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LEVANTAMENTO DE INDICADORES DE QUALIDADE DO SOLO COMO BASE PARA A CONSTRUÇÃO DE UM ÍNDICE DE SUSTENTABILIDADE AGRÍCOLA

ANA LUIZA PRIVADO MARTINS FEITOSA

São Luís – MA
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Tese de doutorado apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Biodiversidade e Biotecnologia da Rede BIONORTE, na Universidade Federal do Maranhão, como requisito parcial para a obtenção do Título de Doutora em Biodiversidade e Conservação.

Orientadora: Alana das Chagas Ferreira Aguiar

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RESUMO

Os atributos do solo podem ser modificados em decorrência das práticas de manejo e dos cultivos, alterando a qualidade edáfica e impactando negativamente a sustentabilidade da atividade agrícola. Visto que o conceito de qualidade é subjetivo, a construção de sistemas de avaliação quantitativos, baseados em indicadores é de suma importância. Este estudo parte da hipótese de que é possível selecionar indicadores de qualidade do solo sob diferentes regimes de fertilização, como base para a elaboração de um índice de sustentabilidade agrícola. O presente estudo teve como objetivo propor indicadores de qualidade do solo sob diferentes regimes de fertilização a serem utilizados em um Índice de Sustentabilidade Agrícola (ISA). A área experimental está situada no município de Brejo, estado do Maranhão, Brasil. Foram instalados dois experimentos com cultivo em aleias de leguminosas arbóreas, cujos galhos foram posteriormente podados para utilização nos tratamentos com leguminosas. Um experimento era correspondente à Leucena (*Leucaena leucocephala*), e o outro, à Gliricidia (*Gliricidia sepium*). A área entre as linhas das leguminosas foi dividida em parcelas em um desenho de blocos casualizados (DBC). A área com Leucena foi dividida em 24 parcelas, com 4 repetições e 6 tratamentos, os quais foram os seguintes: nitrogênio (N), leucena (L), nitrogênio + leucena (N + L); ácido húmico + leucena (AH + L); ácido húmico + nitrogênio (AH + N) e ácido húmico + nitrogênio + leucena (AH + N + L). A área com Gliricidia foi dividida em 32 parcelas, com 4 repetições e 8 tratamentos, os quais foram os seguintes: potássio (K), gliricídia (G), ácido húmico (AH), ácido húmico + potássio (AH + K), potássio + gliricídia (K + G), ácido húmico + gliricídia (HA + G), ácido húmico + potássio + gliricídia (AH + K + G) e solo descoberto (SD). Cada parcela foi cultivada com milho (*Zea mays* L.) para obtenção da produtividade dos grãos. Atributos biológicos e químicos foram utilizados nesta pesquisa. A fauna do solo foi utilizada como indicador biológico e foi coletada através de armadilhas do tipo “pitfall”. Foram determinadas a abundância total, dominância, riqueza, índice de diversidade de Shannon–Wiener e índice de equitabilidade de Pielou da fauna edáfica. Para obtenção de dados químicos, amostras de solo foram coletadas com um trado nas profundidades de 0–5 cm, 5–10 cm e 10–20 cm. Acidez potencial, pH, carbono orgânico do solo (COS), fósforo disponível, potássio, cálcio e magnésio trocáveis, capacidade de troca catiônica (CTC), soma de cátions (SC) e saturação por bases (V%) foram determinados. Foram realizadas análises de componentes principais (ACPs) para correlacionar atributos biológicos e químicos do solo com a produtividade de grãos de milho. Foi sugerido um ISA baseado nos indicadores utilizados neste estudo, cujas ponderações foram obtidas de acordo com os resultados das ACPs. Esta pesquisa indica que atributos biológicos e químicos da qualidade edáfica são sensíveis a mudanças nos regimes de fertilização do solo e que esses atributos podem ser associados com a produtividade de grãos de milho, podendo ser utilizados como indicadores da qualidade do solo na composição de um Índice de Sustentabilidade Agrícola.

Palavras-chave: Indicadores; Qualidade do solo; Índice; Sustentabilidade agrícola; Análise de componentes principais.

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ABSTRACT

Soil attributes can be modified because management practices and crops, changing edaphic quality and negatively affecting the sustainability of agricultural activity. Since the concept of quality is subjective, the construction of quantitative assessment systems based on indicators is very important. This work is based on the hypothesis that it is possible to select soil quality indicators under different fertilization regimes, as a basis for the elaboration of an agricultural sustainability index. The present study aimed to propose soil quality indicators under different fertilization regimes to compose an Agricultural Sustainability Index (ASI). The experimental area is located in the municipality of Brejo, state of Maranhão, Brazil. Two experiments were carried out with alley crop using legume, of which the pruning was used in the treatments with legume. One of experiments corresponded to Leucena (*Leucaena leucocephala*), and the other to Gliricidia (*Gliricidia sepium*). The area between the legume lines was divided into plots in a randomized block design. The area with Leucaena was divided in 24 plots, with 4 replicates and 6 treatments, which were nitrogen (N), leucaena (L), nitrogen + leucaena (N + L); humic acid + leucaena (HA + L); humic acid + nitrogen (HA + N) and humic acid + nitrogen + leucaena (HA + N + L). The area with Gliricidia was divided into 32 plots with 4 replicates and 8 treatments, which were potassium (K), gliricidia (G), humic acid (HA), humic acid + potassium (HA + K), potassium (K + G), humic acid + gliricidia (HA + G), humic acid + potassium + gliricidia (HA + K + G) and uncovered soil (US). Each plot was cultivated with maize (*Zea mays* L.) to obtain grains yield. Biological and chemical attributes were used in this research. Soil fauna was used as biological indicator and was collected through pitfall traps. The total abundance, dominance, richness, Shannon-Wiener diversity index and Pielou equitability index of edaphic fauna were determined. Soil samples were collected at depths of 0–5 cm, 5–10 cm and 10–20 cm to obtain chemical data. Potential acidity, pH, soil organic carbon (SOC), available phosphorus, exchangeable potassium, calcium and magnesium, cation exchange capacity (CEC), sum of base cation (SBC) and base saturation (BS) were determined. Principal component analyzes (PCA) were performed to correlate soil biological and chemical attributes with maize grains yield. An ASI was suggested based on the indicators used in this study, whose weights were obtained on the PCAs results. This research indicates that biological and chemical attributes of soil quality are sensitive to changes in soil fertilization regimes and that these attributes can be associated with maize grains yield and can be used as indicators of soil quality in the composition of an Agricultural Sustainability Index.

Keywords: Indicators; Soil quality; Index; Agricultural sustainability; Principal component analysis.

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1 INTRODUÇÃO GERAL

Visto que o solo é considerado um recurso natural multifuncional, diversas definições têm surgido ao longo do tempo (LOZADA, 2015). De qualquer forma, pode-se dizer que ele consiste em um sistema constituído por uma combinação de fatores bióticos e abióticos. Doran e Jones (1996) definem o solo como um elemento essencial da biosfera, de fundamental importância para a produção alimentar. Segundo a *Soil Science Society of America* (SSSA), o solo é um material orgânico ou mineral que não foi consolidado e está presente na camada superficial da Terra, sobre o qual as plantas terrestres podem crescer naturalmente (USDA, 2018). Ele é um dos mais importantes constituintes do ambiente natural, desempenhando funções ambientais, econômicas e sociais de extrema importância. Essas funções fornecidas pelo solo podem ser separadas em ecológicas (produção de biomassa, reserva gênica e proteção do meio ambiente e de seres humanos) e não ecológicas (fonte de matérias-primas, base física de atividades humanas e patrimônio geogênico e cultural) (BLUM, 2005; DROBNIK et al., 2018; SAFAEI et al., 2019).

Diante da importância desse sistema, sua qualidade deve ser preservada. Nesse contexto, Karlen et al. (1997) defendem que a qualidade do solo (QS) consiste simplificadamente na capacidade que ele possui de funcionar e que essa capacidade pode ser entendida de diferentes formas, de acordo com a função do solo a ser considerada. Assim sendo, D'Hose et al. (2014) destacam a grande influência da QS no contexto agrícola, colaborando com a produtividade dos cultivos e a saúde das plantas.

Apesar da extrema relevância da QS para a produção agrícola, Chaer (2001) ressalta que a própria intensificação da agricultura tem causado a degradação do solo no mundo todo. Ele destaca que essa degradação significa que o solo reduziu sua capacidade de produzir bens e serviços, tanto qualitativamente quanto quantitativamente. De acordo com Aparicio e Costa (2007) e Silva et al. (2015), uma das maiores alterações humanas no ambiente global é de fato o sistema agrícola. Sabe-se que o século XX foi marcado por um grande incremento na agricultura, sendo que a partir de 1960 a agricultura brasileira efetivamente se inseriu no contexto do desenvolvimento do país. A adoção do pacote tecnológico chamado Revolução Verde permitiu a implantação em larga escala de sistemas monoculturais, com emprego intensivo de fertilizantes e pesticidas, além de proporcionar a abertura de um imenso mercado de máquinas, sementes e insumos agrícolas (AGUIAR & MONTEIRO, 2005). Esse crescimento da produção ocorria, segundo Horlings e Marsden (2011), a nível mundial. Contudo, de acordo com Gliessman (2009), as técnicas, inovações, práticas e políticas que permitiram aumentos na produtividade também minaram a sua base.

Com a busca pelo incremento na produção de alimentos, a dependência cada vez maior de pesticidas e fertilizantes levou a graves danos ambientais (WANI et al., 2017), dentre estes, ao ambiente edáfico. Nesse contexto, Niero et al. (2010) explicam que os atributos do solo podem ser modificados em decorrência das práticas de manejo e dos cultivos, alterando a QS e impactando negativamente a sustentabilidade ambiental e econômica da atividade agrícola.

Entendendo-se essa realidade, surge a necessidade de se avaliar a QS. De acordo com Karlen et al. (2008), essa avaliação permite alertar os usuários desse recurso sobre problemas que estão ocorrendo ou que poderão ocorrer. Tal mecanismo pode servir como ferramenta para monitoramento da sustentabilidade dos sistemas agrícolas (FRANZLUBBERS & HANEY, 2006). A *National Research Council* (1993) já ressaltava há décadas atrás a relevância de se avaliar a qualidade edáfica para aprimoramento da sustentabilidade e como instrumento para a tomada de decisões.

Para Karlen et al. (1997), Franzlubbers e Haney (2006) e Niero et al. (2010), deve-se ter o cuidado de realizar essa avaliação de acordo com a função do solo a ser tomada como base. No contexto da produção agrícola, Chaer (2001) e Niero et al. (2010) ressaltam ainda que a qualidade do ambiente edáfico pode ser medida através de atributos associados à sua eficiência em favorecer o crescimento e o desenvolvimento de raízes, em disponibilizar nutrientes aos vegetais e em proporcionar estabilidade estrutural ao solo. Chama-se a atenção para o fato de que esses atributos não podem ser medidos diretamente, havendo a necessidade de selecionar indicadores. Para Franzlubbers e Haney (2006), os próprios atributos consistem em indicadores.

Nesse sentido, Chaer (2001) destaca a possibilidade de práticas de manejo, como por exemplo, a fertilização, causarem efeitos negativos no solo. Segundo Shukla et al. (2006) e Drobnik et al. (2018), elas podem ser avaliadas por meio da utilização dos indicadores de QS, os quais podem ser físicos, químicos ou biológicos. Knoepp et al. (2000) e Purakayastha et al. (2019) esclarecem que os indicadores respondem eficientemente a diferentes práticas de manejo. Para Arshad e Martin (2002) e Muñoz-Rojas (2018), indicadores-chave devem ser estabelecidos para avaliação da qualidade edáfica, com o objetivo de alcançar a sustentabilidade. Chaer (2001) ressalta a importância de uma avaliação sistemática do ambiente edáfico, devido à sua complexidade. Para ele, visto que o conceito de qualidade é subjetivo, a construção de sistemas de avaliação quantitativos, baseados nesses indicadores é de suma importância.

Diante disso, existe a necessidade de que esses indicadores sejam quantificados e integrados em um índice. A utilização de índice e de indicadores assume grande relevância, pois segundo Siche et al. (2007), eles funcionam como instrumentos que informam a condição do sistema avaliado, revelando a situação do momento. De acordo com Verona (2010), um índice é considerado uma manipulação matemática de determinadas mensurações com o objetivo de simplificar esses dados, podendo ser formado por vários tipos de indicadores de diferentes temáticas. Indicadores e índices são, portanto, ferramentas bastante úteis para medição da qualidade do solo e da sustentabilidade, pois consistem em informações que facilitam a compreensão de dados.

Segundo Valle e Carrasco (2018), alguns pesquisadores têm realizado estudos de avaliação da qualidade do solo e das práticas de manejo, utilizando indicadores e/ou índices para essa finalidade. No Brasil, podem-se destacar os seguintes estudos: Carneiro et al. (2009), os quais avaliaram os efeitos de sistemas de manejo e uso do solo sobre indicadores físicos, químicos e biológicos em Goiás; Niero et al. (2010), cuja pesquisa utilizou uma avaliação visual de indicadores do solo para o estabelecimento de um índice de qualidade edáfico, visando avaliar a sustentabilidade de práticas de manejo do solo no estado de São Paulo; e Freitas et al. (2017), os quais analisaram comparativamente a qualidade do solo, utilizando atributos químicos e físicos, sob diferentes sistemas de uso e manejo também no estado de São Paulo. No estado do Maranhão, entretanto, não foi registrada a utilização de indicadores e/ou índices para a avaliação da QS.

A população mundial continuará aumentando, tornando a produção alimentar cada vez mais urgente (HORLINGS & MARSDEN, 2011), é relevante a utilização de indicadores e índices para avaliação da qualidade ambiental e da sustentabilidade sob diferentes práticas de manejo do solo. Para Askari e Holden (2014), um dos principais medidores de sustentabilidade agrícola é a produtividade do cultivo. Levando-se em consideração que não há no Maranhão estudos referentes à temática em questão, a presente pesquisa é de extrema urgência.

Este estudo partiu da hipótese de que é possível utilizar indicadores de qualidade do solo sob diferentes regimes de fertilização, como base para a elaboração de um índice de sustentabilidade agrícola. Dessa forma, objetivou-se propor indicadores da qualidade do solo sob diferentes regimes de fertilização a serem utilizados em um Índice de Sustentabilidade Agrícola. Assim, objetivou-se especificamente (1) investigar indicadores biológicos e químicos da qualidade do solo, (2) relacionar indicadores biológicos e químicos da qualidade do solo com a produtividade de grãos de milho, (3) atribuir pesos aos indicadores e (4) sugerir um índice de sustentabilidade agrícola.

2 REVISÃO BIBLIOGRÁFICA

2.1 Indicadores de qualidade do solo

O tema “qualidade do solo” tem levantado efetivamente o interesse dos pesquisadores desde o fim da década de 1980 (MENDES et al., 2009). Na década de 1990 foi publicado o relatório intitulado *“Soil and Water Quality – An Agend for Agriculture”*, no qual a qualidade do solo foi idealizada considerando-se sua função tanto nos ecossistemas naturais quanto nos agroecossistemas, pois historicamente essa qualidade estava relacionada à produtividade (ARAÚJO et al., 2012).

A QS tem sido definida de diferentes formas ao longo dos últimos anos. Em 1995, surgiu uma definição bem simplificada de que qualidade do solo é a capacidade que ele possui de funcionar. Esse termo pode também ser interpretado, de uma maneira mais ampla, como a capacidade de um tipo específico de solo funcionar, dentro dos limites naturais ou manejados dos ecossistemas, para sustentar a produtividade vegetal e animal, manter ou melhorar a qualidade da água e do ar e sustentar a saúde e a habitação humana (KARLEN et al., 1997). Franzlubbers e Haney (2006) citam ainda, no mínimo, quatro outras definições, sendo que cada uma delas reflete uma perspectiva diferente do uso e valor dos solos, e a maioria liga QS a algum uso específico. Entretanto, para Araújo et al. (2012), apenas uma pequena parte da qualidade do solo é abrangida, independentemente da definição que se utiliza. Eles ressaltam que essa qualidade depende também da utilidade do solo para os seres humanos, sendo muito influenciada pelas práticas antrópicas.

Apesar do termo “qualidade do solo” estar bem estabelecido, alguns pesquisadores ainda preferem utilizar a expressão “saúde do solo”. Isso ocorre pelo fato de entenderem que o uso da palavra “saúde” retrata que o solo é um sistema vivo e dinâmico que possui funções executadas por uma diversidade de organismos vivos, o que requer manejo e conservação. Embora haja alguma discussão sobre qual dessas expressões utilizar, grande parte dos especialistas prefere utilizá-las como sinônimos (DORAN & ZEISS, 2000).

Entretanto, independente do termo a ser utilizado, Knoepp et al. (2000) e Vezzani e Mielniczuk (2009) esclarecem que propriedades químicas, físicas e biológicas do solo se combinam, formando a qualidade do ambiente edáfico e contribuindo para o seu funcionamento. Fidelis et al. (2016) destacam que mudanças nessas propriedades têm sido causadas pela intensificação do uso do solo, o que possibilita a avaliação da QS por meio de indicadores.

Para Vezzani e Mielniczuk (2009), o uso de indicadores da QS auxilia na manutenção das funções do solo e da produtividade local. Nesse sentido, Stefanoski et al. (2016) esclarecem que esses indicadores geralmente são selecionados de acordo com o objetivo de cada estudo. Bünemann et al. (2018) apontam que essa seleção precisa se basear nas interações entre indicadores e funções do solo, enquanto Araújo et al. (2012) defendem que ela depende da finalidade da utilização de determinado solo e das características de cada ambiente.

Bünemann et al. (2018) ressaltam que ao longo do tempo, os objetivos, os métodos e a abordagem geral da avaliação da QS têm sido modificadas. Para Stefanoski et al. (2016), os conceitos e as ferramentas no campo da pesquisa estão ainda sendo elaborados, embora já exista uma variedade de artigos sobre essa temática. Araújo et al. (2012) destacam que selecionar um atributo como indicador dessa qualidade pode ser muito trabalhoso. De fato, definir quais indicadores deverão ser considerados na avaliação da qualidade do solo constitui um grande desafio.

Para Franzlubbers e Haney (2006) e Santos e Maia (2013), esse tipo de avaliação deve usar poucos indicadores, ou seja, o mínimo de dados possível, os quais caracterizem de maneira eficiente as funções chave do solo em questão. Esses autores esclarecem, nesse sentido, que tempo e recurso financeiro são limitados, impedindo que todas as funções potenciais do solo em uma localização sejam estudadas. Bünemann et al. (2018) também destacam a utilização de poucos indicadores devido a esses fatores e também para evitar a colinearidade.

De acordo com Casalinho et al. (2007) e Bueno et al. (2018), deve-se escolher um conjunto mínimo de indicadores que sejam, dentre outras coisas, fáceis de avaliar e aplicáveis em escalas diferentes, tenham a capacidade de integrar, se adequem ao nível de análise da pesquisa e sejam sensíveis às variações de manejo. Eles devem ainda participar de processos ecossistêmicos e ter uma base de dados acessíveis.

Para Doran e Zeiss (2000) e Vezzani e Mielniczuk (2009), qualquer indicador de saúde do solo ou QS deve atender aos seguintes critérios:

1. Ser sensível a variações no manejo;
2. Ser bem correlacionado com as funções benéficas do solo;
3. Ser útil para elucidação de processos ecossistêmicos;
4. Ser compreensível e útil para gestores de terras;
5. Ser fácil e barato de medir.

Franzlubbers e Haney (2006) admitem que a qualidade edáfica ainda é uma temática muito complexa, pois os solos fornecem diversos serviços importantes para a humanidade e existem em uma grande variedade de tipos. Para Karlen et al. (1997), visto que eles possuem grandes diferenças naturais, a quantificação dessa qualidade parece mesmo difícil de ser realizada. Além disso, existe a grande dificuldade em selecionar indicadores adequados para locais com usos variados, principalmente quando se tenta combinar varáveis químicas, físicas e biológicas do solo. Mesmo em uma escala espacial reduzida, a utilização de indicadores para classificar a QS não é tarefa fácil. Cabe ainda ressaltar que definir essa qualidade local, removida de um ecossistema maior, é ainda uma tentativa de avaliação incompleta (KNOEPP et al., 2000).

Apesar disso, a avaliação da QS com indicadores variados é muito válida. Nesse sentido, Bünemann et al. (2018) ressaltam que na maioria das publicações, há no mínimo um indicador de cada categoria (química, física e biológica). Melo et al. (2009) destacam que muitas avaliações realizadas com a participação de agricultores para o manejo da QS utilizam indicadores abióticos e bióticos simples. Eles ressaltam que o uso de organismos do solo atende a muitos critérios para indicadores do manejo sustentável da terra. Nesse sentido, Bünemann et al. (2018) ressaltam que o indicador mais sensível da qualidade edáfica é a biota do solo, pois ela possui alta responsividade a mudanças nas condições ambientais. Os atributos químicos, por sua vez, demonstram maior variação que as propriedades físicas, exceto o pH (CAMARGO, 2016). Além disso, os indicadores químicos e biológicos são muito conectados (JAMIL et al., 2016), o que levou à priorização destes no presente estudo. Cabe lembrar que a escolha dos parâmetros de medição deve considerar também os recursos disponíveis (CAMARGO, 2016).

2.1.1 Indicadores biológicos

Segundo Bünemann et al. (2018), os organismos que vivem no ambiente edáfico executam um papel essencial no funcionamento do solo. O entendimento sobre a importância desses seres já ocorre há algumas décadas. Doran e Zeiss (2000) destacam que em 1998 ocorreu nos Estados Unidos uma conferência intitulada “Saúde do Solo: Manejando o Componente Biológico da Qualidade do Solo”, a fim de proporcionar a conscientização sobre a importância e utilidade dos organismos do solo como possíveis indicadores da qualidade/saúde edáfica.

Os indicadores biológicos do solo ainda são pouco difundidos. Por outro lado, os indicadores que convencionalmente enfatizam a fertilidade são mais comumente utilizados. Nesse sentido, é importante esclarecer o quanto as propriedades biológicas também são relevantes para o bom funcionamento do solo (ARAGÃO et al., 2012).

Bünemann et al. (2018) realizaram um levantamento das pesquisas que tratavam sobre avaliação da QS através de indicadores e averiguaram que apenas 40% desses estudos utilizaram bioindicadores. Segundo eles, o uso desses organismos para essa finalidade é pequeno a nível mundial e indicadores mais específicos da biota ainda requerem muitos conhecimentos específicos. Seguindo essa realidade, no cenário brasileiro há também uma grande demanda por pesquisas utilizando a biota na avaliação da qualidade edáfica (MENDES et al., 2009).

Bagliano (2012) ressalta que os bioindicadores de ambientes edáficos são sensíveis às variações físicas e químicas do solo e estão relacionados à diversidade, abundância e atividade de organismos, podendo levar a mudanças fisiológicas. Além disso, esses organismos satisfazem a maioria dos critérios para avaliação da QS. Eles são sensíveis a práticas de manejo agrícola e são bem associados às funções benéficas do solo e do ecossistema, por exemplo. Organismos visíveis, como insetos, minhocas e fungos são indicadores úteis para os agricultores, pois são de mais fácil compreensão e sua utilização leva a custos mais baixos para avaliação, apesar da necessidade de um bom conhecimento taxonômico (MELO et al., 2009).

Segundo Mendes et al. (2009), as plantas, os micróbios e a fauna do solo podem ser utilizados para medição da qualidade edáfica. Para Bagliano (2012), as minhocas destacam-se em se tratando de organismos da fauna do solo utilizados como bioindicadores. Nesse sentido, ressalta-se também a importância de pequenos vertebrados, protozoários e algas, os quais colaboram com o processo de decomposição orgânica, ciclagem de nutrientes, infiltração de água no solo, aeração, dentre outros (MAHILUM, 2004; BARETTA et al., 2011). Para Errouissi et al. (2011), a fauna do solo interfere em processos biológicos, na estrutura do solo e na ciclagem de nutrientes. De acordo com Rousseau et al. (2012), macroinvertebrados também possuem um grande potencial como bioindicadores edáficos, mas as condições em que eles podem ser utilizados devem ser esclarecidas.

Nesse contexto, é importante enfatizar que a qualidade edáfica é bastante afetada por artrópodos do solo direta e indiretamente, dependendo tanto do tamanho quanto da atividade específica desses organismos. Eles podem interferir inclusive aumentando o espaço entre os poros do solo e revolvendo a mistura dos seus horizontes (KNOEPP et al., 2000; ERROUISSI et al., 2011).

Apesar disso, Elliott (1997) esclarece que em diferentes ecossistemas, os bioindicadores não necessariamente representam os mesmos aspectos. Além disso, ocorrem variações temporais e espaciais que dificultam as medições da fauna edáfica. Contudo, a presença de uma espécie e a análise de sua população ainda podem ser utilizadas para medição da QS utilizando-se amostragens estratificadas do solo, o que diminui essa problemática (KNOEPP et al., 2000).

Recentes descobertas voltadas para a ciência do solo, principalmente no campo da biologia, garantem novas formas de avaliação edáfica no futuro. Elas prometem a utilização de indicadores baseados não somente na diversidade fenotípica, como também na diversidade genotípica da comunidade. O uso do DNA e RNA apresenta grande potencial para execução de avaliações mais baratas, rápidas e informativas da biota e dos processos do solo do que as metodologias mais tradicionais (BÜNEMANN et al., 2018).

Entretanto, na presente pesquisa foram utilizados apenas a composição, a abundância e os índices de diversidade da fauna do solo, como indicadores biológicos da qualidade edáfica, pois proporcionam uma boa resposta às mudanças ambientais, além de também apresentarem um baixo custo de avaliação. Para captura da fauna do solo, utilizaram-se armadilhas do tipo “pitfall”, também conhecidas como armadilhas de queda. Elas consistem em copos de plástico enterrados ao nível do solo, dentro dos quais é adicionada uma solução para matar e conservar animais capturados. Esse tipo de armadilha proporciona a captura de organismos tanto da meso quanto da macrofauna, de maneira rápida e barata (SILVA & AMARAL, 2013).

2.1.2 Indicadores químicos

A avaliação química do solo ajuda na elaboração de mecanismos corretivos, uso e manejo, pois consiste em um instrumento essencial para a caracterização edáfica (LOZADA, 2015). Através dessa avaliação pode-se analisar o grau de vulnerabilidade dos solos de forma que as ações corretivas estejam de acordo com o sistema de produção agrícola (OROZCO et al., 2015).

Para Araújo et al. (2012), a disponibilidade de nutrientes (potássio, magnésio e cálcio trocáveis, fósforo e micronutrientes), assim como a relação entre eles, são de extrema importância para avaliação da QS entre os diferentes sistemas de manejo. Nesse sentido, Lozada (2015) destaca, além desses atributos, a acidez, a capacidade de troca catiônica e a saturação de bases. Em levantamento realizado por Bünemann et al. (2018), os indicadores mais citados para essa finalidade foram pH, carbono orgânico do solo, fósforo disponível e potássio, cálcio e magnésio trocáveis. Askari e Holden (2014) ressaltam que o carbono orgânico, o pH e a capacidade de troca catiônica são considerados muito importantes para a produtividade do cultivo. De acordo com Jamil et al. (2016), os mesmos indicadores químicos que são usados para solos florestais são também utilizados para solos agrícolas.

Diante dessas informações, os atributos abaixo foram utilizados como indicadores químicos no presente estudo:

- Potencial hidrogeniônico (pH): corresponde ao índice de concentração de íons hidrogênio no solo, sendo utilizado para determinar se o solo é básico (pH maior que 7), ácido (pH menor que 7) ou neutro (pH igual a 7). Exerce grande influência sobre a absorção dos nutrientes pela planta, pois controla a solubilidade destes (GOMES & FILIZOLA, 2006).
- Acidez potencial: é essencial para prever a capacidade de troca catiônica a pH 7 (TEIXEIRA et al., 2017). Além disso, ela caracteriza o poder tampão de acidez do solo e sua estimativa exata representa a quantidade de bases que são necessárias para neutralizar o solo ou a necessidade de calcário do solo. Seus componentes são a acidez trocável e a titulável, o que vai depender do extrator utilizado (KAMINSKI et al., 2002).
- Carbono orgânico do solo (COS): possui efeito sobre a estrutura da planta e a disponibilidade de água para ela, sendo que baixos valores podem inclusive afetar a produtividade do cultivo (GOMES & FILIZOLA, 2006). Consiste em um dos principais parâmetros químicos da qualidade do solo, influenciando a porosidade do solo, reações de troca gasosa e relações hídricas. Influencia na liberação e disponibilidade de nutrientes, pois exerce importante função em processos biológicos e químicos (SCHOENHOLTZ et al., 2000).
- Macronutrientes: são representados pelo fósforo, potássio, cálcio e magnésio e suas concentrações costumam influenciar consideravelmente na produtividade do cultivo (GOMES & FILIZOLA, 2006). Eles são absorvidos pela planta em maior quantidade que os micronutrientes (RONQUIM, 2010).
- Capacidade de troca catiônica (CTC): corresponde à quantidade de cátions trocáveis por unidade de peso do solo seco (JAMIL et al., 2016). Consiste na medida de cargas negativas do solo e indica a necessidade de ligação ou liberação de elementos nesse ambiente (LOZADA, 2015). Para sua obtenção é realizado o seguinte cálculo: $Ca^{2+} + Mg^{2+} + K^{+} + H^{+} + Al^{3+}$ (RONQUIM, 2010).
- Soma de bases trocáveis (SB): corresponde à soma dos teores de cátions permutáveis, com exceção do H^{+} e Al^{3+}. Seu valor é obtido por meio do seguinte cálculo: $Ca^{2+} + Mg^{2+} + K^{+}$ (RONQUIM, 2010).
- Porcentagem da saturação de bases (V%): é influenciada pela acidez e varia de acordo com o tipo de solo (LOZADA, 2015). Ela consiste na abundância relativa de

nutrientes base no complexo de troca e é expressa em porcentagem (SCHOENHOLTZ et al., 2000). Consiste em um ótimo indicativo das condições gerais de fertilidade do solo e é obtida pela fórmula seguinte: 100 x SB / CTC (RONQUIM, 2010).

Esses atributos podem servir tanto como indicadores da QS como também indicadores das necessidades nutricionais do cultivo (CAMARGO, 2016).

2.2 Regimes de fertilização, qualidade do solo e produtividade do cultivo

Práticas de manejo do solo correspondem a ações realizadas com o objetivo de manter ou melhorar a QS, a fim de que a produção vegetal seja garantida (AGUIAR et al., 2014). O regime de fertilização, por sua vez, consiste em uma das práticas de manejo do solo mais importantes. Assim, é de fundamental relevância que a fertilização seja de fato investigada.

Cabe ainda conceituar a fertilidade edáfica, a qual consiste na capacidade que o solo tem de liberar elementos essenciais à planta. Contudo, visto que a capacidade de absorção dos nutrientes varia entre as diversas espécies de planta, este conceito apresenta restrições. Ainda assim, é preciso a aquisição de práticas de manejo que conservem essa fertilidade ou a restaurem (CAMARGO, 2016). Nesse sentido, Carneiro et al. (2009) ressaltam que a variação da fertilidade e sua avaliação são de extrema relevância para o estabelecimento de um manejo que almeje a sustentabilidade do sistema.

No contexto dos diferentes regimes de fertilização do solo, destaca-se a discussão sobre a utilização de fertilizantes inorgânicos e/ou orgânicos. Assim, Giacometti et al. (2013) destacam que o desenvolvimento de sistemas agrícolas mais adequados, capazes inclusive de prevenir a degradação do solo, poderia ser obtido por meio de avaliações do impacto gerado pela aplicação de fertilizantes orgânicos ou inorgânicos, ou ainda, pela aplicação combinada de ambos.

Diante disso, cabe enfatizar a importância da utilização de indicadores de QS que detectem mudanças causadas pelo manejo (CASSIMO, 2016). Além de indicadores físicos, químicos e biológicos presentes no solo, para Vezzani e Mielniczuk (2009) e Bosarge (2015), a produtividade do cultivo também consiste em um poderoso indicador dessa qualidade, pois ajuda na visualização dos atributos que interagem no solo. Contudo, eles esclarecem que a produtividade não deve ser utilizada como única medida para essa finalidade.

Para que haja o desenvolvimento de uma ferramenta eficiente de avaliação da QS, Bai et al. (2018) acreditam que deve ser realizada uma análise dos efeitos de práticas de manejo sobre os indicadores do solo, pois, segundo eles, há associação entre ambos. Gomes

(2016) destaca que práticas agrícolas, como o tipo de fertilização, afetam as diversas propriedades edáficas. Vezzani e Mielniczuk (2009), por sua vez, reforçam a ideia de que a QS é influenciada por práticas de manejo. Devido a isso, Aragão et al. (2012) enfatizam que deve haver o monitoramento dos atributos do solo.

Nesse contexto, a avaliação da produtividade de grãos possibilita o conhecimento dos próprios fatores que a limitam. Além disso, alcançar uma alta produtividade requer otimização dos atributos do solo relacionados ao desenvolvimento vegetal (SANTI, 2007).

O presente estudo utilizou a produtividade do milho pelo fato desse cereal consistir em um dos mais importantes cultivos do mundo, o qual funciona como ótimo reservatório energético. Além disso, essa cultura ocorre em todas as regiões brasileiras e é adotada tanto por pequenos, quanto por médios e grandes agricultores em sistemas de produção variados (RIBEIRO, 2014).

2.3 Indicadores e índices em avaliações de sustentabilidade agrícola

Os indicadores são fragmentos de informação que resumem as características ou destacam o que está acontecendo em um sistema. Eles são muitas vezes um ajuste entre precisão científica e as informações disponíveis a um custo razoável. Uma combinação matemática de um conjunto de indicadores é mais frequentemente chamada de "índice" ou "indicador composto" (SAISANA & TARANTOLA, 2002; SOBRAL et al., 2011).

O indicador composto une fontes de informação variadas, ou seja, indicadores diversos, os quais são medidos, fornecendo assim, um resumo do sistema que não pode ser diretamente medido. A saúde do ambiente, por exemplo, não pode ser diretamente medida, pois nenhum indicador mostra completamente a saúde do ecossistema. Por isso, recorre-se à combinação de múltiplos indicadores (DOBBIE & DAIL, 2013). Nesse caso, Bünemann et al. (2018) destacam o possível uso de árvores de decisão, o que pode orientar a seleção de indicadores específicos.

De acordo com Saisana & Tarantola (2002), existem várias etapas para a construção de um índice (Figura 1).

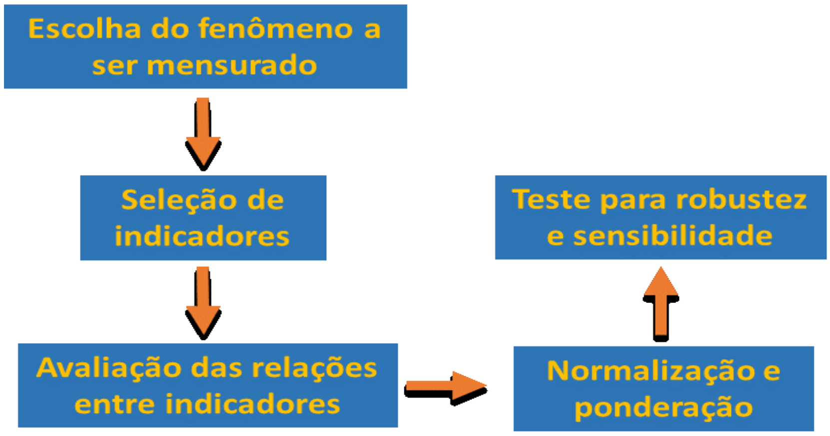

Figura 1. Etapas para a construção de um índice (SAISANA & TARANTOLA, 2002)

A última etapa, entretanto, tem sido realizada em outra pesquisa em grande parte dos estudos, devido principalmente a questões financeiras. Ressalta-se também que qualquer índice útil deve se basear em uma metodologia sólida e ser de fácil entendimento por não-especialistas (SAISANA & TARANTOLA, 2002).

De acordo com Silva (2007), essa ferramenta é essencial para orientar quais decisões serão acatadas, sendo que a necessidade de desenvolvê-la está expressa na Agenda 21 (documento que versa sobre como planejar sociedades sustentáveis). Para Lozada (2015), é preciso que índices constituídos por indicadores sejam utilizados na avaliação do recurso, a fim de que informações sobre sua condição atual e tendências futuras sejam conhecidas.

No contexto do solo, a avaliação da qualidade deve ter o objetivo de detectar tendências de mudanças dos indicadores ao longo do tempo. Dessa forma, eles devem ser agrupados em um índice. Ainda assim, a identificação de indicadores mensuráveis que possam ser usados na análise das práticas de manejo do solo é uma tarefa desafiadora. Soma-se a isso, o difícil trabalho de escolher uma forma de avalição que seja simples e confiável (RAMOS, 2013).

É importante destacar que análises das propriedades químicas, físicas e biológicas de maneira isolada ainda são predominantes nas avaliações edáficas. Entretanto, é a interação destes atributos que determina a QS. Diante dessa realidade, é essencial esclarecer que para que transformações nessa qualidade ocorram, tanto a nível local quanto a nível global, pesquisadores e agricultores devem utilizar ferramentas integrativas, como um índice. Este deve se adaptar às condições locais ou regionais (GRANATSTEIN & BEZDICEK, 1992).

Bünemann et al. (2018) ressaltam, nesse sentido, que caso as funções do solo estudadas tenham importância diferenciada, deve-se utilizar algum tipo de ponderação para o cálculo do índice. Ramos (2013) destaca o quanto essa ferramenta é importante tanto para controlar, quanto para fiscalizar e monitorar a QS sob diferentes sistemas de manejo. Para Verona (2010), indicadores e índices são ferramentas indispensáveis na avaliação de agroecossistemas.

Índices e indicadores relacionados à qualidade e à sustentabilidade constituem alternativas válidas e importantes para descrever os sistemas, mas que precisam considerar seu verdadeiro significado e alcance. O mais importante é que eles já são vistos como padrões utilizados nas decisões políticas, estratégicas e empresariais de alguns países, sob a premissa ambiental (SICHE et al., 2007). Nesse sentido, é possível a utilização de indicadores de qualidade edáfica que possam ser reunidos em um índice que estime a sustentabilidade agrícola.

De acordo com Saisana e Tarantola (2002), o uso de índices para avaliação da sustentabilidade oferece grandes vantagens, destacando-se as seguintes: podem resumir realidades complexas e multidimensionais; são mais fáceis de interpretar do que uma bateria de muitos indicadores separados; podem avaliar o progresso das explorações agrícolas, sistemas agrícolas, regiões e países ao longo do tempo; reduzem o tamanho de um conjunto de indicadores, sem perder a base das informações; e facilitam a comunicação com o público em geral. Segundo Gallopin (1996), um bom índice de sustentabilidade deve considerar também a viabilidade financeira.

Medir a sustentabilidade agrícola é um procedimento essencial para proporcionar a melhoria na agricultura e, nesse contexto, desenvolver e aperfeiçoar esses métodos constitui um desafio (DONG et al., 2015). Para Doran e Zeiss (2000), a sustentabilidade agrícola é determinada pela QS. Embora Gómez-Limón & Sanchez-Fernandez (2010) defendam o carácter multidimensional do desenvolvimento sustentável, Qiu et al. (2007) afirmam que a qualidade do solo ainda constitui o melhor medidor da sustentabilidade agroecológica. Para Cassimo (2016), a QS é garantida dependendo da sustentabilidade da atividade agrícola.

Nesse contexto, cabe ressaltar que o desenvolvimento de alternativas metodológicas que visam a avaliação da sustentabilidade é relativamente recente, apresentando, por isso, problemas conceituais e algumas lacunas. Vários indicadores, por exemplo, têm sido concebidos para aplicação em uma escala nacional ou macrorregional, dificultando a sua aplicação no contexto local (COSTA, 2010). Para Sabiha et al. (2016), a dimensão ambiental da sustentabilidade agrícola é muito importante para as economias em desenvolvimento, apesar de consistir em um grande desafio a construção de uma metodologia adequada que avalie essa sustentabilidade. Nesse sentido, Freitas et al. (2012) chama atenção para o fato de que as práticas de manejo mais apropriadas podem ser identificadas por meio da utilização de índices.

Laroca et al. (2018) destacam a produtividade do cultivo como de extrema importância no processo de avaliação da QS. De acordo com Juhos et al. (2016), demonstrar a associação entre as propriedades do solo e a produtividade agrícola é essencial para o desenvolvimento de um índice. Entretanto, Granatstein e Bezdicek (1992) já previam que unir um conjunto de avaliações dos atributos do solo correlacionando com objetivos de produtividade em um único índice seria desafiador. Diante disso, uma atenção mais rebuscada deve ocorrer na fase de montagem do índice.

2.4 Técnica multivariada e uso de indicadores

A QS deve ser avaliada e monitorada por meio dos seus atributos, os quais consistem em indicadores da qualidade. Esses indicadores, por sua vez, devem ser selecionados para que se obtenham os atributos mais significativos (CAMARGO, 2016). Nesse sentido, um importante instrumento que pode ser utilizado tanto para seleção quanto para ponderação é a técnica multivariada. A aplicação desta pode gerar classificações e interpretações do uso do solo mais sintetizadas, o que proporciona melhores orientações para um planejamento agrícola mais eficiente (RAMOS, 2013).

Sabe-se que a origem da maioria dessas técnicas ocorreu na segunda metade do século 20. Entretanto, os avanços computacionais têm aprimorado ainda mais a estatística multivariada em diversas áreas. Esse importante instrumento indica diferenças e estabelece relações entre os atributos e/ou tratamentos analisados, sendo, portanto, de grande importância na avaliação das informações obtidas (CRUZ-CASTILHO et al., 1994; CARNEIRO et al., 2009).

Uma das técnicas de estatística multivariada mais utilizada é a ACP (análise de componentes principais) (CAMARGO, 2016). Segundo Bünemann et al. (2018), grande parte dos avaliadores da qualidade do solo a utilizam para que o montante dos dados seja reduzido. De fato, ela diminui o total de variáveis a poucos componentes principais. Através de uma rotação ortogonal dos eixos originais, são criados novos eixos, tendo o primeiro deles a máxima variância, enquanto o segundo possui o máximo de variância restante, e assim sucessivamente. Essas variâncias são dadas pelos autovalores, dos quais são escolhidos os de maiores valores. Dessa forma, os aspectos mais importantes podem ser selecionados em um subespaço com menos dimensões (BUCHER, 2002).

Por meio desse instrumento, o conjunto de variáveis é convertido de um espaço n-dimensional para um espaço bi ou tridimensional, passando a constituir uma combinação linear de um conjunto de variáveis (indicadores). Uma correspondência alta entre um determinado indicador e um componente resultará em um peso absoluto alto deste indicador neste componente, de forma que um conjunto similar de pesos entre dois ou mais indicadores indicará correlação entre eles (STEMBERG, 1999; CHAER, 2001).

Para Juhos et al. (2016), a ACP realiza uma redução razoável da dimensão total, sendo, portanto, os seus fatores razoavelmente interpretáveis, podendo revelar relações entre manejo, atributos do solo e produtividade do cultivo. Nesse sentido, Ramos (2013) sugere que a própria qualidade do solo é melhor mensurada utilizando-se para isso vários indicadores do que indicadores individualmente. Nesse contexto, segundo ele, a análise multivariada proporciona uma forma mais robusta e abrangente de unir os indicadores de QS para avaliar efeitos do manejo, por exemplo. Stemberg (1999) ressalta que ferramentas multivariadas são bem adequadas quando existem muitas interações entre as variáveis estudadas, como se esperaria no solo. Essa análise pode ser realizada não somente para a seleção de indicadores a serem utilizados em um índice, como também para a ponderação, com atribuição de pesos mais elevados aos indicadores mais significativos.

Várias pesquisas de avaliação agrícola têm sido publicadas nos últimos anos, as quais aplicaram a ACP na seleção e/ou ponderação de indicadores. Dentre estes, destacam-se a nível internacional as seguintes: Sharma et al. (2005), os quais empregaram a ACP com o objetivo de selecionar manejos apropriados, indicadores chave de QS e a ponderação desses indicadores na Índia; Armenise et al. (2013), cujo estudo se baseou na seleção e ponderação de atributos através da ACP no Mediterrâneo, como base para o desenvolvimento de um IQS (índice de qualidade do solo); e Chen et al. (2013), os quais selecionaram indicadores de QS e compararam a ponderação utilizando ACP com outros métodos no nordeste da China.

No Brasil, destacam-se as seguintes pesquisas: Melloni et al. (2008), cujo estudo avaliou a QS em diferentes coberturas florestais e de pastagens em Minas Gerais, utilizando ACP para seleção dos indicadores, mas não para ponderação; Freitas et al. (2014), os quais selecionaram atributos químicos de QS no nordeste do estado de São Paulo, em uma área com floresta nativa, outra com cultivo de cana-de-açúcar e outra de reflorestamento com espécies nativas, utilizando essa análise; e Stefanoski et al. (2016), cuja pesquisa utilizou três critérios para seleção de indicadores de QS em diferentes sistemas de manejo no cerrado piauiense, destacando-se, dentre estes, a ACP, a qual também foi utilizada para atribuição de pesos. No estado do Maranhão, entretanto, não têm sido realizadas pesquisas sobre essa temática.

2.5 Área de estudo e desenho experimental

A área objeto do presente estudo está situada no município de Brejo, leste do estado do Maranhão, Brasil (Figura 2). Essa cidade é localizada no trópico úmido brasileiro, onde os solos são predominantemente de baixa fertilidade natural, elevada acidez, alta umidade, drenagem deficiente (DIAS FILHO, 1983) e, muitas vezes, apresentam um excesso de lixiviação. Devido aos grandes riscos de erosão e alagamento, Serrão e Falesi (1977) destacam que o manejo das culturas nessas regiões tropicais é mais complexo do que em regiões subtropicais e temperadas.

Dias-Filho e Andrade (2005) destacam que o trópico úmido brasileiro praticamente se confunde com a área da Amazônia Legal (AL), pois ambas ocorrem nos mesmos estados. Entretanto, eles esclarecem que muitos locais do Brasil que não estão dentro dos limites da AL também possuem clima tropical úmido.

A área experimental do estudo ocorreu no povoado Acampamento (3º38' de latitude sul e 42º58' de longitude oeste). A pluviosidade do local varia anualmente de 1200 mm a 1400 mm em média. A temperatura média anual é superior a 27ºC, com máximas de 38°C e mínimas de 21°C. O solo da área é classificado como "Arenic Hapludult" de acordo com *Soil Survey Staff* (2010), apresentando topografia plana (inclinação < 1%). A caracterização das propriedades do solo foi realizada em janeiro de 2015 na profundidade de 0 a 20 cm, através da qual o solo foi definido como de classe textural arenosa com as seguintes características: pH 4.4 em 0.01 M $CaCl_2$; C orgânico 15.5 g kg^{-1}; acidez potencial 4.7, CEC 7.9 $mmol_{(c)}$ dm^{-3}; Ca 2.6, Mg 0.5, K 0.1 $mmol_{(c)}$ dm^{-3}; P 3.7 g dm^{-3} (resina); e saturação de bases 40.2%.

Figura 2. Área de estudo (Município de Brejo, Maranhão, Brasil).

No ano de 2012 foram instalados dois experimentos com cultivo em aleias, cada um com uma espécie de leguminosa arbórea. Leucena (*Leucaena leucocephala*) foi cultivada em uma área de 960 m², enquanto Gliricidia (*Gliricidia sepium*) foi cultivada em uma área de 1.280 m². Ambas foram semeadas no espaçamento de 4,0 m entre linhas e 0,5 m entre plantas. Em janeiro de 2015, foi realizada a poda das leguminosas e a pesagem dos seus galhos, para separação da matéria verde a ser utilizada nos tratamentos com leguminosa. No mesmo período, as áreas entre as linhas das leguminosas foram divididas em parcelas de 4,0 m x 10 m em um desenho em blocos casualizados (DBC), da seguinte forma:

- Área com Leucena (24 parcelas: 6 tratamentos e 4 repetições): 133 kg ha^{-1} de ureia, como fonte de nitrogênio (N); 15 t ha^{-1} de leucena (L); 133 kg ha^{-1} de ureia + 15 t ha^{-1} de leucena (N + L); 500 l ha^{-1} de ácido húmico + 15 t ha^{-1} de leucena (AH + L); 500 l ha^{-1} de ácido húmico + 133 kg ha^{-1} de ureia (AH + N) e 500 l ha^{-1} de ácido húmico + 133 kg ha^{-1} de ureia + 15 t ha^{-1} de leucena (AH + N + L) (Figura 3.a). Todos os tratamentos receberam 120 kg ha^{-1} de P_2O_5, 60 kg ha^{-1} de K_2O e 25 kg ha^{-1} de $ZnSO_4$. Essas doses foram definidas de acordo com o resultado das análises de solo.
- Área com Gliricidia (32 parcelas: 8 tratamentos e 4 repetições): 78 kg ha^{-1} de KCl, como fonte de potássio (K), 15 t ha^{-1} de gliricídia (G), 500 l ha^{-1} de ácido húmico

(AH), 500 l ha^{-1} de ácido húmico + 78 kg ha^{-1} de KCl (AH + K), 78 kg ha^{-1} de KCl + 15 t ha^{-1} de gliricídia (K + G), 500 l ha^{-1} de ácido húmico + 15 t ha^{-1} de gliricídia (HA + G), 500 l ha^{-1} de ácido húmico + 78 kg ha^{-1} de KCl + 15 t ha^{-1} de gliricídia (AH + K + G) e solo descoberto (SD) (Figura 3.b). Todos os tratamentos receberam 120 kg ha^{-1} de P_2O_5, 60 kg ha^{-1} de N e 25 kg ha^{-1} de $ZnSO_4$. Essas doses foram definidas de acordo com o resultado das análises de solo.

Em março de 2015 as áreas foram cultivadas com milho (*Zea mays* L.), variedade QPM BR 473. Cada parcela experimental foi constituída por 166 plantas dispostas em cinco fileiras, espaçadas por 0,8 m entre si e 0,3 m entre plantas.

N+L	N	HA+L	L	HA+N+L	HA+N	**B1**
N	L	HA+L	HA+N	N+L	HA+N+L	**B2**
HA+N	L	HA+N+L	N	N+L	HA+L	**B3**
N+L	N	HA+L	L	HA+N	HA+N+L	**B4**

4 m; 10 m

a

HA	HA+G	HA+K+G	SD	K	K+G	HA+K	G	**B1**
HA+K+G	HA+G	HA+K	HA	SD	K+G	G	K	**B2**
HA+G	HA	HA+K	SD	HA+K+G	G	K	K+G	**B3**
K+G	HA+K	HA+G	HA+K+G	HA	G	SD	K	**B4**

4 m; 10 m

b

Figura 3. Área experimental com Leucena (a) e com Gliricidia (b). B: Bloco.

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CAPÍTULO 1

Prospecção científica sobre índices de sustentabilidade utilizados na agricultura

Revista Gestão, Inovação e Tecnologias (GEINTEC) – Publicado

Scientific prospection on sustainability indexes used in agriculture

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Resumo

A avaliação dos impactos provocados pela agricultura é fundamental para o entendimento do nível de sua sustentabilidade. Nesse contexto, índices de sustentabilidade podem ser utilizados para medição, pois consistem em informações que facilitam a compreensão de dados. Este trabalho teve como objetivo realizar uma prospecção da utilização de índices para avaliação da sustentabilidade agrícola e apresentar uma visão geral das metodologias mais empregadas. Para isso, foram realizadas buscas sobre Índices de Sustentabilidade aplicados à Agricultura no banco de publicações científicas do Science Direct. A pesquisa coletou dados entre os anos de 2004 e 2015, em revistas de várias áreas. Os artigos foram analisados individualmente para certificação de que tratavam sobre o tema abordado. Foi encontrado um total de 496 resultados, sendo que destes, apenas 71 tratavam sobre a temática específica. O ano de 2015 foi o que apresentou maior porcentagem de artigos publicados. A China destacou-se com o maior número de publicações na área entre os anos da pesquisa, com um total de 24 artigos, enquanto o Brasil teve apenas 2 publicações para o *mesmo período. Dentre as metodologias utilizadas, destaca-se o Índice Sustentável de Emergia. Diante do número reduzido de manuscritos sobre a temática, conclui-se que este consiste em um assunto promissor para pesquisa e desenvolvimento.*

Palavras-Chave: desenvolvimento sustentável; metodologias; sistema agrícola; indicadores.

Abstract

The assessment of impacts caused by agriculture is essential to understand the level of its sustainability. In this context, sustainability indexes can be used for measuring, because they consist of information that facilitate the understanding of data. This study aimed to conduct a prospection about the use of index to evaluate the agricultural sustainability and present an overview of the most commonly used methodologies. For this, searches were conducted on Sustainability Indexes applied to Agriculture in the bank of scientific publications of the Science Direct. The survey collected data between 2004 and 2015 in various areas magazines. The articles were analyzed individually for certification that they treated on the discussed topic. A total of 496 results were found, and of these, only 71 treated on the specific theme. The highest percentage of published articles occurred in 2015. China stood out with the highest number of publications in the area between the years of research, a total of 24 articles, while Brazil had only 2 publications for the same period. Among the methods used, Sustainable Emergy Index highlights. On the small number of manuscripts on the subject, it is concluded that this is a promising subject for research and development.

Keywords: sustainable development; methodologies; agricultural system; indicators.

1. Introdução

No final da década de 60 surgiu um novo modelo de agricultura, denominado Revolução Verde, o qual foi implantado em diversas partes do planeta, sobretudo em países subdesenvolvidos. Com o intuito de aumentar a eficiência em termos econômicos, houve uma simplificação dos sistemas agrícolas, com estreitamento das bases genéticas, o que implicou em maior vulnerabilidade às pragas e doenças, aumentando os custos de produção e os riscos ambientais (MOURA, 2002).

Visto que os problemas ambientais aumentavam, dentre eles os relacionados à agricultura, a concepção de que o fator econômico é o mais importante foi questionada, dando lugar à ideia de desenvolvimento sustentável. Segundo Ruscheinsky (2004), o termo "sustentabilidade" começou a ser usado pelos ecologistas modernos nos anos 80. O conceito mais divulgado e utilizado atualmente é o do Relatório de Brundtland – "Nosso Futuro

Comum" – da Organização das Nações Unidas (ONU): "O desenvolvimento sustentável é aquele que atende às necessidades do presente sem comprometer a possibilidade de as gerações futuras atenderem suas próprias necessidades" (BIDONE; MORALES, 2004).

De acordo com Hansen (1996), a "agricultura sustentável" pode ser conceituada como uma atividade que satisfaça de forma permanente um determinado conjunto de condições para um período indefinido de tempo. Para Gómez-Limón e Sanchez-Fernandez (2010), estas condições estão relacionados com o carácter multidimensional inerente do conceito de desenvolvimento sustentável, que requer que essa atividade seja sustentável do ponto de vista triplo: economia (operação rentável), justiça social (distribuição justa e equitativa da riqueza) e respeito pelo ambiente (manutenção dos ecossistemas naturais). Devem, portanto, levar em consideração fatores relacionados à comercialização e ao acesso à alimentação e sua qualidade.

A urgência de avaliar se as práticas agrícolas atuais e futuras estão dentro dos limites da sustentabilidade levou à realização de modelagens do impacto da agricultura e das políticas agrícolas, as quais têm sido utilizadas para gestão da atividade (BOYLE *et al.*, 2015). A análise dos impactos provocados por este setor dentre os diferentes sistemas de produção é fundamental para avaliar mais precisamente os custos ambientais envolvidos (SILVA, 2007).

Nesse sentido, é importante também que estas avaliações possam ser agregadas sob a forma de indicadores e índices de sustentabilidade, de modo a proporcionar uma análise sistemática e contínua da situação em diversos contextos. Segundo Silva (2007), estas ferramentas são essenciais para orientar quais decisões serão acatadas, sendo que a necessidade de desenvolvê-las está expressa na Agenda 21 (documento que versa sobre como planejar sociedades sustentáveis). Para Siche *et al.* (2007), índices e indicadores funcionam como identificadores que informam a situação do sistema avaliado, pois como são valores estáticos, revelam a condição do momento.

Admite-se, portanto, que índices de sustentabilidade consistem em informações que facilitam a compreensão de dados, podendo ser utilizados como instrumentos para medição das condições ambientais, econômicas e sociais. Dessa forma, este trabalho teve como objetivo realizar uma prospecção baseada na busca de artigos científicos sobre a utilização de índices para avaliação da sustentabilidade no meio agrícola e, a partir disso, apresentar uma visão geral das metodologias mais empregadas para o desenvolvimento científico na área.

2. Material e métodos

A pesquisa foi realizada em março de 2016, quando foram feitas buscas utilizando-se o banco de artigos científicos do *Science Direct*. Este foi escolhido pelo fato de permitir um acesso facilitado e apresentar um significativo repositório da produção científica mundial.

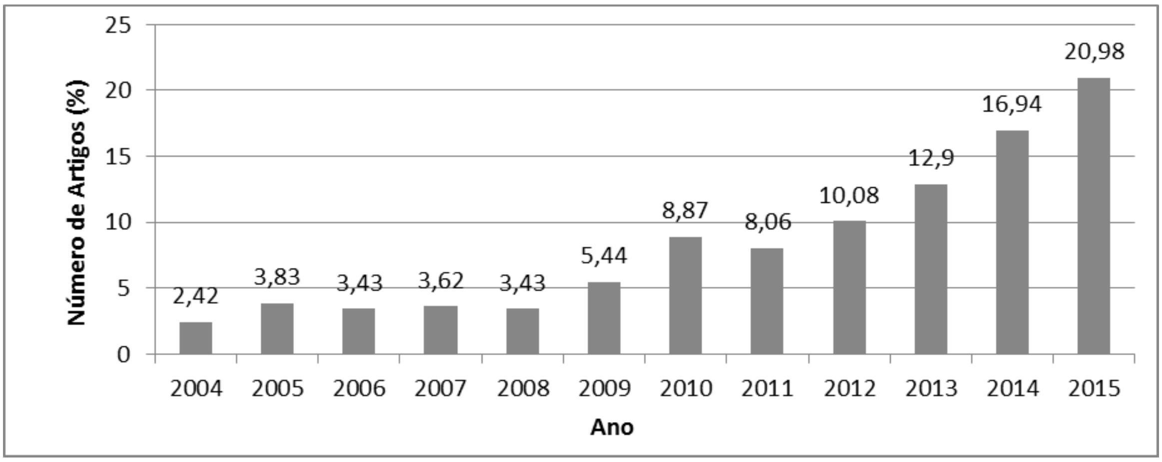
Para refinamento da busca, foram utilizados os seguintes termos: *index* AND *sustainab** AND *agricultur** OR *farming* OR *tillage* OR *crop** OR *cultivation*. Foi selecionada a opção que mostrou apenas estas palavras encontradas no resumo, título e palavras-chave. Buscaram-se artigos publicados entre os anos de 2004 e 2015, em revistas de todas as áreas, pois a sustentabilidade consiste em uma temática multidisciplinar.

Além disso, cada artigo foi analisado para garantia de que tratava sobre o assunto em questão. Foram selecionados todos os artigos nacionais e internacionais que utilizaram um índice para análise da sustentabilidade agrícola.

3. Resultados e discussão

Na busca geral dos artigos, foram encontrados 496 resultados. Entretanto, após leitura dos títulos, resumos e palavras-chave, detectou-se que havia apenas 71 artigos com abordagem específica sobre índices de sustentabilidade aplicados à agricultura.

No levantamento realizado, destacou-se o ano de 2015, com maior porcentagem de artigos publicados sobre a temática (20,98%). Por outro lado, a menor porcentagem de publicação foi observada no ano de 2004 (2,42%) (Figura 1).

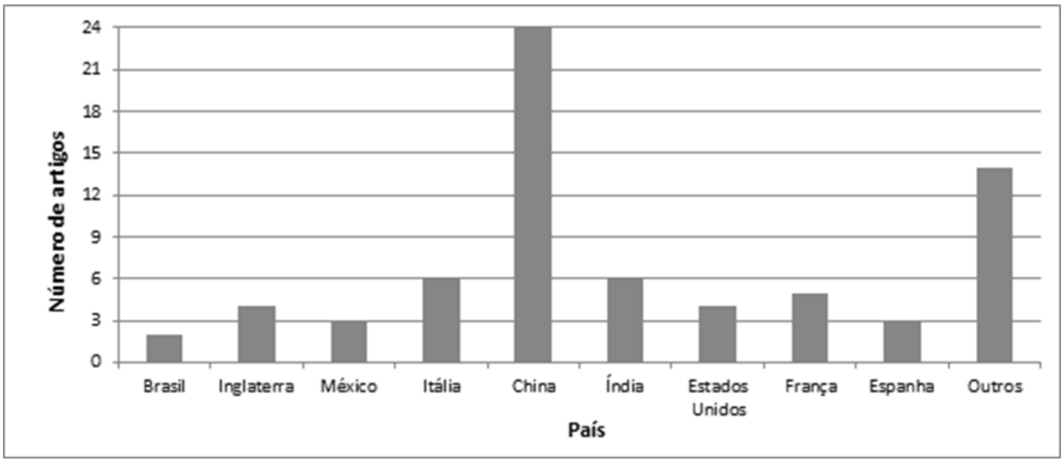


Fonte: Autores (2016)

Figura 1 – Porcentagem de artigos sobre “Índice de Sustentabilidade aplicado à Agricultura”, publicados entre os anos de 2004 e 2015.

Apesar do número de publicações sobre o tema em questão ter aumentado nos últimos anos, a quantidade de estudos ainda é ínfima se considerarmos a grande importância da utilização dessa ferramenta para a tomada de decisão e para o desenvolvimento científico. De acordo com Costa (2010), avaliar o desenvolvimento sustentável é atualmente um pré-requisito essencial para promover uma agricultura sustentável. Para Boyle *et al.* (2015), a procura por esse tipo de agricultura e os seus serviços ecossistêmicos associados crescem, e a capacidade de quantificar essa atividade é de suma importância.

Com relação à quantidade de publicações sobre a temática por país, destacam-se China (24 artigos), Itália e Índia (ambas com 6 artigos) e França (5 artigos). O Brasil aparece com apenas 2 publicações durante todo o período (Figura 2).

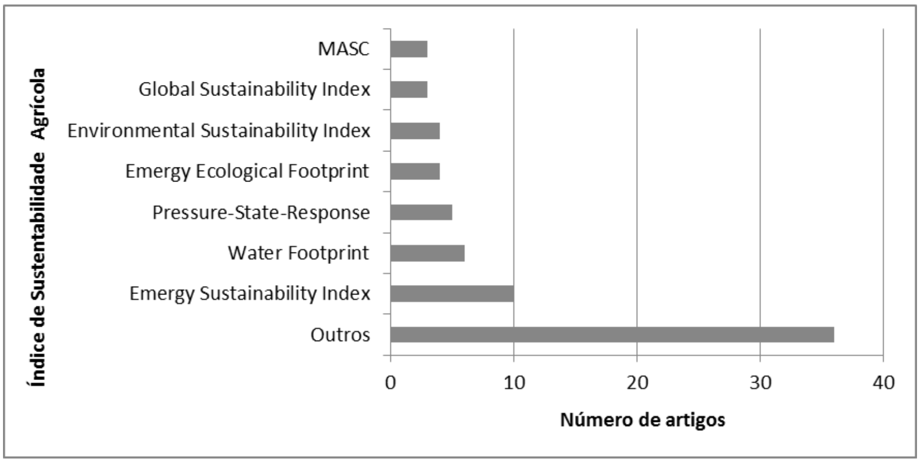


Fonte: Autores (2016)

Figura 2 – Número de artigos sobre "Índice de Sustentabilidade aplicado à Agricultura", publicados por país, entre 2004 e 2015.

De acordo com a FAO (2014), a República Popular da China é o país mais populoso do mundo (quase 20% da população terrestre) e um dos maiores produtores e consumidores de alimentos, além de destacar-se como maior produtor agrícola. Diante dessa realidade, o elevado número de pesquisas nesse país pode ser explicado pela maior necessidade e pressão da sociedade para investimentos em sustentabilidade agrícola.

Nos artigos encontrados, observou-se a utilização de diferentes metodologias, destacando-se dentre estas, o *Emergy Sustainability Index* (Índice Sustentável de Emergia), citado em dez publicações. Outras que se destacaram foram *Water Footprint* (Pegada Hídrica) e *Pressure-State-Response* (Modelo Pressão-Estado-Resposta), citadas em seis e cinco artigos, respectivamente (Figura 3).



Fonte: Autores (2016)

Figura 3 – Índices de Sustentabilidade aplicados à Agricultura utilizados nos artigos, entre os anos de 2004 e 2015.

Os principais índices utilizados são apresentados abaixo:

- *Emergy Sustainability Index* (ESI) – Índice Sustentável de Emergia (ISE)

Toda energia necessária para um ecossistema produzir um recurso é chamada de "emergia". Segundo Odum (1998), esse termo também é utilizado como sinônimo de "energia incorporada" ou "memória energética". Brown (1998) conceitua emergia como a energia que a biosfera investe para produzir seus bens e serviços, incluindo os bens e serviços da sociedade.

Liu *et al.* (2016) ressaltam que um índice de sustentabilidade baseado em emergia é utilizado para avaliar o estado de desenvolvimento sustentável de um ecossistema, combinando rendimento socioeconômico e impacto ambiental. Para Bastianoni *et al*. (2001), uma análise emergente é uma técnica de análise quantitativa que determina os valores dos recursos e é capaz de representar os valores ambientais e econômicos com uma medida comum. O índice utiliza princípios termodinâmicos e pode ser amplamente aplicado no setor agrícola.

- *Pressure-State-Response* (PSR) – Pressão-Estado-Resposta (PER)

Desde 1980, a OECD (*Organisation for Economic Co-operation and Development* – Organização para Economia, Cooperação e Desenvolvimento) tem trabalhado efetivamente na proposição de metodologias que sejam capazes de formular medidas de sustentabilidade, desenvolvendo ao longo do tempo, uma abordagem de pressão-estado-resposta. Essa organização estrutura as informações existentes em três tipos de indicadores: de Pressão (indicam as causas dos problemas ambientais); de Estado (descrevem a qualidade do ambiente) e de Resposta (propõem medidas mitigadoras ou protecionistas tomadas pela sociedade para reduzir ou evitar os impactos negativos da atividade humana sobre o ambiente) (SILVA, 2007).

Para Smeets e Weterings (1999), os condutores levam a atividades humanas que causam “pressões” ambientais, o que resulta em alteração no “estado” do meio ambiente, podendo causar um impacto, que eventualmente pode desencadear uma “resposta” política.

Essa metodologia tem sido bastante utilizada não somente na área agrícola, mas é extensamente aplicada em diversos setores.

- *Water Footprint* (WF) – Pegada Hídrica (PH)

No início de 1990, o conceito de Pegada Ecológica (PE) começou a ser utilizado (SILVA *et al.*, 2013). O lançamento do livro *Our ecological footprint*, de Wackernagel e Rees (1996), um estudo pioneiro sobre esse sistema, marca definitivamente a utilização dessa ferramenta para medir e informar sobre o desenvolvimento sustentável. Apesar desse trabalho não ter sido o primeiro a abordar explicitamente o conceito, foi ele que deu início aos diversos trabalhos de pesquisadores e organizações no desenvolvimento dessa ferramenta (SILVA, 2007).

Hoekstra e Huang lançaram, em 2002, um conceito similar denominado *Water Footprint*, com a finalidade de medir a apropriação humana da água doce global. Embora ambos os conceitos tenham origens e métodos de medição diferentes, apresentam alguns aspectos em comum, pois revelam o uso de recursos naturais pela humanidade. Enquanto a PE expressa o uso de espaço (em hectares), a PH mede o uso total de recursos de água doce (em metros cúbicos por ano) (HOEKSTRA, 2009).

A PH pode ser calculada para uma atividade específica, bem ou serviço (SILVA *et al.*, 2013). Dessa forma, tem sido bastante utilizada no setor agrícola, podendo ser citados os trabalhos de Chapagain *et al.* (2006), o qual elaborou a PH do algodão, e de Chapagain e Hoekstra (2007), que avaliou a PH do café e do chá.

- *Emergy Environmental Footprint* (EEF) – Pegada Ecológica Emergética (PEE)

Zhao *et al.* (2005) propôs o método da Pegada Ecológica Emergética. Essa ferramenta objetiva transformar a demanda humana de recursos naturais e a oferta da natureza em conceitos mais compreensíveis e quantificáveis. Esses autores visam ainda estimar a disparidade entre o consumo humano e a produção (baseada em recursos naturais).

A metodologia propõe que os dados de consumo possam ser transformados em fluxos emergéticos e que a biocapacidade seja uma função das fontes renováveis de energia (PEREIRA, 2008). Consiste em uma ferramenta de uso em várias áreas, inclusive na agricultura.

- *Environmental Sustainability Index* (ESI) – Índice de Sustentabilidade Ambiental (ISA)

O Índice de Sustentabilidade Ambiental é uma medida do progresso geral em direção à sustentabilidade ambiental. Essa metodologia foi desenvolvida em 2002, no Fórum Econômico Mundial, em Genebra, e elaborada para 142 países (JHA; MURTHY, 2003), tendo despertado um interesse considerável.

A ferramenta reúne um conjunto de 68 indicadores básicos. Estes são agregados para a construção de 20 indicadores núcleo, incluindo qualidade do ar, quantidade e qualidade da água, biodiversidade, dentre outros. O processo de construção do ISA reúne esses indicadores em cinco grandes setores gerais de sustentabilidade, os quais são: Sistema de Gestão Ambiental; Redução do Estresse Ambiental; Redução da Vulnerabilidade Humana; Componente da Capacidade Institucional e Social; e Tendência Global. Em seguida, os indicadores são resumidos em um único índice (JHA; MURTHY, 2003), o qual pode ser utilizado nas mais diversas áreas, sendo comum seu uso no setor agrícola.

- *Global Sustainability Index* (GSI) – Índice Global de Sustentabilidade (IGS)

O Índice Global de Sustentabilidade foi criado por triagem em empresas, cuja divulgação e práticas sustentáveis correlacionavam a transparência dos investidores e o desempenho financeiro a longo prazo. Este também incorpora um ponto de partida triplo, ou seja, um conjunto de indicadores-chave com desempenho financeiro, ambiental e social (CRD ANALYTICS, 2012). Além de ser utilizado em outras áreas, o IGS é usado também para a agricultura.

- *Multiattribute Assessment of the Sustainability of Cropping Systems* (MASC) – Avaliação Multiatributo da Sustentabilidade dos Sistemas de Cultivo (AMSC)

O modelo AMSC tem em sua essência uma árvore de decisão que simplifica a avaliação da sustentabilidade, colocando-a em uma estrutura tridimensional (econômica, social e ambiental), gerando um vetor de 32 critérios holísticos elementares (quantitativos e qualitativos) dos sistemas de cultivo. O processo de avaliação envolve o cálculo destes critérios, sua homogeneização em informações qualitativas para incorporação no modelo e sua agregação em toda a árvore, com base em regras de decisão "se-então", inseridos pelo usuário. Essa metodologia tem várias vantagens sobre os métodos existentes, devido à sua capacidade de lidar com a informação qualitativa, além de sua transparência, flexibilidade e viabilidade (SADOK *et al.*, 2009).

Algumas outras metodologias utilizadas nos artigos encontrados foram as seguintes: Índice de Produção Sustentável, Índice de Sustentabilidade Tamar, Índice de Rendimento Sustentável, APOIA-Novo Rural, MESMIS (Marco para Avaliação de Sistemas de Manejo de recursos naturais incorporando Indicadores de Sustentabilidade) e Índice de Sustentabilidade do Uso do Solo.

Para Melo e Cândido (2013), as diversas metodologias para avaliação da sustentabilidade da agricultura que vêm sendo desenvolvidas nos últimos anos ao redor do mundo mostram-se capazes de fornecer um diagnóstico sobre como estão ocorrendo as práticas no campo e de identificar os fatores que possam estar interferindo na sua sustentabilidade. Contudo, a escolha da ferramenta a ser adotada é um dos aspectos críticos do processo, tanto com relação à sua determinação, quanto à sua leitura e interpretação. Independente da escolha, esta deve ser direta e precisa, não deixando dúvidas sobre quais os princípios que estão na base do processo (SICHE *et al.*, 2007).

Gallopin (1996) ressalta a importância da viabilidade financeira para direcionar a escolha de um bom índice de sustentabilidade, enquanto Verona (2010) afirma que é essencial um método em que haja transparência dos resultados. Nesse contexto, para viabilizar a decisão sobre qual ferramenta utilizar, é fundamental que sejam levados em consideração também o tempo e o lugar. Essas especificidades são fator chave para uma boa escolha, pois cada sistema agrícola requer uma metodologia distinta, visto que cada um deles possui características diferentes.

É importante destacar também que a aplicação de um índice de sustentabilidade resulta na explicação dos mecanismos e lógicas atuantes na área sob análise e na quantificação dos fenômenos mais importantes que ocorrem no sistema. Através destes dois itens é possível conhecer como a ação humana está afetando seu entorno, alertar sobre os riscos de sobrevivência humana e animal, prever situações futuras e guiar na tomada de melhores decisões políticas (SICHE *et al.*, 2007). Costa (2010) destaca que a elaboração dessas metodologias ainda apresenta problemas conceituais e lacunas, pois é relativamente recente.

Para Boyle *et al.* (2015), as medições da sustentabilidade agrícola devem incorporar não somente indicadores ambientais, como também econômicos e sociais. Segundo Masera *et al.* (2000), essas avaliações também necessitam de modelos multicritério baseados em indicadores qualitativos e quantitativos, sendo preciso unificar perspectivas temporais mais amplas que as usualmente consideradas na avaliação convencional. Dahl (1997) ressalta que conforme a dimensão e a complexidade do objeto, o desenvolvimento sustentável e a sua compreensão com a utilização de indicadores constituem um grande desafio.

4. Conclusão

Este estudo examinou índices de sustentabilidade que são aplicados à agricultura. A busca de artigos realizada na base de dados do *Science Direct* permitiu constatar que apesar do número de publicações sobre essa temática ter aumentado ao longo do tempo, ainda há poucas pesquisas sobre o assunto. Essa realidade pode ser verificada de forma bastante clara quando se toma o Brasil como exemplo. O tema consiste, portanto, em um assunto que ainda pode ser bastante explorado em pesquisa e desenvolvimento.

Os índices aqui apresentados demonstraram particularidades em sua metodologia. Diante disso, a escolha da ferramenta a ser utilizada deve sempre considerar o contexto do sistema agrícola a ser mensurado e do propósito do estudo. Além disso, quando possível, deve-se também considerar fatores sociais e econômicos, os quais compõem os principais pilares da sustentabilidade, juntamente com o fator ambiental.

Nesse sentido, faz-se necessário um maior incentivo à utilização e desenvolvimento de metodologias inovadoras para medição da sustentabilidade agrícola. Dentre elas, as que usam índices têm demonstrado bastante eficácia, pois um valor numérico pode facilitar a tomada de decisão pelo poder público.

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CAPÍTULO 2

Associations between Different Soil Management Practices, Soil Fauna and Maize Yield

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Abstract

Soil fauna play an important role in ecosystems, and in this context, it is important to better understand how the abiotic and biotic drivers of these organisms interact. We hypothesize that soil fauna are affected by different soil management practices, which has an influence on maize grain yields. The aim of this study was to evaluate the structure of soil fauna under different soil management practices and their associations with maize grain yield. The experiment was conducted in Maranhão, Brazil, in an area divided into 24 plots of 4 × 10 m in a randomized block design with six treatments with four replicates (R). Pitfall traps were placed in the area. The treatments were *Leucaena leucocephala*-Leucaena (L), nitrogen (N), humic acid + nitrogen (HA + N), nitrogen + Leucaena (N + L), humic acid + Leucaena (HA + L) and humic acid + nitrogen + Leucaena (HA + N + L). The soil fauna dominance, abundance, richness, Shannon-Wiener diversity index, Pielou evenness index and maize grain yield were determined. Formicidae was clearly affected by management with Leucaena, while Coleoptera was affected by management with nitrogen. Despite this, Isopoda and Diplura were the only groups associated with the maize yield. Although fauna abundance did not differ among treatments, it was related to the yield. This study confirms that the abundance and some taxa of soil fauna can influence yield and that these organisms can be used to increase agricultural sustainability.

Keywords: abundance, diversity indexes, principal component analysis, soil quality, sustainability.

1. Introduction

Ecosystem functions such as decomposition, nutrient cycling and maintenance of physical and chemical properties are greatly influenced by the contribution of edaphic organisms (Davidson & Grieve, 2006). These organisms play an important role in the formation and stabilization of soil structure (El Titi, 2003). They regulate the rates of movement of nutrients, water and gases, and they lead to the development of macropores, which increase water absorption and reduce run-off, erosion and waterlogging. They also alter the competitive balance between plants with different rooting depths by changing the distribution of water in the soil profile (Sanginga et al., 1992).

The role of soil fauna in litter decomposition has been intensively studied over the past 40 years (Zhang et al., 2015). El Titi (2003) reported that these organisms have an important role in the production and decomposition of organic matter and population stability of other organisms that inhabit the soil. Bedano et al. (2016) highlighted the importance of soil fauna in soil organic matter cycling, mainly mesofauna and macrofauna.

Nevertheless, little has been done to link indicator taxa with their ecosystem functions and services (Rousseau et al., 2013), and it is necessary to take an integrative approach to address these gaps in knowledge (Tsiafouli et al., 2015). Birkhofer et al. (2011) affirmed that it is important to better understand how the abiotic and biotic drivers of soil fauna activity interact at spatial and temporal scales to possibly counteract negative consequences of ecosystem functioning. According to Siqueira et al. (2014), there is not enough knowledge about how arthropods, for example, are affected by extensive and/or intensive agricultural systems. According to Ying-Hua et al. (2013), there are few studies on the effect of different fertilizers on soil fertility and soil fauna.

Many mechanical and chemical changes occur within agricultural environments, and this modifies the responses of the native species populations in the area (Hernández-Ruiz & Castaño-Meneses, 2006). Brussaard et al. (2007) observed that organic matter, for example, is one of the limiting factors of soil organism functions. According Violet (2015), organic inputs modify soil macrofauna, increasing the biomass, abundance and diversity. Reeve et al. (2010) also report that soil fauna structure is affected by fertilizers, because these components alter plant residues and soil properties, interfering in the composition of the community. In this context, Franco et al. (2016) found that Formicidae population increased when content of nitrogen increased in a sugarcane crop.

According to Korboulewsky et al. (2016), biotic and abiotic agents affect these organisms, but Yang et al. (2007) emphasized that in the humid tropics, the soil fauna also affect the environment because they increase the decomposition rate of the soil. Carrillo et al. (2011) suggested that soil fauna alter the effect that litter quality exerts on decomposition and this process is important for fertility. Zhang et al. (2015) showed that when soil fauna were absent, decomposition rate of plant litter decreased. In this context, Huguenin et al. (2006) concluded that soil fauna increases agricultural production. Shukla et al. (2016) showed that soil engineers modify the soil structure and this enhances the yield in cereals. These organisms build tunnels to forage and nest, increasing water infiltration and aeration into the soil, influencing availability of several nutrients. When water infiltration is deeper, evaporation from the soil surface decrease and absorption of water by plants improves (Evans et al., 2011). This effect can be relevant to agricultural yield. The type of soil fauna feeding also may influence grain yield, such as maize, through providing different contents of nutrients to the soil (Jiang et al., 2015).

Thus, it is necessary to understand how soil fauna populations are changed when the environment is modified and how these organisms may modify surroundings. Therefore, we hypothesize that soil fauna are affected by different management practices, and this influences maize grain yields. The aim of this study was to evaluate the structure of soil fauna under different soil management practices and their relation to increases in maize grain yield.

2. Materials and Methods

2.1 Study Area

The experiment was performed at Brejo City (3°38′S latitude and 42°58′W longitude), Maranhão, in the northeast of Brazil. The climate there is humid tropical with 1200-1400 mm of average annual precipitation and an average annual temperature above 27 °C. The soil is an Arenic Hapludult (Soil Survey Staff, 2010), presenting a flat topography (slope < 1%) with the following characteristics: pH 4.4 (0.01 M $CaCl_2$); organic C 15.5 g kg^{-1}; potential acidity 4.7, and CEC 7.9 $mmol_{(c)}$ dm^{-3}; Ca 2.6, Mg 0.5, and K 0.1 $mmol_{(c)}$ dm^{-3}; P 3.7 g dm^{-3} (resin); base saturation 40.2%; and a sandy textural class.

The experimental area was established in 2012 and consists of an alley cultivation system with Leucaena (*Leucaena leucocephala*) planted with an inter-row spacing of 4 m and an inter-plant spacing of 0.5 m.

In 2015, the area between the rows of the Leucaena was divided into 24 plots of 4 × 10 m with six treatments and four replicates (R) in a randomized block design. The treatments were: 133 kg ha^{-1} of urea, as a source of Nitrogen (N); 15 t ha^{-1} of Leucaena (L); 133 kg ha^{-1} of urea + 15 t ha^{-1} of Leucaena (N + L); 500 L ha^{-1} of humic acid + 15 t ha^{-1} of Leucaena (HA + L); 500 l ha^{-1} of humic acid + 133 kg ha^{-1} of urea (HA + N) and 500 l ha^{-1} of humic acid + 133 kg ha^{-1} of urea + 15 t ha^{-1} of Leucaena (HA + N + L). All treatments received 120 kg ha^{-1} of P_2O_5, 60 kg ha^{-1} of K_2O and 25 kg ha^{-1} of $ZnSO_4$. These doses were defined according to the result of the soil analysis.

2.2 Soil Fauna

Soil fauna was sampled using the pitfall trap method in each plot, which allows the capture of different groups of this fauna. The traps were made of plastic, allocated to the ground level, and were approximately 9 cm high and 8 cm in diameter. The collection occurred during a seven-day period in July 2015, and samples were preserved in glasses with 200 mL of formaldehyde solution (4%). The contents of the glasses were transferred to pots with 70% alcohol and properly identified.

In the laboratory, each sample was processed, separated and identified at the order or family level using a binocular microscope and taxonomic keys. Formicidae was separated from Hymenoptera due to the ecological importance it has in the community.

Abundance, dominance and ecological indexes—richness, Shannon-Weaner diversity index (H’) and Pielou equitability index (J’)—were used for evaluation of the soil fauna structure.

The fauna abundance is calculated as the number of individuals per pitfall per day. The dominance is the number of individuals in each taxon per trap per day. The richness is the number of groups that occurred in each sample. The Shannon-Weaner index is calculated by the following formula:

$$H' = -\sum_{i=1}^{s} pi \cdot \log_2(pi) \qquad (1)$$

where pi = probability of meeting a taxon i in a trap per day and s = total number of taxa encountered in a trap per day. The Pielou evenness index indicates how individuals are distributed among the different taxa present in the sample. It is calculated as:

$$J' = \frac{H'}{\log_2(s)} \quad (2)$$

where H' is Shannon index and s is number of groups present in a trap per day.

2.3 Maize Grain Yield

Each plot was cropped with maize (*Zea mays* L.), variety QPM BR 473, in March 2015 in a total area of 960 m^2. At physiological maturity, ten cobs were collected from each plot, and their grains were extracted. The grain yield was estimated in Mg ha^{-1} from the total grain mass in each plot and the number of plants per hectare.

2.4 Statistical Analyses

For the statistical analysis, a one-way ANOVA was conducted to determine the significance of the difference in the means of the soil fauna dominance, abundance, richness, Shannon-Wiener index, Pielou index and maize yield. Diversity and evenness data were transformed to meet the assumptions of normal distribution and homogeneity of variance. The Duncan test was used to determine which differences were significant ($p < 0.05$). For cluster analysis with Ward's method, the Euclidean distance between the mean abundances of soil fauna groups was used as the measure of similarity. The relation between the maize grain yield and the major groups of soil fauna was analysed. The relations between the maize grain yield and the ecological indexes and abundance were also analysed. For this investigation, principal component analysis (PCA) was used after standardization of the data. Statistica version 7 (Statsoft Inc., 2004) was used for all analyses.

3. Results

3.1 Soil Fauna

A total of 1 993 soil fauna individuals belonging to 27 taxa were collected. The maximum number of taxa occurred at HA + N (20), and the minimum occurred at N + L (13). The largest soil fauna community was found at HA + N + L (369), and the smallest was found at L (289) (Table 1). The taxa with the greatest numbers of individuals were Formicidae, Coleoptera, Diplura and Isopoda, accounting for 77.5% of the collected organisms.

Table 1. Total number of individuals collected by pitfall traps in one week per taxonomic group studied.

Taxon	HA + N	HA + N + L	L	HA + L	N	N + L
Araneae	39	27	17	31	16	11
Araneae (Cocoon)	3			1		
Auchenorrhyncha	2			1	2	2
Blattodea		1				
Chilopoda					1	
Coleoptera	45	54	48	68	94	41
Coleoptera (Larva)	1	1	1	3	3	
Dermaptera	1		2	2		
Diplopoda	1		1	7		
Diplura	51	74	35	39	59	78
Diptera	1		1		4	2
Diptera (Larva)					1	2
Entomobryomorpha	3	2	7	11	11	1
Formicidae	103	149	110	121	85	107
Heteroptera	1	1	3	2	5	2
Hymenoptera	11	6	11	5	2	3
Isopoda	36	36	18	15	41	37
Isoptera	3	1				
Lepidoptera	1					
Lepidoptera (Larva)		1	3	2	1	
Neuroptera (Larva)		1	1			
Opillionida	1	1	3	7	5	5
Orthoptera	14	13	27	26	28	25
Phasmatodea	1					
Pseudoscorpionida		1			1	
Sternorrhyncha	1					
Thysanura			1			
Total	319	369	289	341	359	316

Note. HA + N = humic acid + nitrogen; HA + N + L = humic acid + nitrogen + Leucaena; L = Leucaena; HA + L = humic acid + Leucaena; N = nitrogen; N + L = nitrogen + Leucaena.

Formicidae was the group with the largest mean number of individuals (37.25±31.36 at HA + N + L). Significant differences were detected between the mean number of individuals in this group and the other taxa at the HA + N and L, which had 25.25±9.74 and 27.5±11.27 Formicidae individuals, respectively ($p < 0.05$) (Figure 1).

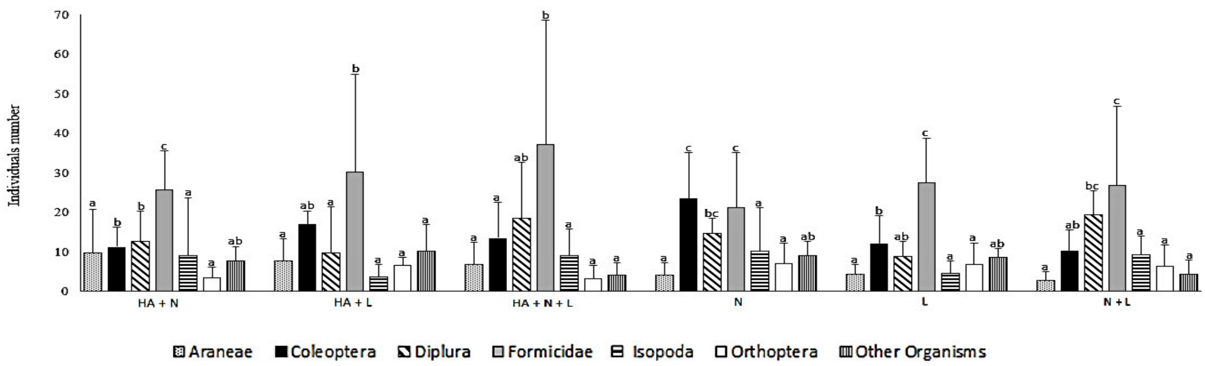

Figure 1. Dominance of taxonomic groups of soil fauna (mean±standard deviation) per treatment.

Note. Taxa with distinct letters within the same treatment are significantly different (ANOVA with Duncan test, $p < 0.05$). HA + N = humic acid + nitrogen; HA + N + L = humic acid + nitrogen + Leucaena; L = Leucaena; HA + L = humic acid + Leucaena; N = nitrogen; N + L = nitrogen + Leucaena.

The Shannon index, Pielou index, richness and abundance values showed no significant differences ($p > 0.05$) (Table 2).

Table 2. Shannon index, Pielou index, total richness and abundance values of soil fauna communities at different treatments (mean±standard deviation).

Treatment	H’ ± std. dev.	J’ ± std. dev.	S ± std. dev.	A ± std. dev.
HA + N	1.681±0.228a	1.676±0.141a	10.5±3.3a	11.39±1.08a
HA + N + L	1.401±0.499a	1.656±0.222a	7.7±4.1.0a	13.18±8.81a
L	1.877±0.076a	1.789±0.094a	11.2±1.0a	10.32±3.96a
HA + L	1.798±0.3a	1.761±0.194a	10.5±1.7a	12.18±4.22a
N	1.788±0.24a	1.819±0.089a	10.0±2.7a	12.82±5.64a
N + L	1.634±0.234a	1.793±0.037a	8.5±2.4a	11.29±6.03a

Note. Same letters within the same column indicate not significantly differences (ANOVA with Duncan test, $p > 0.05$). HA + N = humic acid + nitrogen; HA + N + L = humic acid + nitrogen + Leucaena; L = Leucaena; HA + L = humic acid + Leucaena; N = nitrogen; N + L =

nitrogen + Leucaena; H' = Shannon index; J' = Pielou index; S = total richness; A = abundance; std. dev. = standard deviation.

The treatments with a Euclidean distance between 70 and 80 were classified into three groups, i.e., (1) N, (2) HA + L, L and (3) HA + N + L, N + L, HA + N. Group 1 predominantly contains Coleoptera, group 2 includes treatments at which Formicidae was predominant, and group 3 comprises the treatments at which three taxa were predominant (Formicidae, Diplura and Coleoptera) (Figure 2).

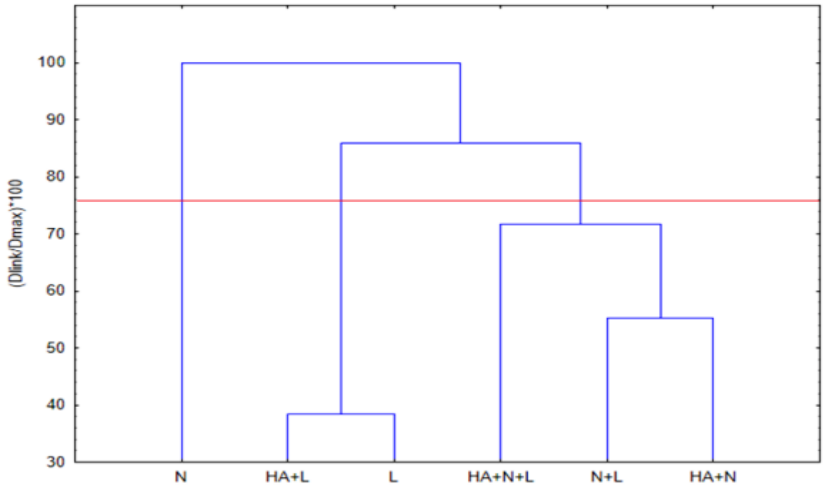

Figure 2. Dendrogram resulting from hierarchical cluster analysis, with the formation of groups based on the Euclidian distance of the taxonomic groups of soil fauna.
Note. N = nitrogen; HA + L = humic acid + Leucaena; L = Leucaena; HA + N + L = humic acid + nitrogen + Leucaena; N + L = nitrogen + Leucaena; HA + N = humic acid + nitrogen.

3.2 Maize Grain Yield

The maize grains yield at N + L was significantly higher than that in the other treatments ($p < 0.05$). In the other treatments that also received nitrogen, the yield was significantly higher than that in the treatments that did not receive it ($p < 0.05$) (Table 3).

Table 3. Maize grains yield at different treatments.

Treatment	Grains Yield (Mg ha^{-1})
HA + N	4.02 b
HA + N + L	4.62 b
L	1.47 c
HA + L	1.60 c
N	3.93 b
N + L	5.38 a

Note. Distinct letters indicate significant differences (ANOVA with Duncan test, $p < 0.05$). HA + N = humic acid + nitrogen; HA + N + L = humic acid + nitrogen + Leucaena; L = Leucaena; HA + L = humic acid + Leucaena; N = nitrogen; N + L = nitrogen + Leucaena.

3.3 Relations Between Soil Fauna and Maize Grain Yield

In the PCA that associated yield with taxonomic groups, 65.22% of the variation was explained by its two main components. Axis 1 was mainly associated with Isopoda, Diplura, Coleoptera and Formicidae, while axis 2 was associated with Orthoptera. Yield showed a strong positive correlation with Isopoda and Diplura (Figure 3a).

In the PCA that associated yield with ecological indexes and abundance, its two main components explained 89.13% of the variation. Axis 1 was mainly associated with the Shannon index and richness, while axis 2 was associated with abundance and the Pielou index. The only positive correlation found was between yield and abundance (Figure 3b).

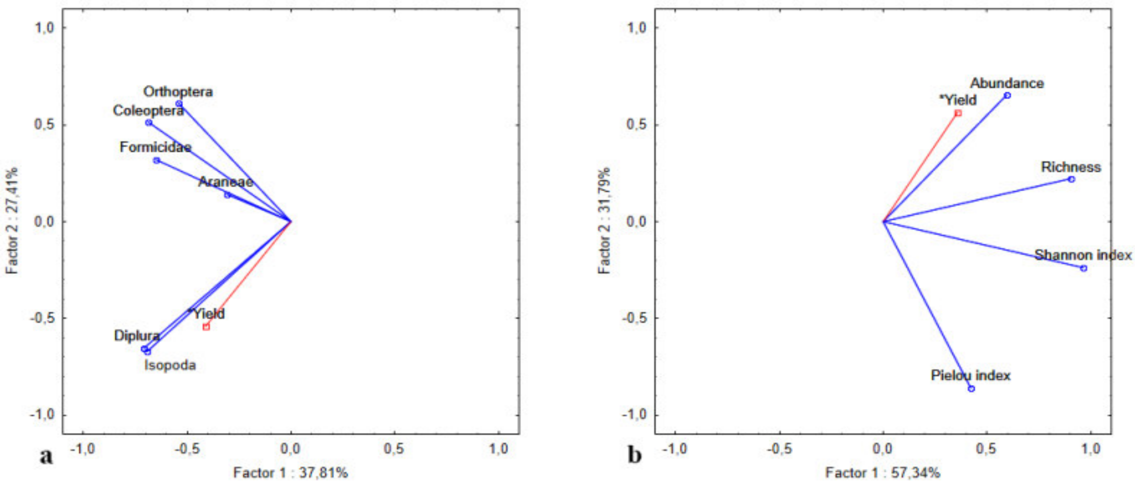

Figure 3. Principal component analysis (PCA) of the yield and major groups of the soil fauna (a); yield and the ecological indexes and abundance (b).

4. Discussion

4.1 Soil Fauna

We found that the total number of individuals and the number of taxa of soil fauna varied between treatments. Soil changes modify soil characteristics such as temperature, water content and nutrients, affecting the environment of soil organisms (Erouissi et al., 2011), and this causes differences in the fauna communities between sites. Ayuke et al. (2009) emphasizes that some management practices, such as the application of organic residues, are among the causes of variations found in soil fauna. In this study, we did not identify specific variations in the total number of individuals or taxa in treatments with organic residues.

Formicidae, Coleoptera, Diplura and Isopoda had the predominant number of individuals at the study site. Ants are engineers and strongly affect the fluxes of gases and water in soil. They incorporate plant litter and crop residues into the soil, providing resources to other individuals, modifying the microhabitats for them and transporting materials for the formation of nests (Paul et al., 2015; Segat et al., 2017; Siqueira et al., 2014; Wolters, 2000). This may explain the coexistence of a high number of Formicidae with other taxa.

In the present study, Formicidae dominated the other groups, especially in two of the treatments. This finding corroborates those of Siqueira et al. (2014), who affirmed that differences in these invertebrate communities can be influenced by how land is used, even at the taxa level. According to Sileshi and Mafongoya (2006a), when the abundance of functional groups such as soil engineers increases, some soil ecosystem functions will be enhanced.

One of the treatments at which Formicidae numbers were particularly high was composed only of Leucaena. In this sense, Moura et al. (2015) emphasized that the presence of some functional groups of soil fauna can be influenced by applying biomass on the soil surface. Blanchart et al. (2006) showed that the presence of a legume stimulated the development of organisms that can promote soil structure and nutrient availability. This result was observed in the present research, where ants dominated the Leucaena biomass treatment. Franco et al. (2016) observed that ant number was related to the nitrogen content in the soil, which occurred in our results when nitrogen was associated with humic acid.

Pellens and Garay (1999) reported that some species of Leguminosae could even be used for natural recolonization of edaphic communities. Blanchart et al. (2006) found that the presence of legumes modified the composition and diversity of soil biota in a maize cropping system. This result was not verified in the present study, where the average diversity and richness between treatments did not show significant differences ($p > 0.05$).

The abundance of soil fauna can be significantly affected by the soil use. For example, the water retention capacity of soil can be increased by the accumulation of organic matter and then influence the soil fauna (Sileshi & Mafongoya, 2006b). For Cluzeau et al. (2012), fertilization intensity also affect the abundance of soil fauna. As Paul et al. (2015) noted, there are studies that have found relationships between the management and abundance of soil fauna. In our results, however, we did not detect significant differences in abundance between treatments ($p > 0.05$).

Cluster analysis verified the formation of three groups based on the shortest Euclidian distance. This distance represents the degree of association between treatments, and according to Lee et al. (2006), the shorter this distance, more intimate the association is; therefore, treatments in the same group represent the nearest relationship. Vasconcellos et al. (2013) verified that Coleoptera was one of the most important taxa for discriminating between sites and that it showed good potential as a bioindicator of soil quality. This result was also found in this research, where the groups had different associations with this taxon. The two groups in which Coleoptera was a major taxon were composed of treatments with nitrogen. Hunt et al. (1992) noted that nitrogen in crops causes faster development of some beetle species. This finding may explain the results found here. As a whole, the treatments grouping according to cluster analysis was consistent with the predominance of some taxa.

4.2 Maize Grain Yield

Maize grain yield was significantly higher in treatments that received nitrogen than in those that did not receive it ($p < 0.05$). This increase may be related to some groups of soil organisms, because fertilization is one of the factors that can influence these organisms (Ying-Hua et al., 2013), for example, when nitrogen content changes (X. Zhu & B. Zhu, 2015). According to Lavelle et al. (1995), nitrogen fertilization alters pH and this changes the composition of soil fauna communities. Ying-Hua et al. (2013) affirm that soil fauna populations that parasite plants decrease when nitrogen is applied. This decrease in parasites populations may increase yield.

4.3 Relations Between Soil Fauna and Maize Grain Yield

Soil ecosystem services associated with sustainable agricultural production are driven in part by edaphic organisms (Creamer et al., 2016). Lavelle et al. (1995) and Ouédraogo et al. (2006) highlighted positive effects of soil fauna on soil fertility via the conservation of organic matter and nutrients, which benefits plant growth. Shukla et al. (2016) found that the ecosystem engineering activities of a species of ant enhanced the yield of cereals. However, in our study with maize, we did not detect an association between ants and crop yield. The only association we found by PCA between yield and soil fauna occurred with Isopoda and Diplura. This result is unlike those of Paul et al. (2015), who found that higher maize grain yields in Kenya were related to the exclusion of groups of soil fauna. Isopods are general detritivores, and they can feed on the foliage of seedlings (Coleman et al., 2004). This ecological function increases the cycling of nutrients in the soil (Culliney, 2013) and may influence yield. Diplura are predators, and according to Rivers et al. (2016), predators may consume insect pests, lowering the overall plant damage. This activity also may increase the crop yield.

The biodiversity of edaphic biota is a key component of soil quality (Creamer et al., 2016), and it leads to production sustainability (Altieri, 1999; van der Putten et al., 2004). According Thakur et al. (2014), disturbances may alter local environmental conditions, and it is very important to understand how local species diversity could be influenced by these disturbances. For Cluzeau et al. (2012), the impact of management systems on soil biodiversity strongly depends on the nature and intensity of the agricultural practices employed. In our results, we did not find an association between the yield and diversity indexes. Nevertheless, we observed a correlation between yield and fauna abundance. The increased yield associated with increased abundance may be related to the presence of invertebrates with different ecological functions in the soil, even without an increase in biological diversity. For Kilowasid et al. (2012), this functional diversity improves ecosystem services such as yield. In this sense, Blanchart et al. (2006) affirmed that biota resources may increase the functional properties of ecosystems and allow better agricultural productivity and sustainability. Sanginga et al. (1992) noted that the management of biological processes could be one way to restore and sustain fertility because biological factors influence the soil nutrient and physical characteristics.

5. Conclusion

The main results of this research indicate that Leucaena treatments may have caused increases in the dominance of ants. Nitrogen also demonstrated an influence over the community of Coleoptera. Despite this, although another studies have associated Formicidae with ecosystems services, we could not observe a relation between this group and maize grain yield. Isopoda and Diplura were the only groups associated with the yield, which may be related to their ecological functions in the environment. We did not observe differences in the ecological indexes between different soil management practices, and we did not find a relation between these indexes and the yield. Although fauna abundance also did not vary among management treatments, it was related to the yield. This finding may be due to the importance of the diversity of ecological functions performed by fauna rather than biological diversity. This study does not confirm the hypothesis that different soil management practices affect soil fauna, thus influencing the yield. However, we do confirm that the abundance and some taxa of soil fauna can influence yield. These taxa could be used to increase agricultural sustainability.

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CAPÍTULO 3

Can different soil fertilization regimes modify soil fauna and interfere in maize grain yield?

Australian Journal of Crop Science – Aceito para publicação

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Abstract

Soil fauna activities transform the soil, but soil organisms are also influenced by changes in the land. We hypothesize that different soil fertilization regimes modify soil fauna and in this way affect maize grain yield. The aim of this study was to evaluate the effects of different soil fertilization regimes on the structure of the soil fauna and the association between these organisms and the maize grain yield. The experiment was conducted in Maranhão State (Brazil), in an alley crop system which was divided into 32 plots of 4×10 m, with four replicates and the following treatments: *Gliricidia sepium* – gliricidia (G), potassium (K), humic acid (HA), humic acid + potassium (HA + K), potassium + gliricidia (K + G), humic acid + potassium + gliricidia (HA + K + G), humic acid + gliricidia (HA + G) and uncovered soil (US). Soil fauna dominance, abundance, richness, Shannon–Wiener diversity index, and Pielou evenness index and maize grain yield were determined. Fertilization with humic acid and potassium caused the dominance of isopods. The dominance of ants was also related to soil potassium (K treatment). The only taxon associated with yield was Araneae. Although fauna abundance did not show differences between treatments, it was related to yield. This study does not confirm the hypothesis that different soil fertilization regimes affect soil fauna and consequently influence maize grain yield. Nevertheless, we confirm that maize grain yield may be improved by the presence of specific groups and by the increased abundance of soil fauna.

Keywords: abundance; Araneae; detritivores; ecological index; legume; predators; principal component analysis; soil quality.

Abbreviations: G_*Gliricidia sepium*; HA_humic acid; HA + G_humic acid + gliricidia; HA + K_humic acid + potassium; HA + K + G_humic acid + potassium + gliricidia; K_potassium; K + G_potassium + gliricidia; US_uncovered soil.

Introduction

Soil fauna provides beneficial services both *in situ* and in the surrounding environment. For example, soil fauna enhances soil drainage, creates passages for plant roots and aerates the soil (Huguenin et al., 2006). In addition, soil fauna takes an active part in the recycling of nutrients back into the soil through the decomposition of plant debris (Wong et al., 1992). Höfera et al. (2001) conclude that these organisms provide valuable ecosystem services that sustain soil quality and vegetable growth.

There is a mechanism of interaction between litter composition and the soil fauna community, as these animals can alter the effect that litter quality exerts on decomposition. This process is important for site fertility (Carrillo et al., 2011). Zhang et al. (2015) suggest that the role of soil fauna in regulating litter decomposition in different ecosystems is essential. Their results showed a 35% slower decomposition rate of plant litter, on average, when soil fauna is absent.

The activities of soil fauna modify the physical structure of soil and hence regulate the rates of movement of nutrients, water and gases. For example, these organisms lead to macropore development, which has various consequences, such as increased water absorption and therefore reduced run-off and erosion, reduced waterlogging, and changes in the distribution of water in the soil profile that may alter the competitive balance between plants with different rooting depths (Erouissi et al., 2011; Sanginga et al., 1992).

In this context, understanding the influence of soil characteristic on the soil fauna is also very relevant (Erouissi et al., 2011). For Sanabria et al. (2014), soil biodiversity is very sensitive to land changes and is an important regulator of key soil processes. Previous studies have detected that the composition and diversity of soil fauna communities are influenced by changes in soil organic matter and fertility. Then, variations in these communities are related to the fertilization regime. Although fertilizer use is important to improved crop yield, it alters soil properties and changes the soil fauna structure (Zhu and Zhu, 2015). Thus, these animals can be used as edaphic quality indicators, since there is a relationship between their community structure and the processes occurring in the soil (Guimarães et al., 2017; Paoletti et al., 1996). Siqueira et al. (2014) assert that there are some advantages to the use of soil fauna to measure soil quality compared to other biological methods. Furthermore, it is possible to identify functional groups within the edaphic fauna that are more sensitive to changes in land (Hu et al., 1997; Tao et al. 2016).

Fertilizers alter abundance of edaphic fauna, affecting the environment of these organisms and changing the crop yield. Soil fauna feeding also alter maize yield (Jiang et al., 2015). Huguenin et al. (2006) argued that edaphic fauna increases agricultural production. Soil engineers, for example, affect plant productivity, regulating the stability of soil biota (Kilowasid et al., 2012).

Therefore, our hypothesis is that the different soil fertilization regimes modify soil fauna and thus interfere in the maize grain yield. The aim of this study was to evaluate the effects of different soil fertilization regimes on the structure of soil fauna and their association with maize yield.

Results

Composition, abundance, dominance and ecological indexes of soil fauna

A total of 3,629 individuals from the soil fauna were collected during the sample period. They were distributed in 32 taxa, with a maximum of 25 taxa at HA + K and a minimum of 17 at HA + K + G. The largest soil fauna community was found at HA + K (698 individuals), and the smallest was collected at HA + K + G (345 individuals) (Table 1). The taxa exhibiting the greatest number of specimens in total were Formicidae, Isopoda, Diplura, Coleoptera, Orthoptera and Araneae, together accounting for 92.7% of the collected organisms.

Table 1. Total number of individuals collected by pitfall traps during a week per taxonomic group studied. G: gliricidia, HA + K: humic acid + potassium, K + G: potassium + gliricidia, K: potassium, HA + K + G: humic acid + potassium + gliricidia, HA + G: humic acid + gliricidia, HA: humic acid, US: uncovered soil.

	G	HA + K	K + G	K	HA + K + G	HA + G	HA	US
Acari	3	1		1			2	
Araneae	28	13	18	19	13	14	14	6
Araneae (cocoon)						1		
Archaeognatha								1
Auchenorrhyncha	2	2	3	3	2	2	3	2
Blattodea	2	3	2	2		1	1	3
Chilopoda		2	1	1	2	2	1	
Coleoptera	25	67	30	61	40	35	73	56
Coleoptera (larva)		7	5	2	1		3	
Dermaptera	2		1				1	1
Diplopoda		4	3		1			4
Diplura	126	107	144	43	69	73	60	51
Diptera	3	1	4	6	2	3	4	3
Diptera (larva)	2	1				9	2	
Entomobryomorpha	4	1	1		4	1	8	3
Formicidae	90	146	120	138	122	197	153	114
Heteroptera		1	1	2	3		1	1
Hymenoptera	5	5	3	2	7	3	3	3
Isopoda	77	307	210	69	62	102	47	89
Isoptera		2	3	2	2		5	1
Lepidoptera (larva)		1	3	1	1	3	2	1
Neuroptera (larva)								1
Opillionida	4	1		2			2	
Orthoptera	23	20	12	18	13	11	17	21
Phasmatodea		1						1
Poduromorpha	7	1						6
Pseudoscorpionida		1						
Sternorrhyncha	2	2		1	1	2	5	1

Symphyla	1							
Thysanura						1		
Trichoptera		1				1		1
Pupa						1	4	
Total	406	698	564	373	345	462	411	370

Isopoda was the group with the largest mean number of individuals per treatment (76.7 ± 55.9 at HA + K). Significant differences were detected between this taxon and the others into this treatment ($p < 0.05$). The mean number of Formicidae was significantly larger than that of other groups at K (34.5 ± 12.9) ($p < 0.05$) (Fig. 1).

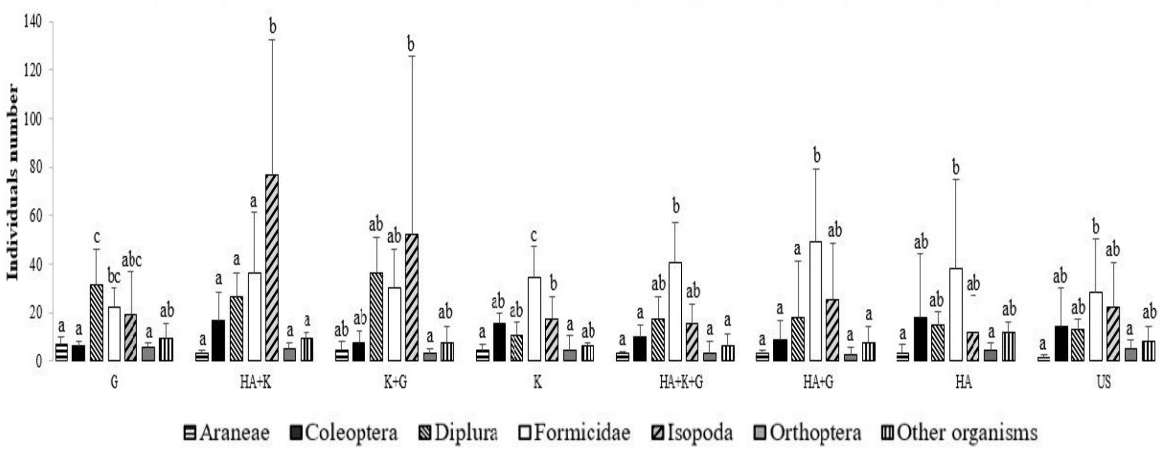

Fig 1. Dominance of taxonomic groups of soil fauna (mean ± standard deviation) per treatment. Taxa with distinct letters within the same treatment are significantly different (ANOVA with Duncan's test, $p < 0.05$). G: gliricidia, HA + K: humic acid + potassium, K + G: potassium + gliricidia, K: potassium, HA + K +G: humic acid + potassium + gliricidia, HA + G: humic acid + gliricidia, HA: humic acid, US: uncovered soil.

The Shannon indexes were significantly higher at G and HA than at K + G and HA + G ($p < 0.05$). The Pielou index was significantly higher at G than at HA + K, K + G and HA + G ($p < 0.05$). The richness and abundance showed no significant difference between treatments ($p > 0.05$) (Table 2).

Table 2. Shannon index (*H'*), Pielou index (*J'*), total richness (S) and abundance (A) of soil fauna communities at different treatments (mean ± standard deviation). Distinct letters within the same column indicate significant differences ($p < 0.05$). G: gliricidia, HA + K: humic acid + potassium, K + G: potassium + gliricidia, K: potassium, HA + K + G: humic acid + potassium + gliricidia, HA + G: humic acid + gliricidia, HA: humic acid, US: uncovered soil, std. dev.: standard deviation.

Treatment	*H'* ± std.dev	*J'* ± std.dev	S ± std.dev	A ± std.dev
G	1.843 ± 0.079 a	1.796 ± 0.160 a	11 ± 2.7 a	14.5 ± 5.5 a
HA + K	1.593 ± 0.232 ab	1.430 ± 0.203 b	13 ± 0.8 a	24.9 ± 11.7 a
K + G	1.446 ± 0.129 b	1.473 ± 0.257 b	10.2 ± 3.2 a	20.1 ± 11.1 a
K	1.734 ± 0.181 ab	1.669 ± 0.198 ab	11 ± 0.8 a	13.3 ± 2.4 a
HA + K + G	1.594 ± 0.301 ab	1.672 ± 0.160 ab	9.2 ± 2.7 a	12.3 ± 3.9 a
HA + G	1.384 ± 0.309 b	1.406 ± 0.178 b	10.2 ± 4.3 a	16.5 ± 8.8 a
HA	1.831 ± 0.189 a	1.723 ± 0.225 ab	12 ± 2.9 a	14.7 ± 12.4 a
US	1.699 ± 0.210 ab	1.714 ± 0.151 ab	10.7 ± 4.6 a	13.2 ± 9.6 a

In the cluster analysis, the treatments with Euclidian distances between 20 and 30 were classified into three groups, i.e., (1) K + G, HA + K, (2) HA + G, HA + K + G, US, HA, K and (3) G. Group 1 includes treatments in which Isopoda stood out, group 2 contains mainly Formicidae, and group 3 isolated the only treatment in which Diplura predominated (Fig. 2).

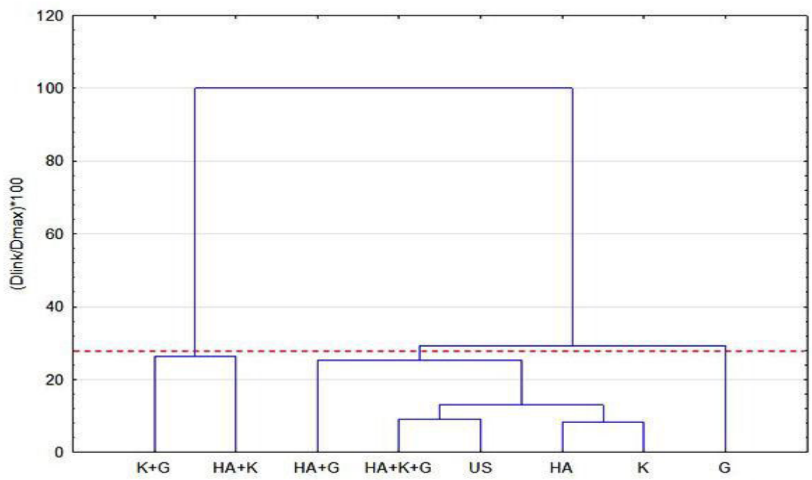

Fig 2. Dendrogram resulting from hierarchical cluster analysis with the formation of groups based on the Euclidean distance of the taxonomic groups of soil fauna. K + G: potassium + gliricidia, HA + K: humic acid + potassium, HA + G: humic acid + gliricidia, HA + K + G:

humic acid + potassium + gliricidia, US: uncovered soil, HA: humic acid, K: potassium, G: gliricidia.

Maize grain yield

The maize grain yield was significantly higher for all treatments that received gliricidia (G, K+G, HA+K+G and HA+G) than for treatments that did not receive it (HA+K, K, HA and US) ($p < 0.05$) (Table 3).

Table 3. Maize grain yield after different treatments. Distinct letters indicate significant differences (ANOVA with Duncan's test, $p < 0.05$). G: gliricidia, HA + K: humic acid + potassium, K + G: potassium + gliricidia, K: potassium, HA + K + G: humic acid + potassium + gliricidia, HA + G: humic acid + gliricidia, HA: humic acid, US: uncovered soil.

Treatment	Grain yield (Mg ha^{-1})
G	5.21 a
HA + K	3.06 b
K + G	5.17 a
K	2.81 b
HA + K + G	4.61 a
HA + G	4.91 a
HA	1.90 b
US	3.03 b

Relations between soil fauna and maize grain yield

In the PCA that associated yield with taxonomic groups, 53.54% of the variation was explained by its two main components. Axis 1 was mainly associated with Coleoptera and Formicidae, while axis 2 was associated with Araneae and Diplura. Yield showed a strong positive correlation with Araneae (Fig. 3a).

In the PCA that associated yield with ecological indexes and abundance, the two main components explained 78% of the variation. Axis 1 was mainly associated with Pielou index and Shannon index, while axis 2 was associated with richness and abundance. The only positive correlation found was between yield and abundance (Fig. 3b).

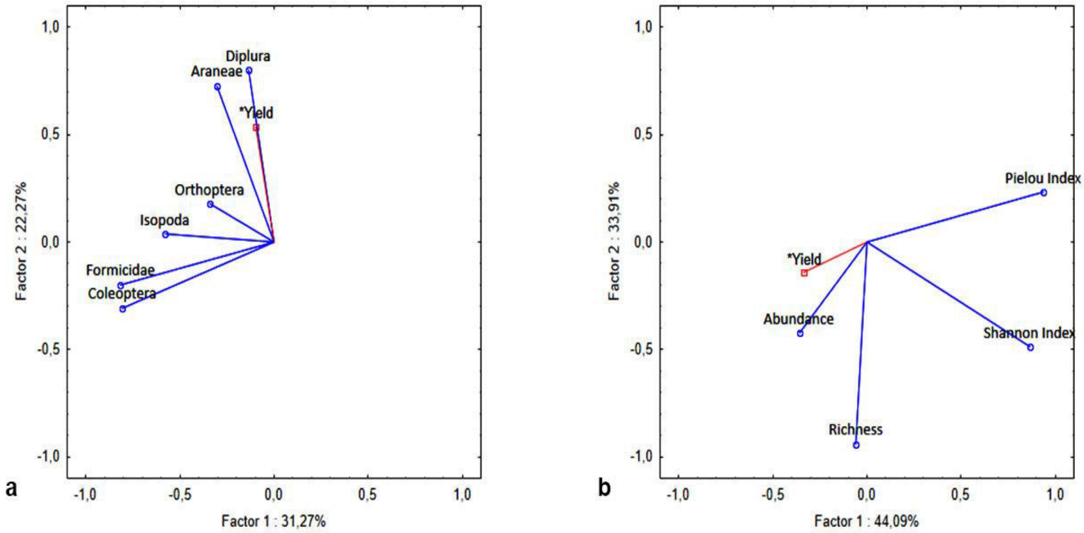

Fig 3. Principal component analysis (PCA) of the yield and the major groups of the soil fauna (a) and of yield and the ecological indexes and the abundance (b).

Discussion

In this research, the number of taxa and the total number of individuals in the soil fauna varied between treatments. Siqueira et al. (2014) and Blanchart et al. (2006) affirm that soil invertebrate communities vary according to the way that land is used. In study by Cluzeau et al. (2012), land uses and certain agricultural practices caused great differences in the populations of these organisms.

Isopoda stood out among all the groups, especially at the HA+K. For Podgaiski et al. (2011), isopods are related to the kind of agricultural crop and the land uses. According to Bahadur et al. (2014), potassium is one of the soil constituents that is most important for plant growth and development. For Bünemann et al. (2006), humic substances also increase plant growth. Since isopods are general detritivores, they can feed upon the foliage of seedlings, and their mandibles are capable of considerable fragmentation of decaying vegetable matter (Coleman et al., 2004). This may have favoured a faster reproduction of this group, which probably had access to plant remains due to fertilization with humic acid and potassium.

Formicidae stood out in the K. Coleman et al. (2004) note that activities of this group reduce the abundance of predators, as was verified in the present study. This taxon is sensitive to changes in land use and to disturbances (Andersen et al., 2002). Because of this, ants may be useful to evaluate the biological status of the cultivated stands. They can also have significant influences on soil and ecosystem functioning, and thus their populations reflect key ecological processes within agroecosystems (Lavelle et al., 2006).

In a study performed in Colombia, ant communities were greatly influenced by soil alterations (Sanabria et al., 2014). According to Siqueira et al. (2014), soil cover is one of the factors affecting the organic matter and litter production in agricultural fields and thus the food availability for soil fauna. In an experiment conducted with tillage and crop residue retention and that included Leguminosae, ants were one of the most abundant groups (Paul et al., 2015). However, in our research, we did not note a specific increase in the Formicidae community under treatments with gliricidia. Zörb et al. (2014) report that potassium enhances the soil structure, for example, the water-holding capacity. This function of potassium may have favoured the presence and activity of the ants, which also improve soil structure, since according to Paul et al. (2015), they are considered engineers. The sum of these factors may have caused the growth of this population in the area fertilized with potassium.

In this study, when G and HA were applied separately, diversity was significantly higher than when they were applied together ($p < 0.05$). Some studies indicate that direct adverse effects on living organisms can be induced by humic substances (Bittner, 2006). In a maize cropping system in a tropical region, the diversity of the soil biota was modified by the presence of Leguminosae. Furthermore, this plant stimulated the development of organisms that can promote soil structure (Blanchart et al., 2006), and this may eliminate other taxa. Moura et al. (2015) argue that the use of some kind of leguminous plants can increase soil acidity and decrease the diversity of the fauna. These added factors may have maximized the negative effect on diversity when humic acid and gliricidia were applied together. De Bruyn (1999) highlight that low biological diversity is characteristic of a less resilient soil that is more vulnerable to perturbations. For Thakur et al. (2014), relationships between disturbance and diversity of soil fauna are dependent on the context. Thus, each case should be analysed carefully.

Franco et al. (2016) verified that the abundance of soil fauna had relationship with K. Sanabria et al. (2014) also found that land use influences the abundance of these organisms. Zhu and Zhu (2015) affirm that there is an association between different types of fertilization and the abundance of the soil fauna community. However, we did not confirm these findings in our research, because abundance did not show significant differences between treatments ($p > 0.05$).

Three groups based on the shortest Euclidian distance were formed by cluster analysis. Treatments in the same group share the closest relationship, because according Lee et al. (2006), the distance represents the degree of association between treatments. Thus, the shorter this distance, the more intimate the association. Blanchart et al. (2006) showed that soil fauna was deeply affected by the introduction of a legume in maize crop areas, favouring the development of Isopoda and decreasing the size of the ant community. Although Isopoda are sensitive to soil alterations (Büchs, 2003), as are Formicidae (Andersen et al., 2002), no pattern was found here. Nevertheless, the grouping according to cluster analysis was consistent with the predominance of some taxa in different groups.

The maize grain yield was significantly higher in treatments that received gliricidia than in those that did not receive it ($p < 0.05$). This finding is consistent with that of Rao and Mathuva (2000), who found that green manuring with gliricidia increased maize yield in an experiment conducted in Kenya. Kamara et al. (2000) attributed the increased maize yield to the presence of gliricidia because this legume has high nitrogen content and is fast decomposing, favouring crop development.

Ouédraogo et al. (2006) highlighted the positive effects of soil fauna on processes of fertility for plant growth. Shukla et al. (2016), for example, found that the ecosystem engineering activities of a species of ant enhance the yield of cereals. In the present study, however, we did not detect this association with maize yield. The only association we found by PCA between yield and groups of soil fauna occurred with Araneae. This finding does not corroborate with that of Paul et al. (2015), who found that higher maize grain yield in Kenya was related to a total exclusion of macrofauna. Rivers et al. (2016) explain that Araneae is a group of generalist predators, and these organisms can consume insect pests, contributing to reduced plant damage. For Sileshi and Mafongoya (2006), important functions such as predation may influence plant development, because they may prevent pest outbreaks and thus improve ecosystem sustainability. Since predator populations and prey populations are generally compatible (Moura et al., 2015), and pests may exist within the prey population, the activity of Araneae may reduce the amount of pests and favour increased maize yield.

For Zhu and Zhu (2015), edaphic fauna community indexes must be used in combination, for example, with productivity, in order to evaluate overall changes in soil fertility. In the present research, however, we did not find an association between yield and diversity indexes, although we observed a correlation between yield and fauna abundance. Increased yield associated with increased abundance may be related to the presence of invertebrates of different ecological functions (predators, engineers, decomposers) in the soil, even though there is no increase in biological diversity. For Kilowasid et al. (2012), this functional diversity improves ecosystem services, such as yield. Blanchart et al. (2006) affirm that a better use of biota resources may increase the functional properties of ecosystems and allow better agricultural productivity and sustainability.

Materials and methods

Experimental design and maize yield

The experiment was conducted at Brejo city (3º38' south latitude and 42°58' west longitude), Maranhão State, Brazil. This region has a humid tropical climate with 1200-1400 mm of average annual precipitation. The soil is an Arenic Hapludult (Soil Survey Staff, 2010), presenting a flat topography (slope < 1%) and sandy textural class with the following characteristics: pH 4.4 in 0.01 M $CaCl_2$; organic C 15.5 g kg^{-1}; potential acidity 4.7, CEC 7.9 $mmol_{(c)}$ dm^{-3}; Ca 2.6, Mg 0.5, K 0.1 $mmol_{(c)}$ dm^{-3}; P 3.7 g dm^{-3} (resin); and base saturation 40.2%.

The experimental area was established in 2012 and consists of an alley crop system with Gliricidia (*Gliricidia sepium*), planted with an inter-row spacing of 4 m and an inter-plant spacing of 0.5 m.

In January 2015, between the rows of the legume, the area was divided into 32 plots of 4×10 m with seven treatments and the control, with four replicates (R) in a randomized block design. The following treatments were performed: *Gliricidia sepium* – gliricidia (G), potassium (K), humic acid (HA), humic acid + potassium (HA + K), potassium + gliricidia (K + G), humic acid + gliricidia (HA + G), humic acid + potassium + gliricidia (HA + K + G) and uncovered soil (US).

The pruning of the legume was carried out and the green matter was separated to be used in the treatments with gliricidia. In these treatments were applied 15 t ha^{-1} of biomass of the legume. In the treatments that received potassium were applied 78 kg ha^{-1} of KCl, while in treatments with humic acid were applied 500 l ha^{-1} of this substance. All treatments received 120 kg ha^{-1} of P_2O_5, 60 kg ha^{-1} of N e 25 kg ha^{-1} of $ZnSO_4$. These doses were defined according to the result of the soil analysis.

Plants of maize (*Zea mays* L.), variety QPM BR 473, were cropped in each plot in March 2015 in a total area of 1.280 m². At the phase of physiological maturity, ten cobs of each plot were collected, and the grains were extracted. The grain yield was estimated in Mg ha-¹, from the total grain mass in each plot and the number of plants per hectare.

Soil fauna

Soil fauna was sampled using the pitfall trap method during a seven-day period in July 2015. These traps were made of plastic and were approximately 9 cm in height and 8 cm in diameter; these were allocated to the ground level. The samples were preserved in glasses with 200 mL of formaldehyde solution (4%). The contents of the glasses was transferred to containers with 70% alcohol and properly identified.

In the laboratory, each sample was processed, separated and identified into order or family using a binocular microscope and taxonomic keys. Formicidae was considered separately from other Hymenoptera due to its ecological importance in the community.

Abundance, dominance and ecological indexes – richness, Shannon–Wiener diversity index (*H'*) and Pielou equitability index (*J'*) – were used for evaluation of soil fauna structure.

Fauna abundance is calculated as the number of individuals per trap per day. Dominance is the number of individuals in a given taxon per trap per day. The richness is the number of groups that occur in the sample. The Shannon–Wiener index is calculated by the formula:

$$H' = -\sum_{i=1}^{s} pi \ log_2(pi)$$

where pi = probability of a member of taxon i occurring in a trap per day and s = total number of taxa encountered in a trap per day. The Pielou evenness index indicates how individuals are distributed between the different taxa present in the sample. It is calculated as:

$$J' = \frac{H'}{log_2 \ (s)}$$

where *H*' is the Shannon index and s is the number of groups present in a trap per day.

Statistical analysis

For statistical analysis, one–way ANOVA was conducted to determine the significance of the difference in means of soil fauna dominance, abundance, richness, Shannon–Wiener index, Pielou index and maize grain yield. Duncan's test was used to determine which differences were significant ($p < 0.05$). Abundance data were transformed to meet the assumptions of normal distribution and homogeneity of variance. For cluster analyses, the Euclidean distance between the mean abundances of soil fauna groups was used as the measure of similarity to the areas by the Ward's method. The association between the maize grain yield and the major groups of soil fauna was analysed, as was the association between maize grain yield and the ecological indexes and abundance. For this investigation, principal component analysis (PCA) was used, after standardization of data. Statistica, version 7 (Statsoft Inc., 2004) was used for all analyses.

Conclusion

Our results show that treatment with humic acid and potassium caused the dominance of isopods, and this may have been favoured by the ecological function exerted by this group as detritivores. The dominance of ants was also related to potassium application, and this can be explained by the improvements in soil structure provided by this taxon and this nutrient. The lower diversity found in the treatment that combined humic acid and gliricidia may be explained by the potentiation of possible adverse effects that this legume and humic substances have on the structure of the soil fauna. Although studies have associated Formicidae with grain yield, in this study, the only taxon associated with yield was Araneae, who are predators that can reduce the pest population, favouring yield. Although the abundance of fauna did not show differences between treatments, it was related to yield. This finding may be due to the importance of the diversity of ecological functions performed by fauna rather than biological diversity. This study does not confirm the hypothesis that different soil fertilization regimes affect soil fauna, influencing the yield. Nevertheless, we confirm that yield may be increased with the presence of specific groups and with the abundance of soil fauna. Our results show the importance of soil fauna to agricultural sustainability, suggesting that these organisms can be used to evaluate soil quality in order to reach a higher yield.

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CAPÍTULO 4

Linkages among soil fertilization regimes, chemical properties and maize grains yield in humid tropic

Experimental Agriculture – Submetido

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ABSTRACT

We hypothesize that there is a linkage among different soil fertilization regimes, soil chemical attributes and maize grains yield. We aimed to evaluate the relationships between different soil fertilization regimes, soil chemical properties and maize grains yield. The experiment was performed in northeastern Brazil, in a randomized block design, at an area divided into 24 plots with six treatments and four replicates (Nitrogen (N); Leucaena (L); Nitrogen+Leucaena (N+L); Humic Acid+Leucaena (HA+L); Humic Acid+Nitrogen (HA+N) and Humic Acid+Nitrogen+Leucaena (HA+N+L)). Each plot was cropped with maize (*Zea mays* L.) and the grains yield was estimated. Soil samples were collected at depths of 0–5 cm, 5–10 cm and 10–20 cm. Potential acidity, pH, soil organic carbon (SOC), available phosphorus, exchangeable potassium, calcium and magnesium, cation exchange capacity (CEC), sum of

basic cations (SBC) and base saturation (BS) were determined. Principal component analysis (PCA) was used to correlate soil chemical attributes with maize yield. Calcium, magnesium, available P and SBC were related to the maize grains yield in upper soil layer, especially at nitrogen fertilization. This research confirms the hypothesis that there is a linkage between different soil fertilization regimes, soil properties and the maize grains yield.
KEYWORDS: fertilizers, principal components analyses, macronutrients, green manure, Leucaena.

Introduction

To better understand about soil and plant system it is necessary to know how the interactions work between both them. In these interactions, any change in soil conditions also causes transformations in the plant. These transformations in plant, in turn, also alter the soil, in other words, there is a feedback. Early civilizations already knew the importance of these interactions and they recognized that agricultural productivity was affected by different soils (Ehrenfeld et al., 2005). In this context, Moura et al. (2009), argue that associations between plant productivity and soil chemical attributes are still unclear.

The soil is a biosphere component and it results of the combination between living and non-living organisms. Macro and micronutrients present in the soils play a key role in the plants life (promoting their growth) and in the evolution of own soil (Morar & Peterlicean, 2014). Calcium, magnesium, nitrogen, phosphorous and potassium are some examples of macronutrients, which are required in large quantities (>0.1% of dry mass) and plants need of each of them to develop and complete their life cycle (Maathuis, 2009). Essential cellular components, as nucleic acids and proteins, are built by macronutrients (Morgan & Connolly, 2013).

In general, the soil is characterized by low concentrations of inorganic macronutrients, being that this availability can change depending on place (Maathuis, 2009). According Morgan & Connolly (2013), agriculture may be greatly impacted by nutrients deficiency, decreasing plant quality and crop yield. In this sense, Ehrenfeld et al. (2005) recognize that probably associations between chemical and biogeochemical features of soil and plants are very difficult to evaluate. A study carried out in northeast Vietnã by Anh et al. (2014) suggests that macronutrient contents can be changed by alterations in land and in ground cover. In this context, there are already some studies about which fertilizer (mineral or organic) is most efficient to increase soil macronutrients contents and crop yield, though the conclusion also depends on many other factors.

Here, we hypothesize that there is a linkage among different soil fertilization regimes, soil chemical attributes and maize grains yield. Since the knowledge about fertilization procedures and macronutrients content is important to enhance crop yield, these interactions need further investigation. Then the aim of this study was to evaluate the relationships between different soil fertilization regimes, soil chemical properties and maize grains yield.

Materials and Methods

Study Site

The experiment was performed at Brejo city, located in Maranhão state, northeastern Brazil (3º38' S, 42°58' W). The climate is humid tropical with 1200-1400 mm of average annual precipitation and average annual temperature is above 27° C. The soil is classified as Arenic Hapludult (Soil Survey Staff, 2010), presenting a flat topography (slope < 1%) with the following characteristics: pH 4.4 (0.01 M $CaCl_2$); organic C 15.5 g kg^{-1}; potential acidity 4.7, and CEC 7.9 $mmol_{(c)}$ dm^{-3}; Ca 2.6, Mg 0.5, and K 0.1 $mmol_{(c)}$ dm^{-3}; P 3.7 g dm^{-3} (resin); base saturation 40.2%; and a sandy textural class.

The experimental area was established in 2012 and consists of an alley cultivation system with Leucaena (*Leucaena leucocephala*), planted with an inter-row spacing of 4 m and an inter-plant spacing of 0.5 m.

In January 2015, the area between the rows of the Leucaena was divided into 24 plots of 4x10 m with six treatments and four replicates (R) in a randomized block design. The treatments were: 133 kg ha^{-1} of urea, as a source of Nitrogen (N); 15 t ha^{-1} of *Leucaena leucocephala* – Leucaena (L); 133 kg ha^{-1} of urea+15 t ha^{-1} of Leucaena (N+L); 500 l ha^{-1} of humic acid+15 t ha^{-1} of Leucaena (HA+L); 500 l ha^{-1} of humic acid+133 kg ha^{-1} of urea (HA+N) and 500 l ha^{-1} of humic acid+133 kg ha^{-1} of urea+15 t ha^{-1} of Leucaena (HA+N+L). All treatments received 120 kg ha^{-1} of P_2O_5, 60 kg ha^{-1} of K_2O and 25 kg ha^{-1} of $ZnSO_4$. These doses were defined according to the result of the soil analysis.

Maize Grains Yield

Each plot was cropped with maize (*Zea mays* L.), variety QPM BR 473, in March 2015 in a total area of 960 m². At physiological maturity, ten cobs were collected from each plot, and their grains were extracted. The grains yield was estimated in Mg ha^{-1} from the total grain mass in each plot and the number of plants per hectare.

Soil Chemical Attributes

Soil samples were collected with a duty auger, at depths of 0–5 cm, 5–10 cm and 10–20 cm from each plot in July 2015. In the laboratory, each sample was analyzed to determine the pH (0.01 M $CaCl_2$ suspension, 1:2.5 soil/solution, v/v), the soil organic carbon (SOC) (Walkley-Black), the exchangeable K, Ca, Mg (resin) and potential acidity (H + Al) (SMP method) according Raij et al. (2001). For K determination, UV–Vis spectrophotometry was used. Available P was determined by the Mehlich 1. We determined the cation exchange capacity ($CEC = K^+ + Ca^{2+} + Mg^{2+} + H^+ + Al^{3+}$) and the sum of basic cations ($SBC = K^+ + Ca^{2+} + Mg^{2+}$), and these were used to calculate base saturation ($BS = [SBC/CEC] \cdot 100$).

Statistical analyses

For statistical analysis, the one-way ANOVA was conducted to determine the significance of the difference in means of soil chemical attributes and maize grains yield. Distributions of all variables were assessed using the Shapiro-wilk test, and they were transformed before analysis where necessary to achieve normal distributions. Duncan test was used to determine which differences are significant. Principal component analysis (PCA) was used, after standardization of data, with the main objective to identify the principal soil chemical attributes associated with maize yield. Statistica version 7 (Statsoft Inc., 2004) was used in all analyses.

Results

Maize grains yield

Plots that received nitrogen fertilizer produced significantly higher maize grains yield than that did not receive it ($p < 0.05$). The maize grains yield at N+L was significantly higher than in the others treatments (Table 1).

Table 1. Maize grains yield under different soil fertilization regimes.

Treatment	Grains Yield ($Mg\ ha^{-1}$)
HA+N	4,025b
HA+N+L	4,617b
L	1,472c
HA+L	1,600c
N	3,935b
N+L	5,385a

Distinct letters indicate significant differences (ANOVA with Duncan test, $p < 0.05$).
HA+N (humic acid+nitrogen), HA+N+L (humic acid+nitrogen+leucaena), L (leucaena), HA+L (humic acid+leucaena), N (nitrogen), N + L (nitrogen+leucaena).

Effect of different soil fertilization regimes on soil chemical properties

The potential acidity concentrations were the lowest in the upper soil layer (0–5 cm), and showed a tendency to increase with increasing soil depth, except at HA+L and N, where the depth of 5–10 cm showed the highest concentration and the lowest concentration, respectively. The different treatments did not change the potential acidity levels within the soil profile (0–20 cm) ($p > 0.05$) (Figure 1).

Within the 0–20 cm soil layer, pH concentrations were the highest at 0–5 cm layer and showed a tendency to decrease at 10–20 cm soil depth, except at HA+N+L. HA+N had significantly greater concentration ($p < 0.05$) in pH than L and HA+L at 0–5 cm depth, with increases of 0.6 in both treatments. There was no significant difference between treatments at the other soil depths ($p > 0.05$) (Figure 1).

The available P concentrations showed a tendency to decrease with increasing soil depth, except at N. However, within the 0–20 cm soil layer no significant differences in available P concentrations were observed between the treatments ($p > 0.05$) (Figure 2).

The SOC concentrations were the largest in the upper soil layer (0–5 cm) and showed a tendency to decrease with increasing soil depth, except at HA+N+L, where the depth of 5–10 cm showed the lowest content. The treatments did not change the SOC levels within the soil profile (0–20 cm) ($p > 0.05$) (Figure 2).

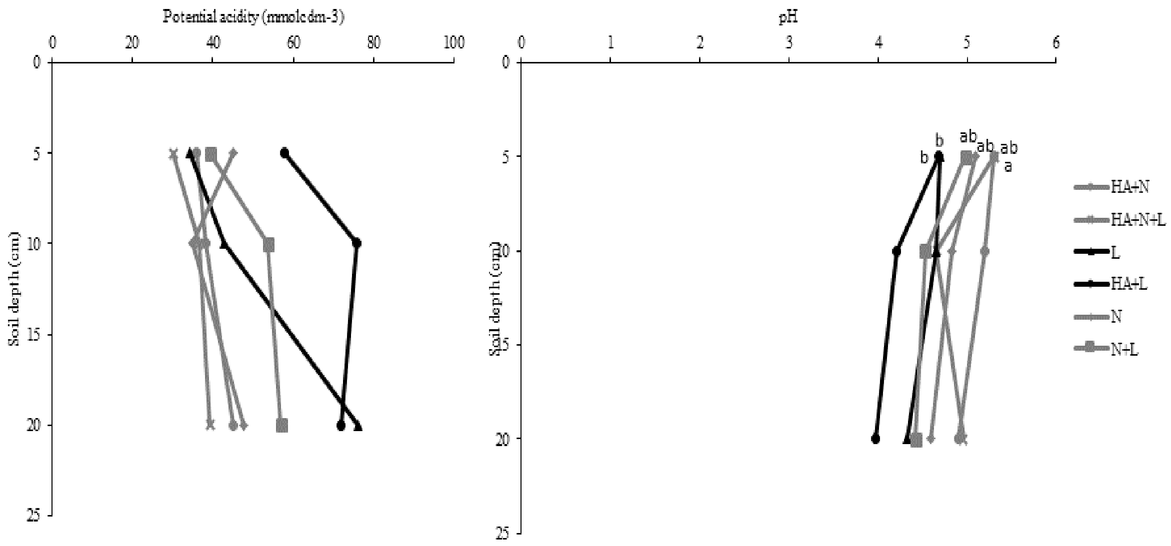

Figure 1. Effects of different soil fertilization regimes on potential acidity and pH at different soil depths. Different letters in the same depth indicate significant differences between treatments ($p < 0.05$) and missing letters in the same depth indicate no significant difference between treatments ($p > 0.05$).

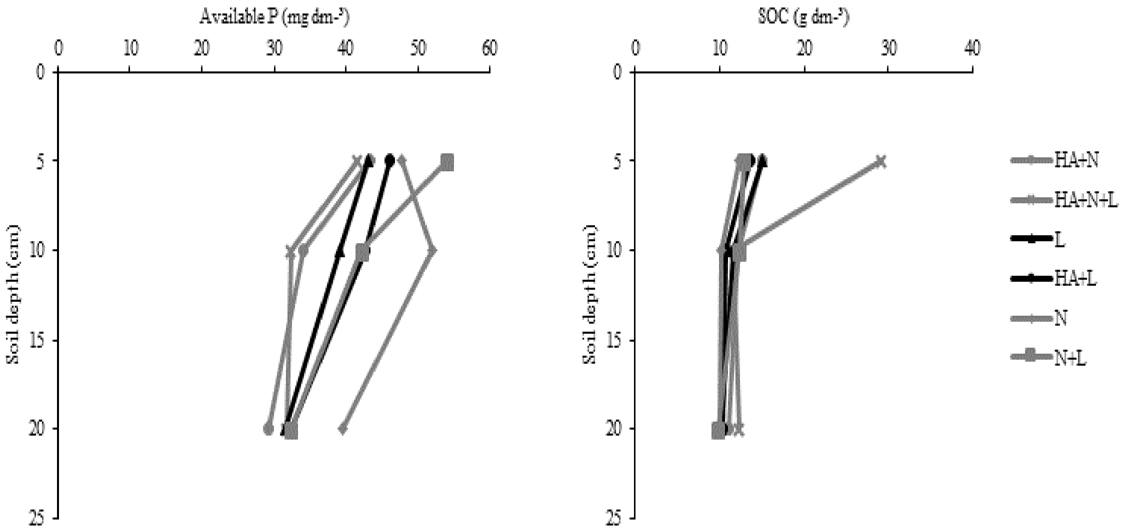

Figure 2. Effects of different soil fertilization regimes on available P and SOC at different soil depths. Missing letters in the same depth indicate no significant differences between treatments ($p > 0.05$).

Compared with N alone, HA+L and N+L showed a significant increase of 0.3 $mmol_c\ dm^{-3}$ in K^+ at 0–5 cm soil depth ($p < 0.05$). Compared with N alone, HA+N, HA+N+L and N+L resulted in significant increments of 12.8, 13.5 and 12.8 $mmol_c\ dm^{-3}$ in Ca^{2+} at 0–5 cm soil depth, respectively ($p < 0.05$). No significant difference in the K^+ and Ca^{2+} concentrations was recorded in the 5–20 cm soil layers and no significant difference in Mg^{2+} concentration was recorded in the 0–20 cm soil layer between all the treatments (Table 2).

The use of HA+N+L resulted in significantly highest concentration of SBC, leading to increases of 6.82, 9.73 and 2.53 $mmol_c\ dm^{-3}$ compared with HA+L, N and N+L at 0–5 cm soil depth, respectively ($p < 0.05$). The use of HA+L recorded a significantly highest concentration of CEC compared with all other treatments, with decreases of 14.88, 20.93, 14.93, 15.54 and 14.30 $mmol_c\ dm^{-3}$ at HA+N, HA+N+L, L, N and N+L, respectively ($p < 0.05$). Compared with HA+L and N, the BS concentrations resulted in significant increments of about 14%–15% in both HA+N and HA+N+L at 0–5 cm soil depth ($p < 0.05$). No significant difference in SBC, CEC and BS concentrations was recorded at 5–20 cm soil depth ($p > 0.05$) (Table 2).

Table 2. Effects of different soil fertilization regimes on exchangeable K^+, Ca^{2+} and Mg^{2+} and SBC, CEC and BS at different treatments (mean ± standard deviation).

Soil depth	Treatment	K^+	Ca^{2+}	Mg^{2+}	SBC	CEC	BS
						$mmol_c/dm^3$	%
0 – 5	HA+N	1.8±0.2ab	35.8±2.2a	10.8±4.9a	48.27 ± 11.60ab	84.13 ± 13.03b	61.27 ± 13.01a
	HA+N+L	1.8±0.2ab	36.5±2.7a	9.8±5.1a	47.97 ± 1.09a	78.08 ± 8.86b	61.46 ± 3.94a
	L	2.1±0.1ab	35.0±4.5ab	12.5±4.0a	49.65 ± 16.95ab	84.08 ± 10.04b	58.97 ± 20.16ab
	HA+L	2.2±0.1a	28.8±3.5ab	10.3±4.6a	41.15 ± 2.03b	99.01 ± 10.95a	46.40 ± 6.45b
	N	1.9±0.1b	23.0±9.9b	13.4±4.3a	38.24 ± 5.56b	83.47 ± 13.5b	46.95 ± 5.43b
	N+L	2.2±0.1a	35.8±2.4a	7.5±0.6a	45.44 ± 0.18b	84.71 ± 13.97b	54.14 ± 18.82ab
5 – 10	HA+N	1.4±0.2a	28.8±15.6a	8.8±1.5a	38.89 ± 14.76a	77.29 ± 21.77a	52.85 ± 21.43a
	HA+N+L	1.4±0.3a	26.5±3.9a	7.9±3.8a	35.80 ± 4.50a	72.40 ± 9.34a	49.68 ± 5.50 a
	L	1.5±0.7a	26.5±10.1a	7.5±6.6a	35.47±15.31a	78.27 ± 11.10a	44.21 ± 14.38 a
	HA+L	1.6±0.5a	18.3±4.6a	8.0±1.4a	27.86 ± 6.06a	103.78 ± 38.55a	29.94 ± 13.53a
	N	1.7±1.0a	31.3±13.7a	6.3±1.5a	39.21 ± 15.30a	74.08 ± 6.92a	53.33 ± 22.06a
	N+L	1.4±0.2a	24.8±7.5a	7.5±2.6a	33.66 ± 8.30a	87.40 ± 26.92a	41.14 ± 13.91a
10 – 20	HA+N	1.6±0.6a	26.0±16.6a	6.8±2.5a	34.39 ± 16.66a	79.63 ± 19.48a	44.28 ± 23.98a
	HA+N+L	1.6±1.1a	30.3±21.0a	7.6±4.0a	39.51 ± 26.05a	78.84 ± 11.92a	48.97 ± 28.04a
	L	1.3±0.6a	20.0±9.9a	7.0±2.9a	28.28 ± 12.92a	104.49 ± 34.08a	27.34 ± 11.65a
	HA+L	1.5±0.3a	15.0±4.1a	4.8±3.0a	21.21 ± 6.82a	93.07 ± 39.81a	25.46 ± 13.57a
	N	1.1±0.3a	24.0±13.5a	6.3±2.9a	31.32 ± 14.71a	79.18 ± 11.16a	41.97 ± 25.43a
	N+L	1.2±0.3a	19.8±6.9a	4.5±3.0a	25.45 ± 9.35a	82.35 ± 20.20a	32.30 ± 14.03a

Distinct letters by column in each soil depth indicate significant differences (ANOVA with Duncan test, $p < 0.05$).

HA+N (humic acid+nitrogen), HA+N+L (humic acid+nitrogen+leucaena), L (leucaena), HA+L (humic acid+leucaena), N (nitrogen), N+ L (nitrogen+leucaena).

Relations between different soil fertilization regimes, soil chemical attributes and maize grains yield

Available P, Ca^{2+}, Mg^{2+} and SBC only showed positive correlations with maize grains yield in the 0–5 cm soil depth, especially at N. CEC, BS, SOC and the acidity parameters (pH and potential acidity) did not show any correlation with maize grains yield in the soil profile (0–20 cm) (Figures 3a, 3b and 3c).

Potential acidity always showed negative correlation with all attributes, except with CEC in all soil depths. The pH was positively associated with both SBC and BS, while Mg^{2+} was always positively related to SBC in the 0–20 cm soil depth. Nitrogen alone or mixed showed positive association with maize grains yield in 0–10 cm soil depth, while HA+L and L did not showed any association in soil profile (0–20 cm) (Figures 3a, 3b and 3c).

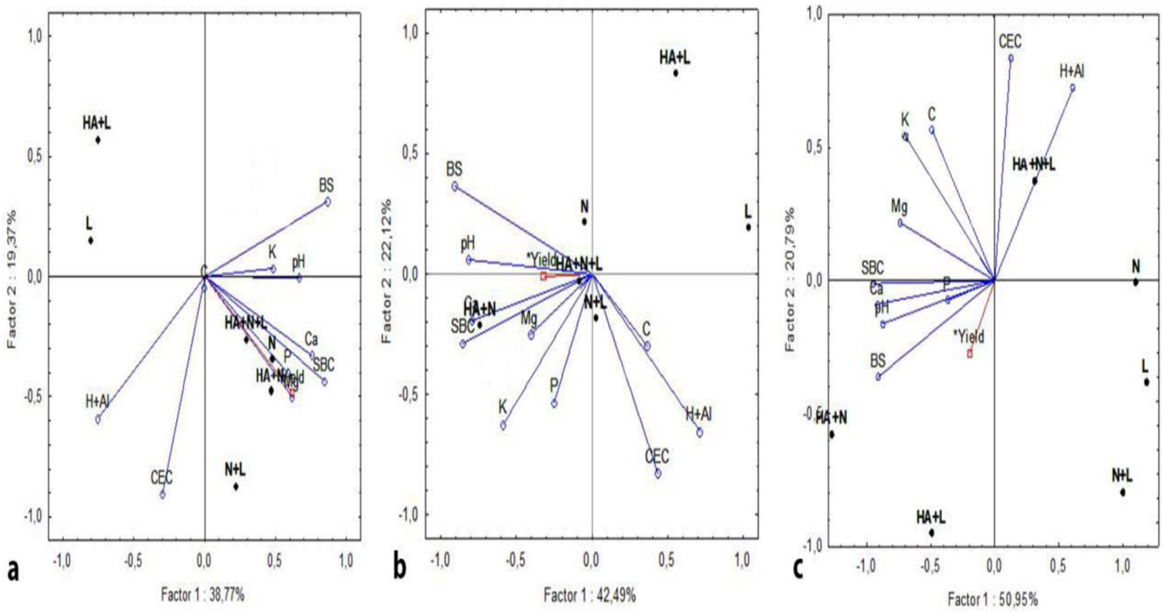

Figure 3. Results of principal components analysis at 0–5 cm (a), 5–10 cm (b) and 10–20 cm soil depth (c) in different soil fertilization regimes.

Discussion

Maize grains yield

Nitrogen fertilizer showed a significant increase in maize grains yield ($p < 0.05$), as predicted by Li et al. (2019) and Yang et al. (2017), who point out that crops generally respond very well to the application of nitrogen fertilizer. Wang et al. (2008) reported that the main nutrient to increase maize yield is N, which also interferes positively in the grain proteins concentration. For Qiang et al. (2019), beyond N availability, the maize genotype also is an essential factor for growth and grains yield. According to Martins et al. (2018), nitrogen fertilization influences soil fauna, which can increase maize grains yield, since it can enhance the soil structure and nutrients composition, due to importance that it occupies as soil engineers and decomposers of organisms remains.

The higher maize grains yield at N+L ($p < 0.05$) is according Gai et al. (2016), for which this combined application enhances soil fertility, crops yield and sustainability, being better than application of chemical or organic fertilizer alone. According Afolayan & Oyetunji (2018), besides improving soil structure, organic materials increase the soil organic carbon content, then enhancing crop yield. In this sense, Zhong et al. (2018) emphasize the importance of green manure using legumes, which alter soil bacterial community structure, enhancing soil fertility. Inclusion of leucaena pruning provides additional nutrients and benefits of organic matter to soils, leading to increase in maize grains yield (Mugendi et al., 1999), as well as to increased removal and efficiency of inorganic N use in tropical cohesive soils in the same region (Aguiar et al., 2018).

Effect of different soil fertilization regimes on soil chemical properties

In general, while the potential acidity increased with increasing soil depth, the pH decreased. According Shukla et al. (2013), this can be caused by the formation of acids due to the percolation of the water in the deeper layers of the soil. In fact, the lower the pH, the higher the acidity. In this sense, it is important to clarify that while pH considers only hydrogen ions, the potential acidity considers hydrogen ions of various chemical combinations and adsorbed on the solid particles surfaces (Allaway, 1957). The pH only showed difference between treatments in the upper soil layer ($p < 0.05$), but no significant difference as a function of depth, as Davenport et al. (2003) also noted in their research. The humic acid may have led to increasing in acidification of the soil at HA+L in upper layer (Dobbs et al., 2009), maximizing its effect by the organic matter from leucaena.

With increasing soil depth, the concentrations of available P tended to decrease, as Franzluebbers & Hons (1996) detected. This decreasing was also recorded for Milić et al. (2019), who affirm that this occurs because the soil upper layer serves as a nutrient deposition site. According Ehrenfeld et al. (2005), cations redistribution through the soil is influenced by plants, and phosphorus is highly concentrated in upper soil because it is a cation with high concentrations in vegetable tissues. Besides that, since agricultural systems do not function as a natural environment, both the dynamics and the quantity and nutrients availability, such as phosphorus, receive great human influence (Milić et al., 2019). In this context, Maharjan et al. (2018) showed that land alterations have a great influence on the phosphorus concentration in soil. However, there were no significant differences in available P concentrations between treatments in the present study ($p > 0.05$).

We found that SOC concentrations showed a tendency to decrease with increasing soil depth, as well as in the study done by Li et al. (2019), who related this decreasing to the vertical distribution of the crop root system. They also suggested that the SOC distribution in the soil profile depends on both the soil type and source material. However, Yang et al. (2018) recorded that soil depth was positively related to the SOC. In this context, Lorenz & Lal (2005) affirm that soil organic matter (SOM) increases with depth due to its chemical recalcitrance and turnover time, and this favors the increase in SOC in deeper layers. For Arif et al. (2016), when organic materials are added in the soil, the SOC tend to increase. Nevertheless, we did not find these results where organic fertilizers were used.

N+L showed a significant increase in K^+ and Ca^{2+} concentrations, compared with N alone, at 0–5 cm soil depth ($p < 0.05$). Leucena is a source not only of N, but also of other nutrients such as potassium and calcium, although influences less the latter (Lupwayi & Haque, 1998). According Ordóñez-Fernández et al. (2015), residues as leucaena, besides providing protection, also enrich the soil with nutrients, depending on both the residue amount and composition, and also on its decomposition process. These researchers found that K^+ content was influenced by pruning residues, as in the present study. In this sense, they pointed out that potassium is easily released from the residues during decomposition when rainfall is favorable, probably due to the presence of this element in mobile cations released when the cell membrane ruptures.

The use of HA+N+L resulted in highest concentrations of SBC and BS at 0–5 cm soil depth ($p < 0.05$). Legumes used as green manures increase soil organic matter and, consequently, SBC and BS, especially in tropical soils (Delarmelinda et al., 2010). Since humic acid is derived from soil organic matter (Mindari et al., 2014), when added to the legume and nitrogen fertilizer, may have potentiated its effects on SBC and BS.

HA+L recorded highest concentration of CEC in the soil upper layer ($p < 0.05$). According Carvalho et al. (2014), organic matter accumulated in the topsoil can lead to the increase in the CEC, due to the increase in soil negative charges. Delarmelinda et al. (2010) explain that the largest percentage of total CEC in tropical soils originates from organic matter (70-90%).

Relations between different soil fertilization regimes, soil chemical attributes and maize grains yield

Available P, exchangeable Ca^{2+} and Mg^{2+} were positively associated with maize grains yield in soil superficial layer, especially at nitrogen fertilization. Salvagiotti et al. (2017) point out that crop growth during grains number formation is positively impacted by nutrients availability, which can consequently to increase maize yield. Some macronutrients as calcium and magnesium collaborate to crop development and metabolism (Cakmak, 2001), through essential constituents fabrication (Cronk & Fennessy, 2001) and strengthening of plant structure, contributing to agricultural yield. Phosphorus is a very important nutrient to increase maize yield (Adepetu, 1993) and its deficiency in soil decreases until the plant photosynthetic rate (Zhang et al., 2018). Furthermore, phosphorus is involved with enzymatic reactions, cell division, carbohydrate synthesis and degradation, crop maturation, fortification of the plant skeletal structure and grains quality (Onasanya et al., 2009). The present study showed that SBC also is related to maize grains yield, but Brunn et al. (2006) did not find this relation in their research using cereal. High SBC may indicate increased soil fertility, which may also lead to increased yield.

Nitrogen alone or mixed and maize grains yield were associated by PCA in 0–10 cm soil depth, confirming ANOVA results. One of the main techniques to enhance crop yield is to increase application of N fertilizers (Guo et al., 2010), and according Moser et al. (2006), this nutrient is one of most limiting factors for maize grains yield.

Acidity-related parameters showed some associations. Potential acidity only was positively related to CEC, since it is used to estimate the concentration of this variable. The pH was positively associated to both SBC and BS in all layers, as Abreu Jr. et al. (2003) also recorded at Brazilian soils. Moreira & Fageria (2009), also researching Brazilian dystrophic soils, showed that pH and BS were positively correlated and presented low contents due to the high degree of intemperization that occurs in this type of soil.

Conclusion

The main results of this research indicate that combination between an organic and an inorganic source of nitrogen at N+L led to the increase in maize grains yield and, in this sense, the legume presence was essential to enhance fertility due to probable alteration of soil bacterial community. The presence of leucaena at N+L led to increase in potassium and calcium concentrations, because leucaena enriches the soil with these nutrients. Legume and humic acid presence together probably increased organic matter content at HA+N+L and HA+L, increasing soil negative charges, leading to the highest SBC and BS concentrations and CEC concentration, respectively. Calcium, magnesium and phosphorus were associated with maize grains yield in topsoil especially in nitrogen fertilization, since these nutrients cooper with crop metabolism, producing essential constituents and enhancing the plant structure. This study confirms the hypothesis that there is a linkage between different soil fertilization regimes, soil properties and the maize grains yield.

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CAPÍTULO 5

Effect of different soil fertilization regimes on soil chemical properties and maize grains yield in humid tropic

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Abstract

Nutrients contained in soil play a fundamental role in plants development. In this research we hypothesize that different soil fertilization regimes modify soil chemical attributes and maize grains yield. Our aim was to evaluate soil chemical attributes in different soil fertilization regimes and their relation to maize grains yield. The experiment was performed in Maranhão state, Brazil. The area was divided into 32 plots of 4x10 m with seven treatments and the control, with four replicates (R) in a randomized block design. The following treatments were performed: *Gliricidia sepium* – gliricidia (G), potassium (K), humic acid (HA), humic acid+potassium (HA+K), potassium+gliricidia (K+G), humic acid+gliricidia (HA+G), humic acid+potassium+gliricidia (HA+K+G) and uncovered soil (US). Each plot was cropped with maize (*Zea mays* L.) and the grains yield was estimated. Soil samples were collected from each plot at depths of 0–5 cm, 5–10 cm and 10–20 cm. Potential acidity, pH, soil organic

carbon (SOC), K^+, Ca^{2+} and Mg^{2+} and available P were determined. Cation exchange capacity (CEC), sum of basic cations (SBC) and base saturation (BS) were calculated. For statistical analysis, the one-way ANOVA with Duncan post-test was used. Principal component analysis (PCA) was used to identify the principal chemical attributes associated with maize yield. Exchangeable K^+, Ca^{2+} and Mg^{2+}, pH and CEC were related to maize grains yield in upper soil layer especially in plots with gliricidia. We confirm the hypothesis that different soil fertilization regimes modify soil chemical attributes and maize grains yield.
Keywords: green manure, gliricidia, principal component analyses, maize yield.

Introduction

Soils are considered essential for life on earth (Brady & Weil, 2008). They are result of association between biotic and abiotic factors, and the macro and micronutrients contained in them play a fundamental role in plants development (Morar & Peterlicean, 2014). Ehrenfeld et al. (2005) point out that the influence that soils different cause on agricultural yield was already observed by ancient civilizations such as the Mayans and the Romans and that it is necessary to understand both soils and plants to know better the interactions between them. In this sense, chemical attributes of soil quality need investigations because they are related to soil ability to provide nutrients to plants (Wang & Yang, 2003).

The concentration and combination of mineral nutrients into the soil influence plants growth and development, which encounter some difficult to obtain the adequate supply of these nutrients due to their relative immobility. If one of nutrients is not in proper concentration, plant productivity may decrease, leading to decline in crop yield (Morgan & Connolly, 2013). According Liu et al. (2010), changes in soil chemical properties are influenced by fertilization practices over time.

Bulluck III et al. (2002) also point out the relevance of fertilization and they consider that the use of organic or synthetic fertilizer modify macronutrients concentrations. Morar & Peterlicean (2014) affirm that chemical fertilizers are more efficient to increase plant production than organic fertilizers, although the latter enhance soil structure. On the other hand, some researches show that organic fertilizers increase the soil nutrients availability and fertility (Ordóñez-Fernández et al., 2015; Zhang et al., 2019) and that their benefits for soil depend on their addition rates and composition (Arif et al., 2016). A better understanding about which fertilizer should be used to ensure high crop yields is needed, especially in cohesive soil (Moura et al., 2012), such as the soil studied in this research.

Without an adequate supply of nutrients in low fertility soils as most of tropical soils, maize (*Zea mays* L.) would not produce a high grains yield because it is a very demanding crop (Adediran & Banjoko, 1995). According Srivastava et al. (2018), this crop is one of most important food crop in the world and its yield increases in according soil fertilization regime, among some other factors.

In this context, we hypothesize that different soil fertilization regimes modify soil chemical attributes and maize grains yield. Since that these interactions need further studies because may enhance crop yield, our aim was to evaluate soil chemical attributes in different soil fertilization regimes and their relation to maize grains yield.

Material and methods

Study Site

The experiment was performed at Brejo city, located in Maranhão state, Brazil (3°38' S, 42°58' W). The climate is humid tropical with 1200-1400 mm of average annual precipitation and average annual temperature is above 27° C. The soil is classified as Arenic Hapludult (Soil Survey Staff, 2010), presenting a flat topography (slope < 1%) with the following characteristics: pH 4.4 (0.01 M $CaCl_2$); organic C 15.5 g kg^{-1}; potential acidity 4.7, and CEC 7.9 $mmol_{(c)}$ dm^{-3}; Ca 2.6, Mg 0.5, and K 0.1 $mmol_{(c)}$ dm^{-3}; P 3.7 g dm^{-3} (resin); base saturation 40.2%; and a sandy textural class.

The experimental area was established in 2012 and consists of an alley crop system with Gliricidia (*Gliricidia sepium*), planted with an inter-row spacing of 4 m and an inter-plant spacing of 0.5 m.

In 2015, between the rows of the legume, the area was divided into 32 plots of 4x10 m with seven treatments and the control, with four replicates (R) in a randomized block design. The following treatments were performed: *Gliricidia sepium* – gliricidia (G), potassium (K), humic acid (HA), humic acid+potassium (HA+K), potassium+gliricidia (K+G), humic acid+gliricidia (HA+G), humic acid+potassium+gliricidia (HA+K+G) and uncovered soil (US).

The pruning of the legume was carried out and the green matter was separated to be used in the treatments with gliricidia. In these treatments were applied 15 t ha^{-1} of biomass of the legume. In the treatments that received potassium were applied 78 kg ha^{-1} of KCl, while in treatments with humic acid were applied 500 l ha^{-1} of this substance. All treatments received 120 kg ha^{-1} of P_2O_5, 60 kg ha^{-1} of N e 25 kg ha^{-1} of $ZnSO_4$. These doses were defined according to the result of the soil analysis.

Maize Grains Yield

Each plot was cropped with maize (*Zea mays* L.), variety QPM BR 473, in March 2015 in a total area of 1,280 m^2. At physiological maturity, ten cobs were collected from each plot, and their grains were extracted. The grains yield was estimated in Mg ha-^{1} from the total grain mass in each plot and the number of plants per hectare.

Soil Chemical Attributes

Soil samples were collected with a duty auger, at depths of 0–5 cm, 5–10 cm and 10–20 cm from each plot in July 2015. In the laboratory, each sample was analyzed to determine pH (0.01 M $CaCl_2$ suspension, 1:2.5 soil/solution, v/v), soil organic carbon (SOC) (Walkley-Black), exchangeable K, Ca, Mg (resin) and potential acidity (H + Al) (SMP method) according Raij et al. (2001). For K determination, UV–Vis spectrophotometry was used. Available P was determined by the Mehlich 1. We determined the cation exchange capacity (CEC = $K^+ + Ca^{2+} + Mg^{2+} + H^+ + Al^{3+}$) and the sum of basic cations (SBC = $K^+ + Ca^{2+} + Mg^{2+}$), and these were used to calculate base saturation (BS = [SBC ∕ CEC] · 100).

Statistical analyses

For statistical analysis, the one-way ANOVA was conducted to determine the significance of the difference in means of chemical attributes and maize grains yield. Distributions of all variables were assessed using the Shapiro-wilk test, and they were transformed before analysis where necessary to achieve normal distributions. Duncan test was used to determine which differences were significant. Principal component analysis (PCA) was used, after standardization of data, with the main objective of identify the principal chemical attributes associated with maize yield. Statistica version 7 (Statsoft Inc., 2004) was used in all analyses.

Results

Maize grains yield

The maize grains yield was significantly higher in all treatments that received gliricidia (G, K+G, HA+K+G and HA+G) than in treatments that did not receive it (HA+K, K, HA and US) ($p < 0.05$) (Table 1).

Table 1. Maize grains yield in different treatments.

Treatment	Grain yield (Mg ha^{-1})
G	5.21 a
HA+K	3.06 b
K+G	5.17 a
K	2.81 b
HA+K+G	4.61 a
HA+G	4.91 a
HA	1.90 b
US	3.03 b

Distinct letters indicate significant differences (ANOVA with Duncan's test, $p < 0.05$).
G (gliricidia), HA+K (humic acid+potassium), K+G (potassium+gliricidia), K (potassium), HA+K+G (humic acid+potassium+gliricidia), HA+G (humic acid+gliricidia), HA (humic acid), US (uncovered soil).

Effect of different soil fertilization regimes on soil chemical properties

Within the 0–20 cm soil layer, potential acidity showed a tendency to increase with increasing soil depth, except at HA+K, K+G and HA+G. HA+G had significantly greater concentrations in potential acidity than all other treatments ($p < 0.05$) at 0–5 cm soil depth, with increases of 26.1 to 50.1 $mmol_c$ dm^{-3}. There was no significant difference between treatments at 5–20 cm soil layer ($p > 0.05$) (Figure 1).

pH was the largest in the upper soil layer (0–5 cm) and showed a tendency to decrease with increasing soil depth at G, K+G, K and US. pH was significantly greater in G than in HA+K and HA ($p < 0.05$), with increases of 0.6 and 0.8 at 0–5 cm soil depth, respectively. The treatments did not change the pH levels at 5–20 cm soil depth ($p > 0.05$) (Figure 1).

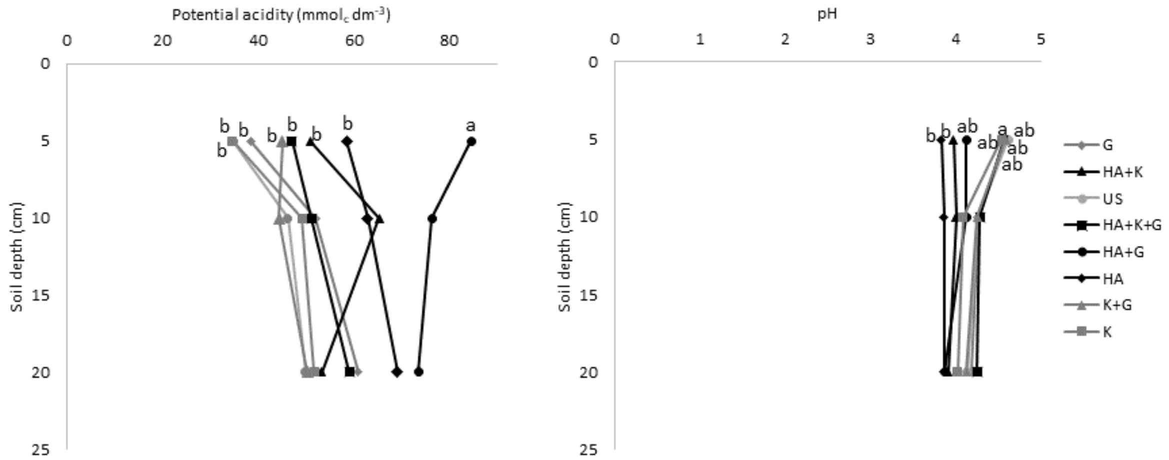

Figure 1. Effects of different soil fertilization regimes on potential acidity and pH at different soil depths. Different letters in the same depth indicate significant differences between treatments ($p < 0.05$) and missing letters in the same depth indicate no significant differences between treatments ($p > 0.05$).

The available P concentrations were largest in the upper soil layer (0–5 cm), and showed a tendency to decrease with increasing soil depth, except at US, where the depth of 5–10 cm showed the highest content. HA+G had significantly greater available P concentrations than HA+K, K, US, HA+K+G and HA ($p < 0.05$), with increases of 39.4, 38.7, 27.5, 19.2 and 30.0 at 0–5 cm soil depth, respectively. The different treatments did not change the available P levels within 5–20 cm soil depth ($p > 0.05$) (Figure 2).

The SOC concentrations showed a tendency to decrease with increasing soil depth, except at K+G e US. However, within the 0–20 cm soil layer no significant difference in SOC concentrations was observed between treatments ($p > 0.05$) (Figure 2).

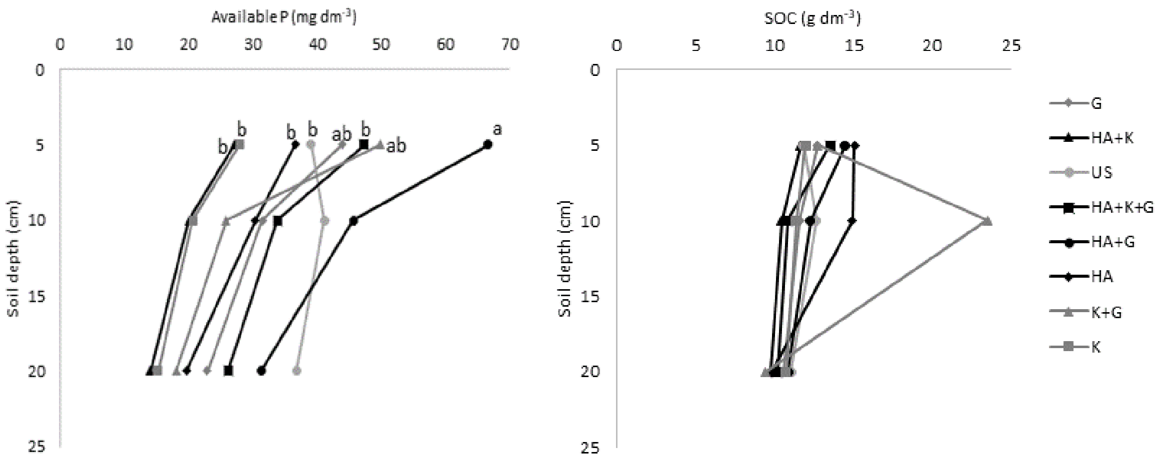

Figure 2. Effects of different soil fertilization regimes on available P and SOC at different soil depths. Different letters in the same depth indicate significant differences between

treatments ($p < 0.05$) and missing letters in the same depth indicate no significant differences between treatments ($p > 0.05$).

The use of HA+K, K+G and HA+K+G recorded a significantly highest concentration of K^+, leading to increases between 0.4 and 1.0 $mmol_c\ dm^{-3}$ compared with G, US and HA at 0–5 cm soil depth ($p < 0.05$). The use of G, K+G and K resulted in significantly highest concentrations of Ca^{2+} compared with HA+K and HA, with increases between 2.2 and 7.2 $mmol_c\ dm^{-3}$ at 0–5 cm soil depth ($p < 0.05$). Compared with HA+K and HA, the Mg^{2+} concentrations resulted in significant increments between 7.5 and 9.8 $mmol_c\ dm^{-3}$ at K+G and HA+K+G at 0–5 cm soil depth ($p < 0.05$). No significant difference in the K^+, Ca^{2+} and Mg^{2+} concentrations was recorded in the 5–20 cm soil layer ($p > 0.05$) (Table 2).

Compared with HA alone, G, K+G and K showed significant increases of 16.65, 9.36 and 9.65 $mmol_c\ dm^{-3}$ in SBC at 0–5 cm soil depth, respectively ($p < 0.05$). Compared with K and US, treatments with HA+G and HA resulted in significant increments between 14.30 and 44.48 $mmol_c\ dm^{-3}$ in CEC at 0–5 cm soil depth ($p < 0.05$). The use of G, K+G, K and HA+K+G recorded a significantly highest BS concentration, leading to increases between 10.43 and 28.19 $mmol_c\ dm^{-3}$ compared with HA+G and HA at 0–5 cm soil depth ($p < 0.05$). No significant difference in SBC, CEC and BS concentrations was recorded in the 5–20 cm soil layer between all the treatments (Table 2).

Table 2. Effects of different soil fertilization regimes on K^+, Ca^{2+}, Mg^{2+}, SBC, CEC and BS at different treatments (mean ± standard deviation).

Soil depth	Treatment	K^+	Ca^{2+}	Mg^{2+}	SBC	CEC	BS
					mmol$_c$ dm^{-3}		
0 – 5	G	1,3±0,4b	32,5±5,0a	16,3±6,0b	50,01±7,93a	88,45±5,76ab	57,28±16,41a
	HA+K	2,0±0,5a	25,3±10,3c	6,8±0,8c	37,00±15,08ab	87,88±9,23ab	41,07±14,61ab
	K+G	1,7±0,5a	28,0±0,4a	14,3±0,3a	42,99±6,67a	88,10±6,76ab	49,87±21,74a
	K	1,5±0,3ab	29,0±0,5a	12,5±0,2b	43,01±6,17a	77,64±1,71b	55,53±12,36a
	US	1,0±0,2b	30,8±7,2ab	9,0±2,9bc	40,71±6,79ab	75,55±3,98b	54,30±13,63ab
	HA+K+G	1,7±0,6a	26,0±12,4ab	15,0±1,1a	42,72±9,34ab	89,83±7,85ab	48,63±16,71a
	HA+G	1,9±1,3ab	23,8±17,0ab	9,8±2,8bc	35,35±21,38ab	120,03±29,18a	29,09±13,45b
	HA	1,1±0,5b	25,8±8,1c	6,5±1,5c	33,36±4,20b	91,94±29,42a	38,20±15,29b
5-10	G	1,1±0,5a	26,3±5,7a	12,0±6,6a	39,33±10,76a	91,35±9,80a	44,26±16,04a
	HA+K	1,2±0,8a	16,8±5,6a	19,3±12,6a	37,42±13,66a	102,82±10,97a	36,35±13,14a
	K+G	1,1±0,2a	22,5±11,3a	8,3±5,8a	31,80±5,04a	76,26±17,81a	43,45±11,17a
	K	0,9±0,1a	22,5±6,2a	10,5±8,0a	33,91±8,83a	83,19±9,01a	41,78±13,73a
	US	0,8±0,2a	30,3±10,4a	6,3±8,8a	37,25±10,86a	83,50±12,43a	46,36±18,01a
	HA+K+G	1,2±0,4a	25,5±8,3a	9,0±6,1a	35,72±8,67a	86,95±14,37a	42,90±16,44a
	HA+G	0,9±0,1a	17,8±11,5a	10,0±5,4a	28,67±14,50a	105,15±46,74a	28,16±15,54a
	HA	0,9±0,4a	20,0±5,7a	6,3±5,8a	27,19±8,54a	90,19±22,66a	32,75±16,41a
10-20	G	0,9±0,8a	24,8±12,8a	5,8±5,6a	31,40±15,07a	92,33±9,05a	35,31±19,33a
	HA+K	2,2±1,8a	20,5±5,3a	11,0±7,7a	33,74±15,08a	87,06±14,73a	41,30±25,18a
	K+G	1,2±0,7a	18,0±10,0a	6,0±3,0a	25,17±7,91a	75,62±23,79a	35,11±11,06a
	K	0,9±0,1a	20,8±6,3a	9,5±7,8a	31,17±10,18a	82,94±10,31a	38,64±15,25a
	US	1,2±0,8a	24,3±3,9a	8,0±2,7a	33,46±6,37a	83,35±13,34a	41,90±14,81a
	HA+K+G	1,0±0,4a	19,8±11,6a	10,8±5,1a	31,48±8,81a	90,60±9,09a	35,79±13,86a
	HA+G	0,9±0,8a	15,5±7,9a	7,8±2,7a	24,19±9,48a	97,84±36,09a	26,31±11,58a
	HA	0,8±0,8a	15,8±5,2a	5,3±2,0a	21,81±6,06a	91,02±19,15a	25,44±11,09a

Distinct letters by column in each soil depth indicate significant differences (ANOVA with Duncan test, $p < 0.05$).

G (gliricidia), HA+K (humic acid+potassium), K+G (potassium+gliricidia), K (potassium), US (uncovered soil), HA+K+G (humic acid+potassium+gliricidia), HA+G (humic acid+gliricidia), HA (humic acid).

Relations between different soil fertilization regimes, soil chemical attributes and maize grains yield

K^+, Ca^{2+}, Mg^{2+}, pH, SBC and CEC showed positive correlations with maize grains yield only in the 0–5 cm soil depth, especially in treatments with gliricidia (Figure 3a). Available P, potential acidity, SOC and BS did not show any correlation with maize grains yield in the soil profile (0–20 cm) (Figures 3a, 3b and 3c).

The following attributes showed a positive correlation in soil profile (0–20 cm): potential acidity and CEC; pH and SBC; Ca^{2+}, SBC and BS; and Mg^{2+} and SBC. Available P and SOC did not show any correlation with other attributes in the soil profile (0–20 cm) (Figures 3a, 3b and 3c).

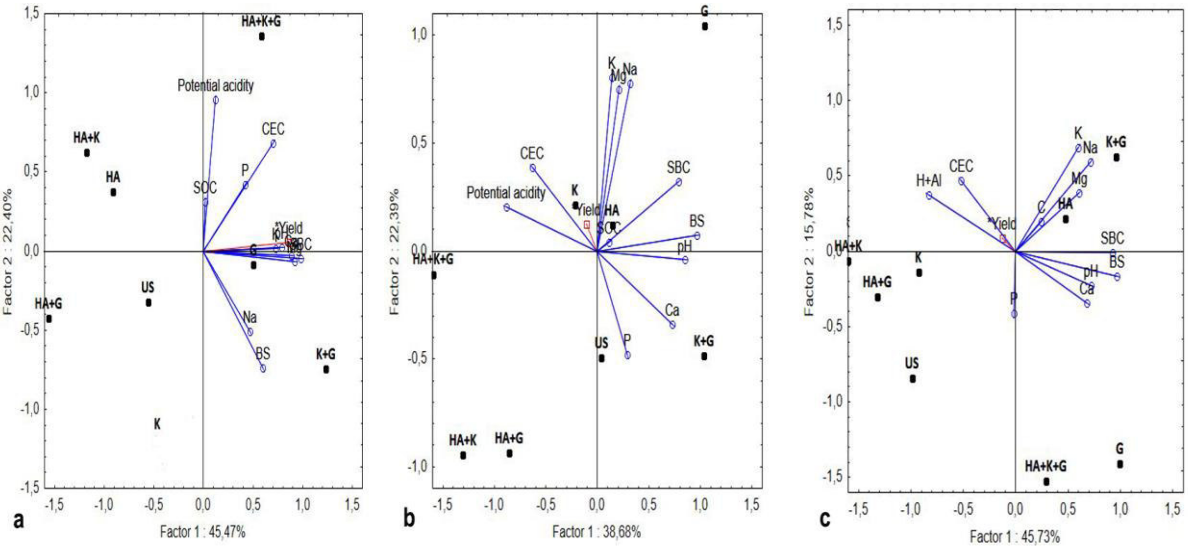

Figure 3. Results of principal components analysis at 0–5 cm (a), 5–10 (b) and 10–20 (c) soil depth in different soil fertilization regimes.

Discussion

Maize grains yield

The maize grains yield was significantly higher in treatments that received gliricidia than in those that did not receive it ($p < 0.05$). Rao and Mathuva (2000) also showed that green manuring with gliricidia increased maize yield in an experiment conducted in Kenya. According Kamara et al. (2000), the increased maize yield was attributed to the presence of gliricidia because this legume has high nitrogen content and is fast decomposing, favouring crop development. For Sakala and Mhang (2003), green manures may increase not only maize yield but also soil fertility. Zhong et al. (2018) emphasize the importance of green manure using legumes, which alter soil bacterial community structure, enhancing soil fertility. Afolayan & Oyetunji (2018) point out that besides improving soil structure, organic materials increase the soil organic carbon content, then enhancing crop yield.

Effect of different soil fertilization regimes on soil chemical properties

According Liu et al. (2010), soil chemical properties are very influenced by soil management practices such as fertilization. In the present study, we also find these results.

In general, while pH showed a tendency to decrease with increasing soil depth, potential acidity increased. Potential acidity considers hydrogen ions of various chemical combinations and adsorbed on the solid particles surfaces, but pH only considers hydrogen ions (Allaway, 1957). Then, the values are usually inversely proportional. As well as in research made by Davenport et al. (2003), we obtained significant differences in pH between treatments in upper soil layer. The significantly higher pH levels found at G ($p < 0.05$) are in agreement with Awodun et al. (2007) and Mweta et al. (2007), which showed that gliricidia residues reduced soil acidity by increasing in pH. In highly weathered soils, as the soil researched in present study, Sakala et al. (2004) affirm that this effect caused by leguminous is much more evident. For them, the possibility of these plants improve soil acidity is influenced by their potential alkalinity and potential to release N minerals.

The available P concentrations tended to decrease with increasing soil depth, as was recorded by Milić et al. (2019), for which available P receive a great human influence at agricultural systems. Furthermore, plants composition influences nutrients redistribution through the soil, and this may be exemplified by phosphorus presence in high concentrations in vegetable tissues and also in upper soil layer (Ehrenfeld et al., 2005), since this layer serves as a nutrient deposition site (Milić et al., 2019). For Maharjan et al. (2018), land alterations greatly influence the phosphorus concentration in soil. We recorded this result in present study, in which HA+G had significantly greater concentrations in available P in upper soil layer ($p < 0.05$). According Mweta et al. (2007), green manure may increase available P since it decreases the P sorption capacity of the soils, which increases the available P concentration in surface. For Awodun et al. (2007), it is possible that gliricidia manure can improve available P, but Mweta et al. (2007) point out that there is little information on the effect of gliricidia manure on P sorption capacity in the soils. When gliricidia mulch is added to soil, the soil organic matter (SOM) increases, then increasing the supply of nutrients (Awodun et al., 2007) due to increase in quantity of decomposing microorganisms in the soil (Parnas, 1975). Humic matter can also increase soil microorganism populations (Visser, 1985; Saruhan et al., 2011). For Comte et al. (2012), the recycling made by these microorganisms increases the availability of P in the soils.

We showed that SOC concentrations tended to decrease with increasing soil depth. These decreasing can be associated with crop root system, since that its decomposition is slower in soil deeper layers (Li et al., 2013, 2019). According Kaur et al. (2005), Li et al. (2019) and Zhang et al. (2015), different managements greatly influences organic carbon content in upper soil layer. For Liu et al. (2010), accumulation of SOC enhances with organic and inorganic fertilizers combined. However, we did not find any significant difference in SOC concentrations between the treatments ($p > 0.05$).

Nutrient concentrations showed some differences between treatments. Bulluck III et al. (2002) found higher concentrations of calcium, potassium and magnesium in soils that received organic amendments, but not in soils receiving synthetic fertilizers. According Ordóñez-Fernández et al. (2015), organic residues of leguminous enrich the soil with nutrients. For Lupwayi and Haque (1998), they are a source both nitrogen and other nutrients such as magnesium, potassium and calcium, since they lead to the accumulation of organic matter (Carvalho et al., 2014). Awodun et al. (2007) found that mulch with gliricidia increased these nutrients content in soil. However, we did not find these results at gliricidia alone, but highest concentrations in K^+, Ca^{2+} and Mg^{2+} occurred at gliricidia added to potassium in upper soil layer ($p < 0.05$). Kaur et al. (2005) found higher concentrations in potassium in chemically fertilized soils than in soils with chemical fertilizers and organic manures combined, but we did not find these results.

HA+G and HA alone recorded significant increments in CEC in upper soil layer ($p < 0.05$). One of the indirect effects of humic compounds on soil is to increase CEC (Saruhan et al., 2011). Nascente et al. (2015) recorded that the decomposition of cover crops provided a significant increase in organic matter and, consequently, in CEC. For Harada & Inoko (1975), the CEC of soils is mainly influenced by organic matter, and according Crusciol et al. (2010), this organic matter is greatly accumulated in the soil surface due to crop residue. This accumulation increases soil negative charges, leading to the increase in CEC (Carvalho et al., 2014). G and K+G showed significant increases in SBC and BS at upper soil layer ($p < 0.05$). Legumes used as green manures can increase soil organic matter and, consequently, SBC (Delarmelinda et al., 2010) and BS (Crusciol et al., 2010). Nascente et al. (2015) also recorded this increase in BS influenced by cover crops.

Relations between different soil fertilization regimes, soil chemical attributes and maize grains yield

K^+, Ca^{2+} and Mg^{2+} were positively associated with maize grains yield in upper soil layer, especially in treatments with gliricidia. For Salvagiotti et al. (2017), nutrients availability in soil increases maize yield since they collaborate with crop growth during grains number formation. According Zörb et al. (2014), potassium is very important to yield in all crops and Kang (1981) points out its importance due to the increase in maize yield. For Cakmak (2001) some macronutrients as calcium and magnesium collaborate to crop development and metabolism and for Cronk & Fennessy (2001), they fabricate some essential plants constituents. Martins et al. (2015) clarifies that magnesium still plays an important role in photosynthesis. Thus, the functions performed by these nutrients contribute to agricultural yield. pH and CEC were also positively associated with maize grains yield in upper soil layer, especially in treatments with gliricidia. Nascimento et al. (2003) points out that legumes act on soil fertility and increase pH and CEC. Furthermore, gliricidia releases mineral elements to the soil, which are available to the plants, also collaborating to crop yield (Afolayan & Oyetunji, 2018). The specific use of gliricidia pruning, according Mweta et al. (2007), enhances maize production since increases organic matter in soil. Higher concentrations in organic matter provide more negative charges to the soil, leading to higher CEC and less possibility of nutrient leaching.

Parameters related to acidity showed some associations. Potential acidity is used to estimate the CEC, which may have led to association between these attributes in all layers. pH was positively associated with SBC in all layers, as Abreu Jr. et al. (2003) also recorded at intemperized Brazilian soils.

Conclusion

Our study showed that gliricidia manures can increase maize grains yield because this legume has high nitrogen content and fast decomposing, favouring crop development. Fertilization with gliricidia changed the chemical properties in upper soil layer, such as pH, available phosphorus, exchangeable potassium, calcium and magnesium, CEC, SBC and BS due mainly to the increase in organic matter content. The association between potassium, calcium, magnesium, pH and CEC and maize grains yield in upper soil layer can be mainly due to the legume presence, which increases the fertility, organic matter and negative charges in the soil. Then, this research confirms the hypothesis that different soil fertilization regimes modify soil chemical attributes and maize grains yield.

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CAPÍTULO 6

Suggestion of an agricultural sustainability index based on biological and chemical indicators of soil quality

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Agricultural sustainability index based on soil quality

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Abstract

Agriculture has been considered one of the activities that most changes the environment. Then, a quantitative measurement of agricultural sustainability using indicators and indices is necessary to monitor agricultural practices aiming a more sustainable agricultural sector. We hypothesize that it is possible to construct an index formed by soil quality indicators to quantitatively assess agricultural sustainability. Our aim was to suggest a simple agricultural sustainability index (ASI) based in biological and chemical indicators of soil quality. Index construction consisted in the compilation and analyze of primary data, selection and aggregation of biological and chemical indicators, constituting the index. The indicators weighting was performed using principal components analyze (PCA) results, which correlated biological and chemical indicators with maize yield. A framework composed by the indicators and their respective weights was elaborated, containing a classification system. For indicators in which reference values were not find in specific literature, the amplitude and medium values used were those found in the base researches of this work. The ASI was developed, which can be classified into one of the sustainability classes. These classes vary according to the ASI score obtained, which can be “very bad”, “bad”, “regular”, “good” or “excellent”. Our study showed that is possible to construct a simple index formed by biological and chemical soil quality indicators to assess quantitatively agricultural sustainability. However, use of this index in other agricultural systems should be done with caution, because particularities of each system should be considered.

Keywords: sustainability assessment, index, indicator, indicators weighting, sustainability classification.

Introduction

Agriculture is one of human activities that most changes the environment (Cast 1994). This transformation has increased since the Green Revolution, which was characterized by increase in agricultural activity, due to the increased use of chemical fertilizers, pesticides and machinery. Since the system itself has damaged its base, this type of production has been considered unsustainable. According WCED (1987), sustainability is ‘meeting the needs of the present without compromising the ability of future generations to meet their own needs’.

Interest in determination of impacts caused by soil management practices has been growing in recent years, as well as their effects on plant productivity, leading to the need to evaluate soil properties (Jamil et al. 2016). In this sense, Doran and Jones (1996) point out the great influence of soil quality in agricultural context, collaborating with plants health and crops yield. For Nambiar et al. (2001), improving soil quality contributes greatly to increasing agricultural sustainability.

There is a concordance that an operational definition (quantitatively measured) of agricultural sustainability using indicators and indices is necessary to monitor agricultural practices aiming a more sustainable agricultural sector, giving us the opportunity to identify which aspects of agricultural sustainability are relevant in practice (Gómez-Limón and Sanchez-Fernandez 2010). Without a more operational tool is difficult to assess the sustainability and therefore achieve it (Sands and Podmore 2000). In this context, Nambiar et al. (2001) point out that to select key indicators to compose this tool is very important.

Many evaluations use simple abiotic and biotic indicators (Doran and Zeiss, 2000). However, Bünemann et al. (2018) point out that the most sensitive indicator of edaphic quality is soil biota, since it has high responsiveness to environmental changes. The chemical attributes also demonstrate greater variation than the physical properties. In addition, according to Jamil et al. (2016), the chemical and biological indicators are very connected.

Then, we hypothesize that it is possible to construct an index formed by soil quality indicators to assess quantitatively agricultural sustainability. Our aim was to suggest a simple agricultural sustainability index (ASI) based in biological and chemical indicators of soil quality.

Material and methods

Index construction

Index construction consisted in the compilation of primary data, which were analyzed and generated indicators. Then, the indicators were aggregated, constituting the index, as proposed by Organization for Economic Co-operation and Development – OECD (1995) (Figure 1).

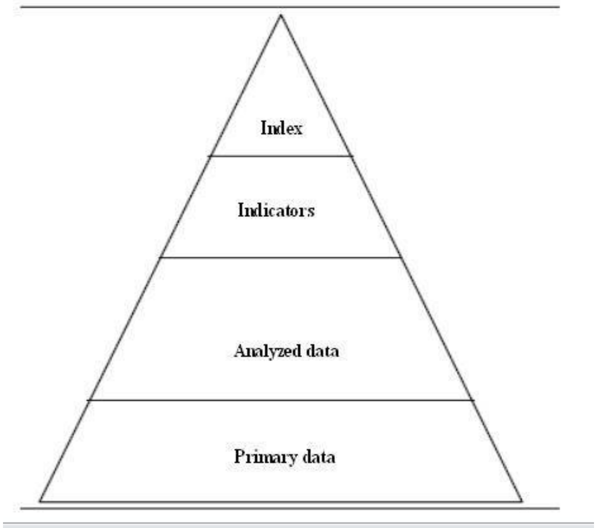

Fig. 1 Information pyramid proposed by the OECD (1995).

The indicators

An extensive set of indicators can be used to determine sustainability. The selected indicators for this research meet the following suitability criteria:

1. Environmental relevance;

2. Economic viability;
3. Analytical soundness and measurability;
4. Suitability for different scales (e.g. farm, small crops);
5. Sensitivity to variations in management;
6. Accessibility to users (e.g. acceptability).

For index composition a total of seventeen indicators of soil quality were obtained from other researches (Martins et al. 2018 and unpublished data), in which they were measured using their own methodology already established in specific literature for each one. These indicators were the following:

- Biological indicators: abundance, diversity index, equitability index and richness of soil fauna, and Isopoda, Diplura and Araneae dominance.
- Chemical indicators: potential acidity, pH, soil organic carbon (SOC), available P, exchangeable K^+, Ca^{2+} and Mg^{2+}, cation exchangeable capacity (CEC), sum of bases cation (SBC) and base saturation (BS).

Using multivariate analysis (principal component analysis – PCA), maize grains yield was associated with biological (Martins et al., 2018 and unpublished data) and chemical (unpublished data) indicators of soil quality under different fertilization regimes in two experimental areas, each with a legume species (*Gliricidia sepium* or *Leucaena leucocephala*), in northeast of Brazil. The indicators weighting was performed using the results of the PCA.

Setting up of evaluation framework

A framework was set up, in which a scale with three scores was assigned for each indicator. Weighting per indicator was also added to the framework. A sustainability classification table was set up to receive the sustainability index acquired in the framework.

Results

The most significant biological indicators due to correlation to maize grains yield were total abundance and Isopoda, Diplura and Araneae dominance (Martins et al. 2018 and unpublished data). The most significant chemical indicators due to correlation to maize grains yield were pH, available P, exchangeable K^+, Ca^{2+} and Mg^{2+}, CEC and SBC (unpublished data). Therefore, a greater weight (2) was attributed to these indicators, while a lower weight (1) was assigned to the other indicators (Table 1).

A framework composed by the indicators and their respective weights was elaborated. This structure contain a classification system ranging between 1 (bad), 3 (intermediate) and 5 (good/suitable), but the reference values are specific for each indicator. For indicators in which reference values were not find in specific literature, the amplitude and medium values used were those found in the base researches of this work (Martins et al. 2018 and unpublished data) (Table 1).

Table 1. Framework composed by biological and chemical indicators of soil quality, with score and weight for each indicator.

Indicator (*k*)	Weight (*W*)	Score (*S*) Bad (1)	Intermediate (3)	Good (Suitable) (5)	Total
Biological					
[1] Total abundance (ind./trap)	2	< 10	10 – 20	> 20	2 *S*
[1] Dominance of Isopoda (%)	2	< 20	20 – 70	> 70	2 *S*
[1] Dominance of Diplura (%)	2	< 20	20 – 70	> 70	2 *S*
[1] Dominance of Araneae (%)	2	< 20	20 – 70	> 70	2 *S*
[2] Diversity index	1	< 1.0	1.0 – 3.0	> 3.0	1 *S*
[3] Equitability index	1	< 0.50	0.50– 0.89	0.90 – 1.00	1 *S*
[1] Richness (taxa)	1	< 10	10 – 20	> 20	1 *S*
Chemical					
[4] Potential acidity ($cmol_c$ dm^{-3})	1	< 2.5	2.5 – 9.0	> 9.0	1 *S*
[4] pH	2	< 5.4	5.4 – 6.0	6,1 – 7,0	2 *S*
[4] Soil organic carbon (SOC) ($cmol_c$ dm^{-3})	1	< 1.16	1.16 – 4.06	> 4.06	1 *S*
[4] Available P (mg dm^3)	2	< 12	12 – 30	> 30	2 *S*
[4] Exchangeable K^+ ($cmol_c$ dm^{-3})	2	< 40	41 – 120	> 120	2 *S*
[4] Exchangeable Ca^{2+} ($cmol_c$ dm^{-3})	2	< 1.2	1.2 – 4.0	> 4.0	2 *S*
[4] Exchangeable Mg^{2+} ($cmol_c$ dm^{-3})	2	< 0.45	0.45 – 1.50	> 1.50	2 *S*
[4] Cation exchangeable capacity (CEC) ($cmol_c$ dm^{-3})	2	< 4.3	4.3 – 15.0	> 15.0	2 *S*
[4] Sum of bases cation (SBC) ($cmol_c$ dm^{-3})	2	< 1.8	1.8 – 6.0	> 6.0	2 *S*
[4] Base saturation (BS) (%)	1	< 40	40 – 80	> 80	1 *S*
ASI					**Σ**

[1] Established from the obtained data in base researches (Martins et al. 2018 and unpublished data)

[2] Modified of Valentin (1991).

[3] Modified of Valentin (2000).

[4] Modified of Alvarez et al. (1999).

The agricultural sustainability index (ASI) was developed as

$$\text{ASI} = \sum_{k=1}^{k=n} W_k \; S_k$$

where ASI is the Agricultural Sustainability Index, k is the indicator, W_k is the weight of indicator k, and S_k is the score of indicator k.

The ASI found in framework can be classified into one of the sustainability classes. These classes vary according to the ASI score obtained, which can be “very bad”, “bad”, “regular”, “good” or “excellent”. A frequency distribution to separate the sustainability classes was carried out according to the minimum and maximum value that the index can reach, taking the sum of the minimum scores and the sum of the maximum scores, respectively (Table 2).

Table 2. Sustainability classification according ASI (agricultural sustainability index).

Sustainability classes	ASI
Excellent	117 ├ 140
Good	95 ├ 117
Regular	73 ├ 95
Bad	51 ├ 73
Very bad	28 ├ 51

Discussion

The indicators used in present study were selected according some suitability criteria, among which economic viability, sensitivity to variations in management and environmental relevance stood out. According Nambiar et al. (2001), the challenge of this type of methodology is to select the main indicators to measure the impacts of management practices on agricultural sustainability. For them, indicators need to be representative and reveal important characteristics of the studied environment. These researchers claim that to assess agricultural sustainability, an approach based in measures variable and other based on management practices can be made. In this research, however, we use both approaches.

Our framework used the soil fauna, its total abundance, composition and diversity indices as biological indicators. For Bagliano (2012), biological indicators of edaphic environments are sensitive to the physical and chemical soil variations, having their diversity, abundance and composition influenced. According Doran and Zeiss (2000), they are sensitive to agricultural management practices and some are easily visible, and this facilitates farmers' understanding. In this context, Rousseau et al. (2012) point out that macroinvertebrates have great potential as edaphic biological indicators, but should be used with caution.

For Araújo et al. (2012), the nutrients availability is extremely important for the evaluation of soil quality between different management systems. In a survey conducted by Bünemann et al. (2018), the most cited indicators for this purpose were pH, SOC, available P and exchangeable K^+, Ca^{2+}e Mg^{2+}. Askari and Holden (2014) emphasize that SOC, pH and CEC are very important for crop yield. In addition to the mentioned indicators, we added potential acidity, BS and SBC. Both biological and chemical indicators used in present research are already known and validated in the literature.

In our framework, the reference values used for each indicator were those found in specific literature or in the base researches of this work (Martins et al 2018 and unpublished data). Marzall (2000) agrees that an indicator should evaluate based on a standard or ideal situation to be achieved. Nambiar et al. (2001) point out that the boundary values for the indicators will vary depending on the specific function of the soil and the chosen agroecosystem. We converted the unities of each indicator into a "common" unit of measure. For Andreoli and Tellarini (2000) this is a good technic and in this case, since all variables are expressed in terms of utility, higher values always have a "positive meaning", as suggested in present research.

The framework elaborated in this study was composed of a simple scoring system, which ranged of 1 (bad), 3 (intermediate) and 5 (good/suitable), according to the situation of each indicator. Then, a more complex normalization was not necessary. Andreoli and Tellarini (2000) affirm that using quantitative data does not always mean that it is easy to reach a general judgment, because it is so difficult to deal with different units of measure. According them, this requires transforming values into a common unit of measure, through normalization or other procedures and a scale can also be used.

The weights for each indicator were attributed according to the presence (weight 2) or absence (weight 1) of association of each indicator with the maize grains yield (Martins et al., 2018 and unpublished data). Instead of assigning weighting for each indicator, signals (+, -, ±, ++, --) can be used. However, the easiest way to simplify a total index for a set of indicators is to add up the value of all the indicators, after having multiplied each by its own weight. Even so, it is difficult to find general agreement on the allocation of weights. In addition, different situations can lead to different levels of importance for each indicator, and then there is no general weighting system that can be applied in all situations (Andreoli and Tellarini, 2000).

The ASI proposed in present study can be obtained by the sum of seventeen indicators already multiplied by their own weights. The final classification was established according to the maximum and minimum amplitude that can be achieved by the suggested score. However, both indicators quantity and the final classification can be modified according to the peculiarities of the agro system. For Nambiar et al. (2001), quantitative sustainability assessments really require consideration, for example, of their variations in time and space, i.e., they may vary according to local and temporal characteristics. Furthermore, it is necessary to consider the specificities with respect to the crop.

According Gómez-Limón and Sanchez-Fernandez (2010), agricultural sustainability quantification through an index that aggregates indicators reduces the operational problems of measuring them, providing a practical tool to support decision-making. For them, the following guidelines should be followed for the construction of an index: 1. selection of indicators and data collection; 2. transformation of basic indicators into dimensionless variables (normalization), with reference values; 3. indicators weighting; and 4. indicators aggregation and sustainability classification. All these steps were followed in the index construction proposed in this research.

Despite the importance of the suggested index, Nambiar et al. (2001) point out that it is possible to develop an index based on soil quality and social, economic and management components. The growing need for more holistic studies is undeniable, which may benefit decision-making (Andreoli and Tellarini 2000; Gómez-Limón and Sanchez-Fernandez 2010). Besides that, Meul et al. (2008) emphasizes the importance of a solid validation of tool through its practical application. Although only the soil quality has composed the ASI and the tool validation has not been done yet, the index proposed in this paper is a valuable first step for a further research, both aiming to improve the tool and use it for measuring and monitoring the sustainability conditions of agricultural systems.

Moreover, Gómez-Limón and Sanchez-Fernandez (2010) points out that indexes use should be done carefully because it is impossible that a single measure accurately assess agricultural performance. Although useful, this tool only partially represents a more complex reality.

Conclusion

Our study showed that is possible to construct a simple index formed by biological and chemical soil quality indicators to assess quantitatively agricultural sustainability. However, use of this index in other agricultural systems should be done with caution, because particularities of each system should be considered. In addition, the proposed index still needs to be tested for its statistical properties and robustness. Further researches to test the scores used for each indicator and the final classification of sustainability are necessary to allow that the comparison between agro systems and regions can be done with confidence.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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CONCLUSÃO

Os resultados desta pesquisa indicam que atributos biológicos e químicos da qualidade edáfica são sensíveis a mudanças nos regimes de fertilização do solo. O estudo também destaca que esses atributos podem ser associados com a produtividade de grãos de milho, podendo ser utilizados como indicadores da QS na composição de um Índice de Sustentabilidade Agrícola (ISA).

A ACP demonstrou ser uma boa ferramenta para ponderação dos indicadores. Nesse sentido, os indicadores biológicos mais significativos, devido à associação com a produtividade, foram a abundância total e a dominância de três grupos taxonômicos (Isopoda, Diplura e Aranea). Os indicadores químicos mais significativos, em decorrência da associação com a produtividade, foram o potássio, o cálcio e o magnésio trocáveis, o fósforo disponível, o pH, a capacidade de troca catiônica e a soma de bases.

O índice de sustentabilidade agrícola sugerido requer ainda validação para que seja futuramente aplicável. Ressalta-se, entretanto, que um estudo mais amplo requer mais tempo e maior investimento financeiro para que o resultado seja o mais aproximado possível da realidade. Desse modo, qualquer fórmula precisa ser adaptada a um ambiente e cultivo específicos. Assim, a seleção dos indicadores deve ser realizada a partir da compreensão de cada sistema analisado. Recomenda-se, portanto, que o método seja utilizado em áreas de cultivo de regiões próximas à região estudada, a fim de que o índice seja validado e a informação gerada seja disponibilizada.

ANEXOS

ANEXO 1. Comprovante de aceite do artigo “Prospecção científica sobre índices de sustentabilidade utilizados na agricultura” e primeira página do artigo publicado pela revista *Geintec*.

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CAPA SOBRE PÁGINA DO USUÁRIO PESQUISA ATUAL ANTERIORES NOTÍCIAS ##API##

Capa > Usuário > Autor > Submissões > #920 > Avaliação

#920 AVALIAÇÃO

RESUMO AVALIAÇÃO EDIÇÃO

SUBMISSÃO

Autores	Ana Luiza Privado Martins, Mayra Nina Araujo Silva, Mayanna Karlla Lima Costa, Alana das Chagas Ferreira Aguiar
Título	Scientific prospection on sustainability indexes used in agriculture
Seção	Prospecção Tecnológica
Editor	João Antonio dos Santos (Avaliação)

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PROSPECÇÃO CIENTÍFICA SOBRE ÍNDICES DE SUSTENTABILIDADE UTILIZADOS NA AGRICULTURA

SCIENTIFIC PROSPECTION ON SUSTAINABILITY INDEXES USED IN AGRICULTURE

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Resumo:

A avaliação dos impactos provocados pela agricultura é fundamental para o entendimento do nível de sua sustentabilidade. Nesse contexto, índices de sustentabilidade podem ser utilizados para medição, pois consistem em informações que facilitam a compreensão de dados. Este trabalho teve como objetivo realizar uma prospecção da utilização de índices para avaliação da sustentabilidade agrícola e apresentar uma visão geral das metodologias mais empregadas. Para isso, foram realizadas buscas sobre Índices de Sustentabilidade aplicados à Agricultura no banco de publicações científicas do Science Direct. A pesquisa coletou dados entre os anos de 2004 e 2015, em revistas de várias áreas. Os artigos foram analisados individualmente para certificação de que tratavam sobre o tema abordado. Foi encontrado um total de 496 resultados, sendo que destes, apenas 71 tratavam sobre a temática específica. O ano de 2015 foi o que apresentou maior porcentagem de artigos publicados. A China destacou-se com o maior número de publicações na área entre os anos da pesquisa, com um total de 24 artigos, enquanto o Brasil teve apenas 2 publicações para o mesmo período. Dentre as metodologias utilizadas, destaca-se o Índice

ANEXO 2. Comprovante do aceite do artigo "Associations between different soil management practices, soil fauna and maize yield" e primeira página do artigo publicado pela *Journal of Agricultural Science*.

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Corresponding Author(s): Ana Luiza Privado Martins

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Associations Between Different Soil Management Practices, Soil Fauna and Maize Yield

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Abstract

Soil fauna play an important role in ecosystems, and in this context, it is important to better understand how the abiotic and biotic drivers of these organisms interact. We hypothesize that soil fauna are affected by different soil management practices, which has an influence on maize grain yields. The aim of this study was to evaluate the structure of soil fauna under different soil management practices and their associations with maize grain yield. The experiment was conducted in Maranhão, Brazil, in an area divided into 24 plots of 4 × 10 m in a randomized block design with six treatments with four replicates (R). Pitfall traps were placed in the area. The treatments were *Leucaena leucocephala*-Leucaena (L), nitrogen (N), humic acid + nitrogen (HA + N), nitrogen + Leucaena (N + L), humic acid + Leucaena (HA + L) and humic acid + nitrogen + Leucaena (HA + N + L). The soil fauna dominance, abundance, richness, Shannon-Wiener diversity index, Pielou evenness index and maize grain yield were determined. Formicidae was clearly affected by management with Leucaena, while Coleoptera was affected by management with nitrogen. Despite this, Isopoda and Diplura were the only groups associated with the maize yield. Although fauna abundance did not differ among treatments, it was related to the yield. This study confirms that the abundance and some taxa of soil fauna can influence yield and that these organisms can be used to increase agricultural sustainability.

Keywords: abundance, diversity indexes, principal component analysis, soil quality, sustainability

1. Introduction

Ecosystem functions such as decomposition, nutrient cycling and maintenance of physical and chemical properties are greatly influenced by the contribution of edaphic organisms (Davidson & Grieve, 2006). These organisms play an important role in the formation and stabilization of soil structure (El Titi, 2003). They regulate the rates of movement of nutrients, water and gases, and they lead to the development of macropores, which increase water absorption and reduce run-off, erosion and waterlogging. They also alter the competitive balance between plants with different rooting depths by changing the distribution of water in the soil profile (Sanginga et al., 1992).

The role of soil fauna in litter decomposition has been intensively studied over the past 40 years (Zhang et al., 2015). El Titi (2003) reported that these organisms have an important role in the production and decomposition of organic matter and population stability of other organisms that inhabit the soil. Bedano et al. (2016) highlighted the importance of soil fauna in soil organic matter cycling, mainly mesofauna and macrofauna.

Nevertheless, little has been done to link indicator taxa with their ecosystem functions and services (Rousseau et al., 2013), and it is necessary to take an integrative approach to address these gaps in knowledge (Tsiafouli et al.,

ANEXO 3. Comprovante do aceite do artigo “Can different soil fertilization regimes modify soil fauna and interfere in maize grain yield?” pela *Australian Journal of Crop Science*.

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ANEXO 4. Comprovantes de submissão do artigo "Linkages among soil fertilization regimes, chemical properties and maize grains yield in humid tropic" à *Experimental Agriculture*.

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Experimental Agriculture

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Full Title:	LINKAGES AMONG SOIL FERTILIZATION REGIMES, CHEMICAL PROPERTIES AND MAIZE GRAINS YIELD IN HUMID TROPIC
Short Title:	Fertilization, chemical properties and yield
Article Type:	Research Article
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Manuscript Region of Origin:	BRAZIL
Abstract:	SUMMARY We hypothesize that there is a linkage among different soil fertilization regimes, soil chemical attributes and maize grains yield. We aimed to evaluate the relationships between different soil fertilization regimes, soil chemical properties and maize grains yield. The experiment was performed in northeastern Brazil, in a randomized block design, at an area divided into 24 plots with six treatments and four replicates (Nitrogen (N); Leucaena (L); Nitrogen+Leucaena (N+L); Humic Acid+Leucaena (HA+L); Humic Acid+Nitrogen (HA+N) and Humic Acid+Nitrogen+Leucaena (HA+N+L)). Each plot was cropped with maize (Zea mays L.) and the grains yield was estimated. Soil samples were collected at depths of 0–5 cm, 5–10 cm and 10–20 cm. Potential acidity, pH, soil organic carbon (SOC), available phosphorus, exchangeable potassium, calcium and magnesium, cation exchange capacity (CEC), sum of basic cations (SBC) and base saturation (BS) were determined. Principal component analysis (PCA) was used to correlate soil chemical attributes with maize yield. Calcium, magnesium, available P and SBC were related to the maize grains yield in upper soil layer, especially at nitrogen fertilization. This research confirms the hypothesis that there is a linkage between different soil fertilization regimes, soil properties and the maize grains yield.
Keywords:	green manure maize yield principal component analyses

ANEXO 5. Comprovantes de submissão do artigo "Effect of different soil fertilization regimes on soil chemical properties and maize grains yield in humid tropic" à *Journal of Soil Science and Plant Nutrition*.

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Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status
View Submission View Reference Checking Results Correspondence Send E-mail	JSSP-D-19-00404	Effect of different soil fertilization regimes on soil chemical properties and maize grains yield in humid tropic	31 May 2019	31 May 2019	New Submission

Page: 1 of 1 (1 total submissions) Display 10 results per page.

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Journal of Soil Science and Plant Nutrition

Effect of different soil fertilization regimes on soil chemical properties and maize grains yield in humid tropic

--Manuscript Draft--

Manuscript Number:	JSSP-D-19-00404	
Full Title:	Effect of different soil fertilization regimes on soil chemical properties and maize grains yield in humid tropic	
Article Type:	Original Paper	
Funding Information:	Fundação de Amparo à Pesquisa do Estado de Minas Gerais (PAEDT-02254/15)	Dr. Ana Luiza Martins-Feitosa
Abstract:	We hypothesize that different soil fertilization regimes modify soil chemical attributes and maize grains yield. Our aim was to evaluate soil chemical attributes in different soil fertilization regimes and their relation to maize grains yield. The experimental area was divided into 32 plots with seven treatments and the control, with four replicates (R) in a randomized block design. The following treatments were performed: Gliricidia sepium – gliricidia (G), potassium (K), humic acid (HA), humic acid+potassium (HA+K), potassium+gliricidia (K+G), humic acid+gliricidia (HA+G), humic acid+potassium+gliricidia (HA+K+G) and uncovered soil (US). Each plot was cropped with maize (Zea mays L.) and the grains yield was estimated. Soil samples were collected at depths of 0–5 cm, 5–10 cm and 10–20 cm. Potential acidity, pH, soil organic carbon (SOC), exchangeable K+, Ca2+ and Mg2+, available K, cation exchange capacity (CEC), sum of basic cations (SBC) and base saturation (BS) were determined. One-way ANOVA with Duncan post-test and principal component analysis (PCA) were used. Exchangeable K+, Ca2+ and Mg2+, pH and CEC were related to maize yield in upper soil layer especially in gliricidia presence. We confirm the hypothesis that different soil fertilization regimes modify soil chemical attributes and maize grains yield.	
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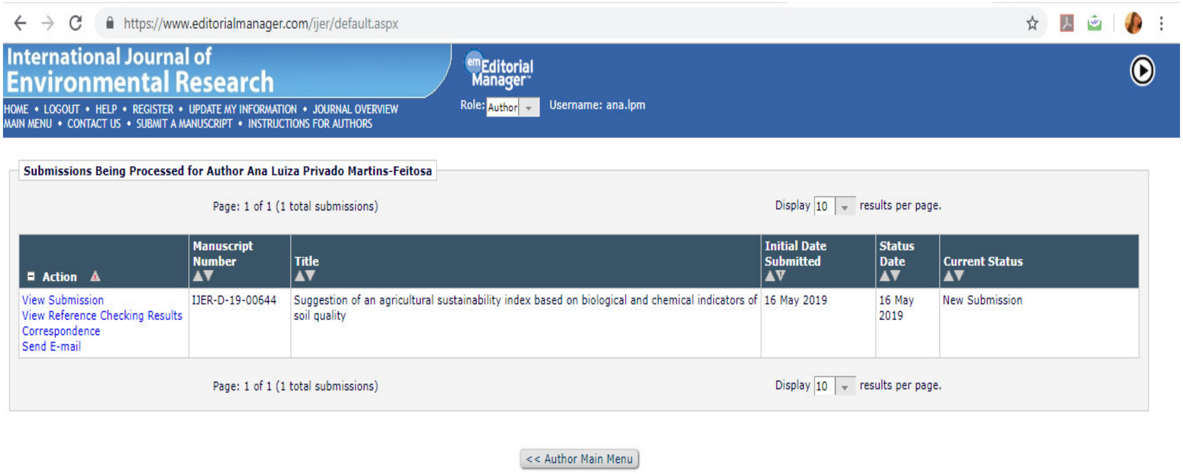
Suggested Reviewers:	Irina Comte CIRAD Afrique orientale et australe irina.comte@ird.fr She has researched agricultural intensification for a long time.	
	Marc Lucotte	

ANEXO 6. Comprovantes de submissão do artigo "Suggestion of an agricultural sustainability index based on biological and chemical indicators of soil quality" à *International Journal of Environmental Research*.



International Journal of Environmental Research

Suggestion of an agricultural sustainability index based on biological and chemical indicators of soil quality

--Manuscript Draft--

Manuscript Number:	IJER-D-19-00644	
Full Title:	Suggestion of an agricultural sustainability index based on biological and chemical indicators of soil quality	
Article Type:	Research paper	
Funding Information:	Fundação de Amparo à Pesquisa e ao Desenvolvimento Científico e Tecnológico do Maranhão	Dr Ana Luiza Privado Martins-Feitosa
Abstract:	Agriculture has been considered one of the activities that most changes the environment. Then, a quantitative measurement of agricultural sustainability using indicators and indices is necessary to monitor agricultural practices aiming a more sustainable agricultural sector. We hypothesize that it is possible to construct an index formed by soil quality indicators to quantitatively assess agricultural sustainability. Our aim was to suggest a simple agricultural sustainability index (ASI) based in biological and chemical indicators of soil quality. Index construction consisted in the compilation and analyze of primary data, selection and aggregation of biological and chemical indicators, constituting the index. The indicators weighting was performed using principal components analyze (PCA) results, which correlated biological and chemical indicators with maize yield. A framework composed by the indicators and their respective weights was elaborated, containing a classification system. For indicators in which reference values were not find in specific literature, the amplitude and medium values used were those found in the basis researches of this work. The ASI was developed, which can be classified into one of the sustainability classes. These classes vary according to the ASI score obtained, which can be "very bad", "bad", "regular", "good" or "excellent". Our study showed that is possible to construct a simple index formed by biological and chemical soil quality indicators to assess agricultural sustainability quantitatively. However, use of this index in other agricultural systems should be done with caution, because particularities of each system should be considered.	
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