UNIVERSIDADE ESTADUAL DO MARANHÃO

CENTRO DE CIÊNCIAS AGRÁRIAS

PROGRAMA DE PÓS-GRADUAÇÃO EM AGROECOLOGIA

CURSO DE MESTRADO EM AGROECOLOGIA

**MARTA JORDANA ARRUDA COELHO**

# UTILIZAÇÃO DE FONTES DE FÓSFORO E RESÍDUOS DE LEGUMINOSAS NO SISTEMA DE PLANTIO DIRETO EM SOLO TROPICAL COESO

São Luís

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**Engenheira Agrônoma**

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

**Orientador: Prof. Dr. Emanoel Gomes de Moura**

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***DEDICO***

*Aos meus pais, Félix e Verediana, meus verdadeiros mestres, modelos reais de perseverança, parceiria, dedicação, confiança e caráter.*

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***Leonardo da Vinci***

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# UTILIZAÇÃO DE FONTES DE FÓSFORO E RESÍDUOS DE LEGUMINOSAS NO SISTEMA DE PLANTIO DIRETO EM SOLO TROPICAL COESO

## CAPÍTULO I

# 1. INTRODUÇÃO GERAL

O Fósforo (P) é essencial para o crescimento das plantas, qualidade e produção das culturas. A deficiência desse nutriente é considerada um dos fatores limitantes para a agricultura, especialmente em solos predominantes nas condições tropicais e subtropicais, devido à sua habilidade em formar compostos de alta energia de ligação e muito estáveis na fase sólida (Schroder *et al.*, 2011). A mobilidade do fósforo nesses solos é controlada por interações com a matriz do solo, nutrientes e reações (Shaheen *et al.*, 2009).

Devido à baixa disponibilidade de P no solo e baixa eficiência do uso de fertilizantes, os agricultores aplicam, muitas vezes, fertilizantes fosfatados além das exigências das plantas. Apenas 10-20% do P aplicado como fertilizante é absorvido pelas plantas durante o ciclo de aplicação, pois a maioria do P aplicado é rapidamente adsorvida ou precipitada em formas pouco disponíveis (Vu *et al.*, 2008).

Duas razões principais levam à baixa eficiência no uso dos fertilizantes minerais na região tropical: a coesão dos solos, resultante de repetidos ciclos de umedecimento e secagem, que reduz o volume do solo enraizável; e a alta taxa de remoção de nutrientes do perfil ocasionada pela precipitação intensa ocorrente na região. Estes processos diminuem o intervalo de tempo durante o qual a disponibilidade de nutrientes é mais elevada após a aplicação dos nutrientes solúveis (Aguiar *et al.*, 2010).

Grande parte dos agricultores da região do trópico úmido trabalha com sistemas familiares carentes de recursos financeiros, que quase sempre são insuficientes para implantar e manter sistemas agrícolas com base em altos *inputs* externos (Aguiar et al., 2010).

As reservas de fósforo no mundo, economicamente viáveis para exploração, podem ser suficientes até 2050 (Vance *et al.*, 2003), essa escassez iminente induzio um grande interesse na alternativa de sistemas de manejo, incluindo a substituição de fertilizantes fosfatados por fontes de fosfóro de rocha natural, como os fosfato aluminosos, como também a combinação destas fontes de P com resíduos de leguminosas.  Entender as formas e dinâmica do P, o monitoramento de suas concentrações e as relações com resíduos de leguminosas no solo é muito importante.

O P ocorre no solo em várias formas, orgânicas e inorgânicas, e que podem ser dividas em P lábil e não lábil (Richardson, 2001). O fracionamento sequencial (Hedley *et al.,* 1982) é utilizado para separar estes vários *pools*. Essa extração sequencial de formas de P inorgânicos e orgânicos consiste no uso de reagentes com diferentes forças de extração, resultando na fragmentação de P no solo, tendo em conta o seu grau de labilidade diferente. Assim, essa técnica permite a obrservação da dinâmica dos pools e da ciclagem do P no solo, fornece informações sobre a quantidade e disponibilidade desse nutriente para as plantas, auxiliando na definição das técnicas de manejos empregados na adubação e uso do solo adequado para cada região.

Na região dos trópicos úmidos, os resíduos de leguminosas adicionados ao solo promovem a diminuição da coesão dos solos, aumentam a disponibilidade de nutrientes para as culturas, principalmente o nitrogênio resultante da capacidade de fixação biológica, reciclagem dos nutrientes e os teores de matéria orgânica, o que resulta na melhoria da fertilidade do solo (Moura *et al.*, 2009, Aguiar *et al.*, 2010). Também tem sido demonstrado que ânions de ácidos orgânicos liberados durante a decomposição dos resíduos pode mobilizar o P e diminuir a capacidade de fixação nos óxidos de Fe e Al (Ayaga *et al.*, 2006). Moura *et al.* (2013), relatam que o fosfato aluminoso combinado com resíduo de leucena resultou em eficiência e produção do milho semelhante àquelas obtidas com o superfosfato simples. Porém, os efeitos dos resíduos de leguminosas nos *pools* de P no solo ao longo do tempo são pouco conhecidos.

Este trabalho parte das seguintes hipóteses que (1), em um solo tropical com característica de alta coesão, o fosfato aluminoso calcinado pode substituir o uso de fosfato solúvel em alimentos básicos, se for combinado com resíduos de leguminosas no sistema de plantio direto; (2) o residual do fosfato de rocha permite reduzir a necessidade de fertilização nos anos subsequentes.

O objetivo deste estudo foi comparar a eficiência de um fosfato aluminoso calcinado com fosfato solúvel, combinados com resíduos de leguminosas, por meio da determinação do destino do P dessas fontes em um solo tropical de alta coesão.

# 2. REFERENCIAL TEÓRICO

## 2.1. O fósforo (P) como elemento essencial

O P é um elemento essencial para toda a vida na terra, pois desempenha inúmeras funções na manutenção da célula orgânica: é o componente-chave dos nucleotídeos que garantem a estrutura helicoidal das moléculas de DNA e RNA; compõe a ATP, fonte indispensável de energia para inúmeros processos bioquímicos; e participa da formação dos fosfolipídios, que garantem a estrutura das membranas biológicas (Childers *et al.*, 2011), e principalmente influencia na qualidade e produção das culturas. No entanto, o crescimento da planta é comumente limitado devido à baixa disponibilidade e mobilidade do P no solo. Assim, a deficiência de P representa um problema global significativo para a produção de culturas (Chen *et al.*, 2008). O abastecimento de fósforo às plantas se dá essencialmente via sistema radicular, estando sua absorção, então, na dependência da capacidade de fornecimento do substrato.

O P é um elemento crítico para as plantas e contribui com, aproximadamente, 0,2% da matéria seca, embora seja um dos nutrientes mais difíceis de ser adquirido pelos vegetais, pois a sua relativa abundância é suprimida pela sua alta reatividade, que diminui consideravelmente a sua disponibilidade nos solos (Smith *et al.*, 2011). Esse nutriente é absorvido na forma aniônica, como ortofosfato primário ($H_2PO_4^-$) ou como ortofosfato secundário ($HPO_4^{-2}$), principalmente por difusão, e é considerado como o fator mais limitante à agricultura tropical, em função das características edáficas predominantes nessas regiões (Abdala *et al.*, 2012).

Apesar de o P ser o décimo segundo elemento químico mais abundante na crosta terrestre, ele é o segundo elemento que mais limita a produtividade nos solos tropicais. Embora a maioria dos solos do mundo contenha uma quantidade significativa de P, cerca de 200-3.000 mg P por kg de solo (Richardson *et al.*, 2005), apenas uma pequena proporção deste (em geral, menos de 1%) é imediatamente disponível para as plantas, devido ao seu comportamento físico-químico e de interação com a interface mineral do solo (Stewart & Tiessen, 1987). Os solos brasileiros em sua maioria são ácidos e, nessa condição química adversa, o P tende a ser fortemente adsorvido por óxidos e hidróxidos de Fe e Al, o que resulta em indisponibilidade desse elemento e comprometimento da produtividade (Aray & Sparks, 2007; Shen *et al.*, 2011).

As principais consequências desse fenômeno são a baixa eficiência do uso do P e a competição entre as plantas e o solo pelo elemento, originando um descompasso entre a necessidade das culturas e a quantidade a ser aplicada para fornecer o que elas precisam. Entre 60 e 90% do P aplicado via fosfatagem é imediatamente fixado no solo e se torna indisponível, de forma que os gastos com fertilizantes tendem a ser muito altos, reduzindo significativamente a eficiência agronômica e elevando o custo de produção (Syers *et al.*, 2008). Portanto, melhorar a eficiência do uso do fósforo poderá reduzir a necessidade de adubos devido ao melhor aproveitamento, o que poderá aumentar a viabilidade econômica da agricultura e minimizará alguns problemas ambientais, pois a fosfatagem excessiva potencializa a eutrofização dos mananciais hídricos (Kant *et al.*, 2011). Assim, os sistemas de cultivo e o manejo da adubação fosfatada podem influenciar o potencial de suprimento do nutriente no solo e o seu aproveitamento pelas culturas.

## 2.2. As fontes de fósforo (P)

Devido sua baixa disponibilidade natural nos solos, o P se redistribui para suprir essa deficiência pela ação antrópica, o qual é retirado das jazidas, onde está concentrado, e depositado, via fertilizante, nos ambientes agrícolas. Essa prática de usar materiais fosfáticos como fertilizantes é tão antiga que não há registro do seu início.

Depósitos de rocha fosfática de interesse para a mineração geralmente ocorrem apenas em condições especiais em algumas áreas específicas, como resultado do ciclo de fósforo (Filippelli, 2011). Os principais depósitos de rocha fosfática são sedimentares ou ígneas, sendo que cada um apresenta mineralogia, estrutura e propriedades químicas diferentes. O minério de fosfato tem uma enorme utilidade socioeconômica, pois é dele que é feito o superfosfato e muitos outros adubos fosfatados largamente usados na agricultura.

O P é, entre os macronutrientes primários, o que apresenta maior opção de fontes no mercado, as quais podem variar quanto à reatividade. Desses fertilizantes fosfatados (fosfatos de cálcio do grupo da apatita), 90% da sua produção são obtidos por via química, 2% por via térmica e 6 % são aplicados sob forma natural. No entanto, o processo de fabricação desses fertilizantes requer o uso de rochas fosfáticas com baixa quantidade (20 a 40 g $Kg^{-1}$) de impurezas metálicas, como o ferro e alumínio (Hoare, 1980). Esses fosfatos de alta reatividade correspondem a mais de 90% do $P_2O_5$ utilizado na agricultura brasileira. Apresentam alta eficiência agronômica em curto prazo e elevado custo por unidade.

Assim, devido à alta solubilidade desses fosfatos, ocorre forte competição entre o solo e planta pelo P. O solo pode se comportar como fonte quando apresentar reservas nutricionais favoráveis às plantas e que possam ser disponibilizadas para estas, mesmo em quantidades insatisfatórias. Já o comportamento do solo como dreno ocorre quando ele compete com a planta pelo nutriente, diminuindo a biodisponibilidade do elemento (Novais & Smith, 1999), ocorrendo principalmente em solos altamente intemperizados com altos teores de óxidos de Fe e Al.

Além disso, o uso de fertilizantes fosfatados acidulados solúveis em água, como superfosfato triplo ou simples, pelos agricultores de baixa renda, é limitado nos países em desenvolvimento, principalmente pelo seu elevado custo (Chien *et al.*, 1996). Dentro desse contexto, estudar outras fontes de P é importante, já que, segundo Vance *et al.* (2003) as estimativas de reservas economicamente viáveis para a exploração de P estão se esgotando. Como alternativa às fontes solúveis, há fosfatos de menor reatividade, como os naturais reativos. Estes, embora apresentem menor disponibilidade imediata de P para as plantas, normalmente apresentam menor custo (Horowitz & Meurer, 2004).

Os fosfatos aluminosos da série Cradallita são minerais secundários que ocorrem devido ao processo de alteração intempérica do material apatítico primário das jazidas fosfáticas, o qual se solubiliza liberando íons ortofosfato que reagem com íons presentes na solução (Toledo, 1999). Blackburn & Denner (1997) apresentam as seguintes formulas estruturais para os minerais do grupo: $RAl_3(PO_4)(PO_3OH)(OH_6)$, quando o R é o Ca (crandallita) ou Ba (gorceixita), $RAl_3(PO_4)_2(OH_6)$, quando o R são elementos de terras rasas, ou $RAl_3(PO_4)_2(OH_5).H_2O$, quando o R é o chumbo (plumbogummita). Contudo, raramente esses minerais ocorrem isolados, sendo mais comum a ocorrência simultânea dos minerais desse grupo.

O fosfato natural aluminoso tem distribuição mundial (Rasmussen, 1996), e é abundante nos estados do Pará e Maranhão no norte do Brasil. O total de reservas conhecidas na região são cerca de 30 milhões de toneladas de minério, com 15 a 30% de $P_2O_5$ (Guardani *et al.*, 1989). Estudos agronômicos realizados usando esta rocha fosfática natural aluminosa

(Cruz, 1981; Goedert & Lobato, 1980) têm demonstrado sua viabilidade como fonte de P para as condições tropicais.

No Maranhão, na região Noroeste do Estado, foram encontrados seis reservas de fosfato aluminoso: Pirocaua, Trauíra, Pedra Grande, Tromaí, Tralhoto e Jacaré (Rezende, 2001). De acordo com Braun (1983), as jazidas fosfáticas de Trauíra somam cerca de 19 milhões de toneladas de $P_2O_5$.

Mesmo com baixa solubilidade em água, esses minerais normalmente apresentam alta solubilidade em citrato neutro de amônio após a calcinação, devido ao colapso da estrutura cristalina (Buchan *et al.*, 1970; Gilkes & Palmer, 1979). Técnicas de calcinação com temperaturas entre 400 e 600 $^{o}$C são utilizadas para aumentar a solubilidade dos fosfatos naturais aluminosos. Altas temperaturas modificam a composição química dos fosfatos naturais devido ao rearranjamento de compostos ligados a água (Guardani *et al.* 1989). Alguns estudos no Brasil mostraram aumento na solubilidade de fósforo e significativos resultados agronômicos após a calcinação (Câmara *et al.*, 1984; Guardani, 1987). Francisco *et al.* (2007) concluíram que o tratamento térmico de fosfatos aluminosos do grupo da candrallita aumenta a solubilidade das amostras, o que melhora as características agronômicas deste mineral como fonte de fósforo, pois o crescimento das plantas pode ser favorecido pela sua maior disponibilidade.

Ahn (1993) informou que o principal interesse da utilização do fosfato natural aluminoso é seu custo relativamente baixo em comparação com os fertilizantes fosfatados acidulados, o efeito residual do P em longo prazo aumenta o uso eficiente deste fertilizante de disponibilidade lenta. Moura *et al.* (2013) constataram um bom efeito residual do fosfato natural aluminoso calcinado quando combinado com biomassa vegetal, e sugerem a possibilidade de sua aplicação a lanço como um maneira de corrigir a deficiência de P em solos tropicais.

## 2.3. Formas de fósforo no solo

As rochas da crosta terrestre apresentam teor total de P, em média 1.000 mg $kg^{-1}$, enquanto que nos solos é de 800 mg $kg^{-1}$, no qual podem ser encontrados valores desde 35 a até 5.300 mg $kg^{-1}$ (Essington, 2004). Esse fósforo do solo, de interesse agronômico ou ambiental, é constituído por compostos derivados do ácido ortofosfórico e, menos comumente, dos pirofosfatos. Os minerais primários fosfatados comuns em rochas são as apatitas, de onde são liberados durante a intemperização, resultando em minerais secundários mais estáveis termodinamicamente, ou incorporados a compostos orgânicos biologicamente (Rheinheimer *et al.*, 2008).

Os minerais fosfatados primários são a fonte de P nos sistemas naturais. Para ser utilizado pelos organismos vivos, deve haver rompimento da estrutura cristalina para ser liberado: intemperização, que depende dos fatores e processos de formação do solo durante a pedogênese (Gatiboni, 2003). Apesar dos altos teores de P total apenas uma pequena porção, denominado de P lábil, está em equilíbrio com a solução do solo, devido às interações químicas de alta energia que podem ocorrer entre o fosfato e os constituintes do solo (Novais & Smyth, 1999).

O P está presente no solo em diferentes estruturas químicas, mas todas elas estão sob duas formas que possuem comportamento e destinos diferentes: forma inorgânica (Pi) e orgânica (Po) (Turner *et al.*, 2007), essa divisão em dois grupos é para facilitar o entendimento da dinâmica do P no solo. Porém, a identificação das formas de P dentro desses dois grupos é difícil devido à infinidade de reações que o elemento pode sofrer e seus compostos resultantes (Gatiboni, 2003), e que se diferenciam pelo grau de estabilidade ou solubilidade, com diferentes disponibilidades à absorção vegetal (Souza *et al.*, 2007).

O fósforo inorgânico (Pi) é o menos móvel dos principais nutrientes na maioria dos solos e frequentemente o principal fator limitante para o crescimento de plantas nos ecossistemas terrestres (Devau *et al.*, 2009). A concentração do Pi varia entre 35 e 70% do total de P no solo e os minerais que contêm essa forma do elemento (Oelkers & Valsami-jones, 2008), podem ser separados em dois grupos, o P dos minerais primários, ou P estrutural, e o P adsorvido ou precipitado à fração coloidal mineral do solo.

O P dos minerais primários, como apatitas e strengitas, é de liberação muito lenta, apesar da constante ação dos agentes do intemperismo, o que os tornam incapazes de sozinhos, fornecerem P de forma sincronizada com as demandas das culturas. Já o P adsorvidos aos minerais secundários, como fosfatos de Ca, Fe e Al, podem apresentar diferentes padrões de disponibilização, pois dependem do tamanho do mineral e do pH do solo (Oelkers & valsami-jones, 2008). Por causa da facilidade que o fosfato tem em formar complexos com alta energia de ligação, o Pi adsorvido ou precipitado à fração coloidal mineral do solo pode ocorrer em todos os minerais do solo. Portanto, o Pi pode ser encontrado no solo ligados ao Fe, Al e Ca, dentre outros, adsorvido a oxihidróxidos de Fe e Al (Parfitt, 1978). A adsorção do fosfato aos oxihidróxidos de ferro e de alumínio ocorre, principalmente, nas formas de baixa cristalinidade e com alto desbalanço de cargas. A magnitude da adsorção depende da quantidade de constituintes com capacidade de adsorver moléculas neutras ou carregadas eletricamente.

Nos solos de regiões tropicais e subtropicais, os óxidos de Fe mal cristalizados, a quantidade de alumínio substituindo Fe e, em menores quantidades, os óxidos bem cristalizados e a caulinita, são os principais responsáveis por esse fenômeno (Rheinheimer *et al.*, 2008). Pois, os óxidos de Fe e Al possuem largas áreas de superfície específica, o que é responsável pela existência de um grande número de sítios de adsorção, e, além disso, esses coloides possuem inúmeros nanoporos capazes de promover a oclusão P, o que também leva à indisponibilidade do elemento (Aray & Sparks, 2007). Em solos básicos as reações provocam a precipitação do P, especialmente quando em contato com a superfície de carbonatos de Ca e minerais de argila (Devau *et al.*, 2010). Nessa condição, os fosfatos reagem com cálcio, gerando fosfato dicálcico (PDC), que é disponível para as plantas; porém, o PDC pode ser transformado em formas ainda mais estáveis, como fosfato octocálcico (POC) ou hidroxiapatita (HAP), que são muito pouco disponíveis para os vegetais (Shen *et al.*, 2011).

O segundo grupo é o fósforo orgânico (Po), que pode constituir de 5 a 80% do fósforo total do solo e, nos solos tropicais, é fonte de fósforo às plantas e deve ser levado em consideração em estudos envolvendo sua dinâmica e biodisponibilidade (Rheinheimer & Anghinoni, 2003). O fósforo orgânico é originário dos resíduos vegetais adicionados ao solo, do tecido microbiano e dos produtos de sua decomposição (Rheinheimer *et al.*, 2000; Conte *et al.*, 2002 e 2003; Martinazzo *et al.,* 2007). A grande variedade de compostos orgânicos no solo faz com que mais da metade das formas de fósforo orgânico ainda não tenha sido identificadas. As principais formas já identificadas são os fosfatos de inositol, que compõem de 10 a 80% do fósforo orgânico total, os fosfolipídios (0,5 a 7%), ácidos nucleicos (~3%) e outros ésteres-fosfato (>5%) (Dalal, 1977). A estabilidade desses compostos depende de sua natureza e de sua interação com a fração mineral, pois são usados como fonte de carbono e elétrons pelos microrganismos, cujo resultado é a sua mineralização e disponibilização do fósforo (Gatiboni *et al.*, 2007). Assim, a transformação do Po desempenha um papel crucial na reciclagem e biodisponibilidade desse nutriente, e esse processo sofre influência de uma série de fatores, tais como umidade do solo, temperatura, pH do solo e potencial redox (Shen *et al.*, 2011).

Em longo prazo, os solos com adição de fertilizantes fosfatados em quantidades suficientes para o crescimento e desenvolvimento das plantas, as formas inorgânicas e orgânicas de P têm capacidade semelhante de fornecer P para as plantas. Em solos com baixa ou nenhuma adição de fertilizantes fosfatados, as formas orgânicas de P são as principais responsáveis pelo fornecimento deste nutriente às plantas (Gatiboni *et al.*, 2007).

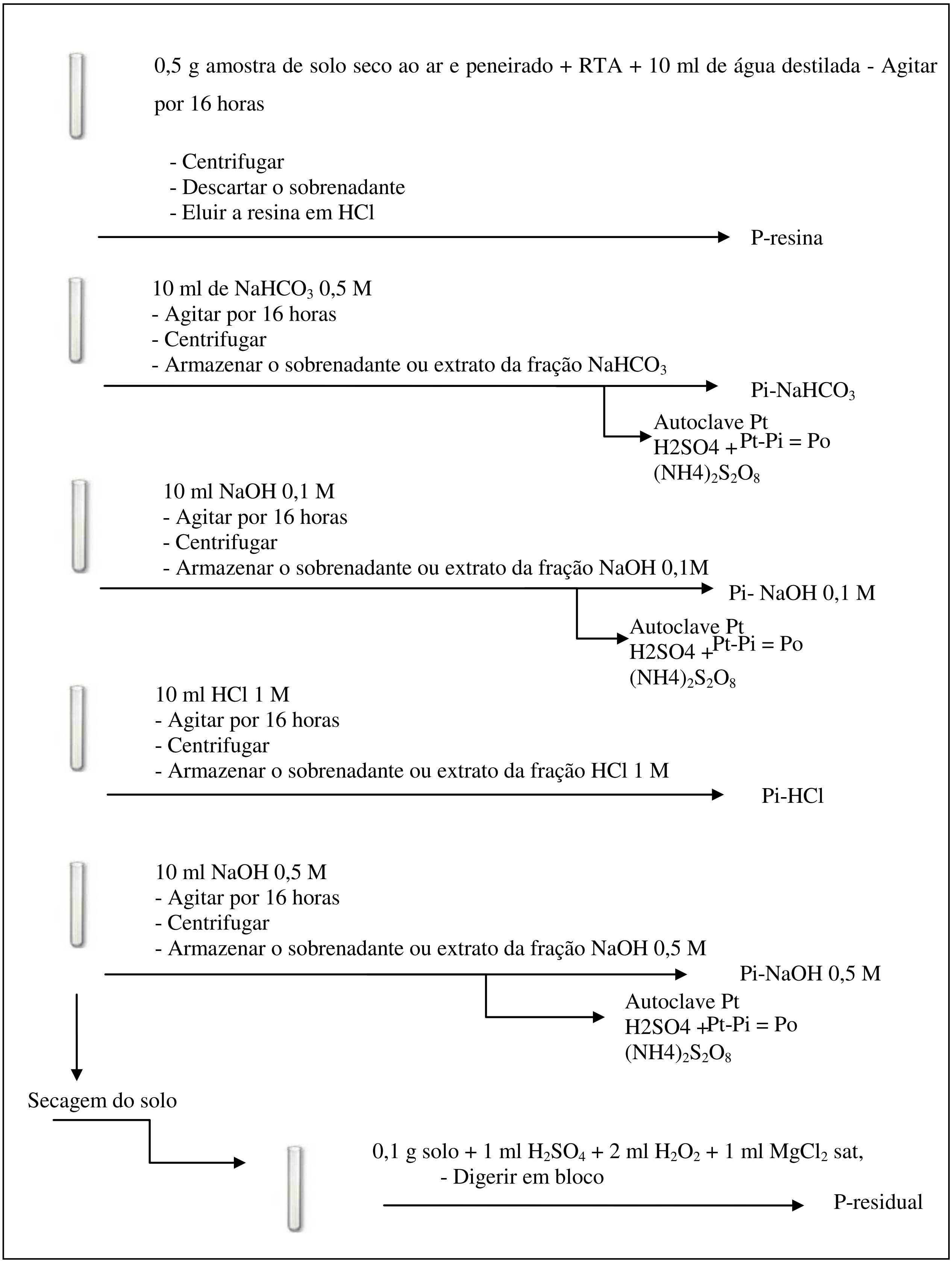
## 2.4 Estimativas das formas de fósforo no solo (Fracionamento)

Para entender melhor a dinâmica do P no solo, é necessário conhecer as diferentes frações do elemento, mediante a utilização sequencial de diferentes soluções extratoras. O conhecimento da natureza e da distribuição dessas frações pode fornecer informações importantes para a avaliação da disponibilidade do P (Rocha *et al.*, 2005), principalmente para a tomada de decisão sobre a necessidade de adição e  na definição das doses e dos modos de aplicação de fertilizantes fosfatados (Rheinheimer *et al.*, 2008). Assim, o fracionamento do P do solo usando diferentes extratores tem sido uma ferramenta para entender a disponibilidade e solubilidade total do P no solo, e tem sido útil no estudo da dinâmica do P no solo sob diferentes sistemas de manejo do solo (Pavinato *et al.*, 2009).

Em termos práticos, a divisão das formas de fósforo no solo é fundamentada nos extratores usados para estimá-las. Chang & Jackson (1957) desenvolveram um método de fracionamento das formas de fósforo, que estabeleceu as bases para a sua identificação de acordo com o extrator usado para acessá-las. A partir daí, foi dada maior ênfase a estudos que identificavam a predominância de determinada fração no solo e a contribuição daquelas preferencialmente absorvidas pelas plantas (Novais & Smyth, 1999). Desde então, inúmeros trabalhos têm usado o fracionamento de Chang & Jackson (1957) para o estudo da dinâmica do P, assim como muitos outros esquemas de fracionamento foram desenvolvidos, chegando a 13 esquemas principais.

Nestes esquemas, o fósforo é dividido de acordo com a facilidade com que repõe a solução do solo sob o ponto de vista da fertilidade, independentemente da natureza química. A separação do fósforo em formas lábeis, moderadamente lábeis e não lábeis, mesmo que essa subdivisão seja imprecisa, ajuda no entendimento da dinâmica da disponibilidade do fósforo. Assim, para estudos do acúmulo e dessorção das formas de fósforo de acordo com sua labilidade, têm-se utilizado a técnica de fracionamento proposta por Hedley *et al.* (1982). Essa técnica usa sequencialmente, extratores com diferentes forças de extração, os quais removem Pi das formas mais fracamente retidas até as mais estáveis, além de identificar separadamente as formas de Po. Com as modificações propostas por Condron *et al.* (1985), os extratores utilizados no fracionamento são: resina trocadora de ânions – RTA (Pi), $NaHCO_3$ 0,5mol $l^{-1}$ a pH 8,5 (Pi e Po); NaOH 0,1 mol $l^{-1}$ (Pi e Po); HCl 1,0mol $l^{-1}$ (Pi), NaOH 0,5mol $l^{-1}$ (Pi e Po); e digestão com $H_2SO_4 + H_2O_2 + MgCl_2$ (Pi + Po), esquema apresentado na figura A. Porém, essa técnica do fracionamento proposta por Hedley e seus colaboradores sofreu várias modificações, para facilitar sua exequibilidade e para adequá-la aos aparatos laboratoriais disponíveis e necessários para sua realização.

Cross & Schlesinger (1995) agruparam as suposições de vários autores sobre quais formas de fósforo são extraídas na sequência do fracionamento de Hedley *et al.* (1982). De uma maneira geral, assume-se que a resina trocadora de ânions extrai formas lábeis de fósforo inorgânico. O $NaHCO_3$ extrai formas lábeis de fósforo inorgânico e orgânico. Ao NaOH 0,1 mol $l^{-1}$ é atribuído o poder de extrair o fósforo inorgânico quimiosorvido a óxidos de alumínio e de ferro, que é moderadamente lábil. Também, com NaOH 0,1 mol $l^{-1}$, é extraído o fósforo orgânico moderadamente lábil. A utilização do NaOH 0,5mol $l^{-1}$ extrai o fósforo inorgânico e orgânico quimicamente e fisicamente protegidos nas superfícies internas dos microagregados. O tratamento do solo com HCl extrai fósforo inorgânico contido nos fosfatos de cálcio e fortemente adsorvido e, finalmente, a digestão do solo com $H_2SO_4$ e $H_2O_2$ extrai o fósforo residual inorgânico + orgânico do solo, chamado também de fósforo recalcitrante.



0,5 g amostra de solo seco ao ar e peneirado + RTA + 10 ml de água destilada - Agitar por 16 horas

- Centrifugar
- Descartar o sobrenadante
- Eluir a resina em HCl

P-resina

10 ml de $NaHCO_3$ 0,5 M
- Agitar por 16 horas
- Centrifugar
- Armazenar o sobrenadante ou extrato da fração $NaHCO_3$

Pi-$NaHCO_3$

Autoclave Pt
H2SO4 + $(NH4)_2S_2O_8$
Pt-Pi = Po

10 ml NaOH 0,1 M
- Agitar por 16 horas
- Centrifugar
- Armazenar o sobrenadante ou extrato da fração NaOH 0,1M

Pi- NaOH 0,1 M

Autoclave Pt
H2SO4 + $(NH4)_2S_2O_8$
Pt-Pi = Po

10 ml HCl 1 M
- Agitar por 16 horas
- Centrifugar
- Armazenar o sobrenadante ou extrato da fração HCl 1 M

Pi-HCl

10 ml NaOH 0,5 M
- Agitar por 16 horas
- Centrifugar
- Armazenar o sobrenadante ou extrato da fração NaOH 0,5 M

Pi-NaOH 0,5 M

Autoclave Pt
H2SO4 + $(NH4)_2S_2O_8$
Pt-Pi = Po

Secagem do solo

0,1 g solo + 1 ml $H_2SO_4$ + 2 ml $H_2O_2$ + 1 ml $MgCl_2$ sat,
- Digerir em bloco

P-residual

**Figura A.** Esquema da técnica do fracionamento de fósforo proposto por Hedley *et al.* (1982) com as modificações de Condron *et al.* (1985), adaptado de Gatiboni (2003)

## 2.5 Relações das formas de fósforo com a aplicação de biomassa vegetal

As leguminosas desempenham um papel importante em ecossistemas naturais e agrícolas. A incorporação de leguminosas como adubo verde em sistemas de cultivo, ou como parte da rotação, afeta positivamente as propriedades do solo e o aumento do suprimento de nitrogênio (N), mas também favorece o suprimento de P para a cultura principal ou para a safra seguinte (Kabir & Koide, 2002). Muitas informações existem sobre os efeitos da qualidade do resíduo sobre as taxas de decomposição e mineralização de N, mas poucos estudos avaliaram a relação entre a qualidade dos resíduos e a liberação do P durante a decomposição. Além disso, o P do solo pode ser mobilizado durante a decomposição de resíduos de leguminosas (Alamgir *et al.*, 2012).

A adição de resíduos orgânicos ao solo pode influenciar a disponibilidade de P diretamente ou indiretamente através de uma série de mecanismos (Guppy *et al.*, 2005). Os efeitos diretos incluem: (i) liberação de P a partir dos resíduos, (ii) troca de P adsorvido com ânions de ácidos orgânicos produzidos durante a sua decomposição (Bolan *et al.*, 1994; Hue *et al.*, 1994), (iii) reações de dissolução (Bolan *et al.*, 1994). Já os efeitos indiretos incluem: (i) a melhoria da capacidade de retenção de água e umidade do solo, promovendo o crescimento das raízes e, assim, a exploração de P do solo, (ii) maior micro-agregação que reduz a área da superfície do solo e diminue o número de locais com potencial sorção de P (Wang *et al.*, 2001), (iii) imobilização microbiana de P inorgânico (Chen *et al.*, 2000), e (iv) a transformação nos pools de P do solo (Xavier *et al.*, 2011).

Agronomicamente, quantidades significativas de P podem estar presentes em resíduos de culturas e da biomassa microbiana, que associado a sua decomposição, ha contribuição potencial destas fontes para a nutrição P de sistemas de cultivo é significativa (Nachimuthu *et al.*, 2009). Alamgir *et al.* (2012) demonstraram que as alterações nos compartimentos de P do solo provocada pela adição de resíduos vegetais, são afetados pela concentração de P no resíduo, e também pela parte da planta utilizada . Além disso, as concentrações dos vários pools de P do solo foram mudando ao longo do tempo, indicando transformação entre compartimentos de P.

A concentração de P de resíduos aplicados é o principal fator que determina se o P será mineralizado em curto prazo, como resultado da decomposição dos resíduos. Geralmente, o P será mineralizado se a concentração de P nos resíduos for maior do que 3 mg $g^{-1}$ e imobilizado se for inferior a 3 mg $g^{-1}$, embora os valores de limiar relatados variam de 2 a 3 mg $g^{-1}$ (Kwabiah *et al.*, 2003; Iqbal, 2009).

Bolan *et al.* (1994), examinaram os efeitos de ácidos orgânicos de baixo peso molecular na adsorção e solubilização/dissolução do fosfato de rocha e monocálcio, e a absorção de P pelas plantas desses fosfato no solo pré-incubado. Eles concluíram que a adição de ácido oxálico e ácido cítrico aumentou a produção de matéria seca das culturas utilizadas e a absorção de P nos solos tratados com ambos os fertilizantes. Como também, a eficácia agronômica de ambos os fertilizantes foi maior na presença de ácidos orgânicos e o aumento foi superior com o fosfato de rocha comparada ao fosfato monocálcico. Portanto, esses resultados indicaram que os ácidos orgânicos aumentam a disponibilidade de P no solo, tanto pela diminuição da adsorção como pelo aumento da solubilização do P dos fosfatos.

De acordo com Moura *et al.* (2009), no solo coberto por resíduos de leguminosas, a condição da camada superior do solo coeso foi significativamente melhorada, com o aumento do volume enraizável de solo. A melhoria foi associada com a maior retenção de água, diminuição da resistência da penetração da raíz, e maior exploração dos nutrientes. Wang *et al.* (2001), afirmam que o aumento da absorção de P com o aumento da dimensão do agregado, foram atribuídos ao aumento da liberação de P a partir de agregados em virtude da redução da fixação P. Portanto, o manejo que favoreça a agregação do solo pode, em alguns casos, aumentar a disponibilidade de P aplicado. E que, talvez o conhecimento da distribuição dos agregados do solo deva ser considerado na tomada de decisões na gestão do P no solo (Wang *et al.*, 2001).

A imobilização de P no solo ocorre quando o conteúdo total de P do resíduo é insuficiente para atender a exigência por P da biomassa microbiana, e também depende de como a biomassa microbiana se prolifera em resposta à adição de um novo substrato (Damon *et al.*, 2014). De modo geral, o conteúdo total de P orgânico aumenta quando o manejo favorece o incremento de matéria orgânica e, ou, com a utilização de fertilizantes, e diminui em sistemas intensivos de cultivo com baixa reposição de P (Reddy *et al.,* 2000). Os sistemas de manejo que promovem adição de matéria orgânica ao solo também contribuem para o aumento de formas mais lábeis de P, com diminuição da adsorção e consequente aumento da disponibilidade de P para as plantas (Andrade *et al.,* 2003).

Negassa & Leinweber (2009), realizaram extensa revisão sobre uso do fracionamento de Hedley em agroecossistemas com diferentes usos e manejos de solo e concluíram que as frações inorgânicas e orgânicas podem atuar como fonte ou dreno do P disponível, dependendo do manejo de solo e da fertilização. Quando o solo não é fertilizado e há adições de resíduos vegetais, a fração orgânica tampona o P da solução do solo. Entretanto, quando há fertilizações ocorre o acúmulo de P nas formas inorgânicas, que tamponam a solução e a fração orgânica é utilizada em menor escala, permitindo sua acumulação. Quando da adição de fertilizantes fosfatados, ocorre a redistribuição do P em todas as frações do solo, porém o acúmulo é mais pronunciado nas frações lábeis.

Xavier *et al.*, (2011), em estudo sobre as formas de P em agroecossistemas, concluíram que as transformações das frações de P estudadas podem ser diretamente relacionadas com a taxa de decomposição dos resíduos orgânicos, que é associado a sua qualidade (por exemplo, a lignina, hemicelulose, teores de polifenóis). Assim, o efeito do manejo agroflorestal na distribuição das frações de P do solo e o papel da Po no ciclismo do P precisa ser salientado por estudos mais detalhados, tendo também em conta o papel dos microorganismos na inter-relação entre os diferentes compartimentos de P.

## 3. REFERÊNCIAS BIBLIOGRÁFICAS

Abdala, D.B., Gosh, A. K., Silva, I. R. & Alvarez, V. H. 2012. Phosphorus saturation of a tropical soil and related P leaching caused by poultry litter addition. *Agriculture, Ecosystems and Environment*, 162: 15-23.

Aguiar, A. C. F., de Freitas, I. C., Carvalho, C. S., Monroe, P. H. M. & Moura, E. G. 2010. Efficiency of an agrosystem designed for family farming in the pre-Amazon region. *Renewable Agriculture and Food Systems*, 26: 24-30.

Ahn, P M. 1993. Tropical Soils and Fertilizer Use. Longman. UK.

Andrade, F. V., Mendonça, E. S., Alvarez, V. H. & Novais, R. F. 2003. Adição de ácidos orgânicos e húmicos em Latossolos e adsorção de fosfato. Revista Brasileira de Ciência do Solo, 27, 1003-1011.

Alamgir, M. D., McNeill, A. & Tang, C. 2012. P Changes in soil P pools during legume residue decomposition etra Marschner. *Soil Biology & Biochemistry*, 49, 70-77.

Aray, Y. & Sparks, D.L. 2007. Phosphate reaction dynamics in soils and soil minerals: a multiscale approach. *Advances in Agronomy*, 94: 135-179.

Ayaga, G., Todd, A., & Brookes, P.C., 2006. Enhanced biological cycling of phosphorus increases its availability to crops in low-input sub-Saharan farming systems. *Soil Biology & Biochemistry,* 38: 81-90.

Blackburn, W. H. & Dennen, W. H. 1997. *Encyclopedia of mineral names*. Ottawa: Mineralogical Association of Canada, 360p.

Bolan, N. S., Naidu, R., Mahimairaja, S. & Baskaran, S. 1994. Influence of low molecular-weight organic acids on the solubilization of phosphates. *Biology and Fertility of Soils*, 18, 311-319.

Braun, W. A. G. 1983. Os fosfatos de alumínio do Brasil, sua tecnologia e uso agrícola. *Fertilizantes*, 5, 3-11.

Buchan, J. A. J., Muller, F. B., Rogers, J., Seager, R. H. & YONG, T. A. 1970. Agronomic use of calcined Christmas Island iron/aluminium phosphates. II. *New Zealand Journal of Agricultural Research*, 13, 465-480.

Câmara, L. M. J. R., Ribeiro, J. F. & Fernandes, M. S. 1984. Efeito da calcinação na eficiência de fosfatos de alumínio como fertilizante. *Revista Brasileira de Ciência do Solo*. 8, 345-347.

Chang, S.C. & Jackson, M.L. 1957. Fractionation of soil phosphorus. *Soil Science*, 84: 133-144.

Chen, C. R., Condron, L. M. & XU, Z. H. 2008. Impacts of grassland afforestation with coniferous trees on soil phosphorus dynamics and associated microbial processes: a review. *Forest Ecology Management*, 255: 396–409.

Chen, G. C., He, Z.L. & Huang, C.Y. 2000. Microbial biomass phosphorus and its significance in predicting phosphorus availability in red soils. *Communications in Soil Science and Plant Analysis*, 31, 655-667.

Chien, S. H., Menon, R. G. & Billingham, K. S. 1996. Phosphorus availability from phosphate rock as enhanced by water-soluble phosphorus. soil science society of america journal, 60, 1173-1177.

Childers, D. L., Corman, J., Edwards, M. & Elser, J. J. 2011. Sustainability challenges of phosphorus and food: solutions from closing the human phosphorus cycle. *BioScience*, 61, 117-124.

Condron, L.M., Goh, K.M., & Newman, R.H. 1985. Nature and distribution of soil phosphorus as revealed by a sequential extraction method followed by 31P nuclear magnetic resonance analysis. *Journal of Soil Science*, 36, 199-207.

Conte, E., Anghinoni, I., & Rheinheimer, D.S. 2003. Frações de fósforo acumuladas em Latossolo argiloso pela aplicação de fosfato no sistema plantio direto. *Revista Brasileira de Ciência do Solo*, 27, 893-900.

Conte, E., Anghinoni, I., & Rheinheimer D.S. 2002. Fósforo da biomassa microbiana e atividade de fosfatase ácida pela aplicação de fosfato em solo no sistema plantio direto. *Revista Brasileira de Ciência do Solo*, 26, 925-930.

Cross, A.F., & Schlesinger, W.H. 1995. A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma*, 64, 197-214.

Cruz, E. D. S. 1981. Eficiência relativa de fosfatos naturais da Amazônia Oriental. EMBRAPA-CPATU (Pesquisa em Andamento nº6), Belém, 5p.

Dalal, R. C. 1977. Soil organic phosphorus. Advances in Agronomy, 29: 83-117.

Damon, P. M., Bowden, B., Rose, T. & Rengel, Z. 2014. Crop residue contributions to phosphorus pools in agricultural soils: A review. *Soil Biology and Biochemistry*, 74, 127 – 137.

Devau, N., Cadre, E., Hensinger, P. & Gérard, F. 2010. A mechanistic model for understanding root-induced chemical changes controlling phosphorus availability. *Annals Of Bottany*, 105, 1183-1197.

Devau, N., Cadre, E. L., Hinsinger, P., Jaillard, B. & Gérard, F. 2009. Soil pH controls the environmental availability of phosphorus:Experimental and mechanistic modeling approaches. *Apllied Geochemistry*, 24: 2163-2174.

Essington, M. E. 2004. *Soil and water chemistry: An integrative approach.*, CRC Press, Boca Raton , 534p.

Francisco, E. A. B., Prochnow, L. I., Ferrari, V. C. & Jesus, S. L. 2007. Thermal treatment of aluminous phosphates of the crandallite group and its effect on phosphorus solubility**.** *Scientia Agricola*, 64, 269-274.

Filippelli, G. M. 2011. Phosphate rock formation and marine phosphorus geochemistry: the deep time perspective. *Chemosphere*, 84, 759–766

Gatiboni, L. C., Kaminski, J., Heinheimer, D.S. & Flores, J. P. C. 2007. Biodisponibilidade de formas de fósforo acumuladas em solo sob sistema plantio direto. *Revista Brasileira de Ciência do Solo*, 31, 691-699.

Gatiboni, L. C. 2003. *Disponibilidade de formas de fósforo do solo às plantas*. Universidade Federal de Santa Maria, (tese de doutorado), Santa Maria, 231p.

Gilkes, R. J. & Palmer, B. 1979. Calcined Christmas Island C- grade rock phosphate fertilizers: Mineralogical properties reversion and assessment by chemical extraction. *Australian Journal of Soil Research*, 17, 467-481.

Goedert, W. J. & Lobato, E. 1980. Eficiência agronômica de fosfatos em solo de cerrado. *Pesquisa Agropecuária Brasileira*, 15: 311-318.

Guardani, R., Drahog, J., Giulietti, M. & Schfigerl, K. 1989. Studies on calcination of aluminium phosphate rock in fluidized bed reactors. *Fertilizer Research*, 20, 181-191.

Guardani, R. 1987. Transformações térmicas e solubilidade de fosfatos de alumínio dos estados do Pará e Maranhão. *Fertilizantes*, 9, 6-10.

Guppy, C. N., Menzies, N. W., Moody, P. W. & Blamey, F. P. C. 2005. Competitive sorption reactions between phosphorus and organic matter in soil: a review. *Australian Journal of Soil Research*, 43, 189-202.

Hedley, M. J., Stewart, J. W. B. & Chauhan, B. S. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of American Journal*, 46, 970-976.

Hoare, J. Phosphate raw materials and fertilizers: Part II – A case history of marginal raw materials. In: Khasawneh, F.E.; Sample, E.C.; Kamprath, E.J. The role of phosphorus in agriculture. Madison: ASA, 1980. 1, 121-128.

Horowitz, N. & Meurer, E. J. 2004. Eficiência agronômica dos fosfatos naturais. In: Yamada, T. & Abdalla, S. R. S. Fósforo na agricultura brasileira. *Potafos*, 665-688.

Hue, N. V., Ikawa, H. & Silva, J. A. 1994. Increasing plant-available phosphorus in anultisol with a yard-waste compost. *Communications in Soil Science and Plant Analysis*, 25, 3291-3303.

Iqbal, S. M. 2009. Effect of crop residue qualities on decomposition rates, soil P dynamics and plant P uptake (Thesis). School of Earth and Environmental Sciences, The University of Adelaide.

Kabir, Z. & Koide, R. T. 2002. Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pennsylvania, USA. *Plant and Soil,* 238, 205-215.

Kant, S., Bi, Y. & Rothstein, S. J. 2011. Understanding plant response to nitrogen limitation for the improvement of crop nitrogen use efficiency. *Journal of Experimental Botany*, 62, 1499-1509.

Martinazzo, R., Rheinheimer, D.S., Gatiboni, L.C., Brunetto, G. & Kaminski, J. 2007. Fósforo microbiano do solo sob sistema plantio direto afetado pela adição de fosfato solúvel. *Revista Brasileira de Ciência do Solo*, 31, 563-568.

Mokolobate, M. S. & Haynes, R. J. 2003. A glasshouse evaluation of the comparative effects of organic amendments, lime and phosphate on alleviation of Al toxicity and P deficiency in an oxisol. *The Journal of Agricultural Science*, 140, 409-417.

Moura, E. G., Monroe, P. H. M., Coelho, M. J. A., Costa Sobrinho, J. R. S. & Aguiar, A. C. F. 2013. Effectiveness of calcined rock phosphate and leucaena prunings as a source of nutrients for corn in a tropical soil. *Biological Agriculture & Horticulture*, 30: 1-13.

Moura, E.G., Araújo, J.R.G., Monroe, P.H.M., Nascimento, I.O. & Aguiar, A.C.F. 2009. Patents on periphery of the Amazon rainforest. Recent Patents on Food, *Nutrition & Agriculture,* 1, 142-149.

Moura, E. G.; Coelho, K. P.; Freitas, I. C. & Aguiar, A. C. F. 2009. Chemical and physical fertility indicators of a weakly-structured Ultisol after liming and mulching. *Scientia Agrícola*, 66: 800-805.

Kwabiah, A. B., Palm, C. A., Stoskopf, N. C. & Voroney, R. P. 2003. Response of soil microbial biomass dynamics to quality of plant materials with emphasis on P availability. *Soil Biology & Biochemistry*, 35, 207-216.

Nachimuthu, G., Guppy, C., Kristiansen, P. & Lockwood, P., 2009. Isotopic tracing of phosphorus uptake in corn from 33P labelled legume residues and 32P labelled fertilisers applied to a sandy loam soil. *Plant and Soil,* 314, 303-310.

Negassa, W. & Leinweber, P. 2009. How does the Hedley sequential phosphorus fractionation reflect impacts of land use and management on soil phosphorus: a review. *Journal Plant Nutrition Soil Science*, 172: 305-325.

Novais, R.F. & Smyth, T.J. 1999. Fósforo em solo e planta em condições tropicais. UFV, DPS, Viçosa, 399p.

Oelkers, E.H. & Valsami-Jones, E. 2008. Phosphates mineral reactivity and global sustainability. *Elements*, 4, 83-87.

Parfitt, R. L. 1978. Anion adsorption by soils and soil materials. *Advances in Agronomy*, 30: 1-46.

Pavinato, P. S., Merlin, A., & Rosolem, C. A. 2009. Phosphorus fractions in Brazilian Cerrado soils as affected by tillage. *Soil & Tillage Research*, 105: 149–155.

Rasmussen, B. 1996. Early-diagenetic REE-phosphate minerals (florencite, gorceixite, crandallite, and xenotime) in marine sandstones; a major sink for oceanic phosphorus. *American Journal Science*, 296, 60-632.

Reddy, D. D., Rao, A.S. & Rupa, T. R. 2000. Effects of continuous use of cattle manure and fertilizer phosphorus on crop yields and soil organic phosphorus in a Vertisol. Bioresour. *Technol*, 75, 113–118.

Rezende, N. G. A. M. 2001. Insumos minerais para agricultura e áreas potenciais no estado do Pará e Amapá. Ministério de Minas e Energia, Superintendência Regional de Belém.

Rheinheimer, D.S., Gatiboni, L.C., & Kaminski, J. 2008. Fatores que afetam a disponibilidade do fósforo e o manejo da adubação fosfatada em solos sob sistema plantio direto. *Ciência Rural*, 38, 576-586.

Rheinheimer, D.S. & Anghinoni, I. 2001. Distribuição do fósforo inorgânico em sistemas de manejo de solo. *Pesquisa Agropecuária Brasileira*. 36, 151-160.

Rheinheimer, D.S., Anghinoni, I. & Conte, E. 2000. Fósforo da biomassa microbiana em solos sob diferentes sistemas de manejo. *Revista Brasileira de Ciência do Solo*, 24, 589-597.

Richardson, A. E, George, T. S, Maarten, H. & Simpson, R. J. 2005. Utilization of soil organic phosphorus by higher plants. In: Turner BL, Frossard E, Baldwin DS (eds) Organic phosphorus in the environment, 1st edn. CABI Publishing, Cambridge, 165–184.

Richardson, A. E. 2001. Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. *Australian Journal of Plant Physiology,* 28, 897-906.

Rocha, A. T., Duda, G. P., Nascimento, C. W. A. & Ribeiro, M. R. 2005. Fracionamento de fósforo e avaliação de extratores de P-disponível em solos da ilha de Fernando de Noronha. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 2, 178-184.

Schroder, J. J., Smit, A. L., Cordell, D. & Rosemarin, A. 2011. Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. *Chemosphere*, 84, 822-831.

Shaheen, S. M., Tsadelas, C. D. & Eskridge, K. M. 2009. Effect of Common Ions phosphorus sorption and lability in Greek Alfisols with diferent pH. *Soil Science*, 174, 21-26.

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W. & Zhang, F. 2011. Phosphorus dynamics: from soil to plant. *Plant Physiology*, 156, 997-1005.

Smith, S.E, Jakobsen, I., Gronlund, M. & Smith, F A. 2011. Roles of arbuscular mycorrhizas in plant phosphorus nutrition: interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. *Plant Physiology*, 156, 1050-1057.

Souza, R. F., Faquin,V., Andrade, A. T. & TORRES, P. R. F. 2007. Formas de fósforo em solos sob influência da calagem e adubação orgânica. *Revista Brasileira de Ciência do Solo*, 31: 1535-1544.

Stewart J. W. B. & Tiessen, H. 1987. Dynamics of soil organic phosphorus. *Biogeochemistry,* 41, 41–60.

Syers, J. K., Johnston, A. E. & Curtin, D. 2008. Efficiency of soil and fertilizer phosphorus use. *FAO Fertilizer and Plant Nutrition Bulletin 18***.**

Toledo, M. C. M. 1999. Os fosfatos aluminosos da série da crandallita – uma revisão. *Revista do Instituto Geológico*, 20, 49-63, 1999.

Turner, B. L., Richardson, A. E. & Mullaney, E. J. 2007. Inositol phosphates: linking agriculture and the environment. *CAB International,* p.304.

Vance CP, U. S. C.; Allan D. L. 2003. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. *New Phytologist***,** 157, 423–447.

Van Enk, R. J., Van der Vee, G., Acera, L. K., Schuiling, R. & Ehlert, P. 2011. The phosphate balance: current developments and future outlook. The Ministry of Economic Affairs, Agriculture and Innovation initiated and finances Innovation Network. ISBN: 978-90-5059-414-1

Vu, D.T., Tang, C. & Armstrong, R. D. 2008. Changes and availability of P fractions following 65 years of P application to a calcareous soil in a Mediterranean climate. *Plant and Soil*, 304: 21-33.

Wang, X., Yost, R. S. & Linquist, B. A. 2001. Soil aggregate size affects phosphorus desorption from highly weathered soils and plant growth. *Soil Science Society of America Journal*, 65, 139-146.

Xavier, F. A. S., Almeida, E. F., Cardoso, I. M. & Mendonça, E. S. 2011. Soil phosphorus distribution in sequentially extracted fractions in tropical coffee-agroecosystems in the Atlantic Forest biome, Southeastern Brazil. Nutrient Cycling Agroecosystem, 89, 31–44.

Xu, J.M., Tang, C. & Chen, Z.L., 2006. The role of plant residues in pH change of acid soils differing in initial pH. *Soil Biology and Biochemistry*, 38, 709-719.

# UTILIZATION AND FATE OF PHOSPHORUS SOURCES APPLIED TO COHESIVE TROPICAL SOIL

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## CAPÍTULO II

Artigo escrito de acordo com as nomas da revista European Journal of Soil Science

# Utilization and fate of phosphorus sources applied to cohesive tropical soil

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## Summary

In tropical regions, P is often a primary factor that limits crop growth. We compared the efficiencies of calcined aluminous phosphate (ALP) and single super phosphate (SSP) under leguminous residues to determine the fate of P sources in a tropical soil with hardsetting characteristics. The experiment followed a randomized block design with four replications and the following treatments: (1) ALPU (ALP plus urea [U]); (2) ALPL (ALP plus leucaena [L]); (3) SSPU (SSP plus U); (4) SSPL (SSP plus L); and (5) BS (bare soil - a control involving no fertilizer application). To assess the residual values of the P sources, we used a sequence of crops consisting of corn, cowpea and cassava, which are listed from the least to the most P depleting. Both aluminous phosphate and the single superphosphate exhibited low efficiency in bare soil. The use of leguminous residues increased the P use efficiency of both P sources because it enhanced the uptake of N and soluble P and the fractions of solubilized recalcitrant P. The replacement of the single superphosphate with aluminous phosphate may be advantageous in the second year of planting using high-demand crops, but the P from single superphosphate retained in the less soluble fractions may be available if the SSP is used in P-depleting crops combined with a no-tillage system underneath mulch of leguminous residues.

## Introduction

In many weathered tropical acid soils with a low content of available P and high phosphate sorption capacity, such as in tropical regions, P is often a primary factor limiting crop growth (Vance *et al.*, 2003). Therefore, high-input systems are strongly dependent on P fertilizers, although these fertilizers are a finite resource (Dordas, 2009). In low-input farming systems, the continual mining of P by crops and the subsequent removal of P decreases the soil fertility. This removal is now recognized as the fundamental cause of deforestation and declining food security in family farms in the Amazon region and its periphery (Aguiar *et al.*, 2011).

Although there are various available sources of P for use in agricultural systems, for a family farm in the humid tropics, the direct application of local phosphate rock (PR) appears to be a more attractive way of alleviating P deficiency than the use of more expensive, imported, processed fertilizers, such as single superphosphate (SSP). At the farm level, calcination can be an alternative for increasing the dissolution rate of PR in direct applications, and even Al phosphate (ALP) rock can be used (Van Straaten, 2002). ALP rock is distributed worldwide and is abundant in northern Brazil and in Australia (Mason & Cox, 1969). The total known reserves in the Brazilian Amazonian region are approximately 30 million tons of ore containing 15–30% $P_2O_5$, consisting primarily of the mineral crandallite–goyazite ($[Ca, Sr]\ A1_3[PO_4]_2\ [OH]_5 \dagger H_2O$) (Guardani *et al.*, 1989).

Whichever the system or the source used, enhancing the efficiency of P usage is mandatory for ensuring the profitability and sustainability of crop systems. In humid tropical soils, repeated wetting and drying cycles usually promotes long-term hardening in the absence of soil aggregation (Mullins, 1999). Under these circumstances, nutrient usage efficiency is the primary factor affecting the sustainable management of agro-systems, because of poor soil rootability and high rates of nutrient loss (Moura *et al.*, 2009).

Several authors have reported the positive effects of soil cover on the soil structure and the increase in P usage efficiency in no-tillage systems. Soil cover provides positive effects (i) by enhancing the rootability of soils susceptible to hardsetting, as covering the soil surface with mulch preserves the soil moisture by reducing evaporative losses and delays cohesion (Becher *et al.*, 1997; Moura *et al.*, 2012); (ii) by promoting the formation of unstable aggregates through continuous application of residues that improve the environment for root growth and via increases in the free light fraction of organic matter (Shepherd *et al.*, 2002); (iii) by decreasing the P sorption in highly weathered soils, promoting competition between residue decomposition products and P by sorption sites (GuPy *et al.*, 2005); and (iv) by producing organic acids and humic substances during decomposition, which are also involved in the P solubilization process (Singh & Amberger, 1990).

Despite all of these potential benefits, only 10-20% of the applied P, even with soluble fertilizers, is taken up by plants during the year of application because the majority is rapidly fixed or precipitated in various chemical and physical forms, which differ in their environmental fate and plant availability (Vu *et al.*, 2008). The P from applied fertilizer that is not used by a crop continues to be an important source for the succeeding crop, and thus the evaluation of the P-source efficiency must also consider this effect. Our ability to increase P usage efficiency and to improve management of cropping systems for sustained production is partially dependent on our understanding of the way in which various P fractions are affected by the complexity of the interactions between the soil components, the source of P used and the management system.

Hence, our hypothesis was that in a tropical soil, calcined aluminous phosphate can replace the soluble phosphate used for staple crops if it is combined with leguminous residue in a no-tillage system. Thus, instead of using single superphosphate, the residual value of phosphate rock reduces the need for fertilizers during subsequent years.

Therefore, the objective of this study was to determine the fate of P from calcined aluminous phosphate and single superphosphate and compare the efficiencies of these sources when a cover of leguminous residues are used over a tropical soil with hardsetting characteristics.

## Materials and Methods

### *Experimental site and trial set-up*

The experiment was conducted during four growing seasons (2010, 2011, 2012 and 2013) at Maranhão State University, Brazil (2°30'S, 44°18'W). The region has a hot, semi-humid, equatorial climate with mean precipitation of 2,100 mm year$^{-1}$ and two well-defined seasons: a rainy season that extends from January to June and a dry season with a pronounced water deficit from July to December. The local soil displayed hardsetting characteristics (Moura *et al.*, 2009), was classified as Arenic Hapludult, and consisted of 260 g kg$^{-1}$ of coarse sand, 560 g kg$^{-1}$ of fine sand, 80 g kg$^{-1}$ of silt and 100 g kg$^{-1}$ of clay. Its chemical characteristics were as follows: pH 4.3 (measured in 0.01 M $CaCl_2$ using a soil:solution ratio of 1:1 (v / v)), organic carbon (Walkley–Black) 9.3 g dm$^{-3}$, P (resin) 1.4 mg dm$^{-3}$, K 0.6 mmol$_c$ dm$^{-3}$, Ca 4.0 mmol$_c$ dm$^{-3}$, Mg 10.0 mmol$_c$ dm$^{-3}$, Al 0.0 mmol$_c$ dm$^{-3}$, potential acidity 26.0 mmol$_c$ dm$^{-3}$, sum of bases 14.6 mmol$_c$ dm$^{-3}$, cation exchange capacity 40.6 mmol$_c$ dm$^{-3}$ and base-saturation 36%. The soil was characterized in accordance with the standard methods of Carter & Gregorich (2008). The soil's dry bulk density was 1.3 g $cm^{-3}$ measured by the method of Thomasson (1978). The soil samples were collected at depths of 0–20 cm in 2010 before sowing corn.

The area had been fallow since 1990 and supported a local type of grass, which was removed using a glyphosate application. The experiment was conducted under no-tillage conditions, and the experimental plot size was 4 x 8 m. The area was limed in December 2009 and 2010 using a surface application of 1 Mg $ha^{-1}$ of calcium, which corresponds to 279 and 78 kg $ha^{-1}$ of Ca and Mg per year [$Ca(OH)_2$) + $Mg(OH)_2$], respectively. The aluminum phosphate rock (ALP) used in this experiment was collected on Trauíra Island in northeastern Maranhão, Brazil, located at 1°16'S 45°37'W. Phosphate from the same area was analyzed by Guardani *et al.* (1989), and its chemical composition was as follows: $P_2O_5$ = 27.2%, CaO = 6.91%, $SiO_2$ = 2.84%, $Fe_2O_3$ = 4.31% and $Al_2O_3$ = 29.3%.

The ALP rock was ground to a particle size of < 0.150 mm and then calcined at a temperature of 500 °C for 2 h. The calcination was performed using handcrafting techniques in furnaces commonly found in rural communities in the region and was monitored using an infrared radiation thermometer. The $P_2O_5$ solubility of the calcined products was measured by extraction in a 2% citric acid solution (Faithfull, 2002) which wos 6.51% $P_2O_5$. The $P_2O_5$ solubility of simple superphosphate (SSP) in the same 2% citric acid solution was 18%. These values were used to calculate the amount of each product to be used in the soluble $P_2O_5$ application.

To assess the residual values of the P sources, we used a sequence of crops consisting of corn, cowpea and cassava, which are listed from the least to the most P depletive. The ALP rock and SSP were applied only in 2010 in a narrow band in a row planting of the corn. Residues from *Leucaena leucocephala* (leucaena) were collected from an area near the experimental site and applied in a quantity that was similar to that commonly produced in an alley cropping system (6 Mg ha$^{-1}$), according to Aguiar *et al*. (2010). The important chemical parameters of the leucaena were as follows: a C/N ratio of 12 and N and P concentrations of 40.17 g kg$^{-1}$ and 1.55 g kg$^{-1}$, respectively.

The experiment followed a randomized block design with four replications and the following treatments: (1) an ALPU treatment consisting of 160 kg ha$^{-1}$ of $P_2O_5$ from ALP and 100 kg ha$^{-1}$ of N from urea (U); (2) an ALPL treatment consisting of 160 kg ha$^{-1}$ of $P_2O_5$ from ALP and 6 Mg ha$^{-1}$ of dry-matter residue from leucaena (L); (3) an SSPU treatment consisting of 160 kg ha$^{-1}$ of $P_2O_5$ from SSP and 100 kg ha$^{-1}$ of N from U; (4) an SSPL treatment consisting of 160 kg ha$^{-1}$ of $P_2O_5$ from SSP and 6 Mg ha$^{-1}$ of dry-matter residue from leucaena (L); and (5) a BS (bare soil) treatment involving no fertilizer application. The leucaena residue was applied in the form of fresh branches at a rate equivalent to 241 kg ha$^{-1}$ year$^{-1}$ of N and 9.3 kg ha$^{-1}$ year$^{-1}$ of P. The urea and leucaena were applied in 2010, 2011, 2012 and 2013.

The total amount of applied P (including organic and insoluble inorganic P) were 292 kg ha$^{-1}$ from ALP and 78.70 kg ha$^{-1}$ from SSP combined with U and 329.20 kg ha$^{-1}$ from ALP and 115.90 kg ha$^{-1}$ from SSP combined with L. The total amount of urea and leucaena was divided as follows: the corn crop received two surface applications, one at the time of sowing and one at approximately the appearance of the fourth pair of leaves; and the cassava crop receive an application at planting and a second at the time of the rainy period of the second vegetative cycle (12 months after planting). All of the plots received 60 kg ha$^{-1}$ of $K_2O$ as potassium chloride and 4 kg ha$^{-1}$ of Zn in the form of $ZnSO_4$. Both of these treatments were applied to all crops for each year. The corn (cultivar Ag 5020) was sown in a no-till system in January

2010 and January 2011. A spacing of 90 cm between rows and 33 cm between plants was used. The cowpea (cultivar xique-xique), which is a short-season crop, was sown in 2011 after the harvest of corn with a spacing of 45 cm between rows and 15 cm between plants was used. The cassava (cultivar João-velho) was sown in January 2012. A spacing of 100 cm between rows and 50 cm between plants was used.

### *Plant analysis*

The P and N concentration in tissue were measured in the dry matter of the corn, cowpea and cassava (including the roots) at physiological maturity. Ten plants from each plot were randomly selected, and all of these plant materials were dried at 60 ºC for 3-4 days to obtain a constant weight. Subsamples were collected and ground to pass through a screen opening size of 1 mm. The concentrations of P and N were determined after digestion using $H_2SO_4$-$H_2O_2$, according to the standard method of Cottenie (1980). At the harvest of the corn and cowpea, the grain yields were evaluated and determined within an area of 10 $m^2$; the yields were reported based on a moisture content of 145 g $kg^{-1}$. The productivity of the cassava crop was evaluated by measuring the dry matter of the roots. The fresh roots of the cassava were harvested (in November 2013) in an area of 16 $m^2$ and then dried for 3-4 days to obtain a constant weight.

### *Soil chemical analyses and P fractionation*

Soil samples were collected from depths of 0-10, 10-20 and 20-30 cm at three points within the plot by excavating a trench 1 m long and 0.05 m wide (Figure B). The samples from each point were passed through a 2 mm sieve and then air-dried prior to the analyses. The contents of Calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), potassium ($K^+$), sodium ($Na^+$); pH in $CaCl_2$ (measured in 0.01 M $CaCl_2$ using a soil:solution ratio of 1:1 (v / v)); and potential acidity ($H^+ + Al^{3+}$) were determined according to the methods of Carter & Gregorich (2008). The sum of basic cations (SBC) was obtained by the formula $Ca^{2+} + Mg^{2+} + K^+ + Na^+$. The cation exchange capacity (CEC) at pH 7 was obtained by the formula $Ca^{2+} + Mg^{2+} + K^+ + Na^+ + (H^+ + Al^{3+})$. The saturation percentage of the bases was obtained by the formula SBC/CEC x 100.

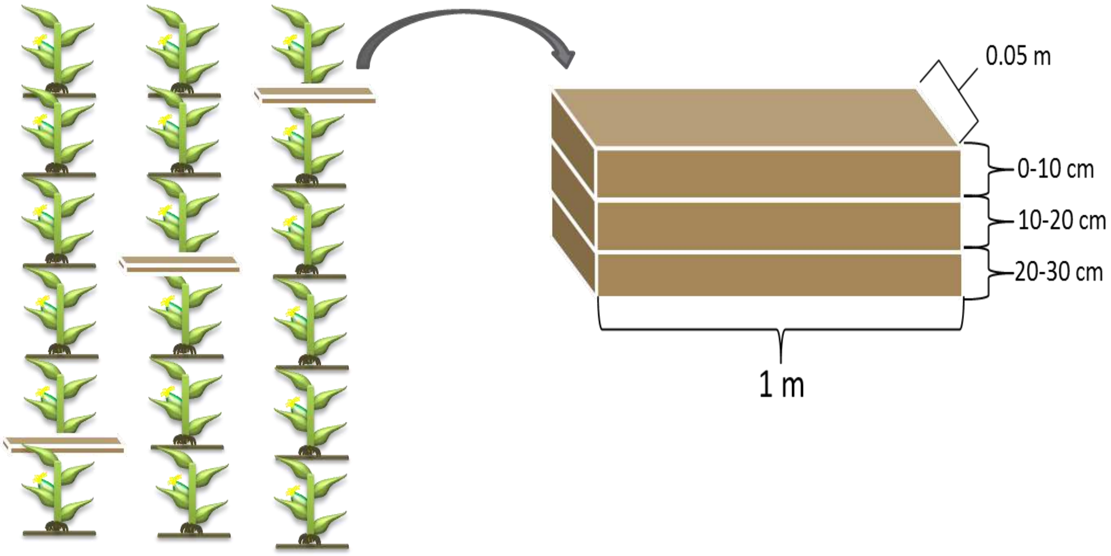

**Figure B** Soil sampling scheme for chemical analysis and P fractionation

The P fractionation in soil samples was determined in accordance to the method of Hedley *et al.* (1982) and modifications of Condron *et al.* (1985). Briefly, a 0.5 g soil sample was extracted sequentially using an anion exchange resin, 0.5 M $NaHCO_3$ (pH 8.5), 0.1 M NaOH, 1 M HCl, 0.5 M NaOH and subjected to residual digestion with concentrated $H_2O_2$ + $H_2SO_4$. The amount of inorganic phosphorus (Pi) in the alkaline extracts ($NaHCO_3$-Pi, 0.1 M NaOH-Pi and 0.5 NaOH-Pi) was determined using the analytical method of Dick & Tabatabai (1977) with a spectrophotometer (CARY 50 POBRE, UV-VIS Varian, New South Wales, Australia). These alkaline extracts were added to a 1:1 sulfuric acid solution and 7.5% ammonium persulfate in an autoclave at 121 °C and 103 kPa for 2 h to determine the Pt (inorganic P + organic P). The P acid extracts (resin-Pi, $NaHCO_3$-Pt, 0.1 M NaOH-Pt, 0.5 NaOH-Pt, HCl-Pi and residual-P) were determined using the method of Murphy & Riley (1962) with a spectrophotometer (CARY 50 POBRE, UV-VIS Varian, New South Wales, Australian). The organic P (Po) of the alkaline extracts was determined by calculating the difference between the total phosphorus (Pt) and Pi in the alkaline extracts.

The fractions of P were classified based on the lability predicted by the extractors. The labile P (LP) consisted of the resin P plus the $NaHCO_3$-P (Pi and Po), the moderately labile P (MLP) consisted of the 0.1 M NaOH-P (Pi and Po) plus the HCl-P, and the hardly labile P (HLP) consisted of the 0.5 M NaOH-P (Pi and Po).

The P fate percentages were estimated as follows: (1) phosphorus recovery efficiency (PRE) = [(kg ha$^{-1}$ P taken up in the treatment – kg ha$^{-1}$ P taken up in the BS) / kg ha$^{-1}$ total of P applied] x 100. The LP, MLP and HLP fractions were calculated as follows: (2) LP = [(kg ha$^{-1}$ P in the treatment - kg ha$^{-1}$ P in the control) / kg ha$^{-1}$ total of P applied] x 100, (3) MLP = [(kg ha$^{-1}$ P in the treatment - kg ha$^{-1}$ P in the BS) / kg ha$^{-1}$ total of P applied] x 100, (4) HLP = [(kg ha$^{-1}$ P in the treatment - kg ha$^{-1}$ P in the BS) / kg ha$^{-1}$ of total P applied] x 100; (5) no-labile P = total P applied in the treatment – (PRE + LP + MLP + HLP). The values of P (mg kg$^{-1}$) in the three depth intervals (0-10, 10-20, 20-30 cm) were added after conversion for kg $ha^{-1}$ as follows: P content (mg $kg^{-1}$) x soil bulk density (g $cm^{-3}$) x 10 cm depth / 10.

### *Statistical analyses*

The data were analyzed via analysis of variance (ANOVA), and the means were compared using Tukey's post hoc test at the $P$ = 0.95 significance level. The data were analyzed using InfoStat software (InfoStat Group, College of Agricultural Sciences, National University of Córdoba, Argentina).

## Results

### *Soil chemical analyses*

The addition of soil cover in the form of residue from the legume appeared to slightly alter several of the chemical soil properties (Table 1). Changes occurred in pH, acidity and base saturation percentage. The combination of residues with SSP decreased the active acidity up to the 30 cm layer and potential acidity up to the 10 cm layer. The ALPL treatment showed a lower active acidity than the BS in the 0-20 cm layer. The saturation of the bases (BSP) was higher in all of the plots with applied residue up to 10 cm and in the SSPL treatment up to 30 cm. The contents of Al were null in all of the treatments.

**Table 1** Chemical analyses at different depths (0-10, 10-20 and 20-30 cm) under different treatments

| | BS | ALPU | SSPU | ALPL | SSPL |
|---|---|---|---|---|---|
| **0-10 cm** | | | | | |
| pH in $CaCl_2$ | 5.43 c | 5.33 c | 5.58 bc | 6.15 ab | 6.33 a |
| Potential acidity / $mmol_c\ dm^{-3}$ | 16.25 a | 16.50 a | 15.50 a | 12.51 b | 12.50 b |
| $Al^{3+}$ / $mmol_c\ dm^{-3}$ | 0 | 0 | 0 | 0 | 0 |
| BSP / % | 64.55 c | 67.71 bc | 69.82 b | 75.41 a | 77.95 a |
| **10-20 cm** | | | | | |
| pH in $CaCl_2$ | 4.63 b | 4.73 b | 4.50 b | 4.65 a | 5.38 a |
| Potential acidity / $mmol_c\ dm^{-3}$ | 23.50 b | 22.50 b | 25.25 a | 21.00 b | 21.00 b |
| $Al^{3+}$ / $mmol_c\ dm^{-3}$ | 0 | 0 | 0 | 0 | 0 |
| BSP / % | 40.93 bc | 43.32 bc | 38.27 c | 45.14 ab | 49.28 a |
| **20-30 cm** | | | | | |
| pH in $CaCl_2$ | 4.23 b | 4.43 b | 3.96 b | 3.90 b | 4.91 a |
| Potential acidity / $mmol_c\ dm^{-3}$ | 27.12 ab | 25.50 b | 30.12 a | 25.24 b | 25.25 b |
| $Al^{3+}$ / $mmol_c\ dm^{-3}$ | 0 | 0 | 0 | 0 | 0 |
| BSP / % | 29.12 b | 31.13 ab | 32.80 a | 30.00 ab | 34.94 a |

BS = bare soil, ALPU = aluminum phosphate rock (ALP) and urea (U), SSPU = simple superphosphate (SSP) and urea (U), ALPL = aluminum phosphate rock (ALP) and leucaena (L), and SSPL = simple superphosphate (SSP) and leucaena (L). Different letters in the same row indicate significantly difference among treatments by Tukey's test ($P < 0.05$).

*Nutrient content and productivity*

The use of the two P sources with the leucaena residue significantly ($P < 0.0001$) increased the accumulation of N in all of the crops when compared to urea in the BS treatment (Table 2).

During the first year, there were differences in the accumulation of N between the treatments with different sources of P; accumulation of N was higher in the SSP treatment than in the ALP under the same style of management.

During the second year (corn II), there was no difference in the N accumulation between the two P sources in the treatments with leucaena, which were higher than all of the other treatments. In terms of N accumulation, the SSPU treatment was equal to the BS and the ALPU was intermediate. During cowpea cultivation (second year), the two P sources with leucaena were coequal and higher than in the other treatments (which were coequal) in terms of N accumulation. During cassava cultivation, the ordering of N accumulation in the plots was SSPL > ALPL > ALPU > SSPU > BS ($P < 0.0001$). The ordering of total N accumulation in general during the study was SSPL > ALPL > ALPU = SSPU > BS ($P < 0.0001$).

In the corn I, corn II and cowpea crops, there were no differences in P accumulation in the plants among the plots when the residue of leucaena. However, in the cassava (third and fourth years) crop, the P accumulation varied, with the SSPL exhibiting higher P accumulation than the ALPL (Table 2). During the first year, the ordering of P accumulation in the various treatments without leucaena was SSPU > ALPU > BS ($P < 0.0001$). During the second year, the P accumulation was approximately four times higher in the plots covered with residue than in the plots receiving other treatments, and there were no differences in P accumulation between the plots without residue and the BS, regardless the P source. Similarly, the accumulation of P in the cowpea was higher in the plots with residue and lower in the uncovered plots than in the BS treatment. The ordering of P accumulated in the cassava and total accumulated P was SSPL > ALPL > ALPU > SSPU > BS ($P < 0.0001$). The total accumulated P in the crops was more than two times higher in the plots covered with residue compared with the other treatments.

**Table 2** Nitrogen and phosphorus content absorbed by crops during four cultivations consecutives under phosphate sources a leguminous cover

| | BS | ALPU | SSPU | ALPL | SSPL |
|---|---|---|---|---|---|
| **Nitrogen (N) / kg ha$^{-1}$** | | | | | |
| Corn I$^{(1)}$ | 19.41 e | 32.74 d | 40.75 c | 57.28 b | 79.09 a |
| Corn II$^{(1)}$ | 28.99 c | 48.27 b | 36.07 c | 101.67 a | 100.65 a |
| Cowpea$^{(1)}$ | 34.16 b | 32.52 b | 38.68 b | 61.69 a | 67.53 a |
| Cassava$^{(1)}$ | 31.38 e | 118.34 c | 91.18 d | 213.28 b | 252.73 a |
| Total N$^{(2)}$ | 113.94 d | 231.87 c | 206.68 c | 433.92 b | 500.00 a |
| **Phosphorus (P) / kg ha$^{-1}$** | | | | | |
| Corn I$^{(3)}$ | 1.91 d | 2.93 c | 3.77 b | 8.30 a | 8.61 a |
| Corn II$^{(3)}$ | 6.09 b | 6.23 b | 5.99 b | 24.99 a | 23.91 a |
| Cowpea$^{(3)}$ | 2.02 b | 1.69 c | 1.63 c | 4.22 a | 4,45 a |
| Cassava$^{(3)}$ | 5.70 e | 14.63 c | 10.63 d | 24.11 b | 30.78 a |
| Total P$^{(4)}$ | 15.72 e | 25.48 c | 22.02 d | 61.62 b | 67.75 a |

BS = bare soil, ALPU = aluminum phosphate rock (ALP) and urea (U), SSPU = simple superphosphate (SSP) and urea (U), ALPL = aluminum phosphate rock (ALP) and leucaena (L), and SSPL = simple superphosphate (SSP) and leucaena (L). (1)Content of nitrogen absorbed by crops; (2)Sum of the contents of nitrogen absorbed by all crops; (3)Content of phosphorus absorbed by crops; (4)Sum of the contents of phosphorus absorbed by all crops; Corn I - first year, Corn II and cowpea - second year, and cassava - third and fourth years. Different letters in the same row indicate significantly difference among treatments by Tukey's test ($P < 0.05$).

Only during the second year (corn II) was the productivity higher in the ALPL treatment than in the SSPL. When the other crops were planted, the productivity was higher in the SSPL (Figure 1). In addition, the productivity in the ALPU was higher than in the SSPU in the corn II and cassava crops. Except for the cowpea crop, in which the productivity of the BS did not differ from the uncovered plots, the productivity of the BS treatment was lower than that of the other treatments. In the cassava (third and fourth years), a crop with low P requirements, the productivity in the ALPU treatment was higher than in the SSPU; however, the application of leucaena residue increased the productivity in the SSP treatment. In all of the crops, the productivity with leucaena was superior to any other N or P source.

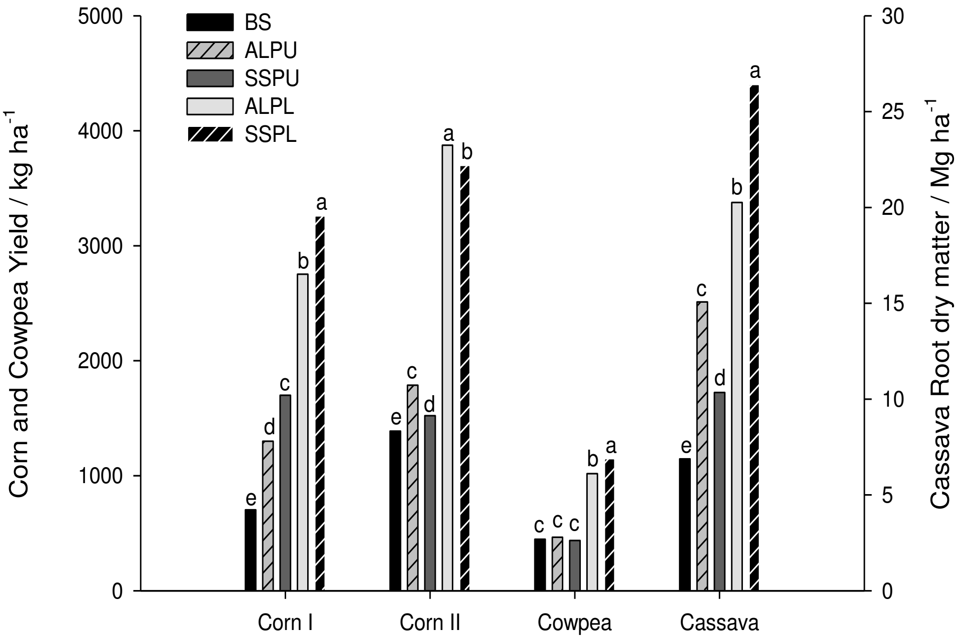

**Figure 1** Productivity of Corn (I and II), Cowpea and Cassava. BS = bare soil,ALPU = aluminum phosphate rock (ALP) and urea (U), SSPU = simple superphosphate (SSP) and urea (U), ALPL = aluminum phosphate rock (ALP) and leucaena (L), and SSPL = simple superphosphate (SSP) and leucaena (L). Corn I - first year, Corn II and cowpea - second year, and cassava - third and fourth years. Different letters in the same row indicate significantly difference among treatments by Tukey's test ($P <$ 0.05)

*Soil P fractionation*

After four years, differences in the P fractions in all intervals were small (Table 3). Among the more labile fractions, the amount of resin P was higher in the SSPL treatment than in the ALPU. In turn, the $NaHCO_3$-Pi fraction was higher in the ALPL treatment than in the SSPU. The remaining treatments did not show significant differences in these fractions. Additionally, $NaHCO_3$-Po was higher in the ALPL than in the BS, ALPU and SSPL.  P regardin to the moderately labile fractions, 0.1 NaOH-Pi was higher in the ALPL treatment than in the BS and did not show significant differences between the other treatments. In addition, the 0.1 NaOH-Po fraction was higher in the SSPU than in the ALPU, ALPL and BS treatments. The HCl-Pi fraction did not show any significant differences among the treatments. Among the hardly labile fractions, only 0.5 NaOH-Po showed differences, with higher values in the ALPL than in the other treatments. The ordering of residual P was ALPU > ALPL > SSPU = SSPL > BS ($P < 0.0001$).

In the 10-20 cm interval, the differences were even less evident than in the topsoil (Table 3). There were no differences among the resin P, $NaHCO_3$-Pi, $NaHCO_3$-Po, 0.1 NaOH-Po and HCl-Pi fractions. However, the treatment with ALP plus urea had a lower 0.1 NaOH-Pi fraction than the ALP with leucaena, and significant differences were not found in the other treatments. Additionally, in this layer, the hardly labile fraction 0.5 NaOH-Pi was smaller in the BS and SSPU treatments than in the ALPU and SSPL. In turn, the 0.5 NaOH Po fraction was lower in the SSPL than in all of the other treatments and higher in the SSPU treatment than in the ALPU. The ordering of residual P was ALPU > ALPL > SSPL = BS > SSPU ($P < 0.0001$).

In the 20-30 cm interval, only three fractions showed significant differences. Thus, the $NaHCO_3$-Pi fraction was higher in the SSPL, lower in the SSPU and intermediate in other treatments (Table 3). The 0.1 NaOH-Pi fraction was higher in the ALPL than in the SSPL. Additionally, the 0.5 NaOH-Po fraction was lower in the BS than in the ALPU, SSPU and SSPL treatments. As expected, higher contents of residual P were found in the ALPU treatments. The order of residual P was ALPU = ALPL > BS > SSPL = SSPU ($P < 0.0001$).

**Table 3** Phosphorus soil fractions at different depths (0-10, 10-20 and 20-30 cm) under different treatments

| Depth | BS | ALPU | SSPU | ALPL | SSPL |
|---|---|---|---|---|---|
| **0 – 10 cm** | mg kg$^{-1}$ | | | | |
| Resin P | 3.43 ab | 3.21 b | 3.94 ab | 3.58 ab | 4.11 a |
| NaHCO$_3$-Pi | 3.11 ab | 3.03 ab | 2.62 b | 3.74 a | 3.36 ab |
| NaHCO$_3$-Po | 3.53 b | 5.43 b | 6.56 ab | 9.54 a | 6.00 b |
| NaOH-Pi 0.1 mol L$^{-1}$ | 5.59 b | 6.03 ab | 7.97 ab | 9.53 a | 6.00 ab |
| NaOH-Po 0.1 mol L$^{-1}$ | 14.88 b | 12.49 b | 19.16 a | 12.17b | 13.10 ab |
| HCl-Pi | 4.23 a | 2.24 a | 3.31 a | 2.87 a | 4,25 a |
| NaOH-Pi 0.5 mol L$^{-1}$ | 20.66 a | 20.20 a | 17.23 a | 18.99 a | 16.83 a |
| NaOH-Po 0.5 mol L$^{-1}$ | 8.36 b | 6.98 b | 7.28 b | 23.28 a | 7.78 b |
| Residual P | 109.58 d | 235.43 a | 159.85 c | 187.79 b | 160.20 c |
| **10 – 20 cm** | | | | | |
| Resin P | 3.46 a | 3.39 a | 3.37 a | 3.51 a | 4.40a |
| NaHCO$_3$-Pi | 2.65 a | 2.68 a | 2.05 a | 2.72 a | 3.31 a |
| NaHCO$_3$-Po | 5.86 a | 4.20 a | 4.88 a | 6.41 a | 6.05 a |
| NaOH-Pi 0.1 mol L$^{-1}$ | 4.90 ab | 4.37 b | 5.84 ab | 8.04 a | 6.74 ab |
| NaOH-Po 0.1 mol L$^{-1}$ | 14.28 a | 16.25 a | 15.28 a | 16.46 a | 12.60 a |
| HCl-Pi | 2.55 a | 1.26 a | 1.67 a | 2.37 a | 2.51 a |
| NaOH-Pi 0.5 mol L$^{-1}$ | 14.67 c | 19.98 a | 14.64 c | 16.91 bc | 18.47 ab |
| NaOH-Po 0.5 mol L$^{-1}$ | 8.53 ab | 8.35 b | 12.05 a | 8.82 ab | 3.39 c |
| Residual P | 123.58 c | 196.59 a | 115.01 d | 169.96 b | 127.69 c |
| **20 – 30 cm** | | | | | |
| Resin P | 3.62 a | 3.24 a | 3.51 a | 3.70 a | 3.51 a |
| NaHCO$_3$-Pi | 2.27 b | 2.04 b | 1.41 c | 2.20 b | 3.10 a |
| NaHCO$_3$-Po | 4.80 a | 4.69 a | 8.52 a | 4.57 a | 4.73 a |
| NaOH-Pi 0.1 mol L$^{-1}$ | 4.71 ab | 4.73 ab | 4.78 ab | 6.85 a | 2.91 b |
| NaOH-Po 0.1 mol L$^{-1}$ | 12.69 a | 13.25 a | 14.78 a | 12.80 a | 14.66 a |
| HCl-Pi | 1.15 a | 1.90 a | 1.32 a | 1.15 a | 1.44 a |
| NaOH-Pi 0.5 mol L$^{-1}$ | 20.61 a | 21.63 a | 21.71 a | 17.14 a | 18.31 a |
| NaOH-Po 0.5 mol L$^{-1}$ | 1.94 b | 6.20 a | 5.85 a | 4.96 ab | 5.30 a |
| Residual P | 123.55 b | 168.98 a | 104.49 c | 178.98 a | 99.21 c |

BS = bare soil, ALPU = aluminum phosphate rock (ALP) and urea (U), SSPU = simple superphosphate (SSP) and urea (U), ALPL = aluminum phosphate rock (ALP) and leucaena (L), and SSPL = simple superphosphate (SSP) and leucaena (L). Different letters in the same row indicate significantly difference among treatments by Tukey's test ($P < 0.05$).

The superficial layer was the only layer to show differences in the total labile fractions and total moderately labile fractions between treatments (Figure 2A). Fractions with lower lability were found in the ALPU and BS treatments compared with the ALPL. The other treatments did not show significant differences. Similarly, the moderately labile fractions were greater in the SSPU than in the ALPU. In the same layer, the hardly labile fraction was greater in the ALPL than in all of the other treatments (which did not differ from one to the next).

In deeper layers, this hardly fraction in the 10-20 cm interval was higher in the ALPU treatment than in the BS and SSPL treatments; the other treatments did not exhibit significant differences (Figure 2B). The hardly labile fraction was also higher in the ALPU treatment than in the ALPL treatment in the 20-30 cm interval, and the source of the applied P did not affect the labile fraction in this deepest interval (Figure 2C).

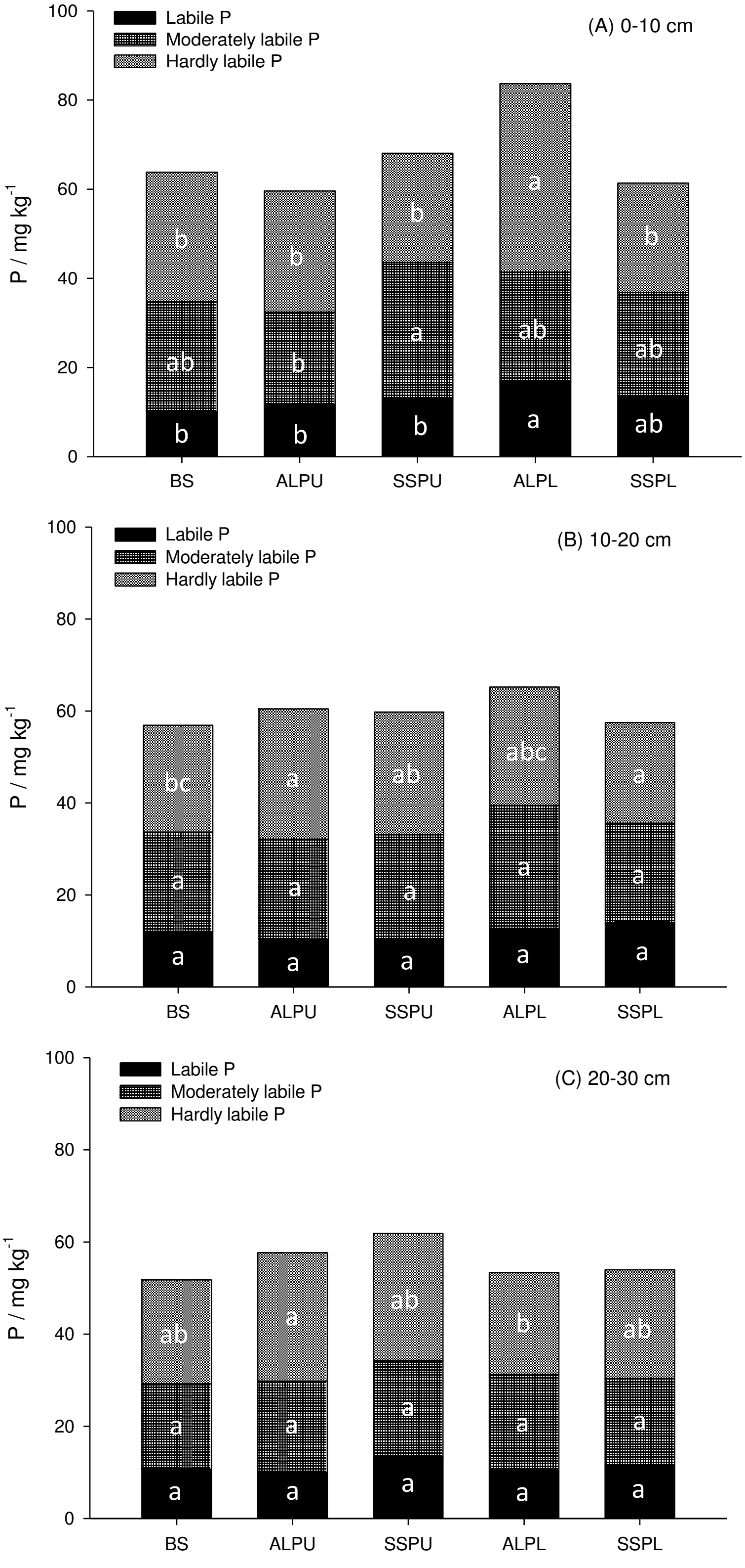

**Figure 2** P fractions quantified according to the P lability predicted by extractors, at depth 0-10 cm (A), 10-20 cm (B) and 20-30 cm (C). BS = bare soil, ALPU = aluminum phosphate rock (ALP) and urea (U), SSPU = simple superphosphate (SSP) and urea (U), ALPL = aluminum phosphate rock (ALP) and leucaena (L), and SSPL = simple superphosphate (SSP) and leucaena (L). Different letters in the same row indicate significantly difference among treatments by Tukey's test (*P* < 0.05)

The fate of the total applied P varied with the source of P and type of soil management (Figure 3). The ALPU treatment exhibited no buildup in the percentage of labile or moderately labile P. Approximately 93% of the total P applied in the ALPU form was transformed into fractions with no lability. In the SSPU and ALPL treatments, this non labile fraction was 63.5% and 74.2%, respectively; in the same treatments, the hardly labile fraction was 6.6% and 6.1%, respectively. In addition, the percentage of P uptake in the ALPL was 13.9% versus 8% in the SSPU. In contrast, the opposite trend was observed in the moderately labile fraction, which was 2.9% and 15.1% in the ALPL and SSPU treatments, respectively. In the SSPL, the P recovery efficiency was approximately equal to the residual fractions of P (44.8 to 48.4%), and the remaining P (6.6%) was transformed into the labile fractions.

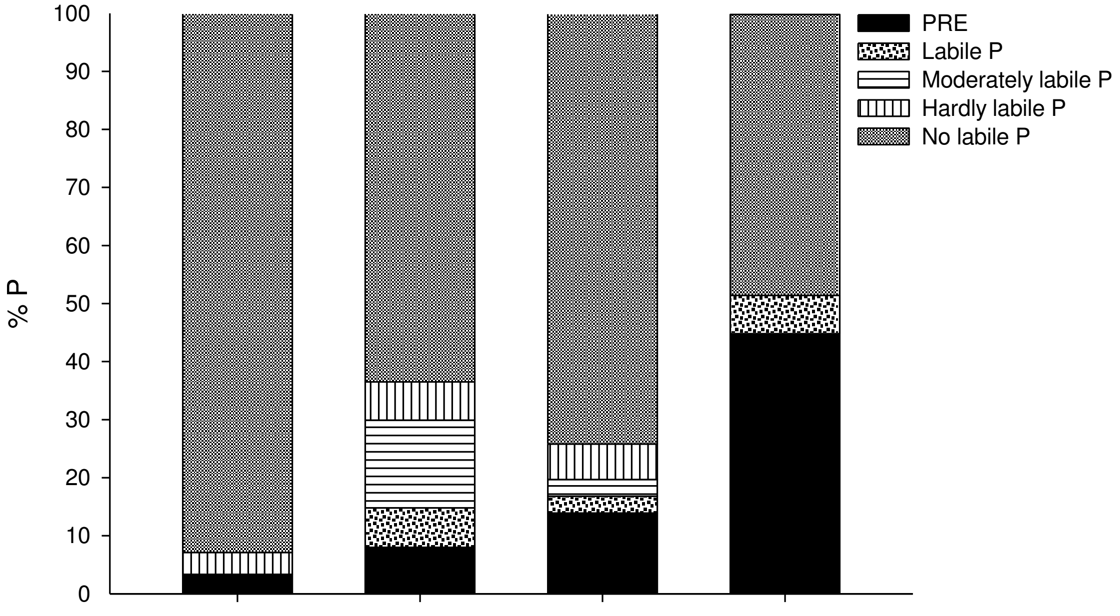

**Figure 3** Fate of P applied: PRE (Phosphorus recovery efficiency), Labile P, Moderately labile P, Hardly labile P and No labile P. ALPU = aluminum phosphate rock (ALP) and urea (U), SSPU = simple superphosphate (SSP) and urea (U), ALPL = aluminum phosphate rock (ALP) and leucaena (L), and SSPL = simple superphosphate (SSP) and leucaena (L)

## Discussion

### *Soil chemical analyses*

Our results indicate that after the application of plant material, the acidity decreased and the base saturated percentage increased. According to Yan et al. (1999), if organic residues are applied to the soil, the soil pH can be increased as a result of the decarboxylation of organic anions through the decomposition of microorganisms. In turn, the increase in soil BSP that resulted from the application of crop residue is attributed to the cations, mainly Mg and Ca, added with the plant material (Aguiar et al., 2010).

### *Nutrient content, productivity and soil P fractionation*

The primary differences shown in this experiment were a result of the higher amounts of P and N uptake in the plots covered with the residue of leucaena because of the higher amounts of labile P and available N compared to urea (Table 2 and Figure 1). Understanding these differences is important for developing beneficial practices of soil management and using P sources to enhance P use efficiency in tropical soils.

A negative correlation between unutilized N and levels of applied soluble P was reported by Ali *et al.* (2002). Under leaching conditions, a steady release of N during the crop cycle from the residue is more important than rapid early availability in achieving high crop growth (Moura *et al.*, 2010). During the first year of our study, the SSP was more efficient than the ALP regardless the leucaena residue, which confirms that fertilizers containing more soluble P have a potential to supply P to plants immediately after application, but these P availability decreases with time (Rivaie *et al.*, 2008).

Since P fertilizer was applied only in the first year, the uptake of P was dependent on the residual effect of that fertilizer, which varied with the crops and soil management that were used over the three subsequent years. Thus, during the second year, the residual effect of the ALP was superior to the SSP, with or without soil cover, increasing the productivity of corn, which is a highly P-demanding crop (Figure 1). The higher release of P from the SSP during the first year may have contributed to the increased amount of P fixed by soil components and the decrease in uptake during the following years, whereas the opposite effect occurred with the ALP fertilizer (Hongqing *et al.*, 2001).

According to Rivaie *et al.* (2008), dissolved P undergoes reactions with organic and inorganic constituents of the soil, resulting in products of varying solubility. Thus, higher values of 0.1 NaOH-Po were found in the SSPU than in the SSPL (Table 3), suggesting that higher concentrations of organic P may have contributed to an increase in P uptake and yield of the cassava in the plots treated with SSPL. Cassava is known to be adapted to low-P soil, with a lower critical level (4–6 mg $kg^{-1}$) than other crop species such as corn (with a critical level of 10–15 mg $kg^{-1}$) (Ribeiro *et al.*, 1999). In general, P uptake by cassava is dependent on vesicular–arbuscular mycorrhiza associations, and the effectiveness of these associations is determined by the extent of the infected root length (Howeler & Cadavit, 1990). The use of residues of leguminous plants enhances the soil rootability and the lengths of the roots, as reported by Moura *et al.* (2012). According to Okon (2011), mulching increases the colonization of vesicular–arbuscular mycorrhiza in cassava due to its effect on the improvement of the soil's physical properties, such as soil moisture content, increased porosity and decreased mechanical resistance to hyphal growth.

Similarly, the higher P uptake of the cowpea crop in the SSPL is also associated with more effective symbiosis with arbuscular mycorrhizae and an increase in symbiotic nitrogen fixation (Jemo *et al.*, 2006). Cultivars of cowpea BRS are selected for their tolerance to P deficiency in tropical acid soils (Barros *et al.*, 2013). Therefore, external requirements of P for nodulation in these cultivars of cowpea are lower than in other legume species (Alkama *et al.*, 2009).

After four years with the sequence of crops used (less to more P-depletive crops), there was little contribution to the labile fraction of P by either source of P. Small differences between P fractions were due to the style of management rather than to the solubility of the P source, and were insufficient to change the critical level of P (range 10 to 19 mg kg$^{-1}$) (Ribeiro *et al.*, 1999). In general, only the ALPL treatment resulted in higher P fractions (hardly labile and labile) in the 0–10 cm interval compared to BS (Figure 2). In contrast, the ALPU treatment did not exhibit any difference in fractionation from BS. According to Mweta *et al.* (2007), the practice of leguminous pruning can increase the total P availability. Phenolic and aliphatic acids produced during decomposition of organic matter are responsible for the solubilization of phosphates in soil (Ramesh *et al.,* 2003).

It is worth highlighting the comparison between the fate and the recovery efficiencies of P associated with the SSPU and SSPL treatments (Figure 3). Nearly 28% of the applied P in the SSPU plot migrated to the moderately labile and hardly labile fractions, whereas the corresponding P in the SSPL plot may have been taken up by the plants, as the soluble fractions were practically equal in two treatments. In addition, the recovery efficiency with the SSPL treatment was 48.4% versus 8% with the SSPU treatment. Certain processes may account for this difference. First, the competition between the residue decomposition products and P for soil sorption sites results in an increased soil solution P concentration in highly weathered soils (GuPy *et al.,* 2005). Second, the presence of residue on the soil surface decreases evapotranspiration, delays soil cohesion and enhances soil rootability (Moura *et al.,* 2012). In addition, the decreased acidity may have contributed to the higher availability and uptake of P in the treatments with leucaena. These conditions favor N and P uptake, thus decreasing the opportunity for P sorption by the soil. Additionally, the differences in terms of the P uptake and the moderately and labile fractions between the ALPU and ALPL (7.2 to 19.7%) treatments confirms the capacity for solubilization of P by leucaena residue, even when aluminous phosphate is used.

## Conclusions

In soils of the humid tropics, which are prone to cohesion, both aluminous phosphate and single superphosphate exhibit low efficiency if they are used on bare soil. The use of leguminous residues in a no-tillage system increases the P usage efficiency of both single superphosphate and aluminous phosphate, as this management practice enhances the uptake of N and soluble P and the solubilization of fractions of recalcitrant P fractions. The replacement of single superphosphate by aluminous phosphate may be advantageous during the second year of planting with high-demand crops, but the P of single superphosphate retained in less soluble fractions may be available if used with P-depleting crops combined with a no-tillage system under leguminous residues.

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## References

Aguiar, A. C. F., Freitas, I. C., Carvalho, C. S., Monroe, P. H. M. & Moura, E. G. 2011. Efficiency of an agrosystem designed for family farming in pre-Amazon region. *Renewable Agriculture and Food Systems*, **26**, 24-30.

Aguiar, A. C. F., Bicudo, S. J., Costa Sobrinho, J. R. S., Martins, A. L. S., Coelho, K. P. & Moura, E. G. 2010. Nutrient recycling and physical indicators of an alley cropping system in a sandy loam soil in the Pre-Amazon region of Brazil. *Nutrient Cycling Agroecosystems, **86***, 189-198.

Ali, J., Bakht, J., Shafi, M. & Khan, W. A. 2002. Uptake nitrogen as affected by various combinations of nitrogen and phosphorus. *Asian Journal of Plant Science*, **1**, 367-369.

Alkama, N., Bi Bolou, E. B., Vailhe, H., Roger, L., Ounane, S. M. & Drevon, J. J. 2009. Genotypic variability in P use efficiency for symbiotic nitrogen fixation is associated with variation of proton efflux in cowpea rhizosphere. *Soil Biology & Biochemistry*, **41**, 1814-1823.

Barros, M. A., Rocha, M. M., Gomes, R. L. F., Silva, K. J. D. & Neves, A. C. 2013. Adaptabilidade e estabilidade produtiva de feijão-caupi de porte semiprostrado. *Pesquisa Agropecuária Brasileira*, **48**, 1-10.

Becher, H. H., Breuer, J. & Klinger, B. 1997. An index value for characterizing hardsetting soils by fall-cone penetration. *Soil Technology*, **10**, 47-56.

Carter, M. R. & Gregorich, E. G. 2008. *Soil Sampling and Methods of Analyses*. CRS Press, New York.

Condron, L. M., Goh, K. M. & Newman, R. H. 1985. Nature and distribution of soil phosphorus as revealed by a sequential extraction method followed by 31 P nuclear magnetic resonance analysis. *European Journal of Soil Science*, **36**,199-207.

Cottenie, A. 1980. Soil and plant testing as a basis of fertilizer recommendations. In: *FAO Soil Bulletin* (Ed. FAO), nº 38/2. FAO Rome, Italy.

Dick, W. A. & Tabatabai, M. A. 1977. Determination of orthophosphate in aqueous solutions containing labile organic and inorganic phosphorus. *Journal of Environmental Quality*, **6**, 82-85.

Dorbas, C. 2009. Dry matter, nitrogen and phosphorus accumulation, partitioning and remobilization as effected by N and P fertilization and source-sink relations. *European Journal of Agronomy*, **30**, 129-139.

Faithfull, N. T 2002. *Methods in Agricultural Chemical Analysis: A Practical Handbook.* CABI Publishing International, New York.

Guardani, R., Drahos, J., Guilietti, M. & Schüger, K. 1989. Studies on calcination of aluminium phosphate rock in fluidized bed reactors. *Fertilizer Research*, **20**, 181-191.

Guppy, C. N., Menzies, N. W., Moody, P. W., & Blamey, F. P. C. 2005. Competitive sorption reactions between phosphorus and organic matter in soil: a review. *Soil Research*, **43**, 189-202.

Hedley, M. J., Steward, W. B. & Chuauhan, B. S. 1982. Changes in inorganic and organic soil phosphorus fraction induced by cultivation practices and laboratory incubation. *Soil Science society of America Journal*, **46**, 970-976.

Hongqing, H., Chunying, T., Chongfa, C., Jizheng, H. & Xueyuan, L. 2001. Availability and residual effects of phosphate rock and inorganic P fraction in a red soil of Central China. *Nutrient Cycling Agroecosystem*, **59**, 251-258.

Howeler, R. H. & Cadavid, L. F. 1990. Short- and long-term fertility trials in Colombia to determine the nutrient requirements of cassava. *Fertilizer Research*, **26**, 61-80.

Jemo, M., Abaidoo, R. C., Nolte, C. & Horst, W. 2006. Genotypic variation for phosphorus uptake and dinitrogen fixation in cowpea on low-phosphorus soils of southern Camerrom. *Journal of Plant Nutrition Soil Science*, **169**, 816-825.

Manson, M. G. & Cox, W. J. 1969. Calcined rock phosphate as fertilizer for pasture and cereal production in Western Australia. *Animal Production Science*, **104**, 9-99.

Moura, E. G., Oliveira, A. K. C., Pinheiro, K. M. & Aguiar, A. C. F. 2012. Management of a cohesive tropical soil enhance rootability and increase the efficiency of nitrogen and potassium use. *Soil Use and Management*, **28**, 370-377.

Moura, E. G., Serpa, S. S., Santos, J. G. D., Costa Sobrinho, J. R. S. & Aguiar, A. C. F., 2010. Nutrient use efficiency in alley cropping systems in the Amazonian periphery. *Plant and Soil*, **335**, 363-371.

Moura, E. G., Moura, N. G., Marques, E. S., Pinheiro, K. M., Costa Sobrinho, J. R. S. 2009. Evaluating chemical and physical quality indicators for a structurally fragile tropical soil. Soil Use Manage. 25, 368-375.

Mweta, D. E., Akinnifesi, F. K., Saka, J. D. K., Makumba, W. & Chokotho, N. 2007. Green manure from phosphorus adsorption and uptake by corn crop in a gliricidia-corn intercropping. *Scientific Research Essays*, **2**, 446-453.

Mullins, C. E. 1999. Hardserring soils. In: *Handbook of soil science* (ed. M. E. Summer), pp. G65-G87. CRC Press, New York.

Murphy, J. & Riley, J. P. 1962. A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, **27**, 31-36.

Okon, I. E. 2011. Field response of two cassava genotypes inoculated with arbuscular mycorrhizal fungus to *Gliricidia sepium* mulch in a tropical alfisol. *Botany Research International*, **4**, 04-08.

Ramesh, T., Chinnusamyand, C. & Jayanthi, C. 2003. Green manuring in sugarcane – a review. Agriculture Research, **24**, 130-135.

Ribeiro, A. C., Guimarães, P. T. G., Alvarez, V. H. V. 1999. *Recomendações para o uso de corretivos e fertilizantes em Minas Gerais-5ª Aproximação.* Viçosa, Minas Gerais.

Rivaie, A. A., Loganathan, P., Graham, J. D., Tillman, R. W. & Payn, T.W. 2008. Effect of phosphorus rock and triple superphosphate on soil phosphorus fractions and their plant-availability and downward movement in two volcanic ash soils under *Pinus radiate* plantations in New Zealand. *Nutrient Cycling Agroecosystem,* **82**, 75-88.

Shepherd, M. A., Harrison, R. & Webb, J. 2002. Managing soil organic matter-implications for structure on organic farms. *Soil Use and Management*, **18**, 284-292.

Singh,

C. P. & Amberger, A. 1990. Humic substances in straw compost with rock phosphate. *Biological Wastes*, **31**, 165-174.

Thomasson, A. J. 1978. Towards an objective classification of soil structure. *European Journal of Soil Science*, **29**, 38-46.

Van Straaten, P. 2002. *Rocks for crops: agrominerals of sub-Saharan Africa*. Nairobi, ICRAF.

Vance, C. P., Unde-Stone, C. & Allan, D.L. 2003. Phosphorus acquisition and use: critical adaptation by plants for securing a nonrenewable resource. *New Phytologist*, **157**, 423-447.

Vu, D. T., Tang, C. & Armstrong, R. D. 2008. Changes and availability of P fractions following 65 years of P application to a calcareous soil in a Mediterranean climate. *Plant and Soil*, **304**, 21-33.

Yan, F., Schubert, S. & Mengel, K. 1996. Soil pH increase due to biological decarboxylation of organic anions. *Soil Biology and Biochemistry*, **28**, 617-624.

# ANEXO

## European Journal of Soil Science: Guidance to authors

**(Updated: August 2011)**

### Publication policy

The Journal reports the latest significant results of research in all aspects of soil science and its applications including the development of new approaches, techniques and types of analysis. It also publishes up-to-date critical reviews, educational papers and comments on papers in the Journal.

We assess each manuscript by five major criteria which you should use as guidance when preparing your manuscript:

i) Is it good science (this includes experimental design and techniques)?

ii) Is it new or novel?

iii) Does it improve significantly our understanding of soil processes?

iv) Is it interesting to an international audience?

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Contributions are invited from all countries. The 'European' in the title implies no discrimination against papers originating outside Europe. The preferred language is English, but papers in French are considered. There are no page charges.

Steve Jarvis and Donald Davidson, Editors of *European Journal of Soil Science* and *Soil Use and Management* gave a presentation on How to Write for *Soil Use and Management* and *European Journal of Soil Science* at the 19th World Congress of Soil Science in Brisbane, Australia in August 2010. Authors should use the presentation, which can be found here, to optimize the chance of acceptance.

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All named authors should see and agree the final version of a paper before it is sent to the Journal. We have had numerous instances in which authors have submitted scripts without such agreement, and others in which authors have not known of the submissions at all. This behaviour is unethical and potentially illegal. It can also be embarrassing, especially when a script is rejected or severely criticized. The corresponding author of any paper must certify on the Exclusive Licence Form that his or her co-authors (if any) have agreed the final script.

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Papers should be no longer than about 6500 words, plus Figures, Tables and References. Authors will be asked to reduce papers that are significantly longer than this although ′s**upporting**

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http://www.blackwellpublishing.com/pdf/ejs_supp_mat.pdf). The Journal does not publish 'Short Communications' as such, but brief papers of about 2000 words or less are welcome; they should conform to the scientific, stylistic and format requirements of longer papers.

Papers should have a Times or similar typeface in 12 pt font, double spacing and single column format throughout the text. Margins should be at least 2.5 cm all round. Pages should be numbered in a single sequence including those listing references, Figure captions and Tables. Lines should be numbered in a continuous sequence throughout the paper.

Please provide a summary of no more than 250 words; you may add a French *résumé*. Papers in French must have an English summary in addition to a *résumé*. The summary should be factual. For a research paper it should state the underlying problem or question (one or two sentences), what you did (three or four sentences), what you found (another three or four sentences), and your conclusions (one or two sentences). Do not regard this as a trivial task.

## English spelling and usage

English spelling should follow the *Concise Oxford Dictionary*. Authors might also wish to consult *Fowler's Modern English Usage* (ed. R.W. Burchfield; Oxford University Press) and *Scientific Style and Format* (eds Council of Scientific Editors; Cambridge University Press).

Authors whose first language is not English must have their manuscript checked by a native English speaker before submission. A list of independent suppliers of editing services can be found at: http://www.blackwellpublishing.com/bauthor/english_language.asp. These services have to be paid for and arranged by the author; their use does not guarantee acceptance or preference for publication.

## Units of measurement

Authors should adhere to SI (*Système International d'Unités*) standards. The most common SI and acceptable related units with their symbols and abbreviations are printed in Tables 1, 2 and 3. Clarity is of over-riding importance; if you are in any doubt write the units in full, e.g. litre (especially where 'l' might be mistaken for the number '1'), minute etc. These instructions concerning numbers and units apply equally to the manuscript text to labels on the axes of Figures, and to material in Tables (both column headings and column entries).

| **Table 1** Basic units Quantity | Name | Symbol |
|---|---|---|
| Length | metre | m |
| Mass | kilogram | kg |
| Time | second | s |
| Electric current | ampere | A |
| Temperature | Kelvin | K |
| Amount of substance | mole | mol |
| Luminous intensity | candela | cd |

| **Table 2** Derived units Quantity | Name | Symbol | Definition |
|---|---|---|---|
| Frequency | hertz | Hz | s–1 |
| Energy | joule | J | kg m2 s–2 = N m |
| Force | newton | N | kg m s–2 = J m–1 |
| Power | watt | W | kg m2 s–3 = J s–1 |
| Pressure | pascal | Pa | kg m–1 s–2 = N m–2 |
| Electric charge | coulomb | C | A s |
| Electrical potential difference | volt | V | kg m2 s–3 = J A–1 s–1 |
| Electrical resistance | ohm | Ω | kg m2 s–3 A–2 = V A–1 = S–1 |

| | | | |
|---|---|---|---|
| Electrical conductance | siemens | S | kg–1 m–2 s3 A2 = Ω–1 |
| Electrical conductivity | | S m–1 | |
| Radioactivity | becquerel | Bq | s–1 |

**Table 3** Other common related units

| Quantity | Name | Symbol | Definition |
|---|---|---|---|
| Area | hectare | ha | 104 m2 |
| Volume | litre[a], cubic decimetre | l, dm3 | 10–3 m3 |
| Volume | cubic centimetre | cm3 | 10–6 m3 |
| Mass | gram | g | 10–3 kg |
| Mass | tonne | t | 103 kg |
| Concentration in solution | molarity | M | mol l–1, mol dm–3 |
| Cation exchange capacity | moles of ion charge | molc kg–1 | |
| Temperature | degree Celsius[b] | °C | K – 273.15 |

[a] Some journals print capital L for litre. EJSS does not; it follows the rule that only units that are the names of people are capitalized. If there is likelihood of confusion between lower case letter l and the number 1 then write out “litre” in full; for example, write ‘a 1-litre flask’ rather than ‘a 1-l flask’.

[b] Celsius temperature is related to that in kelvin by $T$Celsius = $T$kelvin – 273.15.

*Percentage and p.p.m.:* In some instances percentages are more familiar than SI units and reading is easier if they are used. The proportions of sand, silt and clay and the carbon content may be expressed as % rather than g kg-1. Parts per million (p.p.m.) must not be used to express concentrations – use the appropriate SI unit e.g. mg kg-1, mg dm-3 etc. However, p.p.m. (or ppm) is the standard unit for chemical shift in nuclear magnetic resonance spectroscopy and may be used.

For gas concentrations, use µmol mol-1, or µl l-1, instead of p.p.m. or p.p.m.v.; and similarly use nmol mol-1 or nl l-1 instead of p.p.b. or p.p.b.v."

*Time*: The SI unit of time is the second (s). However, it is clearly inconvenient for expressing durations of more than a few minutes or hours. Use minutes, hours, days, weeks and years as appropriate; they are not SI units and should be written in full.

*Numbers:* The integer numbers from 1 to 9 or 10 are spelled out in the text: one, two, …, nine, ten. Larger integers are printed as arabic numerals: 11, 12, …, except at the beginnings of sentences where they are printed as words. So, write, for example, 'four treatments' and '72 plots' in an experiment. The symbol for the decimal point in this Journal is the full stop and it is printed on the line (.). Real numbers are printed in arabic numerals, again except where they begin sentences, with or without decimal points; e.g. 2.4 m, 3 hours.

*Grouping of digits*: If a number contains many digits then divide these into groups of three, starting at zero or the decimal point, and separate them by spaces, not commas. For example, write 1 500 000 Pa for the matric suction at wilting point, **not** 1,500,000 Pa. Alternatively, you may write it as 1.5 x 106 Pa, or better as 1500 kPa or 1.5 MPa. **Please do not write '1.5 E06' or '1.5*106'.** Note that there is no space between numbers in the range 1000 to 9999. For any number less than 1 and greater than -1 insert 0 before the decimal point. For example, print ‘0.25 1’ and not ‘.25 1’.

*Prefixes:* The combination of a prefix and a symbol for a unit is regarded as a single symbol and is written with no space between the prefix and the unit; for example, ‘kPa’ and not ‘k Pa’.

*Derived units*: A derived unit formed from several basic units is separated into the basic units by spaces; thus metre per second is written m s-1, not ms-1 (ms would be millisecond). For amounts of substance leave a space between the unit and the symbol of the substance, e.g. kg P ha-1, not kgP ha-1, and **not** kg ha-1 P. Similarly, insert a space between the number and the unit, as 1.5 MPa.

*Powers:* When a unit is raised to a power, the power refers only to the unit and not to any number preceding it; for example, 2.3 cm3 means 2.3 cubic centimetres, not (2.3 cm)3. Note that, in English, 2 m2 is 2 square metres; 2 m squared means an area 2 m x 2 m, i.e. 4 m2.

*Further guidance on units and symbols*

- The definitive SI website (in English and French) is that of the Bureau International des Poids et Mésures at http://www.bipm.org/.

- International Standards Organization (ISO). 1992. *SI units and recommendations for the use of their multiples and of certain other units, ISO 1000*. International Standards Organization, Geneva.

- International Union of Pure and Applied Chemistry (IUPAC) 1993. *Quantities, Units and Symbols in Physical Chemistry - The Green Book*, 2nd edn (eds I. Mills, T. Cvitas, K. Homann, N. Kallay & K. Kuchitsu). Blackwell Science, Oxford.

- Monteith, J.L. 1984. Consistency and convenience in the choice of units for agricultural science. Experimental Agriculture, 20, 105-117.

## Fonts, symbols and abbreviations

Normal text is printed in upright Roman font (like this here). *Italic* font is used for Latin words and expressions, including the names of plants and animals; thus *a priori*, *et al.*, *Pinus sylvestris* L. Similarly, the Journal prints short titles, and the titles of scientific journals and books in *italic*. You should not use italic font as a means to emphasize text.

SI units should be printed in an upright Roman font. The symbols for chemical elements and compounds are **always** printed in Roman except where they appear in subheadings, in which case they are in *italic*. Note that the unit for ‘molar’ is M (small capital, 10 font) to distinguish it from M (mega-).

Scalar variables and parameters, such as *A* for area, *c* for concentration in a solution, *m* for a mean, *b* for a regression coefficient and *K* for hydraulic conductivity, are always printed in *italic*. Greek characters may be used for population parameters or other quantities following the convention of the discipline concerned. Vectors are printed in **bold Roman** font, with lower case letters of either the Roman or Greek alphabet. Matrices are printed in **BOLD CAPITALS**.

Mathematical operators must be distinguished from variables on which they operate in algebraic expressions. Thus, exp for 'the exponential of', ln and log10 for 'natural' or base10 logarithms respectively, cos for cosine, and the d in differential calculus are printed in roman, whereas the variables are printed in *italic*. We thus write '$\exp(x - y)$', '$\ln z$', '$\cos Q$', $\mathrm{d}x$ and so on.

Subscripts and superscripts: if a subscript or superscript is a variable then it is printed in *italic*. For example, the index $i$ in $z_i$, $i = 1, 2, \ldots, n$, is *italic* because it is an integer variable taking values from 1 to $n$. If on the other hand it is an abbreviation, as in $K_\mathrm{s}$ or $K_\mathrm{sat}$ for saturated hydraulic conductivity in which the 's' or 'sat' are abbreviations for saturated, then it is printed in plain Roman font.

The fonts used in Tables and equations must be the same as those in the text. Symbol fonts and styles on graphs and their axes should be the same as used in the text.

**Abbreviations** should generally only be used if they are widely known, e.g. OC (organic carbon), SOM (soil organic matter), NMR (nuclear magnetic resonance), and should be given in full when they are first used: this includes chemical symbols as with, for example, nitrogen (N). The rule adopted by the Journal is to terminate an abbreviation by a full stop (.) if it is a curtailment of a word (such as ed. for editor). A contraction with the first and last letters intact does not take a full stop (for example, eds for editors). Where an abbreviation, however common, is first used in the text, it must be spelled out in full; for example 'back-scattered electron scanning images (BESI)'. Avoid starting sentences with an abbreviation.

## Statistics

We receive many papers that are weakened by inappropriate and/or mis-used statistical methods. Thus the basic advice from the editors of EJSS is: *Present the results of statistical analysis only where appropriate and ensure that the methods of analysis used are appropriate to your purposes*. If in any doubt you should take advice from a professional statistician. If the Editors have any concerns, the manuscript will be referred to a statistical panel and this may delay the decision-making process.

The following notes are designed to help you with your analysis.

### *Design of surveys and experiments*

For experiments, state the experimental design, taking care to distinguish between replication of plots or samples in the field and replication for determinations in the laboratory. Analyse the data according to the design, and report the results as either tables or graphs of means and their standard errors only. Do not attach letters to estimates to represent the results of multiple range tests (and use these sparingly as they are often meaningless).

For surveys, state the sampling design, the number of samples and provide a statistical summary of the data. The latter should include size of sample, mean, median (optional), minimum, maximum, variance, standard deviation and skewness. Add the coefficient of variation (CV) only if it is sensible in the context (Webster, 2001), for example the CV of pH is not as the pH scale does not have an absolute zero. Please note that data are **plural** when writing about them in the text.

Pseudo-replication is a frequent cause of failure in papers submitted to EJSS (Webster, 2007); however, there may be some circumstances where its use is unavoidable but the rationale behind this needs to be explained fully (the argument that this saves on experimental costs is not an acceptable explanation).

*Significance*

Statistical significance is to some extent a matter of personal judgement, and provided you report the standard errors readers can decide for themselves whether your results are significant. It is also a matter of sample size. If you wish to state your judgement then you should do so in the text. Avoid the use of stars in tables to indicate significance.

Please also consider carefully the use of the word ‘significant’. This should only be used in a statistical context where the significance of a difference or change can be expressed as a probability.

*Correlation and regression*

Express a linear relation by the Pearson product–moment correlation coefficient, denoted $r$. Use regression to express how one variable, the dependent variable, varies in response to change in one or more other predictor variables. Give the regression equation, with standard errors on the coefficients, and the coefficient of determination, $R2$. Quoting $R2$ on its own is not acceptable (Webster, 1997). Note that $R2$ is not necessarily the best way of relating the relationship between measurements; a 1:1 line is very often equally informative.

*Analysis of variance (ANOVA)*

Many authors use ANOVA inappropriately or fail to report the results fully. The latter is also particularly true of so-called multiple-range tests and similar procedures that add little statistical rigour to papers and should be avoided wherever possible. A properly conducted and reported ANOVA is of much greater value. If you carried out such an analysis, then it will greatly improve your paper if you make full use of the output in a table (Webster, 2007).

*Principal components analysis (PCA)*

Many such analyses are described inadequately and have to be returned to authors for improvement. Unless you are thoroughly familiar with PCA, you should study Webster (2001) and/or seek advice from a professional statistician.

*Repeated measurements*

In some investigations, such as field monitoring, studies of leaching and experiments in soil biology, measurements are made non-destructively from the same experimental locations. The data at any one location are then likely to be correlated in time, and the statistical analysis of those data should take into account that possibility. Webster & Payne (2002) describe ways in which that might be done.

**If you are unsure of the best way to use statistics to analyse, interpret and present your work, then consult a professional statistician. It is also our experience that many papers would be much stronger and would yield much more valuable output if authors consulted professional statisticians before they finalised the design of their experiments.**

You should also consult:

Webster, R. 2001. Statistics to support soil research and their presentation, *European Journal of Soil Science*, **52,** 331–340.

Lane, P.W. 2002. Generalized linear models in soil science. *European Journal of Soil Science*, **53,** 241-251.

Webster, R. & Payne, P.W. 2002. Analysing repeated measurements in soil monitoring and experimentation. *European Journal of Soil Science*, **53,** 1-13.

Webster, R. 2007. Analysis of variance, inference, multiple comparisons and sampling effects in soil research. *European Journal of Soil Science*, **58,** 74-82.

## Tables

- Consult a recent issue of the Journal or the sample article (http://www.blackwellpublishing.com/pdf/ejs510.pdf) for examples of layout and format.

- Prepare Tables separately from the text and put each on a separate page with its heading and with double spacing if there is room. Make sure that the table heading can be understood without the need for undue reference to the text.

- Design your Tables so that they will fit either in a single column of the printed Journal or across two columns. Avoid large Tables that are likely to occupy more than one page. Provide all columns with headings, with the first letter of each heading capitalized.

- Values in Tables are pure numbers. The variables to which they refer usually have dimensions, such as mol litre-1 for concentration and g cm-3 for bulk density. The scale of the variable is, therefore, divided by the unit in which it is measured.

- The unit should be specified in column headings etc by placing it after a solidus, /, to indicate the division and not, for example by enclosing in parentheses: thus '/mol litre-1' and '/g cm-3'.

- Be consistent in the number of significant digits used. **Do not give numerical results or their statistics to an unrealistic degree of precision**.

- Footnotes to Tables should be referred to by upright, i.e. not italic, superscript letters (a,b, etc.).

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- Do not use outer boxes or frames (they waste space).

- Label the axes of graphs with the names of the variables followed by the solidus and the units. Similarly, the axes of graphs must be annotated with the names of the variables followed by the solidus and the units, for example, 'Concentration /mol litre-1'. The scales

must be annotated correctly with pure numbers. Do **not** enclose units on tables or figures in parentheses (…).

- Give values on any one axis with the same number of decimals, except at the origin which you should label with a plain '0' and no decimal point.

- **Number each Figure BUT put the captions to the Figures on a separate page.** The online version of the Journal will print only the first 100 characters of any caption, so ensure that all important aspects of any caption are mentioned in those first 100 characters (including spaces).

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- Photomicrographs and other photographs must have clear scales. Digital images must be of fine resolution and of good contrast.

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*Text citations*: Cite in the text by author(s) and year; for example, Chertkov (2001), McGarry & Yule (2002), (Ghassemi *et al*., 1997; Siemens, 2003), with the parentheses placed according to context. For two authors cite both (using “&”, not “and”); for work by more than two authors cite only the first followed by *et al*. Where several references appear together they are arranged chronologically and then alphabetically within each year.

*References*: Refer to your citations at the end of the paper in the list of references. Check all references including your own against the source documents (and not someone else's citations), and ensure that they are correct and complete in every detail and unabbreviated. Beware of transferring references obtained from searches of electronic databases; they are often truncated, omit accents and umlauts, and the less common characters such as oe, ç, å, ø, etc. can be changed in unpredictable ways.

References should be prepared as follows:

- Name(s) and initial(s) of author(s). Where there are more than 6 authors only the first 6 names should be listed followed by *et al*.

- Year of publication.

- If a journal article, the article title, name of journal (*in italic*), volume number (**in bold**), and page numbers.

- If a book, its title (*in italic*) name of publisher, place of publication.

- If a paper in a collected work, title of the paper, In: title of collected work (*in italic*), editor(s) if any, page numbers, publisher and place of publication.

- If a thesis, its title (*in italic*), degree, name of university. Bear in mind that most readers will find it difficult to access theses, especially the unpublished ones of universities in English-speaking countries; so cite theses only if they contain crucial information that is not otherwise available.

- If a report of an institution or agency, its title (*in italic*) and as full information as possible on the publisher and where it might be obtained.

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Websites are increasingly cited. **First check that the web-site still exists** and then cite it along with the date you accessed it.

Arrange the references in alphabetical order by author; where the same author appears more than once, single-author papers come before two-author papers, which come before multi-author papers. Within each class arrange papers in chronological order.

The following examples are for guidance:

- Chertkov, V.Y. 2002. Modelling cracking stages of saturated soils as they dry and shrink. *European Journal of Soil Science*, **53,** 105-118.

- Ghassemi, F., Jakeman, A.J. & Nix, H.A. 1995. *Salinisation of Land and Water Resources*. CAB International, Wallingford.

- McGarry, D. & Yule, D.F. 2002. Shrinkage. In: *Encyclopedia of Soil Science* (ed. R. Lal), pp. 1197-1200. Marcel Dekker, New York.

- Siemens, J. 2003. *Controls of carbon, nitrogen, and phosphorus fluxes in vadose zone and groundwater of protected watersheds in Münster (Germany).* Doctoral dissertation, Technische Universität, Berlin.

- Blackwell Publishing. 2008. *A major publisher of soil science Journals*. (At: http://www.blackwellpublishing.com/. Accessed: 10/03/2008); note that the date format is day/month/year.

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