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

MÁRCIO FERNANDES ALVES LEITE

IMPACTOS DO USO DA TERRA E DO REGIME DO FOGO NA BIOMASSA AÉREA E NA QUALIDADE FÍSICO-QUÍMICA DO SOLO EM FLORESTAS ESPONTÂNEAS E EM AGROFLORESTAS DA AMAZÔNIA ORIENTAL

São Luís - MA
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Dissertação apresentada ao Curso de Mestrado em Agroecologia da Universidade Estadual do Maranhão para obtenção de título de Mestre *strictu sensu* em Agroecologia

Orientador: Prof. Dr. Christoph Gehring

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Márcio Fernandes Alves Leite

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Aprovado em ____/____/____

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São Luís - MA
2014

Ao Prof. Flávio, pelos seus eventos estáveis.
Ao Prof. Christoph, por alguns eventos instáveis
E à minha família, por permanecer estável
em meio a todos esses eventos.
Dedico.

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"Nunca se vence uma guerra lutando sozinho" cantava certo maluco beleza lá pelas bandas de 1979. Não poderia estar mais certo, muitas guerras são travadas todos os dias, nem todos são vencidas, mas não se trata de vencer ou perder e sim de se estar ao lado das pessoas nessa luta. Como me ensinou certa vez o Prof. Jorge Leão, podemos olhar para frente e enraivecer ao constatar que há pessoas que são muito mais favorecidas do que nós. Podemos, ainda, olhar para trás e nos conformar, ao perceber que também há aqueles que estão em situação muito pior do que a nossa. Mas, só quando olharmos para os lados e descobrimos que não estamos só é que se pode fazer a diferença. Juntos podemos ajudar quem está atrás, juntos podemos chegar à frente, ou chegar a algum outro lugar talvez até melhor do que o de quem está na frente. Assim, sabendo que "é sempre mais fácil achar que a culpa é do outro, evita o aperto de mão de um possível aliado", deixei de lamentar para as paredes do quarto só para dormir tranquilo, e fui dobrar os sinos, pois sabia no fundo do peito que não era nada daquilo.

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"Quando você elimina o impossível, o que restar,
não importa o quão improvável, deve ser a verdade"
(Sherlock Holmes, personagem de Sir Arthur Conan Doyle)

SUMÁRIO

RESUMO

A presente pesquisa reúne uma ampla quantidade de indicadores de biomassa aérea, de serrapilheira e de físico-quimica da camada superficial do solo (0-20 cm) comparando diferentes tipos de vegetação da Amazônia oriental. Estudou-se três tipos de sistemas agroflorestais (capoeiras enriquecidas, quintais agroflorestais e sistemas comerciais), abrangendo desde os de estrutura mais simples aos sistemas de subsistência mais complexos e biodiversos, que foram comparados com três tipos de florestas de vegetação espontânea (capoeiras jovens, adultas e florestas maduras) através de ANOVA um fator, regressões lineares e não lineares e análise estatística multivariada de componentes principais, análises entre classes e de co-inércia. Também foi possível isolar os efeitos das diferentes formas de uso do fogo (capoeiras de primeiro vs múltiplos ciclos de corte-e-queima, e o caso particular do sistema de varrição-e-queima presente nos quintais agroflorestais). As agroflorestas diferiram das florestas espontâneas apresentando menores valores de biomassa no sub-bosque, maiores valores de pH e teores de cálcio no solos dos sistemas agroflorestais comerciais, bem como maiores concentrações de potássio no solo dos quintais agroflorestais. A vegetação do dossel influenciou negativamente o sub-bosque ($r^2=0,20$, $p<0,05$), mas não teve influência significativa sobre a camada de serrapilheira. A análise de componentes principais indica uma sequência sucessional ao longo do tempo de pousio e entre os sistemas estudados, no qual os quintais agroflorestais foram o grupo que esteve mais próximo das florestas maduras. De acordo com a análise multivariada entre classes, as diferentes formas de uso do fogo correspondem a 39,7% da variação total dos dados e segunda a análise de co-inércia a biomassa das plantas está mais fortemente relacionada com o solo nas áreas de florestas naturais (coeficiente de correlação multivariada de 75.5%). Múltiplos ciclos de corte-e-queima causam um incremento na concentração de cálcio na camada superficial do solo e o sistema de varrição-e-queima dos quintais agrofloretais está associado a altos teores de potássio e "hotspots" de fósforo disponível no solo. Esses resultados confirmam o status dos quintais agroflorestais como uma forma de uso do solo sustentável, devido a sua capacidade combinada de manter elevada biomassa e disponibilidade de nutrientes no solo.

Palavras Chave: Quintais agroflorestais, capoeiras enriquecidas, sistemas agroflorestais comerciais, floresta secundária, sistema corte-e-queima, varrição e queima.

1. INTRODUÇÃO

O manejo antrópico explorativo e insustentável resulta em diferentes graus de degradação da vegetação e do solo (LU et al., 2007). No Maranhão e nos trópicos úmidos do mundo inteiro, as causas principais disto são os múltiplos ciclos de agricultura itinerante de derruba-e-queima com períodos de pousio cada vez mais curtos, pastos extensivos de longo uso e a ocorrência frequente de queimadas (GEHRING, 2006). Degradação antrópica da vegetação causa degradação da qualidade físico-química do solo (GEISSEN et al., 2009).

Por outro lado, esforços de recuperação da vegetação através de plantios de restauração e sistemas agroflorestais (SAFs) proporcionam melhorias na qualidade físico-química do solo (MARSCHNER et al., 2006). O conceito de sistemas agroflorestais se desenvolveu a partir da concepção de que o uso do solo agrícola combina seja em escala temporal ou espacial arranjos de diferentes componentes, onde árvores perenes são usadas em conjunto com culturas agrícolas e/ou animais, de modo a obter tanto ganho econômico como intensificação das relações ecológicas (NAIR, 1985;1991; GARCÍA-BARRIOS; ONG, 2004; PINHO et al., 2012). Esse tipo de sistema apresenta-se como alternativa sustentável ao sistema de corte-e-queima no trópico úmido, com a oferta de produção mais estável e com menor risco de pragas ou mesmo custo de mão-de-obra (POLLINI, 2009; SHIBU, 2009), graças a fatores como complexação de nichos, bombeamento de nutrientes e redução das perdas por lixiviação (GEHRING, 2006; MOÇO et al., 2010).

O termo agrofloresta descreve a prática de uso da terra em que tanto árvores quanto culturas agrícolas são combinadas no mesmo campo (QUINKENSTEIN et al., 2009). Dependendo da sua estrutura podem ser classificados como sistemas agrosilviculturais (árvores e cultivo), silvopastoris (animais de pastio e árvores) ou agrosilvopastoris (cultivo, árvores e animais de pastio) (NAIR, 1985). A integração dessas diferentes formas de manejo gera uma série de benefícios para as plantas cultivadas, os animais, para ciclagem de nutrientes e água, o microclima e a biodiversidade, resultando em melhoria econômica e proteção ambiental (NAIR, 2013).

O espectro destes SAFs é enorme e abrange diferentes componentes agrícolas, florestais e frequentemente também de produção animal, com origens contrastantes (tradicionais / ‘modernos’) e com finalidades diferentes (subsistência / comercial) (NAIR, 1991). Consequentemente existem também grandes diferenças na intensidade de manejo, na complexidade estrutural e funcional, na biodiversidade espontânea e manejada e em última consequência na sustentabilidade ecológica e social destes sistemas (SCHROTH; HARVEY, 2007), todos esses fatores acabam por afetar de maneira distinta a qualidade dos solos locais (SCHROTH et al., 2001).

Sendo assim, os estudos de qualidade do solo buscam a seleção e avaliação de indicadores que possibilitem fornecer informações sobre a capacidade específica de um determinado solo exercer suas funções ecológicas, tais como, sustentação de plantas e animais, a produtividade ecológica, manutenção ou melhoria da qualidade do ar e da água, e servir de subsídio para a melhoria da qualidade de vida humana e sua habitação (KARLEN et al., 2003).

A avaliação da qualidade físico-química do solo pode ser feita de forma a priorizar os objetivos do manejo, identificando as funções críticas necessárias para alcançar esse objetivo e selecionando indicadores que forneçam informações sobre cada função específica em estudo (KARLEN et al., 1997; LETEY et al., 2003). Além disso identificar as relações da vegetação com o solo é crucial para compreender as transformações dos ciclos de nutrientes tanto para compreender a dinâmica da regeneração de capoeiras (DAVIDSON et al., 2004; COMTE et al., 2012) quanto para desenvolver um manejo otimizado dos recursos locais, principalmente para o caso dos sistemas agroflorestais (DAS; DAS, 2010; PINHO et al., 2012).

Desse modo, diante da necessidade de manutenção da produtividade agrícola em face do ciclo degradante da agricultura itinerante, do desmatamento e suas potenciais consequências das mudanças climáticas, erosão, a degradação do solo e outros problemas ambientais (MOURA et al., 2013), as agroflorestas tem atraído demasiado interesse e despontado como uma alternativa de uso do solo com grande viabilidade para a agricultura familiar (GARCÍA-BARRIOS; ONG, 2004).

2. REVISÃO DE LITERATURA

2.1 O ECOSSISTEMA SOLO

O solo é um sistema biológico composto por uma fase sólida formada por constituintes minerais e orgânicos (plantas, organismos vivos, matéria orgânica, plantas e animais em decomposição), rodeados de água e ar (VAN BREEMEN, 2004; VERHOEF, 2004). Representa um sistema vivo e dinâmico, como consequência da contínua interação entre os fatores bióticos (planta, animais e microrganismos) e abióticos (clima, rocha, relevo e tempo) (VERHOEF, 2004). Devido ao tremendo número de processos biológicos ativos, solos são de crucial importância para a manutenção de outros ecossistemas na biosfera continental.

Diante disso, é interessante observar que essas mesmas características tornam-se o principal empecilho para a introdução de tecnologias de manejo biológico, uma vez que efeitos da ação antrópica no solo são, em geral, muito difíceis de prever (LARSON; PIERCE, 1994; KARLEN et al., 1997; LETEY et al., 2003). Cada solo apresenta uma capacidade distinta no desenvolvimento de suas funções para a sustentação da produtividade biológica (LETEY et al., 2003), sendo limitada pelos recursos nele existentes (VAN BREEMEN, 2004) e a eficiência da ciclagem de nutrientes dos componentes bióticos (CUEVAS; MEDINA, 1988; VAN NOORDWIJK; GARRITY, 1995). Diversos fatores físicos e químicos atuam simultaneamente determinando as condições ambientais, que são dinâmicas devido a essa interação (LIU et al., 2006).

Nesse contexto, para que se permita o estudo dos impactos do uso do solo no seu funcionamento e na sua capacidade de recuperação torna-se necessário o uso de indicadores de qualidade do solo e a comparação de sistemas de manejo (KARLEN et al., 2003), de modo a permitir identificar fatores de degradação e potenciais alternativas que possam melhorar as forma de uso da terra.

2.1.1 Indicadores de qualidade do solo

O uso de indicadores de qualidade visa obter de informações acerca das funções do solo e exige o uso de um conjunto de parâmetros de natureza físico-química e biológica, de modo a tornar possível a interpretação mais correta da eficácia do funcionamento do sistema solo (KARLEN et al., 1997).

Os estudos sobre a qualidade do solo se desenvolveram inicialmente diante da possibilidade do estabelecimento de um índice de qualidade do solo, um valor ou mesmo ainda um conjunto de variáveis facilmente mensuráveis que pudessem servir como ferramenta de diagnóstico das condições do solo, seu estado de degradação ou conservação e potenciais de uso, ou seja, a capacidade do solo de exercer funções (SPOSITO; ZABEL, 2003).

Entretanto esses estudos esbarraram em algumas dificuldades. O conceito de índice de qualidade do solo começou a ser continuamente desenvolvido e debatido pela comunidade científica, mas sua aplicabilidade foi revelando de cada vez menos valor prático (LETEY et al., 2003). Por um lado, sintetizar a informações dos diferentes parâmetros do solo em um único valor pode contribuir para uma maior facilidade de interpretação dos efeitos das diferentes formas de manejo e até mesmo estipular níveis críticos que serviriam para orientar as formas de uso do solo visando uma menor degradação (KARLEN et al., 2003). Por outro lado, uma mesma propriedade do solo pode ser estimulante para um determinado uso ou função e prejudicial para outro o que dificulta o estabelecimento de um único método, ou equação para a determinação do valor desse índice (LETEY et al., 2003).

Isso torna necessário interpretar um mesmo índice de diferentes maneiras ou até mesmo ponderar a equação de cálculo desse índice para determinados tipos distintos de usos, de tal forma que, o fato de existir um único valor para a qualidade do solo não simplifica a análise de sua capacidade de exercer suas funções, podendo até mesmo mascarar alguns dos potenciais impactos prejudiciais de certas formas de uso. Assim, é muito mais proveitoso e informativo o estudo de múltiplos indicadores seguidos de uma interpretação mais holística com visão voltada para o uso ao qual esse solo foi ou será destinado. Essa análise pode ser feita com a adoção de métodos de análise multivariada (SHUKLA et al., 2006).

Portanto, para que os indicadores de qualidade do solo possam proporcionar um maior conjunto de informações devem permitir identificar (i) os mecanismos de manutenção dos serviços ecossistêmicos, (ii) as relações entre os componentes do ambiente (vegetação, microrganismos, ou seja, as relações do sistema solo-planta-microrganismos) e (iii) ser sensíveis as diferentes impactos das ações antrópicas sejam elas degradantes ou de conservação.

Isso pode ser feito de duas maneiras: a primeira consiste em selecionar um conjunto mínimo de variáveis que habilitem a classificar os diferentes sistemas (LARSON; PIERCE, 1994; GOVAERTS et al., 2006), já a segunda, ao invés de trabalhar com uma lista predefinida de indicadores adota uma seleção daqueles de maior relevância (agro)ecológica as condições específicas do local de estudo (MASERA; LÓPEZ-RIDAURA, 1999).

Apesar desses distintos critérios de seleção, os indicadores muitas vezes são os mesmos, principalmente em função da necessidade de comparar as avaliações feitas, seja entre sistemas ou mesmo a dinâmica de um mesmo sistema ao longo do tempo. Assim, é possível identificar os indicadores de qualidade do solo mais usuais, que segundo revisão feita por Rousseau et al. (2012), são: matéria orgânica do solo, carbono na biomassa, densidade do solo, bases (Ca, K, Mg, Na, Al), capacidade de troca catiônica (CTC) e pH. Além deles, podemos mencionar ainda os teores de fósforo, nitrogênio, micronutrientes (Fe, Zn, Mn e Cu, por exemplo) e outros fatores físicos, tais como, capacidade de aeração, resistência a penetração e dia de stress hídrico; e fatores biológicos principalmente biomassa e diversidade de microrganismos e macrofauna do solo.

Desse modo, há uma diversidade de indicadores de qualidade do solo com sensibilidade distinta as mais variadas formas de manejo do solo. Entretanto, ainda há a necessidade de entender como os diferentes componentes do ecossistemas interagem com as mudanças ocorridas nas formas de uso do solo (ROUSSEAU et al., 2012). Nesse ponto, há uma considerável ausência de estudos que visam interpretar os mecanismos de interação dos fatores bióticos e abióticos do solo (avaliados por meio dos indicadores de qualidade) e a biomassa vegetal, temática esta que é objeto de estudo do denominado sistema planta-solo (VAN DER PUTTEN et al., 2013). Apesar de pouco estudado, essas interações apresentam grande relevância para um melhor entendimento do funcionamento dos ecossistemas e das formas de uso do solo.

A qualidade do solo nos sistemas tropicais, por exemplo, tem estreita relação com a sustentação da diversidade acima e abaixo do solo, portanto a eficiência da ciclagem de nutrientes é fundamental para a manutenção da produtividade biológica desses ambientes. O principal mecanismo para isso está na liberação de nutrientes via serrapilheira e raízes (CUEVAS; MEDINA, 1988; VAN NOORDWIJK et al., 1996), o que torna a floresta nativa praticamente insubstituível quanto a sua capacidade de ciclar nutrientes e preservar a biodiversidade tropical (GIBSON et al., 2011), sendo geralmente considerada padrão de equilíbrio ecológico e comumente adotada em estudos de comparação de sistemas de manejo do solo.

2.2 O MANEJO DO SOLO NO TRÓPICO ÚMIDO: PROBLEMAS AMBIENTAIS DO SISTEMA CORTE-E-QUEIMA E A ALTERNATIVA DOS SISTEMAS AGROFLORESTAIS

Segundo Gehring (2006), existe uma séria dicotomia entre a alta produtividade biológica dos ecossistemas naturais do trópico úmido e a baixa produtividade e sustentabilidade da agricultura familiar nas regiões do trópico úmido, sendo essa disparidade o grande desafio para o desenvolvimento local. O principal empecilho reside na dificuldade de adotar tecnologias capazes de transformar essa produtividade biológica elevada em produção agrícola em quantidade suficiente para melhorar a situação socioeconômica dessas famílias.

Nesse contexto, o manejo adequado dos solos deve ser a principal preocupação dos que se dedicam a esse desafio, uma vez que, a combinação dos fatores climáticos e a fragilidade dos solos do trópico úmido exigem práticas e processos diferenciados da agricultura convencional para a garantia de rentabilidade e sustentabilidade (MOURA et al., 2013).

2.2.1 A agricultura itinerante do sistema de corte-e-queima

A agricultura itinerante no trópico úmido se caracteriza pelo uso do fogo para mineralização rápida dos componentes da floresta, limpeza da área, eliminação de ervas adventícias e fertilização do solo (KASS; SOMARRIBA, 1999), sendo considerada uma forma de manejo racional e tradicional dos solos da região (COMTE et al., 2012).

O sistema corte-e-queima, apesar de se mostrar uma forma de uso do solo capaz de produzir alimento com baixo uso de insumos agrícolas e mão-de-obra (KLEINMAN et al., 1995), não se mostra mais capaz de atender as exigências por produção agrícola, principalmente em função da necessidade de longos períodos de pousio após o cultivo da área, necessários para que a área utilizada possa recuperar sua estabilidade inicial antes que possa voltar a ser utilizada (BRADY, 1996; MOURA et al., 2013).

Além disso, esse tempo de pousio passou a se tornar cada vez mais curto com o crescimento populacional que acarretou aumento na demanda por área agricultável, o que resultou no denominado por Gehring (2006) de “círculo vicioso” de degradação. Como consequência dessa alteração na forma tradicional de manejo da agricultura itinerante nessas áreas, tem-se o empobrecimento do ecossistema e perda da qualidade do solo (MOURA et al., 2009), resultando na degradação ambiental dos solos locais (HAUSER; NORGROVE, 2013). Associado a isso temos sérias consequências econômicas, como a redução da produtividade agrícola e aumento da pobreza rural (VARMA, 2003).

Como alternativa a esse círculo viciosos de degradação ambiental tem-se proposto a adoção de sistemas agrícolas que possam substituir esse sistema tradicional e ainda atender a demanda de produção agrícola local (BRADY, 1996). Dentre essas alternativas uma que tem se mostrado bastante promissora é a adoção de sistemas agroflorestais (POLLINI, 2009).

2.2.2 Sistemas Agroflorestais

Sistema agroflorestal (SAF) é a forma de uso da terra caracterizada pela combinação de espécies arbóreas lenhosas e/ou frutíferas com cultivos agrícolas e/ou animais, de forma simultânea ou sequencia temporal e que interagem econômica e ecologicamente (NAIR et al., 2008). Um aspecto que determina a sustentabilidade desses sistemas é a presença de árvores, que tem a capacidade de capturar nutrientes de camadas mais profundas do solo, reciclando-os e reduzindo as perdas por lixiviação, além de proporcionar maior cobertura do solo e conservação dos recursos edáficos (NAIR, 2013). O sistema agroflorestal objetiva otimizar a produção por unidade de área, com uso mais eficiente dos recursos, da diversificação da produção e da interação positiva entre os componentes (NAIR, 1991).

Esse sistema é proposto como alternativa de uso do solo para o trópico úmido com o objetivo de aproveitar o aumento da biodiversidade como fator de equilíbrio dinâmico de ecossistemas complexos, imitando os ecossistemas naturais (MBOW et al., 2014). Os sucessos de plantios de alta diversidade de espécies tem indicado que a biodiversidade pode ser uma ferramenta importante para o equilíbrio na interação entre plantas e microrganismos (CLOUGH et al., 2011).

Dado a multiplicidade de fenômenos determinantes na qualidade do solo e da interação entre os elementos bióticos e abióticos existentes nos sistemas agroflorestais, principalmente para o caso dos sistemas agroflorestais que fazem uso dessas interações para promover o desenvolvimento dinâmico e equilibrado do sistema (EISENHAUER, 2012), é fundamental que as ferramentas de análises dessas formas de uso do solo sejam feitas de modo a avaliar as múltiplas interações existentes entre os fenômenos avaliados. Uma das formas mais proeminentes de se avaliar essas interações é com o uso de análises estatísticas multivariadas, ferramentas essas que vem sendo cada vez mais utilizadas para estudos ecológicos (THIOULOUSE, 2011).

2.3 ANÁLISE MULTIVARIADA PARA ESTUDOS DE ECOLOGIA

Análise multivariada consiste de uma coleção de métodos para avaliar múltiplas medições feitas em um objeto ou indivíduo (RENCHER; CHRISTENSEN, 2012). Essas medições são denominadas de variáveis e os objetos/indivíduos recebem a denominação de unidades amostrais ou de observações, juntos formam o chamado conjunto de dados multivariado, normalmente apresentado em forma de uma matriz (CHI, 2012). A análise desse tipo de dado consiste da adoção de um método que permita a identificação da estrutura de dependência da variabilidade de cada observação constituída pela covariância das variáveis (RENCHER; CHRISTENSEN, 2012).

Métodos multivariados podem ser divididos em duas categorias: métodos de análise exploratória de dados e de análise confirmatória (CHI, 2012). No presente trabalho será dado enfoque na análise exploratória dos dados, mais comumente adotada em estudos ecológicos uma vez que permitem extrair, sintetizar e visualizar a informação sobre a variabilidade das múltiplas variáveis ecológicas de maneira mais simplificada (THIOULOUSE, 2011). Além disso, normalmente em ecologia a ocorrência de fenômenos de retro-alimentação é frequente (APONTE et al., 2013) o que dificulta enormemente a separação de relação causa-efeito nesses estudos que, de modo geral, é a principal razão para a não adoção de métodos multivariados de análise confirmatória.

Em ecologia, a análise multivariada é normalmente utilizada para responder duas questões: (i) quais são as relações entre as variáveis e (ii) quais são as semelhanças/diferenças entre unidades amostrais.

A análise dessas variáveis pelos métodos univariatos (análise de variância, testes de média, regressão e correlação) normalmente é feita pela procura de relações entre cada uma das múltiplas variáveis existentes de modo a detectar as diferenças entre indivíduos ou amostras, uma variável por vez (CHI, 2012). De tal forma que, a compreensão holística da variabilidade geral dos dados fica restrita a capacidade do pesquisador de conectar os resultados obtidos em um todo organizado. Entretanto, muitas vezes essa tarefa é dificultada em função de variações conjuntas (co-variância) que muitas vezes interfere na identificação das relações entre variáveis e entre indivíduos, seja devido a superestimação ou subestimação dos efeitos (RENCHER; CHRISTENSEN, 2012).

O método multivariado busca responder a essas duas perguntas procurando o menor número de dimensões hiperespaciais onde a representação dos indivíduos e das variáveis é o mais próximo possível do original (DRAY; JOMBART, 2011). Essas novas dimensões hiperespaciais, denominadas também de autovetores, são geradas artificialmente e caracterizam-se por serem independentes entre si (THIOULOUSE et al., 1997). Desse modo, cumprem a função de eliminar o efeito de covariância entre eixos, o que geralmente ocorre quando se faz uso das variáveis reais para representação espacial (RENCHER; CHRISTENSEN, 2012).

Além disso, elas permitem a redução do número de eixos (CHI, 2012). Regressões e correlações bivariatas, como, por exemplo, os modelos de regressão linear e o coeficiente de correlação de Pearson, avaliam o grau de relação entre duas variáveis quantitativas para o caso em que há ou não uma relação de dependência entre as duas variáveis, respectivamente (JAMES; MCCULLOCH, 1990). Desse modo cada variável observada é interpretada como um eixo sejam eles independentes ou não. Uma vez que autovetores são gerados, a análise passa a ser feita em eixos independentes entre si, isso possibilita a síntese da informação sobre a variabilidade dos dados (DRAY; DUFOUR, 2007) e permite uma mais apurada compreensão das relações existentes entre variáveis e das semelhanças entre os indivíduos construindo um espaço com poucas dimensões (2 a 3, por exemplo) que retém o máximo de informação sobre a variabilidade dos dados (DRAY; JOMBART, 2011).

Ademais, estudo da variabilidade de um determinado conjunto de dados multivariados é baseado na generalização do estudo de variância de uma variável contínua (CRUZ; HOLMES, 2011), a diferença consiste no fato de que essa variância é analisada considerando as diferentes direções dos eixos multivariados. Essa análise é feita por meio da adoção do conceito de inércia, definida como a soma ponderada do quadrado das distâncias entre as frequências dos pontos observados e esperados, tal qual é utilizado para o cálculo da estatística do chi-quadrado (HOLMES, 2003). Desse modo a inércia dos dados em cada um dos eixos serve como critério para determinação da quantidade de informação sobre os dados que está retida em cada um dos autovetores, isto é a qualidade da informação de cada representação (THIOULOUSE, 2011).

A diferença entre os métodos multivariados de análise exploratória consistirá na forma em que cada um deles irá identificar os autovetores de modo a maximizar diferentes aspectos da variabilidade dos dados, seja maximizando a variância total (inércia), as correlações ou mesmo adotando algum tipo de critério, que no caso são denominados de variáveis instrumentais.

Na presente revisão será dado enfoque aos métodos de análises de componentes principais (do inglês, *Principal Component Analysis* - PCA), análise multivariada entre classes, um caso particular da análise de componentes principais com variáveis instrumentais, denominada em inglês de *Between-class analysis* (BCA) e por fim a análise de co-inércia, que permite avaliar a relação entre dois ou mais conjuntos de dados multivariados (geralmente variáveis ambientais e variáveis relativas a organismos) coletados de um mesmo local ou unidade amostral.

A PCA busca encontrar a combinação linear de variáveis que explicam o máximo da variabilidade dos dados (RENCHER; CHRISTENSEN, 2012). O seu objetivo não é explicar as correlações existentes entre essas variáveis, mas encontrar funções matemáticas, entre as variáveis iniciais que melhor representem a variação existente nos dados e permita descrever e reduzir essas variáveis (CHI, 2012). A PCA trata exclusivamente de variáveis numéricas, que desempenham todas o mesmo papel.

Apesar da PCA maximizar a variância de todos os pontos e permitir a visualização das semelhanças e diferenças entre unidades amostrais, estudos em ecologia ainda consideram importante a identificação do efeito entre grupos (DRAY et al., 2007), pois muitas vezes diferentes unidades amostrais sofrem algum tipo de variabilidade sazonal (efeito do tempo) (ROSSI; BLANCHART, 2005) ou local (efeito espacial) (FRANQUET et al., 1995) que pode ainda incluir efeito de manejos ou níveis de degradação. Assim identificar a variação dos dados em função desses critérios é crucial para uma melhor compreensão dos padrões observados na PCA, para isso faz-se uso do método de análise multivariada denominado de *between-class analysis* (BCA). Esse tipo de análise foi adotado por Rossi e Blanchart (2005) para verificar o efeito de diferentes tipos de vegetação, com grau de perturbação distintos, ao longo das estações do ano na macrofauna do solo e percebeu que boa parte da variação entre espécies pode ser explicada pela formas do manejo e pela dinâmica temporal. Determinando assim, a aplicabilidade do método para identificar esse tipo de variação. Além disso, Dray e Jombart (2011) usaram a BCA para determinar que parte da inércia total dos dados pode ser atribuída a variação espacial dos dados.

Outro ponto importante da análise multivariada para a ecologia é o estudo de relações entre conjuntos de dados multivariados (THIOULOUSE, 2011), normalmente aplicados quando se prentende verificar qual efeito há entre variáveis ambientais e de espécies de organismos (macrofauna, microrganismos, plantas, entre outros), tudo isso em um mesmo local. Com isso, temos uma situação em que duas tabelas de dados multivariados devem ter sua variabilidade investigada para cada um das unidades observacionais que podem representar a variação espacial, temporal o de manejo (DRAY et al., 2003). Esse caso particular é um dos objetos de estudo da análise de co-inércia (CULHANE et al., 2003).

A análise de co-inércia é uma medida geral da co-estrutura de regiões amostradas nos hiperespaços de fatores ambientais e relativos a espécies (FRANQUET et al., 1995; THIOULOUSE, 2011). Baseia-se em uma medida de correlação multivariada, o coeficiente RV, que pode ser considerado uma generalização da correlação de Pearson para dados multivariados (CULHANE et al., 2003). Ela aumenta quando as duas estruturas variam simultaneamente, seja essa variação diretamente ou inversamente proporcional, e é menor quando elas variam independentemente.ou quando não variam entre si (DRAY et al., 2003). Devido a essas características Lavelle et al. (2014) utilizou a análise de co-inércia para identificar as relações entre conjuntos de variáveis relativos a diferentes serviços ecossistêmicos sugerindo uma relação de interdependência entre todos os serviços ecossistêmicos e que o manejo da fertilidade química dos solos da bacia hidrógráfica do rio Orinoco, uma região de savana na Colômbia, é o principal fator para determinar a dinâmica do solo nessa região.

Explorar as relações entre espécies de organismos e fatores ambientais não é uma tarefa fácil (DOLÉDEC et al., 1996), e adicionar as influencias temporais e espaciais torna essa análise ainda mais difícil (FRANQUET et al., 1995), mas é fundamental para que se possa avançar a compreensão do funcionamento dos ecossistemas (DRAY et al., 2003) e dos impactos do manejo antrópico.

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ARTIGO

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Effects of land use and fire regime on aboveground biomass and soil quality indicators in spontaneous forests and agroforests of eastern Amazon

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Abstract

This paper unites a wide array of indicators of aboveground vegetation, litter-layer and topsoil (0-20 cm) physico-chemistry in contrasting vegetation types of eastern Amazonia. We studied three types of agroforestry systems (enriched fallows, homegardens and commercial plantations), and compare these with three spontaneous forest types (young and old secondary forests and mature rainforests) with one-way ANOVA, linear and non linear regressions and multivariate analyses . We also isolated the effects of differing fire-regimes (first-cycle vs. multi-cycle slash-and-burn, and 'sweep-and-burn' in homegardens). Agroforests differed from young secondary forests in their lower understory biomass, higher topsoil pH and Ca-contents in commercial agroforests, and K-contents in homegardens. The overstory negatively impacted the understory, only the understory related significantly with the litter-layer. Principal component analysis identifies a successional sequence along age and between systems, with homegardens closest to mature rainforests. According to between-classes analyses, fire-regime is responsible for 39.7% of data-variation, and plant biomass is stronger related to the soil in spontaneous forests than in the agroforests. Multiple slash-and-burn causes an increase of topsoil calcium and sweep-and-burn in homegardens is associated with high topsoil potassium and P-availability hotspots. Our study confirms the sustainability of homegardens, with the combination of high biomass and nutrient-availability.

Keywords: homegardens; enriched fallows; commercial plantation agroforestry; secondary forest; slash and burn; sweep and burn.

1. Introduction

Anthropogenic pressure continues high throughout the humid tropics, both worldwide and in Amazonia. Next to the ongoing penetration of the frontier of colonization (first-cycle deforestation/slash-and-burn) into pristine rainforests (de las Heras et al. 2011), the subsequent deterioration via multiple slash-and-burn cycles and shortening fallow-periods is worrisome (Satyam Verma 2012; Styger et al. 2007). Degradation-symptoms such as low biodiversity, dominance of aggressive ruderal species and deteriorated soil fertility result in low agricultural productivity and ultimately in rural poverty (Lawrence et al. 2010; Hauser and Norgrove 2013; Varma 2003).

The deeply-weathered soils of the humid tropics are particularly vulnerable to degradation, because of the rapid decomposition and mineralization of organic matter, and of high nutrient-losses caused by leaching (Markewitz et al. 2004) or gaseous nitrogen-losses (Xu et al. 2013). Maintenance or restoration of the soil ‘productive potential’ is a central pillar of sustainable land-use (Boddey et al. 2003).

Agroforestry has been proposed as viable alternative to shifting cultivation in the tropics (Pollini 2009). There exist a great diversity of agroforestry systems, including different types of homegardens, perennial crop systems, alley cropping, improved fallows and rotational tree fallows (Atangana et al. 2014), with contrasting origins (traditional/‘modern’) and purposes (subsistence/commercial) (Nair 1991), and a wide array of management-intensities,complexities, resulting in differing biodiversity, structural and functional complexity of plants and soil-resources, and ultimately differing in their ecological and social sustainability (Schroth et al. 2001).

Depletion of soil nutrients due to unsustainable land-use intensification can cause reductions in above- and belowground biodiversity (Thiele-Bruhn et al. 2012), ecosystem functioning (Power 2010), and stability (Wakelin et al. 2014). By contrast, agroforestry can improve soil quality (Pinho et al. 2012), increase system stability (Lin 2011) and reduce economic risks because of better market flexibility via multiple products (Souza et al. 2012). Trees are key for soil fertility in agroforestry (Nair 2013), due to feedback-interactions which maintain nutrient-cycling via nutrient pumping and safety-net mechanisms (Van Noordwijk and Garrity 1995; Seneviratne et al. 2010).

Biological, chemical and physical processes interact in complex manners between vegetation, litter, and topsoil physico-chemistry, it is crucial to understand the impacts of plants on biotic and abiotic soil properties and functioning (van der Putten et al. 2013), both from a basic-science perspective and especially from the practical side. This could help in the development of improved management-techniques for smallholder agriculture, efficient and sustainable both in ecological and socioeconomic terms, and capable of acting against the vicious circle of environmental degradation and rural poverty.

In this paper, we assessed the impacts of different forms of land-use and fire regimes on vegetation and litter biomass and on topsoil physico-chemistry in eastern Amazonia (north-central Maranhão and eastern Pará states) in: (i) mature rainforests and fallow regrowth following slash-and-burn agriculture, and (ii) in three different types of agroforestry systems (commercial plantation, enriched fallow and homegardens), and we explore system-related differences in relationships along the vegetation-litter-topsoil continuum.

2. Materials and methods

2.1 Study region and site clusters

Research was conducted in the eastern periphery of Amazonia, on 32 study sites, in 5 counties aggregated into two regional clusters (Fig. 1). Maximum distance between sites within each county was <30 km, maximum distance between counties within each regional cluster was < 150 km. Seventeen of the 32 sites are located in central-northern Maranhão state, the others approximately 400 km further westward in Tomé-açu county in eastern Pará state. Pastures and secondary forests have almost entirely replaced the original rainforests in central Maranhão, as well as most of eastern Pará. Climate is classified according to Köppen as Aw and Ami and varies slightly between the two regional clusters (2100 mm annual rainfall in central Maranhão state and 2300 mm in eastern Pará state, with 6 and 5 months hydric deficit, respectively). Soils are nutrient-poor acid Oxisols and Ultisols (USDA 2010), topsoil texture is 'loamy/fine-sand' and varies little between sites and clusters (average and standard deviations of sand 72.88 ± 17.11%, silt 12.97 ± 18.63 and clay 14.15±7.21%), there were no systematic differences of soil texture between systems, counties or regional clusters.

→ insert Figure 12.2 Spontaneous forests and agroforests

We compare 3 types of spontaneous forests with 3 types of agroforest, distributed in two regional clusters and 5 counties according to Figure 1. Site selection and classification is based on previous work of Cardozo (2013) as follows:

(i) Spontaneous forests

Secondary forests following slash-and-burn shifting cultivation or on abandoned pastures. We distinguish into 'young' (≤12 yr-old) secondary forests (**SFY**) and 'old' (20-26 yr-old) secondary forests (**SFO**).

Mature rainforests (MF): Original primary forests without any visible human perturbation (one site) or with low-intensity selective logging >60 yrs ago (one site).

(ii) Agroforests

Enriched Fallow Agroforests (EFA): Agroforestry system established by enrichment planting of fruit and timber species in the understory of 15-25 yr-old secondary forests.

Homegarden Agroforests (HA): Tall multistrata agroforests surrounding the houses, virtually omnipresent in our study region and among the oldest and most widespread forms of agroforestry throughout the humid tropics.

Commercial Plantation Agroforests (CPA): Regularly-spaced agroforestry plantations with inorganic fertilization and liming, elaborated by Japanese immigrants or inspired by them but owned by smallholder farmers. Main products are fruits of cocoa (*Theobroma cacao* L.) and cupuassu (*T. grandiflorum* K. Schum), açaí (*Euterpe oleracea* Mart.), and black pepper (*Piper nigrum* L.).

Due to inexistence, not all systems are covered in both regional clusters. Implications of this unbalanced scheme are further discussed in chap. 2.4 and 3.1.

Sites and systems were subject to differing fire regimes: (i) never burnt (2 mature rainforest sites), (ii) first-cycle slash-and-burn, (iii) multi-cycle slash-and-burn, and (iv) 'sweep-and-burn' of litter and other debris in homegardens (Winklerprins 2009). We exclude EFA and CPA from our fire-regime analyses (partly unknown/inconsistent).

2.3 Within-site sampling scheme

We adopt a joint sampling scheme to guarantee compatibility between data-sets of all components under investigation and to adapt to the scale-sensitivity of all variables. Vegetation and litter sampling strives to capture 'plant influence zones', *sensu* Rhoades et al. (1996). We estimate large tree aboveground biomass in the circular main plot and minor vegetation and litter in five subplots (see Fig. 2). Topsoil (0-20 cm) was obtained as composite samples from the centers of the five subplots.

→ insert Figure 2

In the CPA, we adapted our sampling-scheme to the predominating regular spacing. Instead of a circle we used six sub-plots (3x5 m), in three quadrangular main plots of 25x25 m, in analogy with Kato et al. (2009), the sub-plots and transects followed the same methods as mentioned above.

2.4 Variables under investigation

Large components of biomass were estimated allometrically by Muchavisoy (2013), utilizing diameter-based equations for mature rainforest trees (Overman et al. 1994), secondary forest trees (Nelson et al. 1999), lianas (Gehring et al. 2004) and babassu palms (Gehring et al. 2011), as well as conversions between dbh and diameter measured at 30 cm height for smaller vegetation components (Gehring et al. 2008). Small vegetation (<1.30 m height) was estimated destructively jointly with the litter-layer. We distinguish into large vegetation (trees with dbh $\geq$ 10 cm and palms > 2 m height) (AGB$\geq$10 cm dbh), mid-sized vegetation (trees, shrubs and lianas with dbh < 10cm and palms < 2 m height), and small vegetation (herbaceous and shrubs smaller than 1.30 m height). For statistical analyses, we combine mid-sized and small vegetation (AGB<10 cm dbh). We quantify the necromass of fallen logs in transects (Van Wagner 1968), and standing dead logs in the circular main plots, following methods of Arevalo et al. (2002).

We destructively quantified and sampled the litter-layer in five 1x1m sub-quadrants within each sampling unit, at the end of the rainy season. Litter-layer mass-estimations distinguished between leaves and twigs.

As indicators of topsoil physical quality we measured (i) soil bulk density (volumetric rings), and (ii) soil texture (pipette method), utilizing standard procedures described in Klute et al. (1986). As indicators of topsoil chemistry we measured the pH (0.01 M $CaCl_2$ suspension), soil organic matter (Walkley-Black method), available P (extraction with synthetic anion exchange resin Amberlite IRA-400) and exchangeable K (Mehlich I), Ca, Mg (KCl extraction) and H+Al (SMP Method), following routine methods of the IAC (2001). Carbon and Nitrogen concentrations in leaf litter samples were determined with Walkley-Black (Embrapa 1997; Walkley and Black 1934) and Kjeldåhl digestion (Tedesco et al. 1995), respectively.

2.5 Statistical analyses

2.5.1 Basic and univariate statistics

We checked for normality of data-distribution with Kolmogorov-Smirnov and Lilliefor’s tests. Most data followed normal distribution or could be normalized via $\log_{10}$ or $\log_{10}(x+1)$ transformation. The only variable that doesn’t follow a normal distribution was the leaf litter C:N-ratio , for which we utilized non-parametric procedures (Spearman correlations, Kruskall-Wallis ANOVA with rank-based Dunn’s test). We also checked our data for homogeneity of variance with the Brown-Forsythe test for unequal number of replications (Brown and Forsythe 1974). We observed and excluded outliers and extremes (>1.5*SE), one value for organic matter, two for twig biomass and one for total aboveground biomass (in a CPA with Brazil-nut trees). For between-group comparisons and regressions, we define the default significance level as 5%, and also report on tendencies with <10 % significance-level.

Our experimental design is unbalanced, due to the non-occurrence of some systems in some clusters (see chap. 2.2). We evaluate the extent of this possible problem by searching for between-region differences via t-tests and via a multivariate method of between-class analyses (BCA). T-tests didn’t indicate significant difference in any variable. The regional impacts on BCA tests are presented in more detail in chap. 2.5.2.

We directly compare two types of single systems or groups of vegetation types via t-tests, and jointly via one-way ANOVAs and subsequent *post-hoc* Spjøtfoll-Stoline tests (HSD Tukey for unequal replication numbers). We investigate relationships between two variables via linear and non-linear regressions. These analyses were processed with Statistica 8.0 (StatSoft, 2007).

2.5.2 Multivariate statistics

We used multivariate between-class analyses (BCA) to investigate the potential effects of regional differences on secondary forests and on homegarden agroforests (which occurred in both regions), and subsequently quantify regional effects on the sum of variation of the entire data-set with a Monte Carlo randomization procedure using 9.999 permutations for significance-testing. Differences between regions explained only 7.72% of total variance, and this difference was non-significant.

For data-synthesis we furthermore conducted Principal Component (PCA), Between-class (BCA) (Chessel et al. 2004), Co-inertia analysis (CIA) (Dray et al. 2003), and permutation Monte Carlo significance tests (Romesburg 1985). PCA was adopted to investigate variation of the entire data-set and BCA to isolate systems grouping contributions in data variability. As part of our systems were subject to contrasting fire-management (see 2.2) we also investigate the impact of fire-regimes with BCA.

Co-inertia-Analysis investigates the relationships between two or more data-sets (Culhane et al. 2003), in our case the biomass and the soil data-sets within spontaneous forests and agroforests. We utilize a Between-class Co-inertia analysis (Franquet et al. 1995), where the covariance between groups, rather than between individual cases is maximized. We measure overall similarities using a multivariate extension of the Pearson correlation (the Rv coefficient). We allocate EFA into the group of 'spontaneous forests', because of their dominating spontaneous overstory.

We use the R environment (R Development Core Team 2007) and ade-4 library for the multivariate analyses (Thioulouse et al. 1997; Chessel et al. 2004). Graphs were generated with SigmaPlot 11.0 (Systat, 2008) and in R software.

3. Results

3.1 Vegetation, litter and topsoil in differing land use systems

TAGB differs significantly between systems (Fig. 3a). This was likewise true for AGB$\geq$10 cm dbh (data not shown). Systems furthermore differed significantly in their shrubs and herbaceous biomass (AGB<10 cm dbh) , where SFY had an approximately 100-fold higher biomass than HA, and MF a nearly five-fold higher biomass than CPA (Fig. 3a). There were no significant differences in necromass of standing and fallen logs > 5 cm), nor in littermass, neither for twigs nor for leaf litter (data not shown). There was a tendency of decreasing leaf litter and increasing twig litter along succession ($p<0.10$) (Fig. 3b).

→ insert Figure 3

We found no overall between-system differences in topsoil organic matter (OM) concentrations. Excluding agroforests, there was a significant ($p<0.05$) increase of OM-concentrations along succession and highest values in MF (letters in brackets) (Fig. 4a). Bulk soil density was significantly higher in SFY than in SFO, MF and HA (Fig. 4a). Topsoil pH was highest in CPA and lowest in MF and HA (Fig. 4b). Available P-concentrations were non-normally distributed and didn´t differ between systems due to high data-variability.

→ insert Figure 4

Topsoil K-concentrations were three times higher in HA than in the spontaneous forests (SFY, SFO and MF) (Fig. 5). Topsoil Ca-concentrations were higher in CPA and SFO than in HA and MF, whereas Mg-concentrations didn't differ between systems. We also found higher values of soil potential acidity (H+Al) in MF and in HA soils as compared to the soils of CPA (data not shown).

→ insert Figure 5

Both leaf and twig litter-layer C-contents didn´t differ significantly between systems (data not shown). By contrast, leaf-litter N-contents were highest in MF (average 20% above CPA and HA and 30% above SFO and EFA) (Fig. 6a). Leaf-litter C:N- ratios were significantly higher in SFY and CPA than in EFA (Fig. 6b)

→ insert Figure 6

3.2 Effects of fire regime on vegetation, litter-layer and topsoil

TAGB (Figure 7), AGB≥10 cm dbh (data not shown) and AGB<10 cm dbh differed significantly between fire-regimes (Fig. 7). As expected, the never-burnt mature rainforests (0-burn) had higher TAGB than the secondary forests. In direct comparison between secondary forests following first-cycle (1-burn) vs. multi-cycle (M-burn) slash-and-burn, t-tests identified significantly lower stocks for all major biomass components (TAGB, AGB≥ 10cm, AGB ≤ 10cm and fallen logs) after multiple slash-and-burn (data not shown).

→ insert Figure 7

Total litter biomass tended ($p=0.07$) to differ between systems, with highest values in never-burnt MF, nearly 60% above littermass in HA with their regular sweep-and-burn fire-regime (S-burn) (Fig. 8a). Leaf litter tended ($p=0.07$) to be higher in 1-burn than in S-burn, and twig biomass tended ($p<0.08$) to be higher in 0-burn than in M-burn (Fig. 8b).

→ insert Figure 8

Neither topsoil OM ($p=0.65$), nor bulk soil density ($p=0.19$) differed between fire regimes. The pH values, however, did differ and were significantly higher in M-burn than in 0-burn and in S-burn (Fig. 9). Topsoil available P-content varied strongly in the S-burn (ranging from 2.3-27.3 mg dm^{-3}) (Fig. 4). Figure 9 shows significant differences in K- and Ca-concentrations, with highest K-concentrations in S-burn and highest ($p=0.06$) Ca-concentrations in M-burn.

→ insert Figure 9

3.3 Relationships between variables

Here, we explore a continuum of bivariate relationships between aboveground vegetation–litter–topsoil physico-chemistry over the 32 study sites.

3.3.1 Within-vegetation and vegetation-litter relationships

Figure 10a exhibits the negative-logarithmic relationship between AGB≥10 cm dbh and AGB<10 cm dbh over the 32 study sites. Figure 10b establishes a positive-logarithmic relationship between AGB<10 cm dbh and total litter biomass ($r^2=0.11$, $p<0.07$). However, when distinguishing between leaves and twigs, this relationship was significant only for leaf litter ($r^2=0.14$) (data not shown). There was no apparent relationship between AGB≥10 cm dbh and leaf, twig or total litter biomass. We found a positive non-parametric relationship (Spearman rank $R=+0.61$, $p<0.05$) between total littermass and its C:N ratio (data not shown).

→ insert Figure 10

3.3.2 Litter-topsoil relationships

Neither total nor leaf litter biomass were significantly related with topsoil organic matter (data not shown). By contrast, there was a significant positive relationship between twig biomass and topsoil OM-content (Fig. 11a). Both ‘plant-available’ P- and K-concentrations were negatively related with total litter biomass (Fig. 11b and c).

→ insert Figure 11

3.3.3 Within-topsoil relationships

Soil OM-content positively related with clay-content and negatively related with soil bulk density, without differences between systems (Fig. 12a and b). Clay-content related negatively with soil bulk density ($r^2 = 0.18$), whereas the other granulometric fractions didn´t significantly affect soil density (data not shown).

→ insert Figure 12

We didn´t detect any significant relationships between SOM and its pH or nutrients (data not shown). Within soil-chemical indicators, we found a positive relationship between P and K ($r^2 = 0.32$), as well as between pH and Ca ($r^2= 0.67$).

3.4 Multivariate synthesis of variables and systems

We explore the degree of covariations via PCA (Fig. 13). The two main ‘factors’ together explain 42.4% of total data-variability of vegetation, litter and topsoil physico-chemistry. Figure 13a shows a successional trajectory of spontaneous forests from SFY via SFO and EFA to MF. Remarkably, HA are closest to MF. CPA forms a distinct group clearly separated from the other systems, with one extreme value presumably caused by the high biomass of Brazil-nut trees (*Bertholia excelsa* Humb. & Bonpl.) on this site only. Futhermore, Figure 13b delimits the PCA correlation-circle over all variables of this study, with the first axis dominated by soil physico-chemistry (base saturation, soil potential acidity, pH, K concentration, clay, bulk soil density) as well as the litter layer and small vegetation components, and the second axis mainly driven by SOM, litter-layer N-content, and total and large vegetation biomass (these latter two also strongly contribute to the first axis).

→ insert Figure 13

We investigate differences between land-use systems with BCA. Between-groups inertia corresponds to 30.29% of the total PCA variation (P=0.0001). The first and second axis jointly represent 75.5% of this data-variation. The successional trajectory from SFY to MF is less apparent than in PCA, presumably because the BCA method maximizes the inertia between-groups rather than between-sites (Fig. 14). As with PCA, HA are closest to MF, and CPA again form a distinct group.

→ insert Figure 14

To investigate the effects of fire-regimes we performed two Between-class analyses (BCA). Firstly we strive to understand the variance among and between spontaneous secondary forests following slash-and-burn shifting cultivation, zero-burn mature rainforests and the special case of sweep-and-burn in homegardens, and elucidate how much of overall variance can be explained by the criteria of (i) fire regimes (Fig. 15a), and (ii) spontaneous forests vs. homegardens (Fig. 15b). Classification according to forest successional stages and homegardens explained 34.67% (P=0.0001) of total variance, whereas classification according to different fire-regimes explained 39.68% of total variance (P=0.0001).

→ insert Figure 15

Between-class co-inertia analysis measures the overall similarity between aboveground biomass and litter biomass with soil physico-chemistry data-sets. When considering all systems, this relation was significant but weak (Rv=21.76%, P<0.05), when considering only spontaneous forests the multiple correlation coefficient was higher (Rv=75.5%, P<0.01), whereas the multiple correlation coefficient was lower in agroforests, mainly due to CPA and HA without significant relationships (Table 1). The spontaneous forests also retain more information of variability in the first two axis, even when we added EFA to their group (95.14% and 92.24%, respectively).

→ insert Table 1

4. Discussion

4.1 Regional variance and plot-size effects

According to between-region BCA regional effects on data-variability were small (only 7.7% of total data-variance). T-tests between regions didn't detect any significant differences in secondary forests and homegardens (both of which occurred sufficiently replicated in both regions). Thus, regional variability does not put into question our key findings .

We estimated AGB≥ 10 cm dbh in a 0.20 ha sampling-unit per site, similar in size as sampling-units successfully employed in other studies in tall forests (Keller et al. 2001; Read and Lawrence 2003),. However, we did record two very high (> 80 Mg ha^{-1}) estimates of shrubs, treelets and lianas (AGB 1-10 cm dbh), one for SFY and another for CPA, this may have occurred because of insufficient subplot-size .

4.2 Vegetation and land-use related differences

Both the aboveground biomass of large (≥ 10cm dbh) trees and palms and of smaller / understory (< 10 cm dbh) plants vary widely between systems, though frequently in opposite directions consequence of the negative logarithmic relationship between large and small plants, which presumably is the outcome of competition (Schwinning and Weiner 1998). Within the spontaneous forests, we observe successional trajectories of overstory biomass-increase and of understory biomass-decrease, and within agroforests direct management-effects (differing regimes of understory clearing, sweep-and-burn). Overall, understory biomass was much lower in agroforests than in spontaneous forests, reflecting the management-objective of reducing competition and maximizing crop resource-use. We didn´t find significant differences either in topsoil-OM or bulk density between spontaneous forests and agroforests, confirming results of Bae et al. (2013). However there was a statistical difference in OM-content between MF and SFY, pointing to SOM-restoration along succession (Silver et al. 2000). Management also influenced topsoil chemistry, with higher pH and Ca-concentrations in CPA presumably caused by liming and significant input of chemical fertilizers.

Leaf litter N-concentrations increased along secondary forest succession and N-concentrations were highest in MF. This would be in accordance with a decreasing N-limitation and also a decreasing relevance of biological N_2-fixation in old-growth sites (Gehring et al. 2005; Davidson et al. 2007). N-concentrations in the litter-layer were lower in our agroforests than elsewere (Moço et al. 2010), probably due to the low quantity of N_2-fixing legumes in our agroforests.

Next to the N-contents, litter-layer C:N-ratios are key for litter-topsoil N-dynamics (Constantinides and Fownes 1994). Overall, plant-tissue with C:N-ratio <25 tends to mineralize while tissue with C:N-ratio>25 initially immobilizes mineral N (Myers et al. 1994), consequence of the nutrient-demand for litter-decomposition (Hobbie et al. 2006). Thus, N-immobilization predominates in our litter-layers, with the exception of one HA and two EFA sites. On the other hand, we observe a significant positive relationship between twig-litter mass and topsoil OM-content, possibly the consequence of their high lignin/polyphenol (Tu et al. 2011; Lorenz et al. 2007). Agroforestry-species with larger twig-production could maximize soil carbon-sequestration.

Multivariate analysis provides us a tool which permits deeper insights into the interrelationships between variables (Shukla et al. 2006), as well as the appreciation of land-use and management-effects on such relationships (Rossi and Blanchart 2005). The results of PCA (i) partition two main axes ('soil physico-chemistry' vs. 'large vegetation'), (ii) indicate successional pathways, and (iii) positions HA close to MF, whereas CPA forms a distinct group.

BCA analysis provide indications on the potential of improvements in fields with lowest indicator values and the combination of sites with contrasting functions may give support to a strategically designed landscape mosaic (Lavelle et al. 2014). Variability was highest in the homegardens, pointing to large development potentials in this system.

4.3 Effects of fire-regime

We found significant effects of repeated slash-and-burn shifting-cultivation both aboveground and belowground. Aboveground biomass reductions were strong (on average 58,9% relative to first-cycle slash-and-burn) and affected all major biomass-components. Belowground, we found higher topsoil pH and Ca-contents associated with multiple burns presumably because of the very high temperature necessary for Ca-volatilization (Certini 2005; Raison et al. 1985).

According to BCA, the effects of contrasting fire regimes were overall stronger than the effects of different forms of land-use, explaining 39.7% (as opposed to 34.7%) of overall data-variability. Obviously, BCA doesn't separate the effects of differing fire regimes from those of differing land-use systems, as both features interact and specific fire regimes are inherent to specific land-use systems.

.4.4 Plant-litter-topsoil interactions

The influence of trees on soil nutrients and 'soil quality' has been widely recognized, plants and soils interact via a continuum of multiple individual relationships between components of vegetation, litter-layer and (top)soil (van der Putten et al. 2013).

In our study, we observed (i) a negative logarithmic relationship between the aboveground biomass of large and small plants, presumably caused by competition for light and soil-resources (Schwinning and Weiner 1998); (ii) Litter-layer biomass was affected by small vegetation components, but not by the large trees >10 cm dbh ; (iii) Litter-layer twigs but not leaves contribute to SOM buid-up; (iv) Littermass related to a widening litter C:N-ratio, and to reduced 'plant-available' topsoil P- and K-concentrations , as similarly related for soil P-content in McGrath et al. (2000); and (v) within topsoil we find some expected relationships, such as the positive relationship between clay-content and SOM (Six et al. 2002; Desjardins et al. 2004), and the negative relationship between SOM and bulk density (Bernoux et al. 1998; Feller and Beare 1997).

Management exerts strong impacts on plant:soil interactions, which could partially explain the lack of straight relationships between these components. One conspicuous result of our study is the absence of any significant relationship between topsoil OM-content and nutrient-concentrations or pH. In CPA (and partially in EFA), this can be attributed to liming (CPA only) and localized synthetic fertilizer inputs. The low estimates of plants < 10cm dbh and littermass in the homegardens likely reflect the management-practice of keeping the undergrowth and soil surface clean around the houses.

Co-inertia analysis helps us to synthesize the multivariate relationships between aboveground biomass, litter and soil indicators. Overall vegetation-impacts on the topsoil were stronger in spontaneous forests than in agroforests. Futhermore, we were able to identify two systems (CPA and HA) where this plant-soil discontinuity occurs.

4.5 The special case of homegardens

Ubiquitary homegardens have developed independently in many different cultures throughout both the humid and semi-arid tropics (Nair 2001). They are known as complex multistrata systems, typically with high plant diversity (Jose 2012) and are subsistence- rather than market-oriented (Mohri et al. 2013). In addition to the productive functions, homegardens provide vital shade.

Ubiquitary homegardens are special a.o. with their specific 'sweep-and-burn' fire-regime of the litter-layer (Winklerprins 2009; Benjamin et al. 2001), practiced mainly by women, in order to reduce insects and keep the homegarden 'clean'around the farmer´s houses. Benjamin et al. (2001) suggest that this could offset carbon-liberation and negatively affect nutrient cycling(Benjamin et al. 2001)..By contrast, our study points to positive effects of sweep-and-burn, we attribute the high topsoil K-concentrations to the low-intensity spatially irregular burns of litter piles, which could also have caused local hotspots with high P-concentrations. Such soil heterogeneity could create a mosaic of soil conditions which should positively impact ecosystem-stability (Tittonell et al. 2013). By contrast, pH–values were low in homegardens, similar with mature rainforest and significantly lower than in all other systems. This could be due to the low temperatures of burning piles, insufficient to change pH (Certini 2005). Pinho et al. (2011) likewise report on higher values of soil K-concentrations and widespread values of P-concentration in homegardens of Roraima, Brazil. Sweep-and-burn of litter-piles combines quick nutrient-mineralization and the creation of spatial heterogeneity with protection against leaching by the large trees with dense canopies and root systems.

In spite of their ubiquitarity (Kumar and Nair 2004), ecological sustainability (Mohri et al. 2013) and socioeconomic success (Cardozo 2013; Alam 2011), homegarden agroforests still are definitely under-researched (Nair 2014). Complex geometries and interactions have so far largely evaded science (Seneviratne et al. 2010), and homegarden agroforests have never been part of systematic agronomic improvement-efforts (Kumar and Nair 2004). Their high between-site data-variability points to a substantial potential for management improvements (optimized composition, spacing, pruning etc).

5. Conclusions

We find strong impacts of land use on soil-quality indicators and aboveground biomass, within agroforests partly related to contrasting effects of understory and soil management, whereas changes in spontaneous forests are related to the successional regrowth trajectories and long-term effects of fire. Plant-soil interrelationships were weaker in agroforests than in spontaneous forests, consequence of management. Alltogether, biomass of the agroforests was statistically similar with mature rainforests and litter and topsoil nutrients were higher than in young secondary forests, confirming their ecological sustainability and potential as alternative to slash-and-burn in eastern Amazonia. Our study confirms the exceptional standing of homegarden agroforestry, due to the conspicuous combination of high biomass and hotspots of P- and K-availability, this definitely warrants more research.

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FIGURE HEADINGS

Fig. 1 – Number (in brackets) and distribution of the 32 study sites within the 2 regional clusters and 5 counties.

Fig. 2. Sampling-unit with differently-sized and replicated sampling-areas for vegetation, litter and topsoil.

Fig. 3 – (a) Total aboveground biomass and biomass of small (<10 cm dbh) trees, lianas, shrubs and herbaceous plants and (b) twigs and leaf litter in the understory of spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level. The letters in brackets corresponds to the Spjøtfoll-Stoline test for spontaneous forests only, at a 10% probability-level.

Fig. 4 – (a) Topsoil (0-20 cm) organic matter (OM) concentration and bulk soil density, and (b) pH-values and resin-extractable P-concentrations in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level. The letters in brackets corresponds to the Spjøtfoll-Stoline test for spontaneous forests group. Lines and Boxes represent medians and 25-75 percentiles of P concentrations, respectively, whiskers are the 90 and 10 percentiles.

Fig. 5. Topsoil 0-20 cm) concentrations of K and Ca in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level.

Fig. 6 – Leaf litter N-concentrations (a) and Carbon:Nitrogen ratios in leaf litter (b) of spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level. Lines and Boxes represent medians and 25-75 percentiles, respectively, whiskers are the 90 and 10 percentiles. Systems with the same letter don't differ between another, as indicated by Dunn's nonparametric test at the 5% probability-level.

Fig. 7 – Total aboveground biomass (TAGB) and biomass of plants smaller than 10 cm dbh (AGB <10) in areas with contrasting fire-regimes (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level.

Fig. 8 – (a) Biomass of total litter, and (b) of leaf and twig litter in the rainy-season O-horizon in systems with contrasting fire-regimes (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at a 7% probability-level for total litter biomass and for leaf litter and at an 8% probability-level for twig litter biomass.

Fig. 9 – Topsoil (0-20 cm) K- and Ca-concentrations and pH values in systems with different fire-regimes (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level and at 6% for soil Ca-concentration.

Fig. 10 – Relationships between (a) the aboveground biomass of plants larger than 10 cm (AGB ≥ 10 cm) and plant biomass smaller than 10 cm dbh (AGB < 10 cm), and (b) the aboveground biomass of plants smaller than 10 cm (AGB < 10 cm) and total litter biomass (leaves and twigs) in spontaneous forests (closed symbols) and agroforests (open symbols) (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest).

Fig. 11 – Relationships (a) between twig biomass and topsoil organic matter content, and (b) between total litter biomass (leaves and twigs) and topsoil available P-concentrations and (c) K-concentrations in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest).

Fig. 12 – Relationships between topsoil (a) clay content and organic matter, and (b) organic matter and bulk soil density in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest).

Fig. 13 – (a) Principal Component Analysis (PCA) over the 32 sites of spontaneous forests and agroforests in eastern Amazonia, and (b) PCA correlation circle of soil physical and chemical indicators and vegetation components (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest)

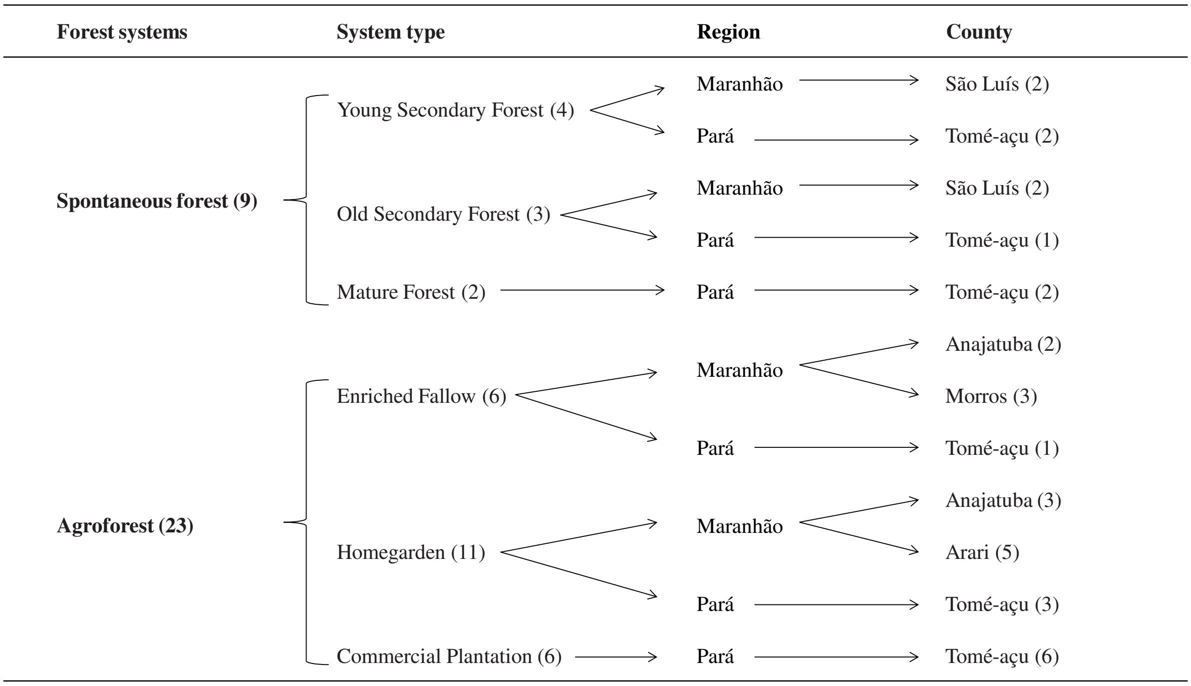
Fig. 14 – Between-class analysis (BCA) of the 32 sites of spontaneous forests and agroforestry systems in eastern Amazonia (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). The inertia between classes was of 30.29%, the Monte Carlo permutation level of significance was P=0.001.

Fig. 15 – Between-class analysis (BCA) over 20 sites (excluding EFA and CPA) in eastern Amazonia, (a) grouped by forest systems (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; HA = Homegarden Agroforests); and (b) grouped by fire regime (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest). . The inertia between classes was of 34.67% (a) and 39.68% (b), the Monte Carlo permutation level of significance was P=0.001.

Table 1. Coefficient of matrix correlation (Rv) between tables of soil data-set and biomass data-set for spontaneous forests and agroforestry systems.

Systems	Co-inertia ratio (Rv)	Cumulative project inertia (%)[a]	P[b]
All systems	0.2176*	81.96	0.0429
SFY+SFO+MF	0.7550**	95.14	0.0026
EFA+HA+CPA	0.2573	87.72	0.0817
SFY+SFO+MF+EFA	0.5741**	92.24	0.0035
CPA+HA	0.2942	83.14	0.1213

[a] Total inertia percentage of the two principal axis of CIA; [b] Significance-level based on 9,999 Monte Carlo permutations; * Co-inertia ratio was significant at $P<0.05$; ** Co-inertia was significant at the level of $P<0.01$.



Forest systems	System type	Region	County
Spontaneous forest (9)	Young Secondary Forest (4)	Maranhão	São Luís (2)
		Pará	Tomé-açu (2)
	Old Secondary Forest (3)	Maranhão	São Luís (2)
		Pará	Tomé-açu (1)
	Mature Forest (2)	Pará	Tomé-açu (2)
Agroforest (23)	Enriched Fallow (6)	Maranhão	Anajatuba (2)
			Morros (3)
		Pará	Tomé-açu (1)
	Homegarden (11)	Maranhão	Anajatuba (3)
			Arari (5)
		Pará	Tomé-açu (3)
	Commercial Plantation (6)	Pará	Tomé-açu (6)

Fig. 1 – Number (in brackets) and distribution of the 32 study sites within the 2 regional clusters and 5 counties.

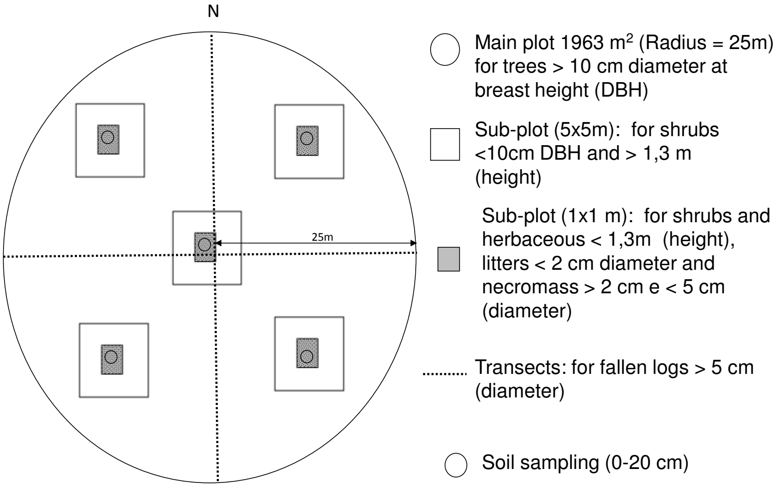


Fig. 2. Sampling-unit with differently-sized and replicated sampling-areas for vegetation, litter and topsoil.

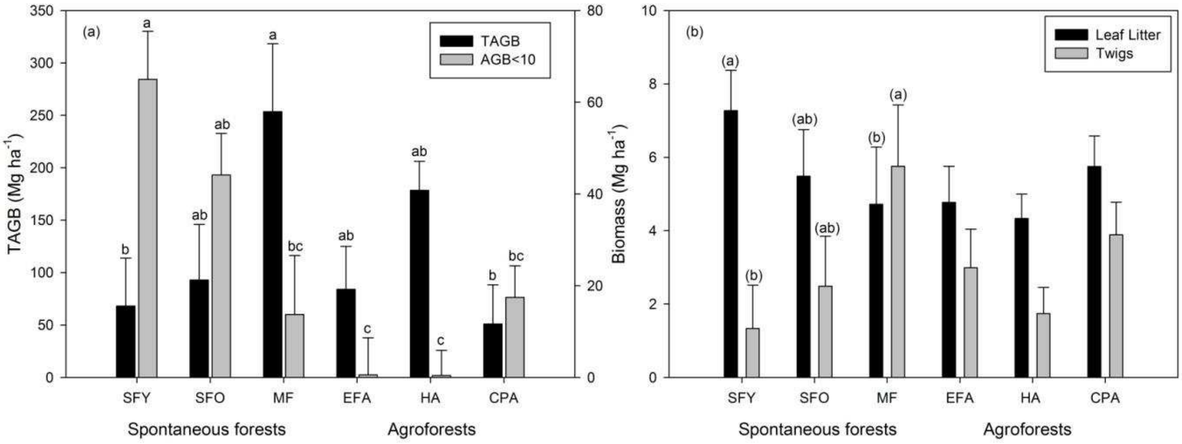


Fig. 3 – (a) Total aboveground biomass and biomass of small (<10 cm dbh) trees, lianas, shrubs and herbaceous plants and (b) twigs and leaf litter in the understory of spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level. The letters in brackets corresponds to the Spjøtfoll-Stoline test for spontaneous forests only, at a 10% probability-level.

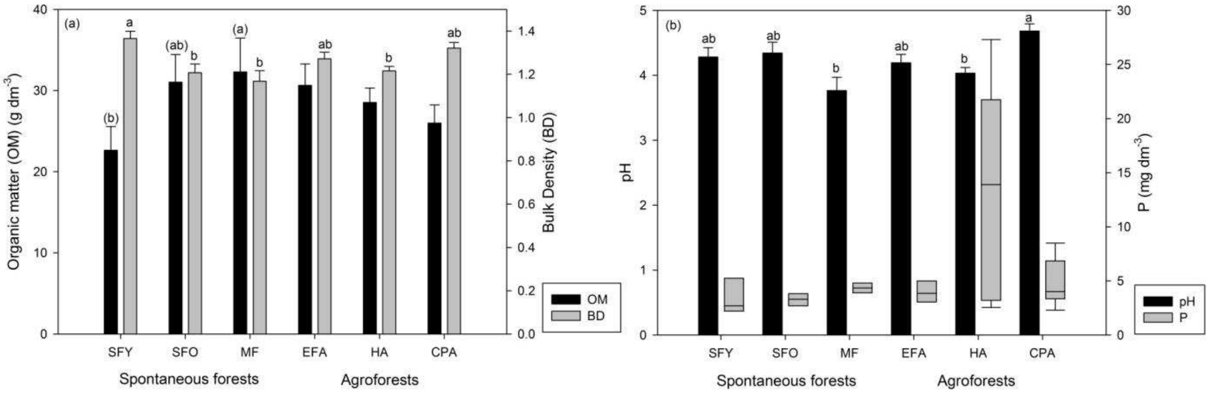


Fig. 4 – (a) Topsoil (0-20 cm) organic matter concentration and bulk soil density, and (b) pH-values and resin-extractable P-concentrations in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level. The letters in brackets corresponds to the Spjøtfoll-Stoline test for spontaneous forests group. Lines and Boxes represent medians and 25-75 percentiles of P concentrations, respectively, whiskers are the 90 and 10 percentiles.

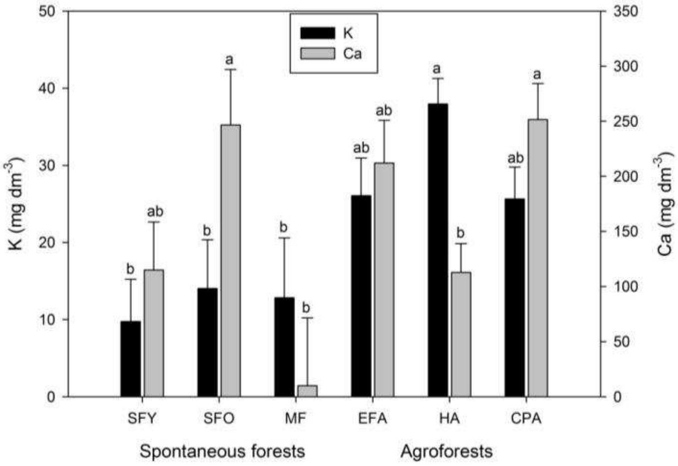


Fig. 5. Topsoil 0-20 cm) concentrations of K and Ca in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level.

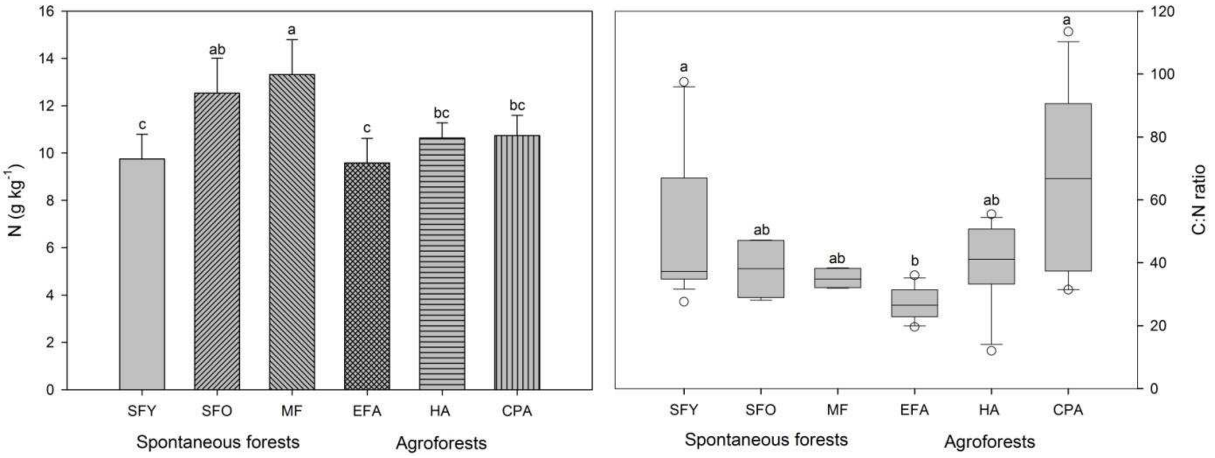


Fig. 6 – Leaf litter N-concentrations (a) and Carbon:Nitrogen ratios in leaf litter (b) of spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level. Lines and Boxes represent medians and 25-75 percentiles, respectively, whiskers are the 90 and 10 percentiles. Systems with the same letter don't differ between another, as indicated by Dunn's nonparametric test at the 5% probability-level.

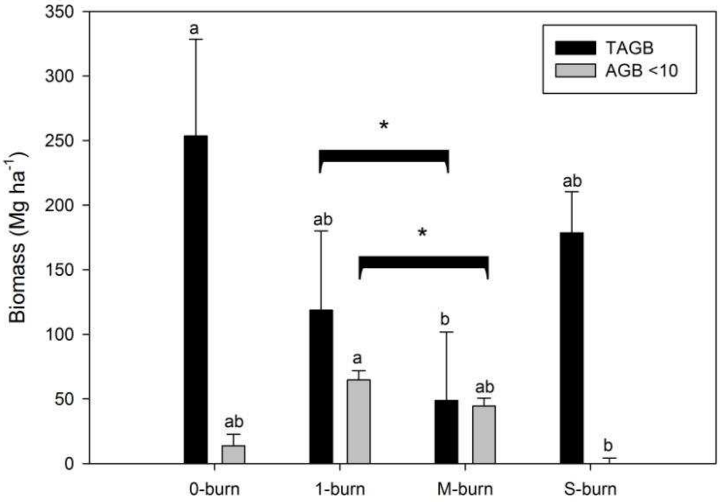


Fig. 7 – Total aboveground biomass (TAGB) and biomass of plants smaller than 10 cm dbh (AGB <10) in areas with contrasting fire-regimes (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level. Means under the same line doesn't differ between each other by the t-test at 5% probability-level.

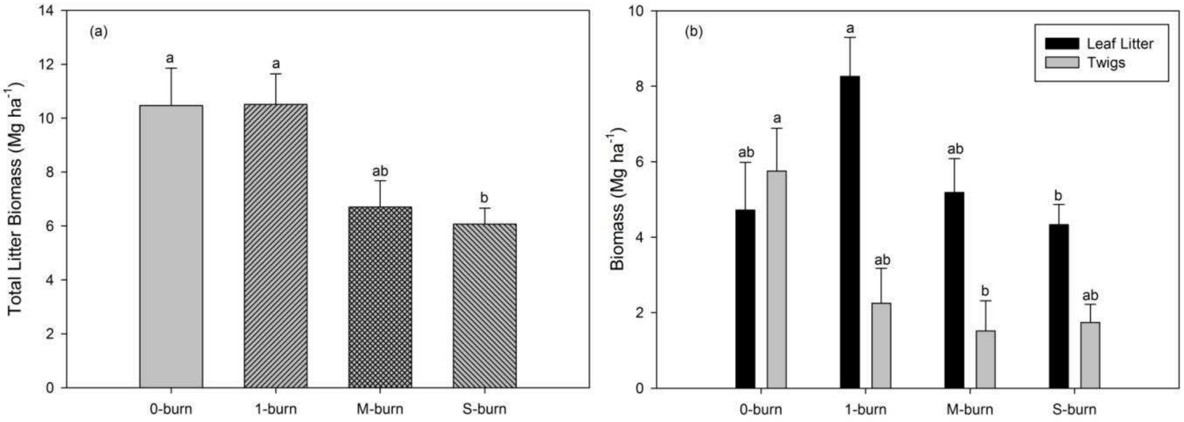


Fig. 8 – (a) Biomass of total litter, and (b) of leaf and twig litter in the rainy-season O-horizon in systems with contrasting fire-regimes (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at a 7% probability-level for total litter biomass and for leaf litter and at an 8% probability-level for twig litter biomass.

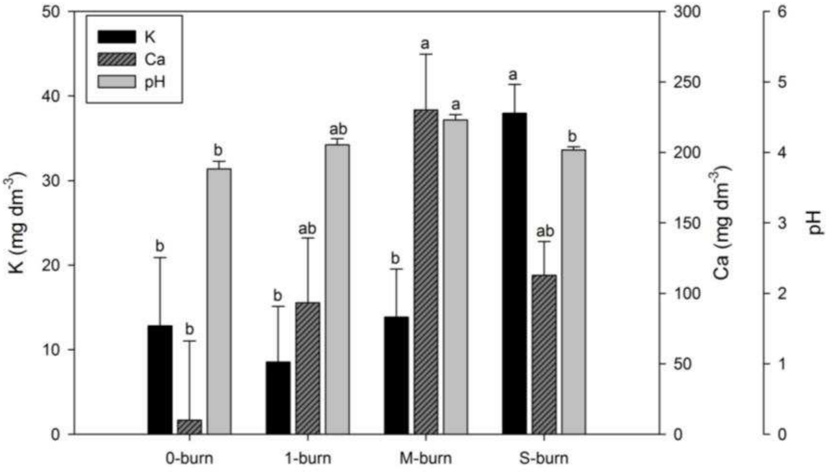


Fig. 9 – Topsoil (0-20 cm) K- and Ca-concentrations and pH values in systems with different fire-regimes (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest). Means+SE followed by the same letter don't differ between another, as indicated by Spjøtfoll-Stoline test at the 5% probability-level and at 6% for soil Ca-concentration.

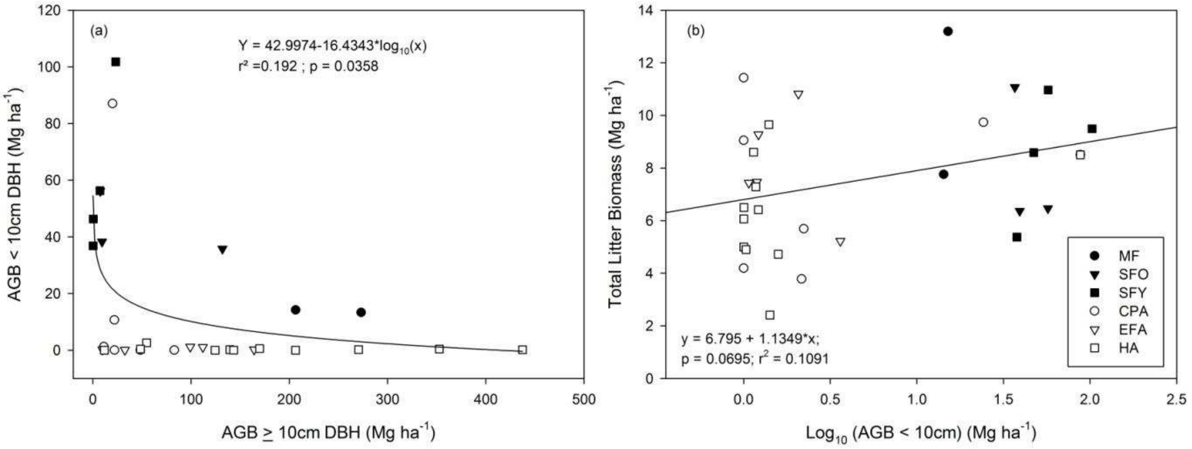


Fig. 10 – Relationships between (a) the aboveground biomass of plants larger than 10 cm (AGB ≥ 10 cm) and plant biomass smaller than 10 cm dbh (AGB < 10 cm), and (b) the aboveground biomass of plants smaller than 10 cm (AGB < 10 cm) and total litter biomass (leaves and twigs) in spontaneous forests (closed symbols) and agroforests (open symbols) (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest).

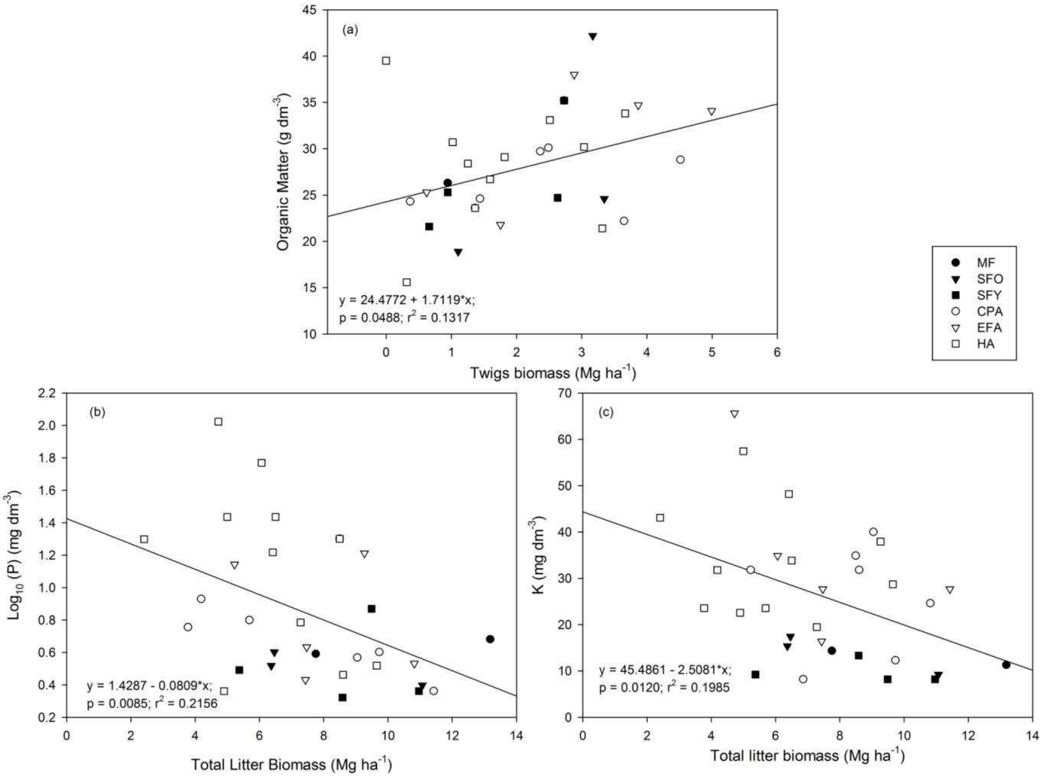


Fig. 11 – Relationships (a) between twig biomass and topsoil organic matter content, and (b) between total litter biomass (leaves and twigs) and topsoil available P-concentrations and (c) K-concentrations in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest).

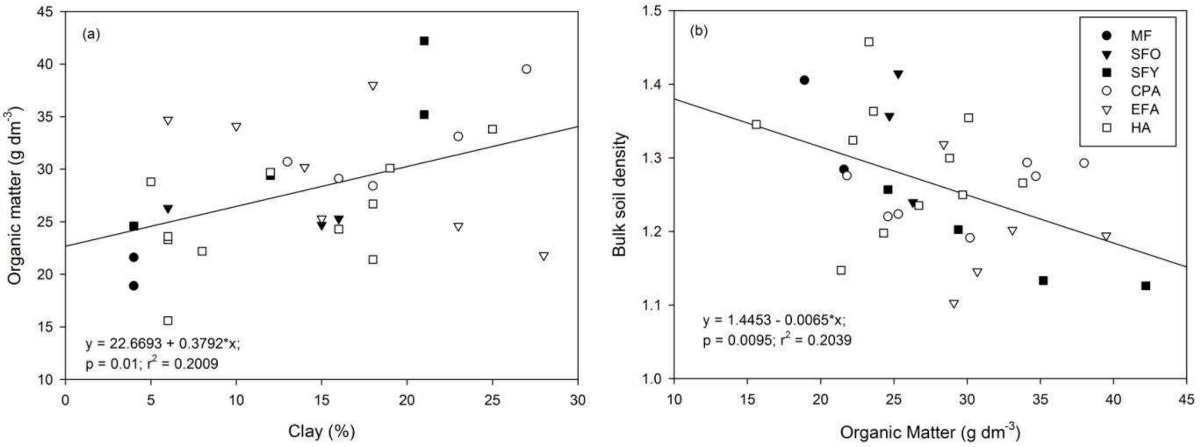


Fig. 12 – Relationships between topsoil (a) clay content and organic matter, and (b) organic matter and bulk soil density in spontaneous forests and agroforests (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest).

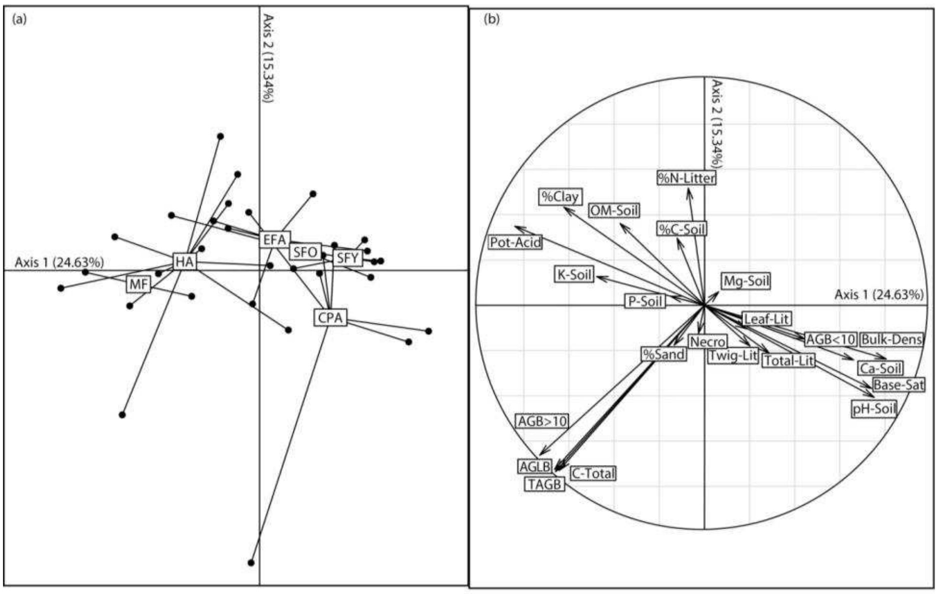


Fig. 13 – (a) Principal Component Analysis (PCA) over the 32 sites of spontaneous forests and agroforests in eastern Amazonia, and (b) PCA correlation circle of soil physical and chemical indicators and vegetation components (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest)

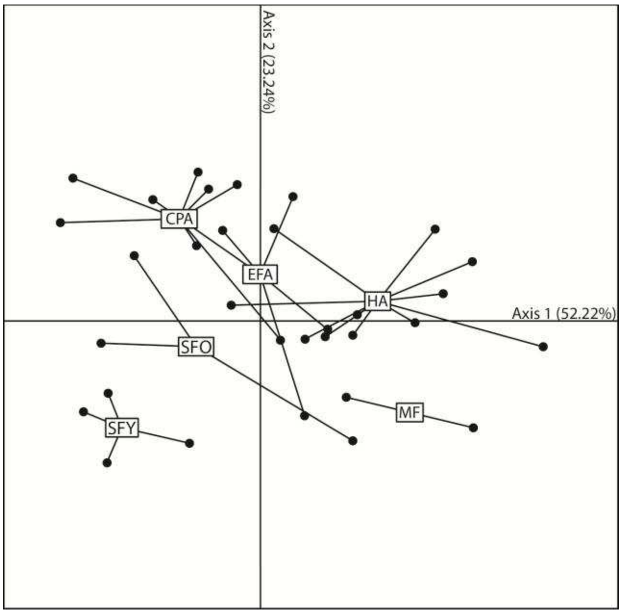


Fig. 14 – Between-class analysis (BCA) of the 32 sites of spontaneous forests and agroforestry systems in eastern Amazonia (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; EFA = Enriched Fallow Agroforest; HA = Homegarden Agroforest; CPA = Commercial Plantation Agroforest)

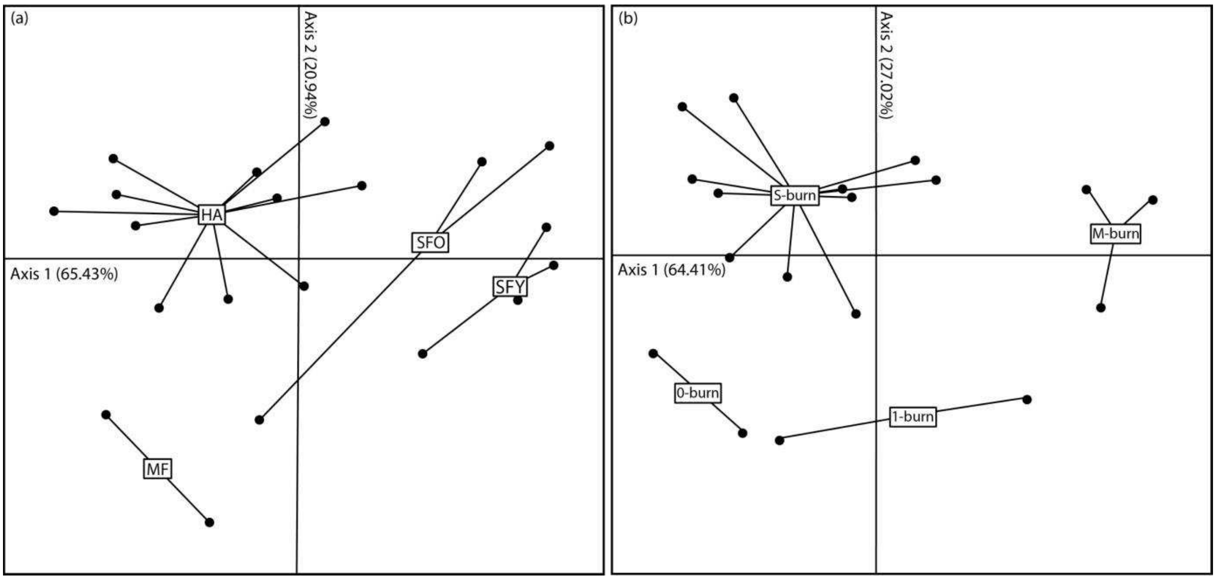


Fig. 15 – Between-class analysis (BCA) over 20 sites (excluding EFA and CPA) in eastern Amazonia, (a) grouped by forest systems (SFY=Young Secondary Forest; SFO = Old Secondary Forest; MF= Mature Forest; HA = Homegarden Agroforests); and (b) grouped by fire regime (0-burn = never-burnt rainforest; 1-burn = first-cycle slash-and-burn secondary forest; M-burn= multi-cycle slash-and-burn secondary forest; S-burn = Sweep-and-burn in homegarden agroforest).

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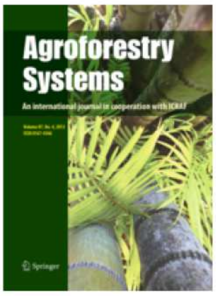

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Book chapter

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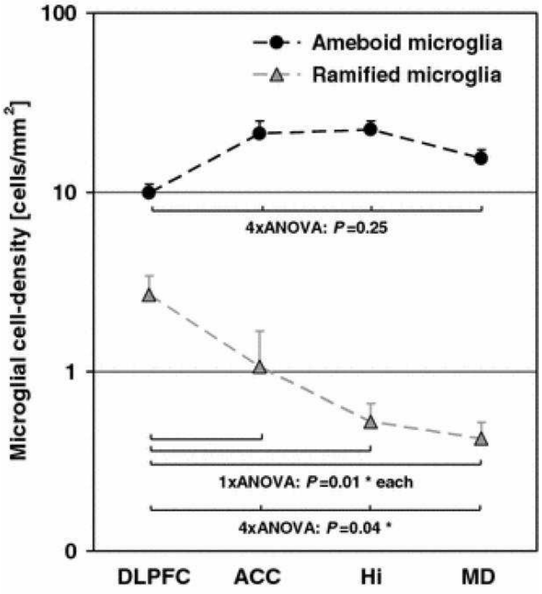

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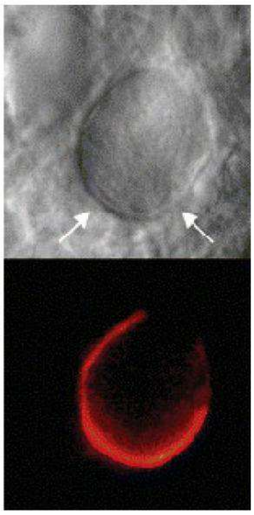

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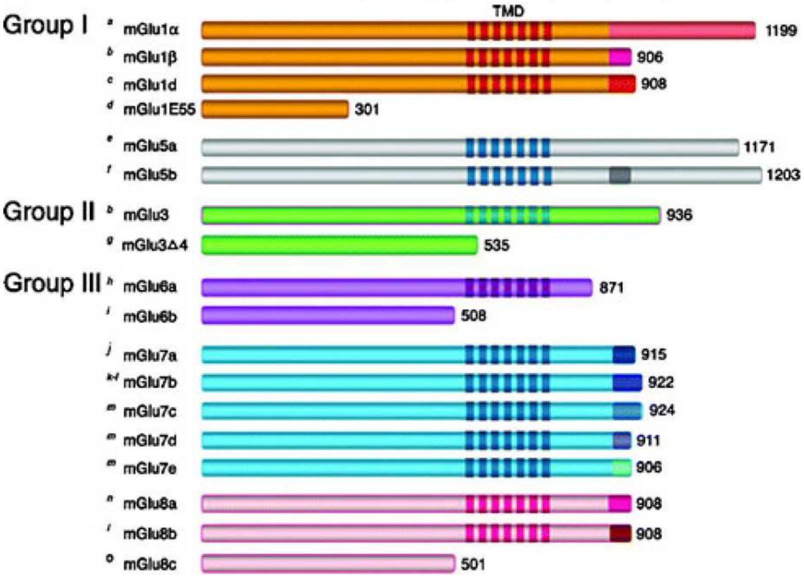

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