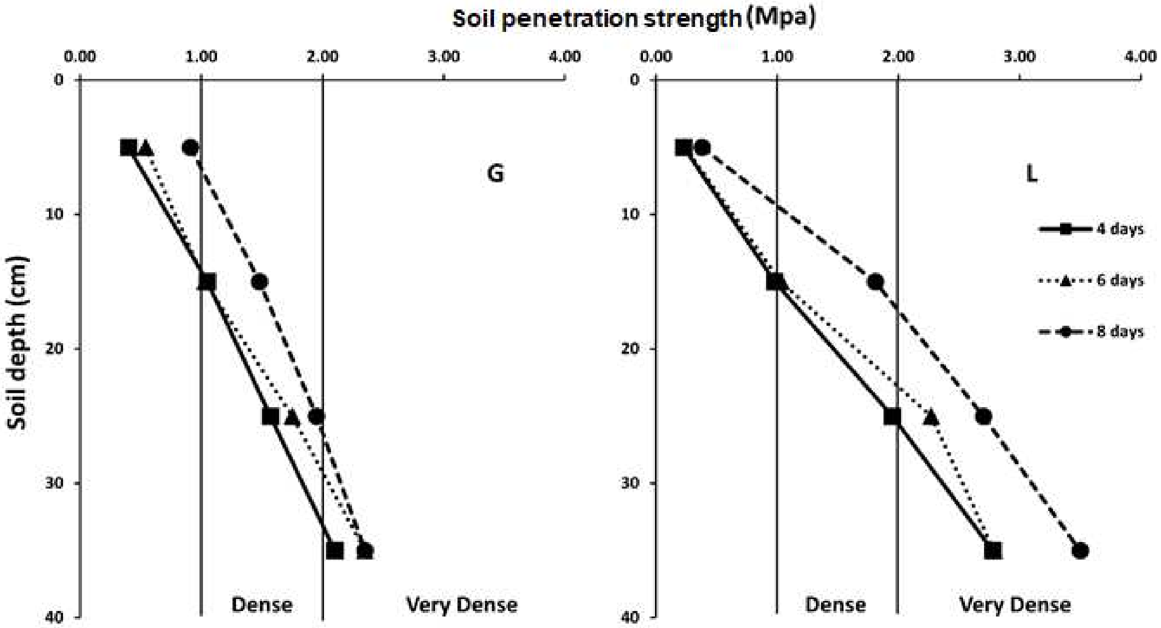

Fig. 8. Soil penetration strength 4, 6 and 8 days after irrigation in 2018 in the 0 – 40 cm soil deph. Study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with cohesive characteristics. Leguminous trees used to supply biomass: *Gliricidia sepium* + *Acacia mangium*. G = gypsum; L = leguminous. Vertical bars represent the critical levels by Hazelton and Murphy (2016).

Effects of biomass and gypsum on SPS are more evident on treatments comprising both components compared to the control. Six days after irrigation, rootable layer was 15 cm in control and 25 cm in LG treatment (Fig. 9). Eight days after irrigation, rootable layer was 20 cm wide in LG treatment and all the layers were dense or very dense in control treatment (Fig. 9).

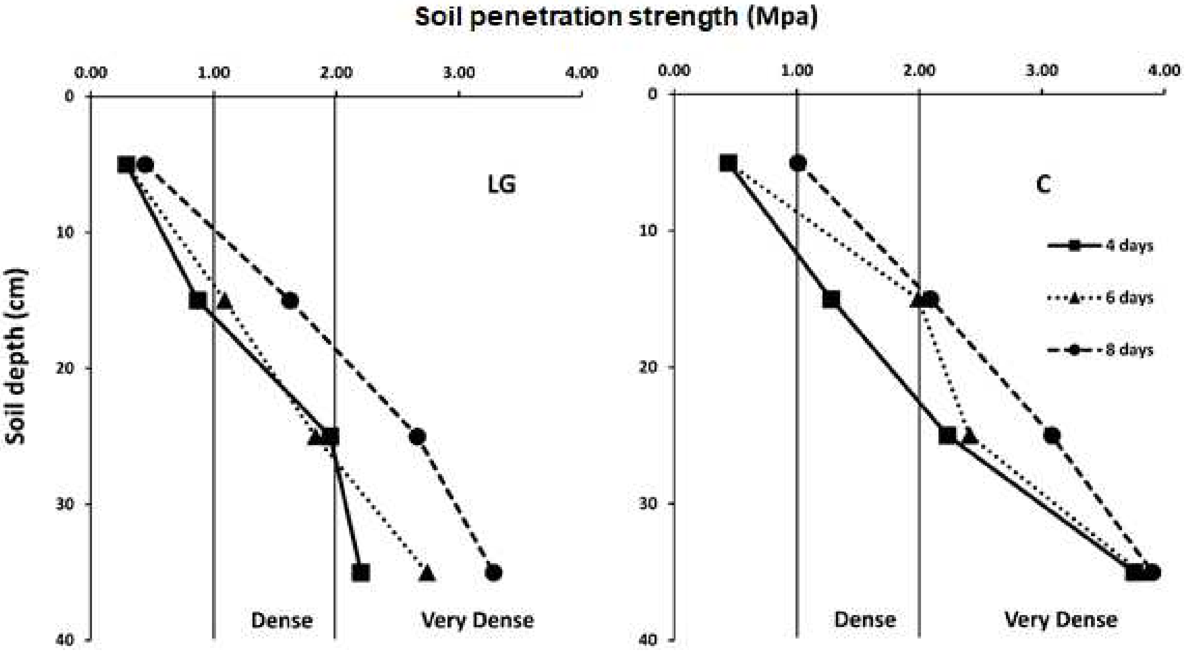

Fig. 9. Soil penetration strength 4, 6 and 8 days after irrigation in 2018 in the 0 – 40 cm soil deph. Study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with cohesive characteristics. Leguminous trees used to supply biomass: *Gliricidia sepium* + *Acacia mangium*. LG = leguminous and gypsum; C = control. Vertical bars represent the critical levels by Hazelton and Murphy (2016).

Maize harvest data showed a positive effect of gypsum and leguminous biomass on grain yield, when compared to urea (U) X gypsum and urea (UG), from 2015 to 2018, and LG X G treatments from 2016 to 2018 (Tabel 1). Effects of leguminous biomass and urea were similar, excepted for the year 2017. Only the treatment combining leguminous biomass, gypsum and urea (LUG) could maintain maize grain yield above six tons per ha in all years, apart from the second one. Thus, in four years maize grain yield in LUG treatment was 30% higher than in U treatment (Table 1).

Table 1. Maize grain yield in a study conducted between 2011 up to 2018 in São Luís, Maranhão - Brazil in a Hapludult Arenic soil with cohesive characteristics.

Grain Yield t. ha^{-1}	**LUG**	**LG**	**L**	**UG**	**U**	**G**	**C**
2011	6,62 a	5,25 bc	5,38 bc	6,37 ab	5,6 b	4,43 c	2,81 d
2012	5,46 a	4,40 b	4,38 b	4,61 ab	4,2 b	3,00 c	2,02 c
2013	6,34 a	5,30 bc	5,70 ab	6,37 a	5,5 ab	4,41 c	2,26 d
2015	6,41 a	6,33 a	5,74 ab	6,95 a	4,33 bc	5,76 ab	3,12 c
2016	6,53 a	5,42 b	4,16 c	5,27 b	4,59 c	3,37 d	2,87 d
2017	6,37 a	4,38 d	4,28 d	5,56 b	4,86 c	3,5 e	3,56 e
2018	6,49 a	5,59 bc	4,83 d	6,19 ab	5,04 cd	2,95 e	2,78 e

LUG = leguminous, urea and gypsum; LG = leguminous and gypsum; L = leguminous; UG = urea and gypsum; U = urea; G = gypsum; C = control. Different letters in the same row indicate differences at the 5% level by Duncan’s test.

Discussion

Application of plant biomass is generally associated only with addition and conservation of SOC (soil organic carbon) explained, most of the time, by biological bias. Gypsum application in tropical soils is usually indicated for being an excellent source of calcium and sulfur, increasing soil aggregation, improving soil physical indicators, promoting SOC increment, neutralizing Al^{3+} , and improving crop productivity (Shainberg *et al.* 1989; Moura *et al.* 2018; Walia *et al.* 2018). The individual and simplistic approach of those effects has long masked the potential of combining legume biomass with gypsum applications in agriculture, especially in the tropics. It is known that high insolation and humidity, environmental conditions commom in humid tropics, stimulate microbial activity and nutrient cycling. Thus, the use of mulch may attenuate the effects of soil cohesion in the humid tropics (Christensen 2000). On the other hand, it has been shown that organic matter can be retained in the solid phase as complexes linked by cations (Whittinghill and Hobbie 2012; Ellerbrok and Gerke 2018).

Moura *et al*. (2020a) observed a strong interaction among cations, added through lime and gypsum, and SOC. The addition of carbon through legume biomass and its interaction with gypsum can promote the formation of bridges between soil organic carbon and calcium (Rowley *et al.* 2018). The bridges between calcium and carbon constitute strong chemical bonds. Numerous studies have focused on organo mineral interactions that delay SOM's turnover due to physical-chemical protection by the association of minerals and maintainance of calcium in the root zone (Von Lutzow *et al*. 2002; Ellerbrock and Gerke 2018).

Critical level consists of the level below which a response to the application of nutrients can be expected, and above which no response from the crop is expected (Heckman 2006). We found that the use of gypsum associated with legumes could conserve adequate calcium critical levels during all the years studied, in the superficial soil layer. In the treatment comprising only chemical fertilization and in the control, the calcium content droped down to deficient from the third year after gypsum application, which may limit crop yield to a certain level. Performance of treatments that include gypsum and legume biomass, mainly LUG and LG, in the critical high calcium level for a longer period of time means that the use of this strategy may retain this nutrient in the soil profile and delay the need for gypsum reapplication to sustain calcium levels in an ideal level and stimulate the maintenance of SOM. Organic matter can be retained in the solid phase as complexes linked by protons and divalent ions, mainly calcium (Whittinghill and Hobbie 2012; Ellerbrock and Gerke 2018). The individual effect of legume biomass, conserving the calcium at a medium level until the last year, may favor farmers with difficulty to acquire fertilizers and gypsum. The shorter effect of applying gypsum individually on critical calcium levels suggests the need to reapply gypsum in a shorter period of time to increase productivity and improve efficiency in harnessing the benefits of this input.

Modification of calcium pools in soil depth, with the maintenance of Ca^{2+} at critical high and medium levels over time in treatments containing gypsum, is explained both by calcium content and by its solubility and percolation in the soil (Shainberg *et al.* 1989). Under similar conditions observed in our study, Moura *et al* (2018) reported that the combination of high rainfall levels and high water infiltration rate in soil can explain the fast downward movement of calcium in the soil profile. Besides that, according to Zaharah and Bah (1999), a rapid initial phase was identified, followed by a much slower one in the patterns of decomposition and release of nutrients in gliricidia. Calcium was the nutrient released more quickly, with the initial phase lasting 6 days, and in the second phase its rate constants were 10 and 8 times greater than its slow phases. This means that the total calcium was released from the biomass when samples from this experiment were collected. In addition, Sena *et al.* (2020) reported higher levels of calcium where gliricidia biomass was applied compared to areas with mombaça grass. Therefore, the lower input of calcium and biomass, and the reduction in the interaction of these two factors is responsible for the drastic drop in calcium levels in the urea and control treatments over the years. In fact, our results suggest that the increase in soil organic carbon and the maintenance of calcium in the root zone were also a consequence of the interaction between calcium and transformed compounds, which occurs in the soil environment created by the application of legume biomass at long-term. Because a high saturation of clay particles with calcium helps the complex organic mineral to remain more flocculated and condensed, in addition to reducing the efficiency of microbial and enzymatic attacks (Baldock and Skjemstad 2000).

Dexter et al. (2008) established that the relationship between SOC and clay content can better clarify soil physical properties than considering these parameters isolated. Based on that and other studies, Prout et al (2020) created an index that provides an adequate mean to monitore SOC. Monitoring critical values of organic matter in soil is essential, due to MOS importance in improving soil indicators, rootability, and viability, especially in tropical soils. For structural soil quality, biomass effect was greater than gypsum effect when compared isolated. However, biomass along with gypsum maintained clay saturation with SOC, which conserved soil structural quality as good or very good during all the years evaluated. This can be explained by the constant carbon input over the years, through legume biomass, associated with SOC stabilization via I. substrate physical separation by decomposers; II. interactions among SOC and cations or minerals, including calcium; III. temperature or humidity incompatible with enzymatic reactions or IV-toxic effects from metals (Rowley *et al.* 2018). According to Feller and Beare (1997), clay saturation with SOC is fundamental for soil structural quality. On the other hand, the lower is SOC content, the lower is aggregate stability (Schaffer *et al.* 2008; Goutal-Pousse *et al.* 2016). According to Tisdall and Oades (1980), for each 0.1% increase in organic carbon, there may be a 2% increase in unstable macroaggregates (> 250 µm in diameter), lead by a greater activity of roots and hyphae. Because soil organic carbon acts as an aggregate formation nucleus, stimulating localized activity of microorganism communities, which excrete extracellular polysaccharides / polymeric substances that adhere to soil particles, which unite them, creating a shell around the nucleus of decomposing SOC and eventually occluding (Chenu and Cosentinuo 2011).

The increase in SOC in urea plots can be attributed to the increase in C sequestered by plant biomass, which returns to soil as crop residue (Aula *et al.* 2016). Nevertheless, this carbon has not been stabilized and accumulated over the years, probably due to the edaphoclimatic conditions inherent to the region, which are unfavorable for organic matter accumulation (Moura *et al.* 2020b). In addition, the close correlation between calcium and organic carbon in soil shown by regression analysis suggests that increased calcium may have a positive effect on the accumulation of carbon derived from biomass.

These results reflected in soil moisture and to soil penetration strength. Applicantion of biomass with gypsum retained water in the soil. The combined effect of legume biomass in soil superficial layers and gypsum action in the deeper layers explains humidity conservation above the critical level up to 40 cm deep in the LG treatment. And the positive results obtained for soil water retention demonstrate the importance of gypsum and mulch components in the tropics. In cohesive soils, widely distributed in the tropics, rooted layer is limited in depth due to low concentration of aggregator elements and SOC, in addition to the increased fine particles. In these cohesive sandy loam soils, water stress days can be counted from four days without rain, but the application of biomass combined to gypsum is may improve the root environment of the soil by increasing the level of calcium and organic matter and by reducing soil resistance to penetration (Moura *et al*. 2012; 2018).

A better soil root environment results from the formation of “ephemeral” structures, capable of increasing flocculation, soil aggregation and root activity (Shepherd *et al.* 2002). Calcium added during the pre-treatment with lime and gypsum interacting with the organic carbon provided by mulch can form bridges among soil particles that create aggregation (Whittinghill and Hobbie 2012). The main mechanisms behind calcium-mediated SOC stabilization are probably related to its ability to bridge negatively charged surfaces; when increased, calcium bridge also positively affects soil structure (Rowley *et al.* 2018). Therefore, there is a greater volume of organic complexes formed among calcium and high molecular weight organic compounds, such as microbial polysaccharides or root mucilages (Erktan *et al*. 2017). It has been shown that these substances easily complex calcium and create structures similar to a gel that binds aggregates. In particular, galacturonic acid, a common root mucilage, which exhibits high affinity with Ca, and links polymeric chains to form an adhesive matrix (Kerchove and Elimelech 2007).

According to Czarnes *et al*. (2000) polygalacturonic acid increases the hydrophobicity of aggregates, thus increasing their stability during the wetting and drying cycles, which can be promising to reduce soil cohesion in the humid tropic, as in this region, the great challenge is to reach and conserve an aggregated soil structure to guarantee proper water movement and infiltration and to sustain that under the continuous impact of rain and drought. As soil compaction increases, roots are physically prevented from stretching in the soil due to oxygen lack, decreasing soil pores size and increasing soil penetration strength (MOSADDEGHI; Mahboubi; Safadoust 2009). Therefore, a pre-treatment of the soil with gypsum and limestone consists of a common practice to improve soil structural stability and reduce soil strength (Moura *et al.* 2018; 2020a).

In this study, we found out that mulch and gypsum can delay the onset of water stress and this reflected in a positive effect on maize grain yield when compared to U x UG and LG x G treatments. These results suggest that mulch and gypsum, applied with urea, can delay the shortage of soil water supply for 3 or 4 days due to improvements in the soil rooting capacity. The rate of root elongation is highly correlated with the strength to uniform soil penetration, so that roots that grow in hard soil are morphologically different from those that grow in friable soil (Passioura 1991). On the other hand, except for year 2017, the equivalence between U and L treatments showed the importance of biomass as green manure in humid tropical conditions, to improve soil moisture and to provide N and SOC. In addition, when comparing LUG and U treatments, the 30% increase in grain yield achieved in LUG treatment suggests that the combined use of green manure, gypsum and synthetic fertilizers is a strategy more interesting to increase maize grain yield than the isolated use of synthetic fertilizers (U) in the humid tropics. This result can help extension workers to switch the slash and burn agriculture to a more sustainable system, showing farmers that the gain in additional productivity will be above 3.0 tons / ha (LUG) when compared to the control. These differences in grain yield can be attributed to two processes: (i) increase in soil rooting capacity, which can lead to greater root growth and (ii) greater availability of N, both positively influenced by the application of biomass and gypsum (Sena et al. 2020). In summary, application of legume biomass associated with gypsum promotes beneficial effects in soil, such as soil water retention, less resistance to soil penetration, greater soil rootability, improved water use efficiency, cation and SOC retention. All this aspects culminated in higher maize productivity.

Conclusions

In cohesive soils showing cohesion structure from the humid tropics, legume biomass and gypsum combination allows the conservation of adequate levels of calcium in the soil, water retention and improved the ephemeral structure of tropical soil, consisting of a simple and profitable strategy to enhance soil rootability and crop productivity that can be used by farmers.

Conflict of interest

The authors declare there are no conflicts of interest.

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CONSIDERAÇÕES GERAIS

CAPÍTULO III

CONSIDERAÇÕES GERAIS

1 – A cobertura do solo e a adubação verde, por meio do uso de biomassa de leguminosas arbóreas, é capaz de fornecer nitrogênio e carbono orgânico e melhorar a umidade do solo, possibilitando redução do uso de fertilizantes, perdas de nutrientes no campo agrícola e menor susceptibilidade a degradação ambiental.

2 - A utilização do gesso diminuiu a resistência à penetração na camada de 20-40 cm de profundidade, o que é capaz de permitir um desenvolvimento radicular mais profundo e aumentar a produtividade das culturas. Contudo, devido ao efeito de lixiviação associado a sua alta taxa de solubilidade, a aplicação de gesso deve ocorrer periodicamente. A necessidade de aplicação pode ser determinada por meio de monitoramento anual e utilização do nível crítico estabelecido por Heckman (2006).

3 - Relações mais estreitas dos íons de cálcio foram encontradas com o carbono orgânico do solo. Essa íntima relação entre as variáveis pode ser um indício de que o cálcio atua como um protetor do COS, possivelmente das frações mais lábeis. O que manteve a estrutura do solo boa ou muito boa em todos os anos avaliados, nos tratamentos que combinaram gesso e biomassa de leguminosas na camada de 0-10 cm de profundidade do solo;

4 - A combinação de biomassa de leguminosas arbóreas com gesso permite a manutenção de níveis adequados de cálcio no solo, melhora a retenção de água e a estrutura efêmera de um solo tropical estruturalmente frágil, constituindo uma estratégia simples a ser utilizada pelos agricultores para aumentar a enraizabilidade do solo e a produtividade do milho.

ANEXO

Normas de Formatação da Revista Soil Research

Author Instructions – Soil Research

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- **Publishing Policies**
- **Peer review**
- **Authorship**
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- **Open access**
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- **Submission procedure**
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- **Use of referencing software**
- **Units**
- **Concentration of ionic species**
- **Exchangeable ions and ion exchange capacity**
- **Electrical conductivity**
- **Enzyme nomenclature**
- **Mathematical formulae**
- **Chemical nomenclature**
- **Microbiological nomenclature**
- **Crop variety pedigrees**
- **Soil classification nomenclature**
- **Statistical evaluation of results**
- **Tables**
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- Include addresses for all authors and an email address for the corresponding author.

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The work should be presented in concise and clear English. The Introduction should not exceed what is necessary to indicate the reason for the work and its essential background. Sufficient experimental detail should be given to enable the work to be repeated. The Discussion should explain the significance of the results in the context of existing knowledge on the topic. An internal institutional review of content and English prior to submission is strongly recommended.

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Manuscripts must be double-spaced throughout and printed on one side of good quality paper. Make the left-hand margin at least 3 cm wide, with lines numbered in the left-hand margin. Place tables, figures, and captions to figures after the text, and number all pages of the manuscript consecutively. Refer to each figure and table in the text.

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The Abstract (preferably less than 200 words) should state concisely the scope of the work and give the principal findings. It should be complete enough for direct use by abstracting services. Acronyms and references should be avoided in the Abstract.

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Acknowledgements

The contribution of colleagues who do not meet all criteria for authorship should be acknowledged. Financial and material support should also be acknowledged. All sources of funding for the research and/or preparation of the article should be listed, and the inclusion of grant numbers is recommended. Authors should declare sponsor names along with explanations of the role of those sources if any in the preparation of the data or manuscript or the decision to submit for publication; or a statement declaring that the supporting source had no such involvement. If no funding has been provided for the research, please include the following sentence: "This research did not receive any specific funding".

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- **Journal article**

  Woelkerling WJ, Irvine LM, Harvey AS (1993) Growth-forms in non-geniculate coralline red algae (Corallinales, Rhodophyta). **Australian Systematic Botany 6**, 277-293.

- **Chapter in a book**

  Andrew CS (1978) Mineral characterisation of tropical forage legumes. In ´Mineral nutrition of legumes in tropical and subtropical soils´. (Eds CS Andrew, EJ Kamprath) pp. 93-111. (CSIRO Publishing: Melbourne)

- **Whole book**

  Simmonds DH (1989) ´Wheat and wheat quality in Australia.´ (CSIRO Publishing: Melbourne)

- **Report/Bulletin**

  Chippendale GM, Wolf L (1981) The natural distribution of **Eucalyptus** in Australia. Australian National Parks and Wildlife Service, Special Publication No. 6, Canberra.

- **Web pages**

  Referencing from web pages is acceptable and should give the author´s names, year of publication and title as for a report, followed by the URL, and access date.

Use of referencing software
If using ´EndNote´ software, you can obtain the style file for this journal at http://www.endnote.com/support/enstyles.asp.

Units
Authors are requested to use the International System of Units (Système International d´Unités) for exact measurements of physical quantities and where appropriate elsewhere. For SI units please use L, mL, µL, year, day, month, h (hour), Bq (not Ci), s (second), min. Centrifuge speeds should be in g not r.p.m. Use the negative index system , e.g. g m^{-2}, kg ha^{-1}, mol m^{-2} s^{-1}.

Concentration of ionic species
When a known ionic charge concentration is referred to, units of moles of charge per m^3 (mol_c/m^3) or moles of charge per L (mol_c/L) should be used. Inclusion of (+) or (-) is not needed; it should be apparent from the context in which the usits are used.

Exchangeable ions and ion exchange capacity
The units of moles of charge per kg (mol_c/kg) or centimoles of charge per kg

($cmol_c/kg$) should be used. The latter has the advantage of being numerically identical to the non-SI, but still widely recognised, milliequivalents per 100 g. Inclusion of (+) or (-) is not needed; it should be apparent from the context in which the usits are used.

Electrical conductivity

The recommended unit is dS/m, but mS/cm is acceptable.

Enzyme nomenclature

The names of enzymes should conform to the Recommendations of the Nomenclature Committee of the IUB on the Nomenclature and Classification of Enzymes as published in \`Enzyme nomenclature 1984´ (Academic Press, Inc., New York, 1984). If there is good reason to use a name other than the recommended name, at the first mention of the alternative name in the text it should be identified by the recommended name and EC number. The Editor-in-Chief should be advised of the reasons for using the alternative name.

Mathematical formulae

Mathematical formulae should be carefully typed with symbols in correct alignment and adequately spaced. Judicious use should be made of the solidus to avoid 2-line mathematical expressions wherever possible and especially in the running text. Each long formula should be displayed on a separate line with at least 2 lines of space above and below. **Equations must be in editable electronic format**, i.e. not inserted as ´pictures´.

Chemical nomenclature

The nomenclature of compounds such as amino acids, carbohydrates, lipids, steroids, vitamins, etc. should follow the recommendations of the IUPAC-IUB Commission on Biochemical Nomenclature. Other biologically active compounds, such as metabolic inhibitors, plant growth regulators, buffers, etc., should be referred to once by their correct chemical name (which is in accordance with IUPAC rules of

Chemical Nomenclature) and then by their most widely accepted common name. For pesticides, the latest issue of ´Pesticides - synonyms and chemical names´ (Australian Government Publishing Service) should be followed. Where there is no common name, trade names or letter abbreviations of the chemical may be used.

Microbiological nomenclature

The names of bacteria should conform to those used in ´Approved list of bacterial names´ (American Society for Microbiology, Washington, DC, 1980). Fungal nomenclature should conform to the International Code for Botanical Nomenclature. The names used for viruses should be those approved by the International Committee on Taxonomy of Viruses (ICTV) and published in the fourth report of the ICTV ´Classification and nomenclature of viruses´, **Intervirology**, 1982, **17** (1-3), 1-199. Synonyms may be added in parentheses when the name is first mentioned. Approved generic (or group) and family names should also be used.

Crop variety pedigrees

The Purdy system (**Crop Science**, 1968, **8**, 405-406) should be followed.

Soil classification nomenclature

Owing to the international scope, as well as local classification, authors should also use internationally recognised nomenclature such as Soil Taxonomy, FAO Unesco, or the World Reference Base for Soil Resources (WRB). For local soil classification the Australian Soil Classification (ASC) (Isbell and NCST 2016) or the New Zealand Soil Classification (Hewitt 1993) would normally be used. The relevant hierarchical level to be used in any of the above schemes will depend on the nature of the scientific study being reported. It would also be appropriate for Australian and New Zealand authors to base their soil morphological descriptions on either The National Committee on Soil and Terrain (2009) (Australian Soil and Land Survey Field Handbook) or Milne **et al.** 1995 (Soil description handbook).

References:

- Hewitt AE (1993) ´New Zealand soil classification.´ Landcare Research Science Series No. 1. 131 pp. (Manaaki-Whenua Press: Lincoln, NZ)
- Isbell RF and National Committee on Soil and Terrain (2016) ´The Australian soil classification.´ 2nd edn (CSIRO Publishing: Melbourne) http://www.publish.csiro.au/pid/7428.htm
- The National Committee on Soil and Terrain (2009) 'Australian Soil and Land Survey Field Handbook'. 3rd edn (CSIRO Publishing: Melbourne) http://www.publish.csiro.au/book/5230/
- Milne JDG, Clayden B, Singleton PL, Wilson AD (1995) ´Soil description handbook.´ Revised edn (Manaaki-Whenua Press: Lincoln, NZ)

Statistical evaluation of results

The design and conduct of experiments must be sufficiently explained that readers can judge for themselves the validity of the results. Details of treatments such as genotype, soil properties, and levels of factors must be matched by adequate description of the field and controlled environment conditions, including the number of sites and years over which the validity of the conclusions is established. Authors should describe how measurements were made and indicate how treatments were assigned to units or blocks, and the number of replicates. When common experimental designs such as randomised block or split-plot designs are used a reference is not necessary, but it is appropriate to cite a reference for little-used methods or designs, in which case the use of these methods should be justified.

The experimental design dictates the proper method of statistical analysis and the basis of assessing the precision of treatment means. The precision achieved should be reported by a standard error of the treatment mean or a coefficient of variation. Wherever possible the assumptions implicit in the analysis should be checked. Treatment comparisons such as the least significant difference (l.s.d.) may be made when the variance ratio (**F** value) is significant, but authors must be aware of the limitations to the use of multiple comparisons. Where treatments have logical structure, as in factorial designs, orthogonal contrasts among treatments should be made. Brief analysis of variance (ANOVA) tables with mean squares and degrees of freedom may be published where, in designs with logical treatment structure, as in factorial designs for instance, they are an efficient way to summarise the relative importance of the various effects. Ultimately, the statistical analyses should highlight the scientific principles embodied in the results.

Tables

Editable tables should be prepared in Word using the 'Table' tool (not tabs), without any hard returns within cells, or can be set up in Excel. Number each table and refer to it in the text (Table 1, Table 2, etc.) in order of appearance. There is no need to add instructions on the placement of tables as long as each table is referred to in the text. Do not provide tables as images.

Table titles should be concise and clear and should fully explain the table. Use sentence case throughout the table. Supporting information relating to the whole table should be placed in the headnote. Any symbols, abbreviations or acronyms used in the table should also be defined in the headnote. Additional information relating to specific cells should be placed as table footnotes using superscript capital letters as identifiers. Symbols for units of measurement should be placed in parentheses beneath the column heading.

Tables should appear at the end of the main document, not within the text. Keep tables as simple as possible, without excessive subdivision of column headings.

Figures

Figures should be supplied as separate files but the captions should be included in the main document (at the end). Refer to each figure in the text (Fig. 1, Fig. 2, etc.), and number each figure according to the order in which it appears in the text. There is no need to add instructions on placement of figures as long as each figure is referred to in the text. If your figure has multiple parts label with (a), (b), (c), etc. and place the labels in the top left of each image where possible. Figure parts can be supplied as separate images if needed. Please make sure all images are supplied are at highest possible resolution.

Format

Where possible, line diagrams (graphs, charts, etc.) should be provided as editable files and prepared using either a graphics or chart/graph program such as MacDraw, Illustrator, CorelDraw, Excel, Sigmaplot, Harvard Graphics or Cricket Graph and files should be saved in one of the following formats: encapsulated PostScript (EPS), Illustrator or Excel (provided the Excel files have been saved with the chart encapsulated in it). The submission of scanned images or illustrations prepared in a paint program, e.g. Photoshop (and PICT and JPEG files) is discouraged, because of the difficulty in making editorial corrections to these files. If illustrations must be created in a paint program, save the file as a TIFF or EPS (these files should be 600 dpi for line drawings and 300 dpi for halftone figures). Photographs can be supplied in the highest resolution possible.

Fonts

Please prepare figures using a standard sans serif font. Arial preferred. Font sizes for main axis labels, part labels should not be more than 8pt. Legends and data points should be 7pt font size where possible. Font should never be smaller than 5pt to ensure readability.

Style

- Use sentence case for text within figures
- Use Australian English spelling (ise, not ize, etc.) throughout
- Use 'and' not '&'
- For ranges in numbers (5–10) or minus signs (–20) please use an en rule rather than a hyphen as this is clearer for the reader.

Graphs

Should be prepared with one main x and y axis line. Grid lines are not required. Line weight of x- and y-axes should be ~1.0 (not below 0.7). State on the axes of a graph what is being measured and give the appropriate units in parentheses. Ensure any symbols/colours used are explained in a legend on the figure, or in the caption. Ensure numbers on axes have the same number of decimal places.

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