UNIVERSIDADE FEDERAL DE LAVRAS

VANÊSSA LOPES DE FARIA

SOIL QUALITY AND ECOSYSTEM SERVICES IN THE CHANGING AGRICULTURAL AND REFORESTED LANDSCAPE OF THE PONTAL DO PARANAPANEMA

LAVRAS – MG
2025

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Prof. Dr. Bruno Montoani Silva
Orientador

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VANÊSSA LOPES DE FARIA

SOIL QUALITY AND ECOSYSTEM SERVICES IN THE CHANGING AGRICULTURAL AND REFORESTED LANDSCAPE OF THE PONTAL DO PARANAPANEMA

QUALIDADE DO SOLO E SERVIÇOS ECOSSISTÊMICOS NA PAISAGEM AGRÍCOLA E REFLORESTADA EM TRANSFORMAÇÃO DO PONTAL DO PARANAPANEMA

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para obtenção do título de Doutor.

APROVADA em 25 de fevereiro de 2025

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Orientador

LAVRAS – MG

2025

A um apoio incondicional e por estar ao meu lado em cada passo desta jornada, Geovanny.

Dedico

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Minha origem não me permitiu sonhar em chegar aonde hoje estou. Com a quarta série incompleta, meus pais trabalharam na roça de domingo a domingo para garantir que nunca faltasse o básico em nossa casa. Ainda assim, faltou muito, o que nunca nos impediu de seguir. Com todas as limitações físicas e cognitivas que meu irmão enfrentou ao receber um diagnóstico de paralisia cerebral quando nasceu, eles ainda tentaram proporcionar uma educação que permitisse sua socialização e o desenvolvimento de habilidades básicas do dia a dia, como tomar um banho sozinho (34 anos depois, isso foi possível). Morávamos na roça, não tínhamos carro, e o único meio de transporte era o coletivo o qual minha mãe levava meu irmão até a cidade e esperava pelo fim das suas aulas em uma escola especial. Após uma semana, os custos com as passagens tornaram-se insustentáveis. As limitações financeiras impostas naquele momento, adiaram essa realização. Um projeto nunca reestabelecido.

Durante um processo de depressão, minha mãe se viu incapaz de seguir. Meu pai e eu saíamos para trabalhar e incumbíamos meu irmão de cuidar dela com a sua companhia. Era tudo o que ele conseguia fazer. Num processo que eu ouso dizer enviado por Deus, cerca de 30 frangos que ela criava nos fundos da nossa casa, cresceram rapidamente, gerando grandes custos financeiros. Ela começou a vendê-los por R$ 10,00 (meados dos anos 2000). Não que eles valessem este preço, mas era o valor que ela conseguia facilmente retornar de troco, caso alguém precisasse. Tamanha foi a procura que ela deu continuidade à criação. Comprei uma calculadora e, noites afora, simulávamos valor de compra e venda para ela aprender os números e conseguir comercializá-los. Hoje, ela tem sua própria mercearia na roça, a qual abastece com produtos da cidade e mantém uma linda horta durante todo o ano no quintal da nossa casa. Meu pai se aposentou como trabalhador rural. E, meu irmão, conhecido pelo apelido de Preto, se ocupa cuidando da organização das mercadorias e chamando-a quando chegam fregueses, mesmo que muitas vezes tenha sido pego dormindo no próprio chão da mercearia com a nossa cachorrinha, a Pretinha.

Por tudo isso, estudar nunca foi uma prioridade possível. Mas, mesmo diante de tantas adversidades, meus pais me ensinaram o valor do esforço, da honestidade, humildade e da perseverança, que me trouxeram até aqui. Aqui, significa muito mais do que um título ou um lugar. É a prova concreta que reflete que nossas escolhas nos direcionam a caminhos que acreditamos não sermos capazes de trilhar. Tenha as melhores pessoas possíveis para caminhar ao seu lado. Elas te conduzirão a lugares que, sozinho, seriam impossíveis ou quase inalcançáveis, os quais, agora, agradeço!

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Afinal, tudo isso um dia já foi um sonho!

“Continue a nadar”

(Dory, Procurando Nemo)

“Ostra feliz não faz pérola”

(Rubem Alves)

“Não é sobre chegar, é sobre aproveitar o caminho”

(Vanêssa Lopes)

“Quando você quer alguma coisa, todo o universo conspira para que você realize o seu desejo”
(Paulo Coelho)

RESUMO

A importância de preservar o solo através de práticas de manejo apropriadas reside nos diversos benefícios que os solos proporcionam à sociedade, como aqueles advindos dos serviços ecossistêmicos do solo. Por isso, a utilização de protocolos da avaliação da qualidade do solo e estudos como o potencial de recarga hídrica, são vitais para monitoramento dos impactos da qualidade ambiental e garantia do adequado funcionamento do solo. Assim, o impacto do uso da terra nos serviços ecossistêmicos pode ser avaliado por meio de um conjunto mínimo de indicadores para o cálculo das funções aditivas e de um índice de qualidade física do solo. Nesse sentido, o objetivo consistiu em avaliar as propriedades físicas associadas aos serviços ecossistêmicos relevantes do solo na região do Pontal do Paranapanema/SP, considerando os diferentes usos, sistemas de manejo e classes de solos predominantes na região. A avaliação considerou uma combinação de seis usos do solo (fragmento florestal, restauração florestal, pastagem, cana-de-açúcar, cultivo de grãos e mandioca) e duas classes de solo (Latossolo e Argissolo), predominantes na região. Amostras deformadas e indeformadas de solo foram coletadas na camada superficial 0-5 cm e subsuperficial 95-100 cm para análise dos indicadores físicos e químicos, e em superfície para os biológicos. Para alcance dos objetivos, a tese foi estruturada em três artigos científicos. O artigo 1 aborda a análise cienciométrica da produção científica global sobre restauração florestal e sua relação com a recarga hídrica por meio de uma análise de mapeamento científico global, investigando os padrões e tendências de pesquisa sobre o tema. Foram avaliadas 162 publicações extraídas dos bancos de dados com maior cobertura sobre o tema, incluindo: Scopus, Scielo e Web of Science – WoS. O segundo artigo utilizou a metodologia Soil Management Assessment Framework (SMAF) para avaliar a saúde do solo, onde pondera atributos físicos, químicos e biológicos, mas utiliza um banco de dados de solos americanos, destacando a importância de gerar índices para solos tropicais. As principais conclusões evidenciam que as áreas restauradas podem se aproximar da qualidade dos fragmentos florestais, mas a eficácia varia entre os tipos de solo, com o Argissolo mostrando melhores resultados em comparação ao Latossolo. Por fim, o artigo 3 avaliou a qualidade física do solo relacionadas a cinco funções do solo resultando em um índice de qualidade do solo (SPQI). Além disso, este capítulo ainda mapeou as cinco funções para toda a região do Pontal do Paranapanema com o objetivo de identificar e quantificar a distribuição espacial dos serviços ecossistêmicos, relacionando-os aos diferentes usos e coberturas do solo na região.

Palavras-chave: recarga hídrica; qualidade física do solo; susceptibilidade à erosão.

ABSTRACT

The importance of preserving soil through appropriate management practices lies in the many benefits that soils provide to society, such as those arising from soil ecosystem services. For this reason, the use of soil quality assessment protocols and studies such as water recharge potential are vital for monitoring impacts on environmental quality and ensuring the proper functioning of the soil. Thus, the impact of land use on ecosystem services can be assessed using a minimum set of indicators for calculating additive functions and a soil physical quality index. With this in mind, the objective was to evaluate the physical properties associated with relevant soil ecosystem services in the Pontal do Paranapanema/SP region, considering the different uses, management systems and predominant soil classes in the region. The assessment considered a combination of six land uses (forest fragment, forest restoration, pasture, sugar cane, grain cultivation and cassava) and two soil classes (Oxisol and Ultisol), predominant in the region. Deformed and undeformed soil samples were collected from the surface layer 0-5 cm and the subsurface layer 95-100 cm to analyze physical and chemical indicators, and from the surface for biological indicators. In order to achieve the objectives, the thesis was structured into three scientific articles. Article 1 addresses the scientometric analysis of global scientific production on forest restoration and its relationship with water recharge through a global scientific mapping analysis, investigating research patterns and trends on the subject. 162 publications were evaluated from the databases with the greatest coverage on the subject, including: Scopus, Scielo and Web of Science - WoS. The second article used the Soil Management Assessment Framework (SMAF) methodology to assess soil health, which considers physical, chemical and biological attributes, but uses a database of American soils, highlighting the importance of generating indices for tropical soils. The main conclusions show that restored areas can come close to the quality of forest fragments, but effectiveness varies between soil types, with Argissolo showing better results compared to Latossolo. Finally, article 3 assessed the physical quality of the soil in relation to five soil functions, resulting in a soil quality index (SPQI). In addition, this chapter also mapped the five functions for the entire Pontal do Paranapanema region with the aim of identifying and quantifying the spatial distribution of ecosystem services, relating them to the different land uses and land covers in the region.

Keywords: water recharge; soil physical quality; erosion susceptibility.

IMPACTOS SOCIAIS, TECNOLÓGICOS, ECONÔMICOS E CULTURAIS

O trabalho avaliou os impactos da restauração florestal na qualidade física do solo e nos serviços ecossistêmicos no Pontal do Paranapanema, região com uso da terra em mudança devido a expansão agrícola para cultivo de grãos, mas que pastagens e cana-de-açúcar ainda predominam, convivendo também com assentamentos na qual a cultura da mandioca é vital. Essa pesquisa gerou impactos sociais ao propor estratégias de recuperação de áreas degradadas, beneficiando comunidades rurais ao favorecer a conservação da água e a melhoria da qualidade do solo, essenciais para a sustentabilidade agrícola. Também apresentou impacto ambiental significativo, ao proteger recursos naturais e contribuir para a manutenção dos serviços ecossistêmicos, como a recarga hídrica e a resistência à erosão. Tecnologicamente, o trabalho promoveu avanços metodológicos ao adaptar e aplicar ferramentas de avaliação da qualidade do solo, como o *Soil Management Assessment Framework* (SMAF), para solos tropicais, contribuindo para validação científica dessa ferramenta para a realidade brasileira. Do ponto de vista econômico, ao indicar que áreas restauradas podem se aproximar da qualidade de solos sob vegetação nativa, os resultados sugerem a possibilidade de aumento de produtividade agrícola sustentável e redução de custos com insumos agrícolas e manutenção de reservatórios hidrelétricos, fundamentais para a geração de energia. Culturalmente, fortaleceu a valorização da biodiversidade e da conservação ambiental como práticas relevantes para o desenvolvimento sustentável local. O estudo envolveu diretamente solos classificados como Latossolo e Argissolo, abrangendo áreas de fragmentos florestais, restauração florestal e produção agrícola (cana-de-açúcar, mandioca, cultivo anual e pastagem), impactando positivamente comunidades agrícolas e unidades de conservação do Pontal do Paranapanema. As ações foram realizadas em cooperação com o Instituto de Pesquisas Ecológicas (IPÊ), favorecendo a integração entre universidade, pesquisadores, comunidades locais e instituições ambientais. O território impactado é estratégico tanto para a conservação da Mata Atlântica quanto para a proteção de bacias hidrográficas importantes para a geração de energia no Brasil. Embora os impactos sejam majoritariamente potenciais, eles oferecem subsídios para políticas públicas de recuperação de áreas degradadas, planejamento agrícola sustentável e conservação de recursos hídricos. O trabalho se alinha a seis Objetivos de Desenvolvimento Sustentável (ODS) da ONU: Fome Zero e Agricultura Sustentável (ODS 2), Água Potável e Saneamento (ODS 6), Cidades e Comunidades Sustentáveis (ODS 11), Consumo e Produção Responsáveis (ODS 12), Ação contra a Mudança Global do Clima (ODS 13) e Vida Terrestre (ODS 15). A participação da sociedade externa ocorreu principalmente na implementação e validação das práticas de manejo, fortalecendo o caráter extensionista da pesquisa. O estudo está vinculado às áreas temáticas de Meio Ambiente, Tecnologia e Produção e Trabalho, conforme a Política Nacional de Extensão Universitária, atendendo aos grandes focos de política social e ambiental.

SOCIAL, TECHNOLOGICAL, ECONOMIC AND CULTURAL IMPACTS

The work assessed the impacts of forest restoration on the physical quality of the soil and ecosystem services in Pontal do Paranapanema, a region subject to agricultural and energy expansion. This research generated social impacts by proposing strategies for recovering degraded areas, benefiting rural communities by favoring water conservation and improving soil quality, which are essential for agricultural sustainability. It also had a significant environmental impact by protecting natural resources and contributing to the maintenance of ecosystem services, such as water recharge and resistance to erosion. Technologically, the work promoted methodological advances by adapting and applying soil quality assessment tools, such as the Soil Management Assessment Framework (SMAF), to tropical soils, filling an important gap in scientific validation for the Brazilian reality. From an economic point of view, by indicating that restored areas can approach the quality of forest soils, the work suggests the possibility of increasing sustainable agricultural productivity and reducing costs with agricultural inputs and maintenance of hydroelectric reservoirs, which are fundamental for energy generation. Culturally, it has strengthened the appreciation of biodiversity and environmental conservation as relevant practices for local sustainable development. The study directly involved soils classified as Oxisol and Ultisol, covering areas of forest fragments, forest restoration and agricultural production (sugar cane, cassava, grains and pasture), positively impacting farming communities and conservation units in Pontal do Paranapanema. The actions were carried out in cooperation with the Ecological Research Institute (IPÊ) and local organizations, fostering integration between universities, researchers, communities and environmental institutions. The affected territory is strategic both for the conservation of the Atlantic Forest and for the protection of important river basins for power generation in Brazil. Although the impacts are mostly potential, they offer concrete subsidies for public policies on the recovery of degraded areas, sustainable agricultural planning and the conservation of water resources. The work is aligned with the UN's six Sustainable Development Goals (SDGs): Zero Hunger and Sustainable Agriculture (SDG 2), Clean Water and Sanitation (SDG 6), Sustainable

Cities and Communities (SDG 11), Responsible Consumption and Production (SDG 12), Action against Global Climate Change (SDG 13) and Life on Land (SDG 15). The participation of external society took place mainly in the implementation and validation of management practices, strengthening the extensionist nature of the research. The study is linked to the thematic areas of Environment, Technology and Production and Work, in accordance with the National University Extension Policy, meeting the major focuses of social and environmental policy.

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SUMMARY

PRIMEIRA PARTE – INTRODUÇÃO GERAL

INTRODUÇÃO

As mudanças no uso e manejo do solo têm exposto sua superfície em razão da redução da cobertura vegetal, constituindo um fator desencadeante do processo erosivo (BORRELLI et al., 2017; VANWALLEGHEM et al., 2017). A erosão hídrica é uma das principais causas da perda de capacidade produtiva dos solos (BARROS et al., 2018) e das alterações da quantidade e qualidade da água nas bacias hidrográficas. Além disso, operações de manejo e colheita mecanizada intensificam a perda de sedimentos por erosão hídrica (BAKKER et al., 2004; CHERUBIN et al., 2016; PANAGOS et al., 2015) e reduzem a capacidade de armazenamento de água dos reservatórios hidrelétricos (SILVA et al., 2010). O processo erosivo, impulsionado pelo escoamento superficial, além de carrear partículas de solo para os corpos hídricos, provoca a desagregação do solo (AVANZI et al., 2013; DECHEN et al., 2015; TELLES et al., 2013). Isso implica em aumento dos custos de produção, uma vez que acarreta perdas de fertilizantes, corretivos e nutrientes essenciais ao crescimento das plantas (BERTOL et al., 2007; SILVA et al., 2014).

A vegetação desempenha um papel fundamental na redução do impacto direto das gotas de chuva no solo (BRANDÃO et al., 2007), favorecendo a infiltração de água, a manutenção do teor adequado de matéria orgânica e o efeito agregador nas partículas do solo (CARVALHO et al., 2015; DIDONÉ et al., 2014), o que reduz a perda de água por escoamento superficial (GUADAGNIN et al., 2005). Assim, práticas conservacionistas, como a manutenção da cobertura vegetal e a restauração de áreas degradadas (VIZIOLI et al., 2021) são de suma importância para garantia da capacidade de infiltração e armazenamento de água no solo (DERPSCH et al., 2014) e conservação da água nos reservatórios das bacias hidrográficas (SILVA et al., 2010).

No Brasil, a supressão da vegetação nativa e a fragmentação de biomas, como a Mata Atlântica, têm se intensificado (FAO, 2015; JOLY et al., 2014; RODRIGUES et al., 2009). A Mata Atlântica, conhecida por sua biodiversidade e variedade de ecossistemas florestais com diferentes estruturas e composições florísticas (MITTERMEIER et al., 2011), ocupava originalmente uma área de 1.110.182 km^2, e correspondia a 15% do território nacional (RIBEIRO et al., 2009). No entanto, devido à urbanização, à expansão das áreas agrícolas e à industrialização, existem apenas 12,5% da floresta original (ROCHA-SANTOS et al., 2016a). Mesmo reduzidas e fragmentadas, as áreas de mata continuam exercendo função essencial na proteção do clima, na regulação dos processos de infiltração de água no solo e na mitigação dos processos erosivos e das perdas de solo (CARLUCCI et al., 2020; SHIMAMOTO et al., 2018; TEIXEIRA et al., 2020).

O bioma Mata Atlântica tem grande importância estratégica para a conservação dos recursos hídricos (LIMA et al., 2014, 2016; NOGUEIRA et al., 2016), uma vez que a cobertura do solo é responsável por processos, como a infiltração de água no solo, que ocorre pelo aumento e manutenção da porosidade do solo (REYNOLDS and REDDY, 2012). Isso facilita a percolação da água para camadas mais profundas, abastecendo o lençol freático (KLEIN and KLEIN, 2014). A restauração florestal tem se tornado um mecanismo essencial para proteger o restante da mata, sendo importante não somente para a preservação de espécies da fauna e flora (MATOS et al., 2021; LIRA et al., 2019; SHENNAN-FARPÓN et al., 2022; UEZU and METZGER, 2016), mas também para regular a vazão dos rios. Esse processo permite a infiltração de água no solo, a recarga do lençol freático e manutenção do nível dos reservatórios hidrelétricas para geração de energia (SCHMERBECK; FIENER, 2015).

Entre os principais fatores da degradação e desmatamento da Mata Atlântica, está o alagamento de grandes áreas para a formação de reservatórios destinados à construção de usinas hidrelétricas (DALE et al., 2013; JORDAAN et al., 2021; MAHMUD et al., 2018), que são a principal fonte de energia elétrica do Brasil (DALE et al., 2013). A dependência por este tipo de energia está diretamente relacionada às condições naturais do país, que possui uma vasta rede de rios e lagos (BARROS et al., 2018). Atualmente, cerca de 67% da energia gerada no país vêm de fontes hidráulicas, que aproveitam o movimento das águas para a produção de eletricidade (ANEEL, 2024). Mediante a demanda de expansão da capacidade de produção de energia elétrica no país, muitas regiões com potenciais hidrelétricos vêm atraindo cada vez mais investimentos no setor.

O estado de São Paulo conta com um dos mais importantes cursos d’água para a região, o Rio Paranapanema. Ele é um divisor natural entre os estados de São Paulo e Paraná e nasce na Serra de Agudos Grandes, no sudeste do Estado de São Paulo (CBH, 2024). Ao longo do seu curso, as atividades antrópicas têm se intensificado, resultando em degradação ambiental como, poluição, assoreamento, inundações frequentes e processos de erosão (GIAVARA, 2009). Fatores como estes estão associados à redução da vegetação natural e da biodiversidade em razão do desmatamento (MASUD et al., 2018). Diante de diversos desafios, o Rio Paranapanema ainda é considerado o rio menos poluído do estado de São Paulo (CBH, 2024). Em reconhecimento à sua importância, o dia 27 de agosto foi estabelecido como o Dia do Rio Paranapanema pela Lei Estadual 10.488/99 (CBH, 2024).

O Rio Paraná é outro importante curso d'água para o estado de São Paulo, sendo o oitavo maior rio do mundo em extensão (4.880 km) e o segundo maior da América do Sul, atrás apenas do Rio Amazonas. Sua bacia hidrográfica cobre mais de 10% do território brasileiro e, juntamente com seus afluentes, forma uma vasta bacia de drenagem que se estende por uma grande parte da região central e sul da América do Sul. Assim como o Rio Paranapanema, o Rio Paraná também enfrenta os impactos da construção de usinas hidrelétricas e da expansão econômica. Estudos indicam que esses processos resultam em erosão e na redução da capacidade de armazenamento dos reservatórios devido ao assoreamento de áreas desprovidas de cobertura vegetal (GINAK et al., 2020).

O extremo oeste do estado de São Paulo, onde o Rio Paranapanema deságua no Rio Paraná, marca o início da região do Pontal do Paranapanema. Devido ao grande potencial energético desses rios, a região tem atraído cada vez mais investidores interessados no desenvolvimento de projetos de geração de energia. Desde 2013, o Brasil tornou-se um país estratégico para empresas que buscam expandir sua atuação em usinas hidrelétricas, com várias dessas usinas localizadas ao longo do Rio Paranapanema. No Rio Paraná, entre os estados de São Paulo e Mato Grosso do Sul, estão localizadas outras grandes usinas hidrelétricas, como Jupiá e Ilha Solteira, que juntas somam 4.995 megawatts (MW) de capacidade instalada.

Além de contribuir para o fortalecimento da matriz energética brasileira, a região do Pontal do Paranapanema possui uma infraestrutura industrial em expansão, com foco na agroindústria, especialmente na produção de açúcar e biocombustíveis. A disponibilidade de terras, aliada à inclusão da região na rota do etanol, impulsionada pela instalação de novas usinas de processamento de cana-de-açúcar e pela expansão dos canaviais, tornou a área altamente atrativa para o cultivo dessa cultura (BARRETO; THOMAZ JUNIOR, 2020; BENTO, 2020). Entre 2003 e 2013, a área plantada com cana-de-açúcar na região aumentou de 17.906ha para 121.47ha em 2013, denotando um crescimento de 578, 38% em 10 anos (CANASAT, 2013).

Nas últimas décadas do século XX, a região também foi palco de intensos conflitos sociais relacionados à concentração de terras, envolvendo disputas entre movimentos populares, como o MST (Movimento dos Trabalhadores Rurais Sem Terra) e os latifundiários (BARRETO and THOMAZ JUNIOR, 2020; THOMAZ JUNIOR, 2009). O MST luta pela reforma agrária, reivindicando o uso de terras em desuso e, ou em especulação (THOMAZ JUNIOR, 2017). A estratégia adotada pelos posseiros e grileiros consistiu, basicamente, em desmatar as áreas florestais e converter em áreas de pastagem, na presunção de garantia da posse dessas terras (FELICIANO, 2018).

Diante da desordenada e ilegal posse de terras, iniciou-se na região um amplo processo de desmatamento e ocupação agrícola. Atualmente, permanece apenas 1,8% da vegetação nativa do Pontal do Paranapanema, dispersa em fragmentos florestais (VALLADARES-PADUA et al., 2002). O Parque Estadual Morro do Diabo localizado na cidade de Teodoro Sampaio-SP é o último remanescente significativo de Mata Atlântica no interior de São Paulo e foi criado em 1942 com o objetivo de proteger 247 mil hectares de sua vegetação natural original (ARANA and ALMIRANTE, 2007). Ao longo dos anos, o Parque passou por um intenso processo de fragmentação florestal associado a conflitos fundiários, ocupações de terras por grandes fazendeiros e desmatamento com o argumento que as terras poderiam se tornar altamente produtivas, e também com o objetivo de liberar a área para inundação de usinas hidrelétricas, restando apenas 33 mil hectares (FELICIANO, 2018).

A fragmentação florestal é uma ruptura da continuidade das unidades de uma paisagem frequentemente causada por processos antrópicos que resultam em alterações na composição e diversificação das comunidades ecológicas (UEZU and METZGER, 2011). Juntamente com a expansão da fronteira agrícola, essa fragmentação vem gerando graves impactos ambientais, principalmente devido ao uso inadequado e ao manejo do solo, que afetam diretamente suas propriedades físicas ligadas aos serviços ecossistêmicos (CAVALCANTI et al., 2020). A colheita mecanizada, o tráfego de maquinário intensivo como, caminhões bitrens e treminhões que circulam transportando a cana-de-açúcar, podem contribuir para a degradação física do solo devido aos processos de compactação (CHERUBIN et al., 2016), por ocasionarem o aumento da densidade (BAQUERO et al., 2012; SOUZA et al., 2015), redução na capacidade de infiltração de água (BRAUNACK and MCGARRY, 2006) e intensificação dos processos erosivos com perdas de água e solo (CHERUBIN et al., 2016).

Diante da conjuntura da expansão da monocultura de cana-de-açúcar na região do Pontal do Paranapanema e a importância da recarga hídrica para os reservatórios das usinas hidrelétricas para geração de energia elétrica, faz-se relevante discutir a degradação da qualidade física do solo e suas implicações nos serviços ecossistêmicos. Nesse contexto, avaliar a qualidade física do solo, por meio de análises e indicadores que descrevam suas funções ambientais, é essencial para identificar os impactos, sejam eles positivos ou não, do uso e manejo do solo (KARLEN et al., 1997; RINOT et al., 2019). A avaliação integrada de propriedades como capacidade e intensidade, e sua correlação com os processos ambientais, torna-se uma ferramenta importante para monitorar a capacidade do solo em sustentar suas funções físicas e os serviços ecossistêmicos relacionadas ao fluxo e armazenamento de água.

Outra importante estratégia, cada vez mais considerada nos processos de tomada de decisão, envolve a atribuição de valor econômico aos serviços ecossistêmicos e as implicações dos impactos ambientais. Assim como o capital físico (máquinas, veículos, construções, etc) é fundamentado em valores expressos em unidades monetárias, por meio da valoração econômica ambiental e das estimativas métricas monetárias, é possível estabelecer um conjunto de indicadores que melhor representem os benefícios obtidos do meio ambiente e estimar por meio das estratégias de recuperação da vegetação em áreas de restauração florestal.

Neste contexto, o problema de pesquisa que esta tese pretende elucidar é: através da restauração florestal, de que forma as práticas de recuperação da vegetação em áreas degradadas podem contribuir para a mitigação da erosão hídrica e a melhoria dos serviços ecossistêmicos relacionados à recarga hídrica no Pontal do Paranapanema, SP? Como a implementação dessas práticas impacta a qualidade física do solo e a capacidade de armazenamento de água, favorecendo a conservação dos recursos hídricos em bacias hidrográficas estratégicas para a geração de energia?

HIPÓTESES, OBJETIVOS E ESTRUTURA DA TESE

Com base na problemática apresentada, este trabalho propõe as seguintes hipóteses:

1) a produção científica sobre restauração florestal associada à recarga hídrica tem crescido com uma significativa contribuição de países desenvolvidos, onde a pesquisa recebe mais recursos e investimentos. Em contrapartida, os países emergentes, apesar dos esforços realizados para ampliar sua participação, ainda enfrentam desafios devido às limitações financeiras, o que restringe a capacidade de expandir suas contribuições científicas e aplicar soluções tecnológicas em larga escala;

2) O SMAF não fornece uma avaliação adequada da saúde de solos tropicais, devido às diferenças nos atributos químicos, físicos e biológicos em relação aos solos temperados para os quais foi desenvolvido;

3) a restauração florestal em áreas degradadas, independentemente do tipo de solo, aumenta a qualidade física do solo, melhora a infiltração e condução da água e contribui para a melhoria dos serviços ecossistêmicos;

Neste sentido, o objetivo geral desta tese foi: avaliar a qualidade do solo, bem como seu potencial de recarga hídrica e variação de armazenamento de água considerando os principais solos, seus usos e manejos no Pontal do Paranapanema. Para isso, foram traçados os seguintes objetivos específicos:

1) realizar uma análise de mapeamento científico global para investigar os padrões e tendências de pesquisa sobre restauração florestal associada à recarga hídrica, analisando as tendências históricas e temporais nas publicações, identificando os periódicos, autores, instituições de pesquisa e suas colaborações mais relevantes no tema;

2) quantificar a qualidade do solo pelo Soil Management Assessment Framework (SMAF) para monitorar a recarga hídrica em áreas estratégicas para abastecimento de reservatórios de usinas hidrelétricas em solos tropicais;

3) avaliar a qualidade do solo por meio do Índice de Qualidade Física do Solo (SPQI) por meio das propriedades físicas e análise multivariada das propriedades físico-hídricas do solo.

Para alcance dos objetivos, a tese foi estruturada em três artigos científicos. O Artigo 1 aborda a análise cienciométrica da produção científica global sobre restauração florestal e sua relação com a recarga hídrica por meio de uma análise de mapeamento científico global, investigando os padrões e tendências de pesquisa sobre o tema. Foram avaliadas 162 publicações extraídas dos bancos de dados com maior cobertura sobre o tema, incluindo: Scopus (https://www.scopus.com/), Scielo e Web of Science – WoS (http://apps.webofknowledge.com). A seleção dos periódicos foi realizada por meio de buscas nos títulos, resumos e palavras-chave, utilizando uma chave de busca específica. O segundo artigo utilizou a metodologia Soil Management Assessment Framework (SMAF) para avaliar a saúde do solo, onde pondera atributos físicos, químicos e biológicos, mas utiliza um banco de dados de solos americanos, destacando a importância de gerar índices para solos tropicais. Os resultados conclusivos indicaram que as áreas restauradas podem se aproximar da qualidade dos fragmentos florestais, mas a eficácia varia entre os tipos de solo, com o Argissolo mostrando melhores resultados em comparação ao Latossolo. O artigo 3 avaliou a qualidade física do solo em dois diferentes tipos de solo e seis usos. Foram avaliadas 10 propriedades físicas e relacionadas a cinco funções do solo resultando em um índice de qualidade do solo (SPQI).

Além disso, este capítulo ainda mapeou as cinco funções para toda a região do Pontal do Paranapanema com o objetivo de identificar e quantificar a distribuição espacial dos serviços ecossistêmicos, relacionando-os aos diferentes usos e coberturas do solo na região.

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SECOND PART - PAPERS

This paper was submitted to Environmental Development

PAPER 1 - GLOBAL TRENDS ON THE RESEARCH OF FOREST RESTORATION FOCUSING ON WATER RECHARGE: A SCIENTOMETRIC ANALYSIS EMPHASIZING BRAZIL

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Highlights

- Research on forest restoration and water recharge has increased, reflecting greater global interest in the subject
- The international scientific collaboration is growing, with partnerships between Brazil, Ethiopia and Kenya standing out
- Recent studies emphasize soil quality and its influence on water infiltration, highlighting words such as ecosystem services
- Despite Brazil's relevance in research its international visibility is limited, indicating the need for greater collaboration
- Forest restoration is essential for regulating water resources

Abstract

Research on forest restoration associated with water recharge continues to evolve, with significant contributions from various countries published in influential journals that shape knowledge and sustainable practices in this field. Research on forest restoration associated with water recharge continues to evolve, with significant contributions from various countries published in influential journals that shape knowledge and sustainable practices in this field. Given the relevance of the topic, this study carried out a scientometric analysis of publications on forest restoration associated with water recharge, highlighting historical and temporal trends in research. The methodology consisted of collecting and analyzing scientific articles indexed in the Scopus, Scielo and Web of Science databases. Papers published between 1980 and 2023 were considered, using a set of keywords related to forest restoration, soil erosion and hydrological processes. The analysis included scientific production metrics, collaboration networks between countries and institutions, as well as identifying the most used keywords and the most influential journals. The results indicated a significant growth in publications from 2019 onwards, with China and the United States standing out as the most productive countries on the subject. The journals Catena and Ecological Engineering were the most influential. In addition, it was observed that research has increasingly focused on aspects related to soil quality and its influence on water infiltration. Despite Brazil's relevant role in the study of forest restoration aimed at water recharge, its visibility and international impact are still limited, suggesting the need for greater global scientific collaboration. It was concluded that forest restoration plays an essential role in regulating water resources and is a growing field of research. The expansion of international collaborations can strengthen the dissemination of knowledge and improve sustainable practices for the conservation of ecosystems and water.

Keywords: vosviewer; trend analysis; scientometric; infiltration

1. Introduction

Forest restoration is largely debated in the context of sustainable development, environmental conservation and climate change mitigation. It is considered an essential strategy for attaining global goal, such as those established in the Convention on Biological Diversity (CBD) and in the Sustainable Development Goal (SDG) of the United Nations (UN), which recognize the importance of restoring degraded ecosystems to protect biodiversity and ensure food and water security (Chen et al., 2022; Xu et al., 2020). In the 17 proposed SDG and its 169 targets, SDG 15 indicates that forests compose the most essential component pf terrestrial ecosystems and thus must be protected, restored and managed in a sustainable manner, since their conversion to agriculture may cause negative effects, such as biodiversity loss, soil degradation and desertification (Tóth et al., 2018; Wang et al., 2023; Wunder; Bodle, 2019).

Forest restoration is often defined as the process of recovering forest ecosystems that undergone some form of degradation, aiming at restoring their ecological functions and reestablishing their ecosystem services (Lamb et al., 2005; Mansourian et al., 2014). These services include climate regulation, soil conservation and water recharge, playing an essential role in water retention, allowing it to infiltrate into the soil, recharging underground aquifers (Vries; Simmers, 2002). This recharge process thus affects water quality and availability for its different uses, as human and animal consumption, industrial uses, irrigation and support of aquatic ecosystems (Akhtar et al., 2021; Trabelsi; Zouari, 2019). Additionally, water scarcity may also impact hydropower generation and reservoir lifespan (Batista et al., 2017; Verstraeten et al., 2003).

To ensure these services, especially in regions where groundwater is an important source of supply, it is important to establish connections between forest restoration and water recharge. Soil cover from native vegetation and restored forests regulate water flow, minimizing extreme events such as floods and droughts (Mekonnen; Hoekstra, 2016). With forest fragmentation and the discontinuity of these ecosystems, the soil's functions are hampered, along with its associated economic value. Degraded soils become more susceptible to erosion processes, reducing their productive capacity (Avanzi et al., 2013; Telles et al., 2013). Water erosion is one of the main causes of soil productivity loss and changes in both water quantity and quality (Severiano et al., 2011).

Due to its importance, forest restoration has gained more and more attention in recent years in international agreements, such as the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement. The

Paris Agreement was recognized as a nature-based solution for climate change mitigation and adaptation, aiming to stabilize greenhouse gas concentrations in the atmosphere at a level that prevents dangerous human interference in the climate system (United Nations Treaty Collection, 2016). Initiatives like the Bonn Challenge and the United Nations Decade on Ecosystem Restoration 2021–2030 reflect the global commitment to restoring vast areas of degraded forests. These efforts involve a wide range of stakeholders, including governments, non-governmental organizations, local communities, the private sector, and the academic community, all working together to restore forests and ensure a more sustainable and balanced future for the planet.

To understand the evolution of research addressing forest restoration and water recharge, as well as its historical and temporal trends, scientometrics stands out as a field of study that analyzes scientific production using quantitative metrics and indicators (Bu et al., 2018; Van Raan, 1998). Based on methods such as citation analysis, collaboration network mapping, and productivity assessments of researchers and institutions, scientometrics allows identifying patterns, trends, and the evolution of knowledge in specific areas. While several studies emphasize the importance of forest restoration and water recharge (Apori et al., 2022; Lobo-Moreira et al., 2023; Xie et al., 2020), to date, no scientometric study has characterized current and future trends in research development on forest restoration associated with water recharge using major databases such as Web of Science, Scielo, and Scopus in a single study.

Our objective was to conduct a global scientific mapping analysis to investigate research patterns and trends on forest restoration associated with water recharge. For this purpose, we analyzed historical and temporal trends in publications, identifying the most relevant journals, authors, research institutions, and their collaborations within this field. This study aimed at elucidating the following questions: i) What are the trends in scientific production and the main research focuses on forest restoration associated with water recharge, and how they evolved over time?; ii) Which scientific journals are the most influential, classified by the H-index, and how their publications impact the scientific field?; iii) Which countries lead scientific production on this topic, how has international collaboration evolved, and which institutions are the most relevant?

2. Material and Methods

Publications on forest restoration associated with water recharge were retrieved from Scopus, Scielo and Web of Science, the databases with the highest coverage on the topic. The records were retrieved by searching titles, abstracts, and keywords using the following search criteria: restoration AND degrad* AND ("soil" OR "erosion" OR “soil erosion”) AND ("water" OR "infiltration" OR "soil hydrology" OR "water recharge"). The search covered the entire publication period available in each database, i.e., from 1980 to December 2023. Scientific articles were visually inspected for eligibility, with reviews, meta-analyses, notes, and articles outside the scope of the research being excluded. Duplicate articles were removed using the Bibliometrix 4.1.3 package implemented in R 3.4.1 (R Core Team, 2022).

The validation of the search procedure for scientometric analysis was conducted following the recommendations of the PRISMA 2020 guidelines (Page et al., 2021). This model provides a detailed description of the study methodology, illustrating the data search and analysis process (Figure 1). The final dataset comprised 162 publications from 1995 to 2023, written in English, Portuguese, and Spanish (Appendice A - Supplementary material). Their metadata were exported for processing using the softwares Biblioshiny (Aria; Cuccurullo, 2017) and VOSviewer (van Eck & Waltman, 2010).

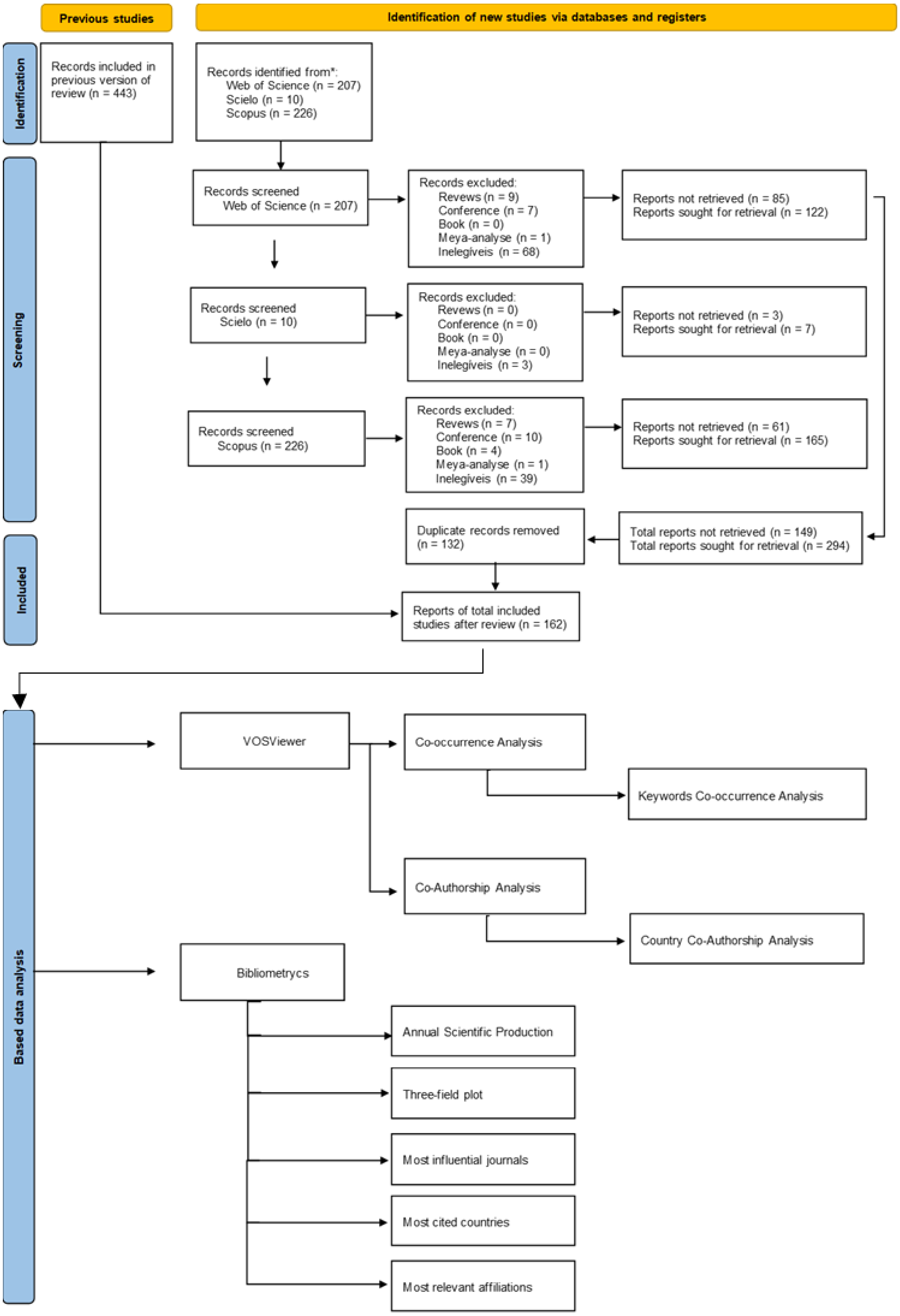

Figure 1. Scientometric analysis flow diagram. Adapted from Preferred Reporting Items for Systematic reviews and Meta-Analyses PRISMA 2020.

3. Scientometric analysis

3.1. Database metrics and temporal trends

Summary information in the scientific production on forest restoration associated with water recharge are presented in Table 1. Between 1995 and 2023, 101 scientific journals and 162 scientific articles were identified, involving a total of 657 authors. Of these, 7 articles were single-authored, while the average number of co-authors per article was 4.88. International co-authorship accounted for 6.79% of the publications, with an average of 24.24 citations per article.

Table 1. Key information from the retrieved articles indexed in Scopus, Scielo, and Web of Science databases.

Metrics	**Values**
Analysis period	1995-2023
Sources (journals)	101
Documents (articles)	162
Authors	657
Single-authored Articles	7
International co-autorship	6.79%
Average co-authors per article	4.88
Average article Citation	24.24

Over the years, a general increase in scientific production can be observed (Figure 2), although from 1995 to 2010 there are marked publication peaks followed by steep decreases, whereas from 2012 on the growth trend is better defined (except for 2018), with a steeper increase from 2019 on, reaching more than 20 articles per year by 2023.

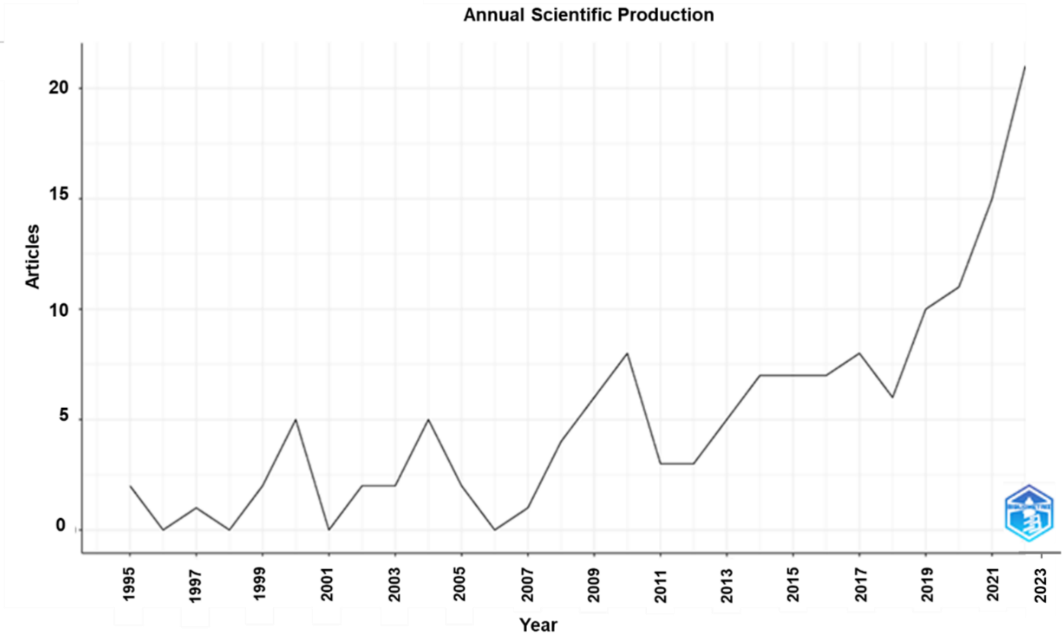

Figure 2. Annual article production on forest restoration associated with water recharge 1995-2023.

3.2. Scientific journals

The Three-Field Plot (Figure 3) illustrates the correlation among the fifteen most-cited keywords, countries, and journals. Among the most frequently cited keywords are some of the search criteria (restoration, degradation, erosion, infiltration), but interestingly also include soil physical properties, in addition to specifically bulk density and aggregate stability.

The most-cited countries were China, USA, Spain, Brazil, Mexico, UK, Germany, Australia, Iran, Kenya, Italy, Ethiopia, India, Belgium, and Argentina. The most frequent journals include Ecological Engineering, Journal of Hydrology, Catena, Restoration Ecology, Science of the Total Environment, Land Degradation and Development, Journal of Arid Environments, Environmental Management, Ecohydrology, Water, among others.

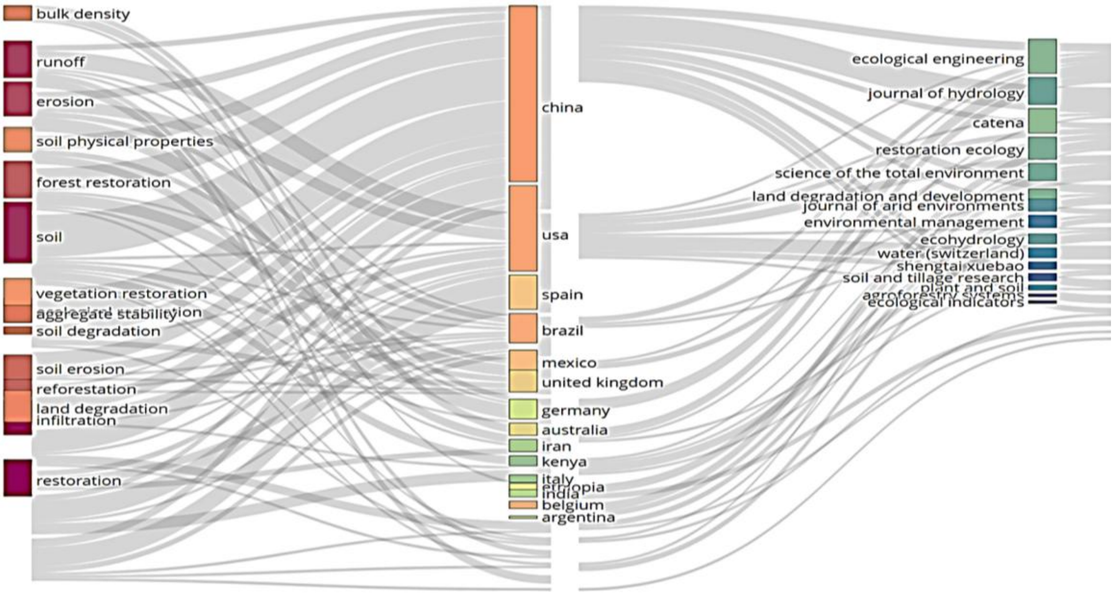

Figure 3. Three-field plot relating the 15 most cited keywords (left), the most productive countries (center) and the related journals (right).

The main correlations indicate that China is frequently associated with keywords relating soil (“soil”, “soil physical properties”, “aggregate stability”) and restoration (“forest restoration”, “vegetation restoration”). Alternatively, the USA was more strongly related to “runoff” and “erosion”. Studies from these countries are often published in journals such as Journal of Hydrology and Water.

The keywords "soil erosion" and "forest restoration" are strongly associated with countries like China and Brazil. These studies frequently appear in journals such as Land Degradation and Development and Restoration Ecology. Countries like the USA and Spain emphasize publications using the keyword "soil physical properties", with their research frequently published in journals such as Ecological Engineering and Journal of Arid Environments. "Vegetation restoration" and "soil degradation" are keywords cited in studies conducted by countries like Mexico, with their research often published in the journal Environmental Management.

The visualization generated by Bibliometrix presents a scatter plot of the fifteen most relevant scientific journals related to forest restoration and water recharge, classified according to their H-index (Figure 4). The H-index, or Hirsch index, is a metric that quantifies both the productivity and the impact of articles published by a scientist or journal (Rad et al., 2010). The journals Catena and Ecological Engineering stood out with the highest H-indices, 8 and 7 respectively, indicating that they are highly influential and frequently cited in research on forest restoration and water recharge. Land Degradation and Development, Restoration Ecology, and Science of the Total Environment also demonstrated high relevance in this field of research, with H-indices of 5.

Figure 4. Most influential journals for the field of research on forest restoration and water recharge, according to their H index.

3.3. Keyword analysis

The most used keywords in scientific articles related to forest restoration and water recharge, along with their time trend, are presented in Figure 5. The color bar in the lower right corner of the figure indicates a temporal progression of publications from 2010 to 2020, highlighting the prominence of certain keywords during that period. Keywords in green and yellow reflect more recent topics, while terms in purple and blue represent previous interests.

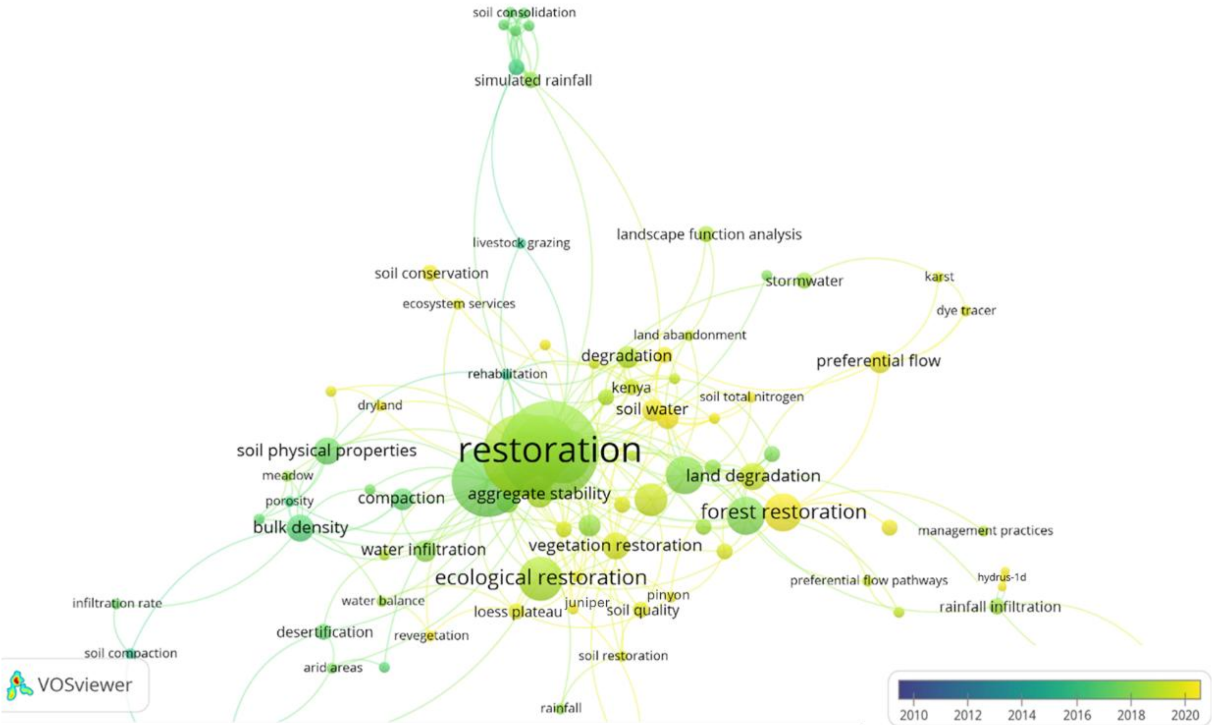

Figure 5. Co-occurrence network for the most frequent keywords (at least 3 occurrences). Each node represents a keyword, and the line thickness relates to the connection strength between them (frequence of co-occurrence). Colors represent average publication year according to the scale in the bottom.

The keyword “restoration”, central to the research, highlights a focus on soil ecological restoration, suggesting it as a dominant theme in the studies. Related terms, such as “ecological restoration”, “forest restoration” and “vegetation restoration” also appear centrally, indicating a strong interest in various forms of ecosystem restoration.

Keywords like “soil physical properties”, “compaction”, “bulk density”, “porosity” and “water infiltration” emphasize the role of soil physical properties in restoration and conservation efforts. Issues like “soil compaction” and “aggregate stability” are particularly notable, reflecting concerns about soil structure, compaction, and aggregation. Terms like “degradation”, “land degradation” and “soil conservation” highlight the focus on addressing soil degradation and exploring conservation techniques. The connection between “degradation” and “rehabilitation” underscores an interest in strategies to recover degraded areas.

Research trends also extend to specific geographic regions and climates, as indicated by terms such as “dryland”, “arid areas” and “loess plateau”. Keywords like “Kenya” and “land abandonment” suggest studies focusing on specific regions and the impact of land abandonment on soil degradation. Meanwhile, “juniper” and “pinyon” point to studies on specific vegetation types and ecosystems.

Hydrological processes, a critical aspect of forest restoration, particularly when related to water recharge, are evident in terms like “water infiltration”, “preferential flow”, “rainfall infiltration” and “simulated rainfall”. These terms indicate a research focus on understanding water dynamics in soil as part of restoration efforts. Computational tools such as HYDRUS-1D highlight the use of modeling software to simulate water infiltration processes.

Recent studies have increasingly emphasized the broader benefits of forest restoration, such as its role in enhancing ecosystem services and landscape function. This focus is reflected in terms like “ecosystem services” and “landscape function analysis”. Soil quality and nutrient content are also gaining attention, as shown by terms like “soil quality”, “soil total nitrogen” and “soil water.” The inclusion of terms like “rainfall infiltration” and “simulated rainfall” suggests an interest in simulating and studying water-soil interactions within restoration studies.

The co-occurrence network can be divided into six clusters, representing groups of strongly related terms that may identify specific subfields within the broader research area. Cluster 1, Ecological Restoration and Vegetation, indicated by the terms: restoration, ecological restoration, vegetation restoration, forest restoration, revegetation, rehabilitation, ecosystem services, land abandonment and dryland. Cluster 2, focusing on Soil Physical Properties, including the terms: soil physical properties, compaction, bulk density, water infiltration, infiltration rate, soil compaction, aggregate stability, porosity and soil quality. Cluster 3, of Soil Degradation, encompassing the terms degradation, land degradation, soil conservation, desertification, soil restoration and arid areas. Cluster 4, focusing on Hydrology and Soil Water Infiltration, including the terms water infiltration, preferential flow, rainfall infiltration, simulated rainfall, stormwater, water balance and landscape function analysis. Cluster 5, for Soil Quality and Nutrients, with the keywords soil total nitrogen, soil water, soil consolidation, soil physical properties and management practices. To finalize, Cluster 6, focusing on Specific Regions and Contexts, as indicated by keywords such as Kenya, loess plateau, dryland and meadow.

3.4. Countries, affiliations and collaborative networks

The distribution of citations by country (Figure 6) evidences that China and the USA are the most cited countries, followed by Australia and Spain, which stand out with a considerable margin over other nations. Countries such as the UK, India, and Tunisia also appear with a significant number of citations. The presence of a variety of countries from different continents is noteworthy, indicating a field with broad application worldwide. While the bottom five countries listed have lower citation numbers compared to the leaders, they still host high-quality research institutions and globally renowned universities.

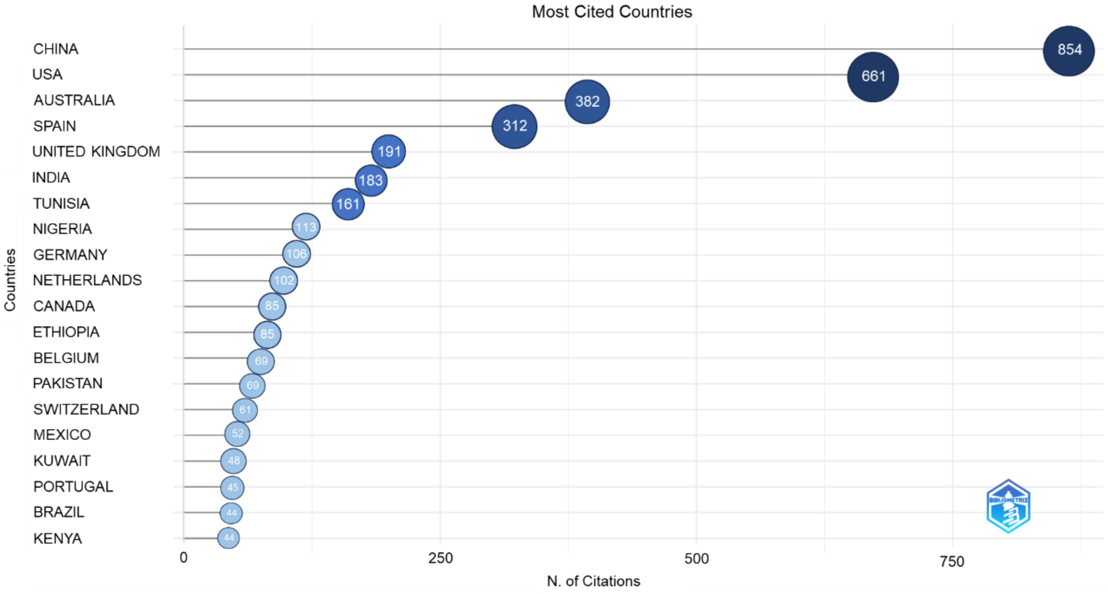

Figure 6. List of the 20 most cited countries for scientific articles on forest restoration and water recharge 1995-2023.

The scientific collaboration network among countries (Figure 7), revealed several important trends. There is evident collaboration among major scientific powers, such as the United States and China. Furthermore, the increasing global collaboration is clear, with significant interactions among countries from various continents. This trend is demonstrated by the connections between countries like Ethiopia, Kenya, India, and Brazil, involving prominent scientific institutions, reflecting a shift toward more globalized science, as can be noted from the average publication year of each of these countries, indicting a shift in balance from the USA (average publication year around 2013) to China (average publication year close to 2019). Countries such as Mexico, Germany, and Australia are also actively participating in these networks, expanding their scientific collaborations.

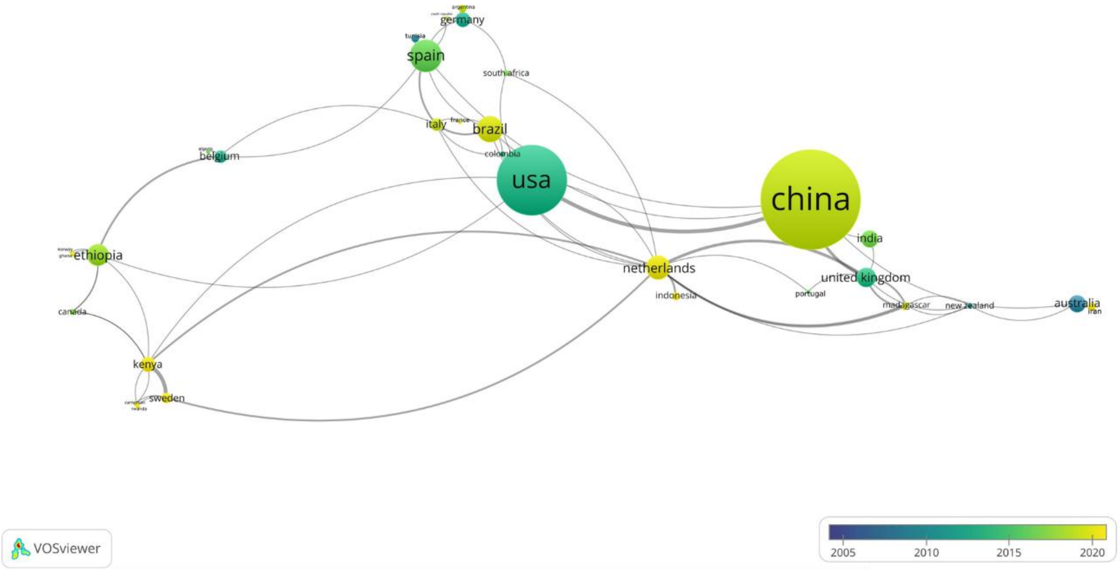

Figure 7. international collaboration network between countries with at least 1 published article on forest restoration and water recharge 2005-2020. Node size is proportional to the number of publications and line width is proportional to the number of collaborations established.

The list of the most prominent institutions in terms of the number of published articles (Figure 8) offers a clear view of the leading contributors to the current body of scientific research. Based on the data, many of the top publishing institutions are from China, such as the Beijing Forestry University, Chinese Academy of Sciences, and Northwest A and F University. In addition to the dominance of Chinese institutions, there is considerable representation from other regions, including Katholieke Universiteit Leuven (Belgium), Universidad Autónoma del Estado de México (Mexico), Wageningen University and Research (Netherlands).

This distribution highlights the contributions of diverse institutions across continents to the field of forest restoration and water recharge, emphasizing its global scope. In the specific context of Brazil, the main scientific collaboration partners include Italy, Spain, USA, and Netherlands. In addition, Brazil is expanding its partnerships by forming new collaborations with countries such as Ethiopia and Kenya.

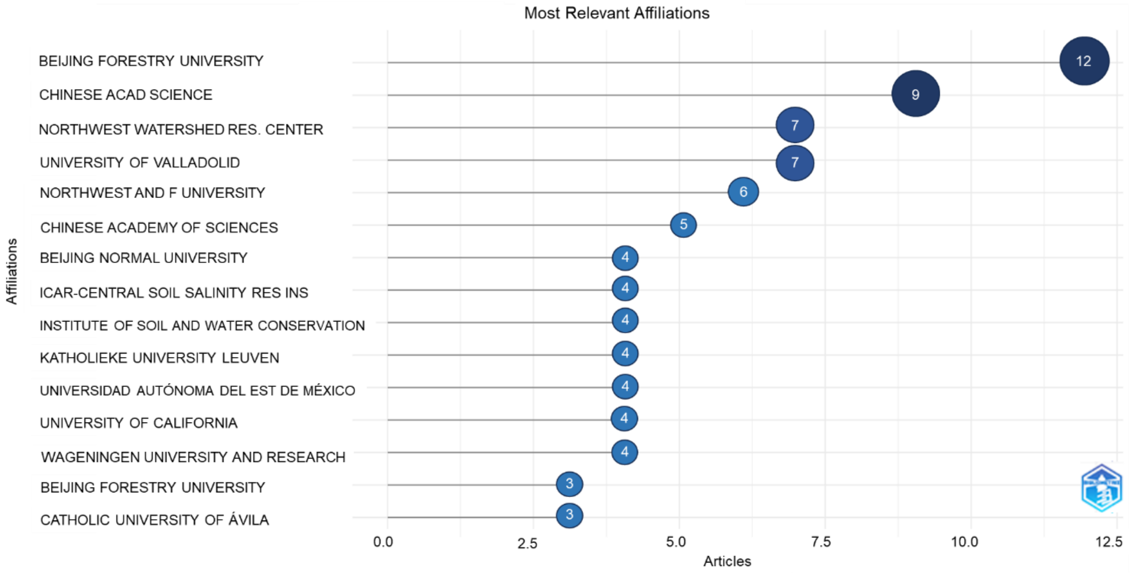

Figure 8. List of the 15 most relevant affiliations according to the number of published articles on forest restoration and water recharge 1995-2023.

4. Discussion

4.1. Research focus

The use of keywords in scientific articles is fundamental to maximizing the visibility and accessibility of research stored on specialized repositories. Well-chosen keywords facilitate the proper indexing of articles in academic databases, enabling other researchers to locate that work more easily. Additionally, relevant keywords increase the likelihood of the article being retrieved in specific searches, thereby broadening the study's impact and dissemination.

Key terms like “bulk density”, “soil compaction” and “aggregate stability” have emerged as essential for addressing soil health and its role in supporting restored vegetation. Numerous studies highlight how soil compaction negatively affects water infiltration and soil structure, posing challenges for restoration strategies (Ahmadabad et al., 2023; Ramineh et al., 2023; Saifuddin et al., 2022). Aggregate stability is also critical for improving soil resistance to erosion, maintaining soil porosity, promoting water infiltration, and facilitating root growth (Pavei et al., 2021), and thus is an important topic on the field of forest restoration and water recharge.

Soil degradation is frequently associated with keywords such as “degradation”, “land degradation” and “soil conservation.” This issue is a global concern, particularly in arid and semi-arid regions, where desertification poses significant risks to soil health, agricultural productivity, and food security (Pozza; Field, 2020; Smith et al., 2020). Restoration efforts in these areas aim to enhance soil fertility and reverse the loss of arable land, serving as a cornerstone for environmental and economic sustainability.

Another key trend in keyword usage involves nutrient content, which is fundamental to the success of forest restoration. Nutrients such as nitrogen and phosphorus are vital for plant growth and development, biomass production, and ensuring high yields in agriculture (Anas et al., 2020; Vitousek et al., 2009). Maintaining and improving soil quality through sustainable management practices is essential for achieving long-term restoration goals (Lal, 2015).

Terms such as “dryland”, “arid areas” and “Loess Plateau” highlight the focus on ecosystems particularly vulnerable to soil degradation and desertification, for example due to arid and sem-iarid climates and anthropogenic pressures. These ecosystems cover approximately 40% of the Earth's surface and are home to around 2 billion people (Maestre et al., 2016). Restoration in such areas is crucial to addressing soil degradation, water scarcity, and desertification (Xiu et al., 2021; Zhang et al., 2021). Studies demonstrate that sustainable management and restoration practices can significantly improve soil health and biodiversity in these regions (Kéfi et al., 2024; Lü et al., 2021; Smith et al., 2020; Yu et al., 2020). The Loess Plateau in China is one of the world's most degraded areas due to severe soil erosion (Yu et al., 2020). Restoration initiatives, such as the Loess Plateau Soil Erosion Control Project, have been extensively studied for their success in restoring soil fertility and improving vegetation cover (Chen et al., 2007; Qiu et al., 2021).

Research in specific regions like Kenya reflects the importance of understanding local contexts for soil degradation and restoration. In Kenya, sustainable agricultural practices and forest restoration efforts have been implemented to combat soil degradation and improve food security (Kizito et al., 2021; Magaju et al., 2020; Mansourian et al., 2022). Keywords such as “Juniper” and “Pinyon” point to a focus on specific vegetation types. Juniper and pinyon ecosystems are common in arid and semi-arid regions of the southwestern USA and are vital for biodiversity and ecosystem services (Williams et al., 2018). Studies have shown that restoring these ecosystems enhances water retention, reduces soil erosion, and increases biodiversity (Jacobs; Gatewood, 1999; Roundy et al., 2014; Williams et al., 2018)

The emphasis on hydrological processes is reflected in keywords such as “water infiltration”, “preferential flow”, “rainfall infiltration” and “simulated rainfall.” These processes are critical for the success of ecological restoration, particularly in ecosystems where water availability is a limiting factor. Interest in “rainfall infiltration” and “simulated rainfall” is tied to the need to understand how rainwater infiltrates and moves through the soil. This knowledge is essential for applications such as water resource management, erosion prevention, and the restoration of degraded ecosystems.

To better understand water movement in soils, specific tools such as the HYDRUS-1D model are utilized to simulate water infiltration processes. HYDRUS-1D is a numerical modeling software that simulates the movement of water, solutes, and heat in porous media (Šimůnek et al., 2008). It is based on Richards' equations for water flow in variably saturated porous media, allowing researchers to evaluate different water management scenarios, predict the impact of restoration practices on soil hydrological behavior, and optimize soil and water management strategies (Šimůnek et al., 2008). Several studies have employed simulations and modeling to investigate water infiltration in the context of ecological restoration and water resource management (Prima et al., 2019; Jiang et al., 2019; Schwarzbach et al., 2024; Wang et al., 2022)

The analysis of the keywords “soil erosion” and “forest restoration” reveals a strong association with countries such as China and Brazil, reflecting their focus on combating soil degradation and promoting forest restoration. Studies conducted in these countries often appear in renowned journals like Land Degradation & Development and Restoration Ecology. This trend is evident in studies such as Wang et al. (2023) in China, which explores forest restoration techniques to mitigate soil erosion, and Rodrigues et al. (2009) in Brazil, which discusses strategies for the recovery of degraded areas. The choice of these journals for publication reflects their high quality and relevance, contributing to the knowledge on ecological restoration and soil management, addressing specific challenges faced by these countries due to the pressure exerted on natural resources and the need to promote environmental sustainability.

Conversely, countries such as the USA and Spain stand out for their publications that use the keyword “soil physical properties” frequently appearing in journals such as Ecological Engineering and Journal of Arid Environments. Studies in these countries, such as those by Blanco-Canqui and Lal (2010) in the USA, investigate soil physical properties to develop sustainable agricultural practices and conservation strategies. Similarly, research in Spain, exemplified by the works of Lado et al. (2004) focuses on understanding soil structure and water infiltration in arid environments.

In countries such as Mexico, the terms “vegetation restoration” and “soil degradation” are frequently cited, with their research often published in journals such as Environmental Management. This is evident in the studies by Bestelmeyer et al. (2004), Martin et al. (2021), and Romo-Leon et al. (2016), which focus on vegetation restoration in degraded areas. These publications highlight the importance of ecological restoration practices and soil management tailored to specific contexts, contributing to the global dissemination of essential knowledge for ecosystem conservation.

4.2. Scientific journals

The journals Catena and Ecological Engineering are highly influential and frequently cited in research on forest restoration and water recharge. Studies published in Catena often address topics such as soil dynamics, erosion, water infiltration, and sustainable management practices (Zinn; Rocha, 2024). These topics are essential for forest restoration and water recharge. Additionally, the journal is known for publishing high-quality research that is widely cited, underscoring its relevance and influence in the global scientific community (Ma et al., 2021; Sun & Yuan, 2023).

Ecological Engineering is a journal that focuses on applying engineering principles to the design, construction, and management of sustainable ecosystems (Elsevier, 2021). This journal publishes studies on ecological engineering techniques to restore degraded habitats, manage water resources, and improve environmental quality (Barot et al., 2012; Vymazal, 2024). Its CiteScore (8.0) and impact factor (3.9) reflect its position as a reliable source of advanced research in ecological restoration and natural resource management (Elsevier, 2021).

Brazilian researchers frequently choose to publish in high-impact international journals to achieve greater visibility and global recognition. Such practices can enhance the dissemination of research, facilitate international collaborations, and improve researchers' positions in global rankings (Grosseck et al., 2019). International journals with higher impact factors are generally more influential and credible, which often influences researchers to submit their work to these journals (Gallifant et al., 2023; Grosseck et al., 2019; Huang; Yang, 2022).

Although Brazilian journals may lack the same international visibility, research conducted in Brazil is significant and contributes meaningfully to the field of ecological restoration and water recharge. Brazil is a regional leader in environmental and agricultural research, with numerous universities and research institutes producing high-quality work (Oliveira Filho; Pereira, 2021; Strehl et al., 2016). However, the language barrier and competition with more influential international journals can limit the visibility of Brazilian journals (Grácio et al., 2020; McManus et al., 2020). Liu et al. (2018) reinforces this by stating that scientific publications in languages other than English are a primary factor contributing to lower impact factors.

4.3. Collaboration networks, countries and affiliations

Some hypotheses for differences in scientific production between countries can be considered, such as investment in Research and Development (R&D). Generally, the most productive countries tend to invest more on R&D, including funding for universities, research centers, and support for researchers (Bai et al., 2020; Jungmittag, 2004; Liping, 2011). Studies show that R&D investment is positively correlated with scientific production and technological innovation (Anser et al., 2020; Bai et al., 2020; Jungmittag, 2004). Research infrastructure also contributes to higher scientific production, as it provides well-equipped laboratories and access to advanced technologies, making research faster and more efficient (Abodunde; Jegede, 2020; Liping, 2011). This not only accelerates achieving results but also enables the exploration of new areas of study, fostering innovations and significant advancements in various scientific disciplines (Bai et al., 2020). Moreover, robust infrastructure attracts researchers from various institutions, facilitating international collaborations and strengthening partnerships between countries in the scientific arena (Abodunde; Jegede, 2020; Anser et al., 2020).

National priorities and interests also influence scientific production. A country with a strategic focus on information technology may produce more research in this specific field. Furthermore, areas of research considered priorities by a country may receive more funding and consequently generate more publications and citations (Meneghini et al., 2008). In the Brazilian context, despite the country having a robust research system with several high-quality universities and research institutions, the second-to-last position among the most cited countries, with a relatively low number of citations, suggests challenges in terms of visibility and international impact of its publications (Bitetti; Ferreras, 2017; González-Alcaide et al., 2017). Although the quality of research in Brazil is recognized, turning this quality into greater international impact requires strategies that go beyond increasing the volume of publications. Increasing international collaboration, ensuring consistent funding, and focusing on research areas of high global relevance can help increase the number of citations in the future (Bitetti; Ferreras, 2017; Johri et al., 2021; Meneghini et al., 2008).

Scientific collaboration between countries such as USA and China reflect their robust research infrastructures, funding, and policies encouraging international collaboration. These are the countries that produce the most scientific articles in the world on forest restoration associated with water recharge, and collaboration between scientists has increased significantly, especially in high-technology and natural sciences areas, resulting in high-impact research (Matthews et al., 2020; Wang et al., 2013). Collaborations between German and Dutch institutions are frequent, especially in environmental sciences, engineering, and biomedicine (Kwiek, 2021). The European Union also promotes collaborative research programs that facilitate these interactions (Kwiek, 2021). In Brazil, international scientific collaboration is an important strategy for improving research quality and impact. The country's main scientific collaborations (with Italy, Spain, USA, and Netherlands) often result in high-impact joint publications and significant advances in various scientific fields (González-Alcaide et al., 2017; Kwiek, 2021; Matthews et al., 2020). In addition to these collaborations, Brazil is forming new South-South collaborations with countries like Ethiopia and Kenya, promoting diversity and inclusion in scientific research to address regional and global challenges (Grácio et al., 2020; McManus et al., 2020).

The fact that institutions with the highest number of publications are Chinese suggests high investment and significant prominence in scientific research, particularly in areas related to environment and sustainability (Wang et al., 2023). Government support through funding and favorable policies have been instrumental to the country's research progress (Bai et al., 2020; Liping, 2011; Wang et al., 2013). As environmental concerns evolve, new research areas may emerge, such as applying technologies for environmental conservation, green biotechnology, and sustainable agriculture systems (Chen et al., 2022; Qiu et al., 2021).

The diversity of institutions from other regions indicates a high level of international collaboration and the incorporation of multiple perspectives into this scientific field, potentially increasing the quality and impact of these studies due to exchange of knowledge and resources among different countries (Abodunde; Jegede, 2020; Bai et al., 2020). As pointed out by (Liu et al., 2015), these international collaborations are essential for addressing complex problems such as the growing concern over climate change and environmental degradation.

Research on forest restoration associated with water recharge continues to evolve, with significant contributions from various countries published in influential journals that shape knowledge and sustainable practices in this field.

5. Conclusions

The number of scientific articles related to forest restoration associated with water recharge has been growing annually, with a significant increase since 2019.

Catena and Ecological Engineering were the most influential journals on forest restoration related to water recharge, as indicated by the H index, reflecting a pursuit for greater impact and visibility, facilitating international collaborations and strengthening researchers' positions globally.

Keywords revealed new research interests on forest restoration and water recharge related to soil quality and its changes under soil management. Specific subareas of research highlighted the importance of understanding local contexts of soil degradation and restoration, such as degraded regions and arid and semi-arid ecosystems.

China and USA published most of the articles on forest restoration associated to water recharge, most likely reflecting national interests and R&D investments in this particular field.

Brazil plays a major role on research focused on forest restoration associated to water recharge, although its impact and visibility are still limited, which could improve by increasing international collaboration.

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Conflict of interest statement

All authors certify that they have no affiliations or involvement with any organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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Appendice A - Supplementary material

GLOBAL TRENDS ON THE RESEARCH OF FOREST RESTORATION FOCUSING ON WATER RECHARGE: A SCIENTOMETRIC ANALYSIS EMPHASIZING BRAZIL

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n	Authors	DOI	Journal	Title	Year
1	AHIRWAL J;MAITI S	10.1016/j.catena.2016.01.028	CATENA	ASSESSMENT OF SOIL PROPERTIES OF DIFFERENT LAND USES GENERATED DUE TO SURFACE COAL MINING ACTIVITIES IN TROPICAL SAL SHOREA ROBUSTA FOREST INDIA	2016
2	AKALE A;DAGNEW D;BELETE M;TILAHUN S;MEKURIA W;STEENHUIS T	10.3390/land6040078	LAND	IMPACT OF SOIL DEPTH AND TOPOGRAPHY ON THE EFFECTIVENESS OF CONSERVATION PRACTICES ON DISCHARGE AND SOIL LOSS IN THE ETHIOPIAN HIGHLANDS	2017
3	AKHTER J;MURRAY R;MAHMOOD K;MALIK K;AHMED S	10.1023/B:PLSO.0000016551.08880.6b	PLANT AND SOIL	IMPROVEMENT OF DEGRADED PHYSICAL PROPERTIES OF A SALINESODIC SOIL BY RECLAMATION WITH KALLAR GRASS ILEPTOCHLOAI IFUSCAI	2004
4	AL-AWADHI J	10.1002/ldr.1090	LAND DEGRADATION AND DEVELOPMENT	A CASE ASSESSMENT OF THE MECHANISMS INVOLVED IN HUMANINDUCED LAND DEGRADATION IN NORTHEASTERN KUWAIT	2013
5	AZIMI R;HESHMATI G;KIANIAN M;JAFARI S;ZAKERI D		JOURNAL OF RANGELAND SCIENCE	ROLE OF PLANT SPECIES AND ECOLOGICAL PATCHES IN CONSERVING AND FIXING NATURAL LANDS SOIL USING LANDSCAPE FUNCTIONAL ANALYSIS LFA CASE STUDY DEHBAR RANGELAND TORGHABEH MASHHAD IRAN	2018
6	BALAZS K;MUNSON S;BUTTERFIELD B	10.1111/1365-2435.14129	FUNCTIONAL ECOLOGY	FUNCTIONAL COMPOSITION OF PLANT COMMUNITIES MEDIATES BIOMASS EFFECTS ON ECOSYSTEM SERVICE RECOVERY ACROSS AN EXPERIMENTAL DRYLAND RESTORATION NETWORK	2022
7	BARBERA I;RENISON D;TORRES R	10.31055/1851.2372.v53.n3.21314	BOLETIN DE LA SOCIEDAD ARGENTINA DE BOTANICA	REGENERATION OF ISEBASTIANIA COMMERSONIANAI EUPHORBIACEAE IN RELATION TO LIVESTOCK AND DISTANCE FROM FOREST IN THE MOUNTAINS OF CENTRAL ARGENTINA	2018
8	BELETE M	10.1016/j.ecohyd.2023.08.011	ECOHYDROLOGY AND HYDROBIOLOGY	ECOHYDROLOGICAL NATUREBASED SOLUTION FOR CLIMATE RESILIENCE AND BIODIVERSITY ENHANCEMENT IN WATERLIMITED ECOSYSTEM PERSPECTIVES AND PROOF OF CONCEPTS	2023
9	BELL M;BRIDGE B;HARCH G;ORANGE D	10.1071/s97005	AUSTRALIAN JOURNAL OF SOIL RESEARCH	PHYSICAL REHABILITATION OF DEGRADED KRASNOZEMS USING LEY PASTURES	1997
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11	BONELL M;PURANDARA B;VENKATESH B;KRISHNASWAMY J;ACHARYA H;SINGH U;JAYAKUMAR R;CHAPPELL N	10.1016/j.jhydrol.2010.07.004	JOURNAL OF HYDROLOGY	THE IMPACT OF FOREST USE AND REFORESTATION ON SOIL HYDRAULIC CONDUCTIVITY IN THE WESTERN GHATS OF INDIA IMPLICATIONS FOR SURFACE AND SUBSURFACE HYDROLOGY	2010
12	BRASIL N A;SCHWARTZ G;NORONHA N;GAMA M;FERREIRA G	10.1016/j.ecoleng.2021.106392	ECOLOGICAL ENGINEERING	NATURAL REGENERATION FOR RESTORATION OF DEGRADED AREAS AFTER BAUXITE MINING A CASE STUDY IN THE EASTERN AMAZON	2021
13	BRUCE R;LANGDALE G;WEST L;MILLER W	10.2136/sssaj1995.03615995005900030003x	SOIL SCIENCE SOCIETY OF AMERICA JOURNAL	SURFACE SOIL DEGRADATION AND SOIL PRODUCTIVITY RESTORATION AND MAINTENANCE	1995

14	CHEN C;ZOU X;SINGH A;ZHU X;JIANG X;WU J;LIU W	10.1002/ldr.4368	LAND DEGRADATION AND DEVELOPMENT	EFFECTS OF GRAZING EXCLUSION ON SOIL INFILTRABILITY AND PREFERENTIAL FLOW IN SAVANNAH LIVESTOCK GRAZING SYSTEMS	2022
15	CHEN H;SHAO M;LI Y	10.1016/j.jhydrol.2008.07.037	JOURNAL OF HYDROLOGY	THE CHARACTERISTICS OF SOIL WATER CYCLE AND WATER BALANCE ON STEEP GRASSLAND UNDER NATURAL AND SIMULATED RAINFALL CONDITIONS IN THE LOESS PLATEAU OF CHINA	2008
16	CHEN M;MA L;SHAO M;WEI X;JIA Y;SUN S;ZHANG Q;LI T;YANG X;GAN M	10.1016/j.catena.2021.105248	CATENA	CHINESE ZOKOR MYOSPALAX FONTANIERII EXCAVATING ACTIVITIES LESSEN RUNOFF BUT FACILITATE SOIL EROSION A SIMULATION EXPERIMENT	2021
17	CHENG Y;ZHAN H;YANG W;FENG W;LU Q;WANG Y;JIANG Q;WANG B;SHI M;WANG T;XIN Z;HAO R	10.1016/j.iswcr.2022.03.008	INTERNATIONAL SOIL AND WATER CONSERVATION RESEARCH	REDISTRIBUTION PROCESS OF PRECIPITATION IN ECOLOGICAL RESTORATION ACTIVITY OF PINUS SYLVESTRIS VAR MONGOLICA IN MU US SANDY LAND CHINA	2023
18	CHUNJUAN L;CHEN D;GUO X;WANG Y;GUO Y	10.16843/j.sswc.2019.04.008	SCIENCE OF SOIL AND WATER CONSERVATION	WATER STORAGE CAPACITY AND THE INFILTRATION CHARACTERISTICS OF SOIL IN DIFFERENT RECLAMATION MODES IN IRON TAILINGS	2019
19	CLEMENTS A	10.1007/s10661-004-4024-4	ENVIRONMENTAL MONITORING AND ASSESSMENT	AN ECOSYSTEM APPROACH TO COMBAT DESERTIFICATION ON THE COLORADO PLATEAU	2004
20	COGGER C	10.1080/1065657X.2005.10702248	COMPOST SCIENCE AND UTILIZATION	POTENTIAL COMPOST BENEFITS FOR RESTORATION OF SOILS DISTURBED BY URBAN DEVELOPMENT	2005
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22	COX S;BOOTH D;LIKINS J	10.1007/s00267-015-0610-1	ENVIRONMENTAL MANAGEMENT	HEADCUT EROSION IN WYOMINGS SWEETWATER SUBBASIN	2016
23	DAI L D;ZHANG Y Z;LIU Y L;XIE L X;ZHAO S Z;ZHANG Z Z	10.1016/j.chemosphere.2020.129008	CHEMOSPHERE	THICK ROOTS AND LESS MICROAGGREGATES IMPROVE HYDROLOGICAL CONNECTIVITY	2021
24	DE JONG N	10.1071/MF99037	MARINE AND FRESHWATER RESEARCH	WOODY PLANT RESTORATION AND NATURAL REGENERATION IN WET MEADOW AT COOMONDERRY SWAMP ON THE SOUTH COAST OF NEW SOUTH WALES	2000
25	DESCHEEMAEKER K;RAES D;NYSSEN J;POESEN J;HAILE M;DECKERS J	10.1071/RJ09010	RANGELAND JOURNAL	CHANGES IN WATER FLOWS AND WATER PRODUCTIVITY UPON VEGETATION REGENERATION ON DEGRADED HILLSLOPES IN NORTHERN ETHIOPIA A WATER BALANCE MODELLING EXERCISE	2009
26	DIMICK B;STUCKY J;WALL W;VEPRASKAS M;WENTWORTH T;ARELLANO C	10.2179/09-063.1	CASTANEA	PLANTSOILHYDROLOGY RELATIONSHIPS IN THREE CAROLINA BAYS IN BLADEN COUNTY NORTH CAROLINA	2010
27	ENTZ M;STAINSBY A;RIEKMAN M;MULAIRE T;KIRIMA J;BERISO F;NGOTIO D;SALOMONS M;NICKSY J;MUTINDA M;STANLEY K	10.1007/s13593-022-00824-1	AGRONOMY FOR SUSTAINABLE DEVELOPMENT	FARMER PARTICIPATORY ASSESSMENT OF SOIL HEALTH FROM CONSERVATION AGRICULTURE ADOPTION IN THREE REGIONS OF EAST AFRICA	2022
28	ERKOSSA T;GELETI D;WILLIAMS T;LAEKEMARIAM F;HAILESLASSIE A	10.1017/S1742170519000425	RENEWABLE AGRICULTURE AND FOOD SYSTEMS	RESTORATION OF GRAZING LAND TO INCREASE BIOMASS PRODUCTION AND IMPROVE SOIL PROPERTIES IN THE BLUE NILE BASIN EFFECTS OF INFILTRATION TRENCHES AND CHLORIS GAYANA RESEEDING	2022
29	FALK D;WINOWIECKI L;VAGEN T;LOHBECK ;MADELON M;ILSTEDT U;MURIUKI J;MWANIKI A;TOBELLA A	10.1016/j.scitotenv.2023.168038	SCIENCE OF THE TOTAL ENVIRONMENT	DRIVERS OF FIELDSATURATED SOIL HYDRAULIC CONDUCTIVITY IMPLICATIONS FOR RESTORING DEGRADED TROPICAL LANDSCAPES	2024
30	FANELLI R;PRESTEGAARD K;PALMER M	10.1002/hyp.11266	HYDROLOGICAL PROCESSES	EVALUATION OF INFILTRATIONBASED STORMWATER MANAGEMENT TO RESTORE HYDROLOGICAL PROCESSES IN URBAN HEADWATER STREAMS	2017
31	FERREIRA A;ALEGRE S;COELHO C;SHAKESBY R;PÁSCOA F;FERREIRA C;KEIZER J;RITSEMA C	10.1016/j.catena.2014.09.002	CATENA	STRATEGIES TO PREVENT FOREST FIRES AND TECHNIQUES TO REVERSE DEGRADATION PROCESSES IN BURNED AREAS	2015
32	FICK S;BARGER N;DUNIWAY M	10.1002/eco.2089	ECOHYDROLOGY	HYDROLOGICAL FUNCTION OF RAPIDLY INDUCED BIOCRUSTS	2019
33	FRANCIS J;WUDDIVIRA M;FARRICK K	10.1016/j.jhydrol.2023.129650	JOURNAL OF HYDROLOGY	REFORESTING DEGRADED HILLSLOPES WITH EXOTIC PINES IN TRINIDAD AND TOBAGO INFILTRATION REPELLENCY AND IMPLICATIONS FOR RUNOFF AND RECHARGE	2023
34	GALLI A;PERUZZI C;BELTRAME L;CISLAGHI A;MASSERONI D	10.1016/j.scitotenv.2021.147612	SCIENCE OF THE TOTAL ENVIRONMENT	EVALUATING THE INFILTRATION CAPACITY OF DEGRADED VS REHABILITATED URBAN GREENSPACES LESSONS LEARNT FROM A REALWORLD ITALIAN CASE STUDY	2021
35	GAO Y;LIBERA D;WANG D;KIBLER K;CHANG N	10.1016/j.jhydrol.2020.125491	JOURNAL OF HYDROLOGY	EVALUATING THE PERFORMANCE OF BAMBASED BLANKET FILTER ON NITRATE REDUCTION IN A KARST SPRING	2020
36	GEBREGERGS T;TESSEMA Z;SOLOMON N;BIRHANE E	10.1002/ece3.5223	ECOLOGY AND EVOLUTION	CARBON SEQUESTRATION AND SOIL RESTORATION POTENTIAL OF GRAZING LANDS UNDER EXCLOSURE MANAGEMENT IN A SEMIARID ENVIRONMENT OF NORTHERN ETHIOPIA	2019
37	GEBRETSADIK W	10.1007/s11676-013-0398-x	JOURNAL OF FORESTRY RESEARCH	EVALUATION OF THE ADAPTABILITY AND RESPONSE OF INDIGENOUS TREES TO ASSISTED REHABILITATION ON THE DEGRADED HILLSIDES OF KURIFTU LAKE CATCHMENT DEBRE ZEIT ETHIOPIA	2014

38	GENG R;YIN P;YUAN Q	10.11975/j.issn.1002-6819.2016.19.030	NONGYE GONGCHENG XUEBAO/TRANSACTIONS OF THE CHINESE SOCIETY OF AGRICULTURAL ENGINEERING	ZONATION FOR NONPOINT SOURCE POLLUTION CONTROL IN HONGFENGHU RESERVOIR WATERSHED	2016
39	GONZÁLEZ C G;NAVA B G;ARTEAGA R T T;GARCÍA F B	10.14350/rig.59998	INVESTIGACIONES GEOGRÁFICAS	ANÁLISIS DEL PROGRAMA DE CONSERVACIÓN DE SUELOS EN EL ÁREA DE PROTECCIÓN DE FLORA Y FAUNA NEVADO DE TOLUCA	2020
40	GONZÁLEZ-ALCARAZ M;ARÁNEGA B;TERCERO M;CONESA H;ÁLVAREZ-ROGEL J	10.1016/j.ecoleng.2014.08.009	ECOLOGICAL ENGINEERING	IRRIGATION WITH SEAWATER AS A STRATEGY FOR THE ENVIRONMENTAL MANAGEMENT OF ABANDONED SOLAR SALTWORKS A CASESTUDY IN SE SPAIN BASED ON SOILVEGETATION RELATIONSHIPS	2014
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43	HAO H;WEI Y;CAO D;GUO Z;SHI Z	10.1016/j.still.2019.104542	SOIL AND TILLAGE RESEARCH	VEGETATION RESTORATION AND FINE ROOTS PROMOTE SOIL INFILTRABILITY IN HEAVYTEXTURED SOILS	2020
44	HARDEN C;MATHEWS L	10.1111/1467-8470.00169	AUSTRALIAN GEOGRAPHICAL STUDIES	HILLSLOPE RUNOFF SOIL DETACHMENT AND SOIL ORGANIC CONTENT FOLLOWING REFORESTATION IN THE COPPER BASIN TENNESSEE USA	2002
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46	HARTMAN B;CLEVELAND D;CHADWICK O	10.1111/rec.12347	RESTORATION ECOLOGY	LINKING CHANGES IN KNOWLEDGE AND ATTITUDES WITH SUCCESSFUL LAND RESTORATION IN INDIGENOUS COMMUNITIES	2016
47	HE S;RICHARDS K	10.1002/eco.1844	ECOHYDROLOGY	KOBRESIA MEADOW DEGRADATION AND ITS IMPACT ON WATER STATUS	2017
48	HEVIA J;DE A J;MANSO J	10.1002/esp.3541	EARTH SURFACE PROCESSES AND LANDFORMS	ASSESSMENT OF 80 YEARS OF ANCIENTBADLANDS RESTORATION IN SALDAÑA SPAIN	2014
49	HOU W;GAO J	10.1007/s11442-019-1608-z	JOURNAL OF GEOGRAPHICAL SCIENCES	SIMULATING RUNOFF GENERATION AND ITS SPATIAL CORRELATION WITH ENVIRONMENTAL FACTORS IN SANCHA RIVER BASIN THE SOUTHERN SOURCE OF THE WUJIANG RIVER	2019
50	HUANG Z;OUYANG Z;LI F;ZHENG H;WANG X	10.1016/S1001-0742(09)60317-X	JOURNAL OF ENVIRONMENTAL SCIENCES	RESPONSE OF RUNOFF AND SOIL LOSS TO REFORESTATION AND RAINFALL TYPE IN RED SOIL REGION OF SOUTHERN CHINA	2010
51	HUBBART J;GEBO N	10.1080/1065657X.2005.10702248	EROSION CONTROL	QUANTIFYING THE EFFECTS OF LAND USE AND EROSION	2010
52	JEDDI K;CHAIEB M	10.1016/j.flora.2009.03.002	FLORA: MORPHOLOGY, DISTRIBUTION, FUNCTIONAL ECOLOGY OF PLANTS	CHANGES IN SOIL PROPERTIES AND VEGETATION FOLLOWING LIVESTOCK GRAZING EXCLUSION IN DEGRADED ARID ENVIRONMENTS OF SOUTH TUNISIA	2010
53	JEDDI K;CORTINA J;CHAIEB M	10.1016/j.jaridenv.2009.05.005	JOURNAL OF ARID ENVIRONMENTS	ACACIA SALICINA PINUS HALEPENSIS AND EUCALYPTUS OCCIDENTALIS IMPROVE SOIL SURFACE CONDITIONS IN ARID SOUTHERN TUNISIA	2009
54	JIANG G;LIU F;WANG Q;GUO F	10.11932/karst2021y32	CARSOLOGICA SINICA	LOW IMPACT DEVELOPMENT CONSTRUCTION OF PEAK CLUSTER DEPRESSION BASED ON REGULATION OF EPIKARST ZONE	2022
55	JIANG N;SHI D;JIANG G;SONG G;SI C;YE Q	10.3864/j.issn.0578-1752.2020.09.012	SCIENTIA AGRICULTURA SINICA	EFFECTS OF SOIL EROSION ON PHYSICAL AND MECHANICAL PROPERTIES OF CULTIVATED LAYER OF PURPLE SOIL SLOPE FARMLAND	2020
56	JIANG X;WANG H;ZAKARI S;ZHU X;SINGH A;LIN Y;LIU W;LIU J;CHEN C	10.1016/j.geoderma.2023.116712	GEODERMA	ASSESSING THE IMPACT OF FOREST CONVERSION TO PLANTATIONS ON SOIL DEGRADATION AND FOREST WATER CONSERVATION IN THE HUMID TROPICAL REGION OF SOUTHEAST ASIA IMPLICATIONS FOR FOREST RESTORATION	2023
57	KAN X;CHENG J;HU X;ZHU F;LI M	10.3390/w11081634	WATER (SWITZERLAND)	EFFECTS OF GRASS AND FORESTS AND THE INFILTRATION AMOUNT ON PREFERENTIAL FLOW IN KARST REGIONS OF CHINA	2019
58	KAN X;ZHENG W;CHENG J;ZHANGZHONG L;LI J;LIU B;ZHANG X	10.3390/w15213823	WATER (SWITZERLAND)	INVESTIGATING SOIL PORE NETWORK CONNECTIVITY IN VARIED VEGETATION TYPES USING XRAY TOMOGRAPHY	2023
59	KAOUTHAR J;CHAIEB M	10.1080/12538078.2009.10516149	ACTA BOTANICA GALLICA	THE EFFECT OF STIPA TENACISSIMA TUSSOCKS ON SOME SOIL SURFACE PROPERTIES UNDER ARID BIOCLIMATE IN THE SOUTHERN TUNISIA	2009
60	KAUFFMAN J;THORPE A;BROOKSHIRE E	10.1890/03-5083	ECOLOGICAL APPLICATIONS	LIVESTOCK EXCLUSION AND BELOWGROUND ECOSYSTEM RESPONSES IN RIPARIAN MEADOWS OF EASTERN OREGON	2004
61	KINYUA D;MCGEOCH L;GEORGIADIS N;YOUNG T	10.1111/j.1526-100X.2009.00594.x	RESTORATION ECOLOGY	SHORTTERM AND LONGTERM EFFECTS OF SOIL RIPPING SEEDING AND FERTILIZATION ON THE RESTORATION OF A TROPICAL RANGELAND	2010

62	LASANTA T;ARNÁEZ J;NADAL-ROMERO E	10.1016/bs.apmp.2019.07.002	ADVANCES IN CHEMICAL POLLUTION, ENVIRONMENTAL MANAGEMENT AND PROTECTION	SOIL DEGRADATION RESTORATION AND MANAGEMENT IN ABANDONED AND AFFORESTED LANDS	2019
63	LEU S;MUSSERY A;BUDOVSKY A	10.1007/s00267-014-0286-y	ENVIRONMENTAL MANAGEMENT	THE EFFECTS OF LONG TIME CONSERVATION OF HEAVILY GRAZED SHRUBLAND A CASE STUDY IN THE NORTHERN NEGEV ISRAEL	2014
64	LEVI N;HILLEL N;ZAADY E;ROTEM G;ZIV Y;KARNIELI A;PAZ-KAGAN T	10.1016/j.ecolind.2021.107571	ECOLOGICAL INDICATORS	SOIL QUALITY INDEX FOR ASSESSING PHOSPHATE MINING RESTORATION IN A HYPERARID ENVIRONMENT	2021
65	LI X;GAO Y	10.5846/stxb201204010458	SHENGTAI XUEBAO/ ACTA ECOLOGICA SINICA	EFFECTS OF SHRUB ENCROACHMENT IN DESERT GRASSLAND ON RUNOFF AND THE INDUCED NITROGEN LOSS IN SOUTHEAST FRINGE OF TENGGER DESERT	2012
66	LI X;RAO L;XU Y	10.11975/j.issn.1002-6819.2022.05.017	NONGYE GONGCHENG XUEBAO/TRANSACTIONS OF THE CHINESE SOCIETY OF AGRICULTURAL ENGINEERING	CHARACTERISTICS OF SOIL NITROGEN AND PHOSPHORUS NUTRIENTS IN DIFFERENT PISHA SANDSTONE AREAS	2022
67	LI Z;YUAN Y;HU Y;MENG W;ZHANG X;GUO X;ZHANG W;HU D;NIU D	10.5846/stxb201701090068	SHENGTAI XUEBAO	EFFECTS OF ELEVATION AND TOURISM DISTURBANCE ON MEADOW SOIL INFILTRATION ON WUGONG MOUNTAIN	2018
68	LIU Y;ZHAO L;LIU Y;HUANG Z;SHI J;WANG Y;MA Y;ESTEBAN L M;LÓPEZ-VICENTE M;WU G	10.1016/j.catena.2022.106632	CATENA	RESTORATION OF A HILLSLOPE GRASSLAND WITH AN ECOLOGICAL GRASS SPECIES ELYMUS TANGUTORUM FAVORS RAINFALL INTERCEPTION AND WATER INFILTRATION AND REDUCES SOIL LOSS ON THE QINGHAITIBETAN PLATEAU	2022
69	LOZANO-BAEZ S;DOMÍNGUEZ-HAYDAR Y;ZWARTENDIJK B;COOPER M;TOBÓN C;PRIMA S	10.3390/f12121716	FORESTS	CONTRASTS IN TOP SOIL INFILTRATION PROCESSES FOR DEGRADED VS RESTORED LANDS A CASE STUDY AT THE PERIJÁ RANGE IN COLOMBIA	2021
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72	MA H;ZHONG B;YUE H;CAO S	10.5846/stxb201401210161	SHENGTAI XUEBAO	RESEARCH ON THE APPLICATION OF NATURAL ECOLOGICAL RESTORATION IN A TYPICAL REGION OF CHINA WITH RED SOILS	2015
73	MA Z;ZHANG M;XIAO R;CUI Y;YU F	10.1016/j.geoderma.2016.11.037	GEODERMA	CHANGES IN SOIL MICROBIAL BIOMASS AND COMMUNITY COMPOSITION IN COASTAL WETLANDS AFFECTED BY RESTORATION PROJECTS IN A CHINESE DELTA	2017
74	MAESTRE F;CORTINA J;BAUTISTA S;BELLOT J;VALLEJO R	10.1007/s10021-002-0222-5	ECOSYSTEMS	SMALLSCALE ENVIRONMENTAL HETEROGENEITY AND SPATIOTEMPORAL DYNAMICS OF SEEDLING ESTABLISHMENT IN A SEMIARID DEGRADED ECOSYSTEM	2003
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77	MEENA D;PAL S;CHAND P	10.18520/cs/v123/i11/1352-1358	CURRENT SCIENCE	ASSESSMENT OF WATERSHED MANAGEMENT ECOSYSTEM SERVICES IN INDIA A METAANALYSIS	2022
78	MENS L;BARGUÉS-TOBELLA A;STERCK F;VÅGEN T;WINOWIECKI L;LOHBECK M	10.1111/1365-2664.14311	JOURNAL OF APPLIED ECOLOGY	TOWARDS EFFECTIVELY RESTORING AGRICULTURAL LANDSCAPES IN EAST AFRICAN DRYLANDS LINKING PLANT FUNCTIONAL TRAITS WITH SOIL HYDROLOGY	2023
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80	MILESI D L A;ULLÉ J Á;ANDRIULO A E		CIENCIA DEL SUELO	APLICACIÓN DE BIOCHAR EN UN SUELO DEGRADADO BAJO PRODUCCIÓN DE BATATA EFECTO SOBRE PROPIEDADES EDÁFICAS	2020
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82	MISAK R;AL-AWADHI J;OMAR S;SHAHID S	10.1002/ldr.522	LAND DEGRADATION AND DEVELOPMENT	SOIL DEGRADATION IN KABD AREA SOUTHWESTERN KUWAIT CITY	2002
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86	MONGIL-MANSO J;NAVARRO-HEVIA J;SAN M R	10.1007/s11629-020-6636-8	JOURNAL OF MOUNTAIN SCIENCE	DOES FOREST RESTORATION INFLUENCE SOIL INFILTRABILITY A CASE STUDY IN THE RESTORED WOODLAND OF SIERRA DE ÁVILA CENTRAL SPAIN	2021
87	MONGIL-MANSO J;NAVARRO-HEVIA J;SAN M R	10.3390/land11071043	LAND	IMPACT OF LAND USE CHANGE AND AFFORESTATION ON SOIL PROPERTIES IN A MEDITERRANEAN MOUNTAIN AREA OF CENTRAL SPAIN	2022
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159	ZHOU J;LIU Q;LIANG L;HE J;YAN ;DENGHUA D;WANG X;SUN T;LI S	10.1016/j.jhydrol.2022.128707	JOURNAL OF HYDROLOGY	MORE PORTION OF PRECIPITATION INTO SOIL WATER STORAGE TO MAINTAIN HIGHER EVAPOTRANSPIRATION INDUCED BY REVEGETATION ON CHINAS LOESS PLATEAU	2022
160	ZOU Y;ZHANG S;YU X;FU G;LU X	10.1016/j.fmre.2022.11.001	FUNDAMENTAL RESEARCH	ISOTOPIC EVIDENCE FOR SOIL WATER SOURCES AND RECIPROCAL MOVEMENT IN A SEMIARID DEGRADED WETLAND IMPLICATIONS FOR WETLAND RESTORATION	2023
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PAPER 2 – Forest restoration contrasting with land use impacts on tropical soils' health: a Soil Management Assessment Framework (SMAF) approach

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Highlights

- Areas undergoing forest restoration had SQI close to natural fragments

- SMAF was effective in assenssing soil quality under different land uses

- Soil recovers better in restored areas with greater structural stability

- Forest restoration improves water and ecosystem services

Abstract

Land use changes significantly impact soil health, particularly in tropical regions where deforestation and agricultural expansion alter soil properties and ecosystem services. This study evaluates soil health in the Pontal do Paranapanema region, western São Paulo state, Brazil, using the Soil Management Assessment Framework (SMAF). The objective was to quantify the influence of different land uses on soil physical, chemical, and biological properties, emphasizing their role in groundwater recharge and hydroelectric power supply. Soil samples were collected from six land use systems—forest fragment, forest restoration, pasture, sugarcane, grain cultivation, and cassava—across two predominant soil types, Oxisol and Ultisol. Nine soil health indicators were assessed, including soil organic carbon (SOC), microbial biomass carbon (MBC), β-glucosidase activity (BG), bulk density (BD), available water capacity (AWC), water-filled porosity (WFPS), pH, Mehlich-1 extractable phosphorus (P), and potassium (K). SMAF scoring curves were applied to integrate these indicators into a comprehensive soil quality index (SQI). Results indicated that forested areas (forest fragment and restoration) exhibited higher biological quality, with increased SOC, MBC, and BG scores, whereas cassava cultivation showed the lowest soil quality scores due to minimal organic matter input and intensive soil disturbance. Sugarcane and grain cultivation had better chemical quality, linked to fertilization practices, while pasture maintained intermediate soil health scores. Soi physical soil quality varied, with bulk density scores indicating compaction in managed land uses compared to natural forest systems. PCA analysis revealed distinct soil property dynamics across depths, with biological indicators prevailing at the surface and physical properties governing deeper layers. This study underscores the need for sustainable land management practices to enhance soil health and water recharge capacity, promoting long-term ecosystem resilience and energy security in hydroelectric-dependent regions. The SMAF proved effective in evaluating soil health under diverse land use scenarios, supporting evidence-based conservation strategies.

Keywords: Soil health indicators; ecosystem services; soil quality index; forest restoration; water infiltration.

1. Introduction

Soil health plays an essential role in maintaining ecosystem services related to groundwater recharge, and is critical for the environmental sustainability of regions susceptible to soil degradation (Bünemann et al., 2018a; Rinot et al., 2019; Santana, dos Santos, et al., 2023). Due to the growing demand for food, fiber, and fuel (Food and Agriculture Organization, 2015), the Atlantic Rainforest biome, particularly the Pontal do Paranapanema region, western São Paulo state, Brazil, has been highly affected by the sugarcane (*Saccharum officinarum*) and energetic sectors, pasture areas, and agricultural expansion (Francisco, 2023; Barreto and Thomaz Junior, 2012). Among the factors contributing to the Atlantic Rainforest's degradation and deforestation is the flooding of large areas from dams and hydroelectric power plants (Kliemann et al., 2015; Rocha-Santos et al., 2016b), which represent the major source of electric energy in Brazil (Dale; Lucena, 2013). Its use is facilitated by Brazil's relief conditions and the country's countless rivers and lakes (Barros et al., 2018). According to the Electric Energy National Agency (Aneel), about 67% of the energy generated in the country comes from hydraulic sources [i.e. the energy produced by the water movement force (ANEEL, 2017)]. Given the need to expand the country's electricity production, several regions with hydroelectric potential are receiving great attention and attracting more investments in this sector.

The Pontal do Paranapanema region has one of the most relevant rivers in the country, the Paranapanema River. It is a natural divisor between the states of São Paulo and Paraná. Another regionally important river is the Paraná River, which is the eighth-longest river in the world (4,800 km) and the second-longest in South America (Agência Nacional de Águas, 2016), considering its total extension up to the mouth of the La Plata River estuary. Owing to the high energetic potential of these rivers, the Pontal do Paranapanema region has four important hydroelectric power plants, with a combined installed capacity of 3,970 MW.

Considering the economic and strategic importance of these hydroelectric power plants for the country, it is essential to preserve the surrounding areas of their reservoirs to ensure a reliable water supply. However, the intense and rapid land use changes in the region could severely impact water availability. Forest fragmentation and the conversion of native forest areas into monocropping systems have resulted in significant changes in soil properties, impairing the infiltration and retention capacity of water in the soil (Bonetti et al., 2023; Cherubin et al., 2020). Therefore, these alterations can affect the water availability and the regulation of the hydrological cycle, directly impacting the water storage capacity in the hydroelectric reservoirs for generating electric power (Luz et al., 2016; Vianna et al., 2020). This can result in less power generation capacity, especially during dry seasons, besides increasing the pressure over water resources, threatening energy security and system's sustainability (Luz et al., 2016; Vianna et al., 2020; Wang et al., 2012). Identifying low-impact strategies seeks to monitor, evaluate, and restore soil quality changes from land use and management, promoting sustainable agriculture and enhancing soil health and functions (Cherubin, et al., 2016; Karlen & Rice, 2015; Nunes et al., 2020).

Soil health is the continuous capacity of soil to perform its functions, sustaining ecosystems, improving water and air quality, and supporting human well-being (Karlen et al., 1997). The Soil Management Assessment Framework (SMAF), developed in 2004, is a key quantitative tool for evaluating soil health under different land use and management scenarios (Andrews et al., 2004). Initially designed for temperate regions, SMAF has since been applied globally, including in Brazil, India, South Africa, and Turkey (Bhaduri & Purakayastha, 2014; Çelik et al., 2021; Cherubin et al., 2017; Gura et al., 2022), among others.

By integrating physical, chemical, and biological indicators into a single soil quality index (SQI), SMAF enables effective monitoring of management impacts and supports sustainable practices (Andrews et al., 2004; Karlen et al., 2014; Nunes et al., 2020). Its three-step protocol—selecting indicators, interpreting them via scoring curves, and integrating results—yields insights into functions like crop yield and nutrient cycling. SMAF includes scoring curves for 13 indicators, encompassing physical (e.g., bulk density), chemical (e.g., pH, extractable phosphorus), and biological (e.g., soil organic carbon, microbial biomass carbon) properties (Andrews et al., 2004; Karlen et al., 2014; Nunes et al., 2020).

The SMAF has been widely used to assess the various impacts of cropping systems on different soil types and management practices in tropical and subtropical soils (Bonetti et al., 2023; Cherubin et al., 2017; Cherubin et al., 2016; Nunes et al., 2020). However, to the best of our knowledge, no study has assessed the effectiveness of forest restoration on water recharge and quantified changes on soil physical, chemical, and biological health. Previously studies shown that vegetation restoration can improve the soil properties and therefore impact ecosystem services (Babur et al., 2021; Fagnano et al., 2015; Santana, dos Santos, et al., 2023) Therefore, this study aims to quantify soil health and ecosystem services via SMAF to monitor forest restoration in contrast to other regionally relevant land uses in strategic areas for the supply of hydroelectric plants reservoirs. Our hypotheses are: (i) forest restoration (FR) improves soil health compared to areas under intensive agricultural use, such as sugarcane and pasture, contributing to greater water retention and infiltration capacity in the soil; and (ii) soil quality, measured through the Soil Management Assessment Framework (SMAF), will be higher in forest areas, such as the forest fragment (FF) and forest restoration (FR), compared to soils used for grains and cassava (*Manihot esculenta*) cultivation, indicating that forest restoration is more effective in maintaining soil health.

2. Material and Methods

2.1 Study location and sample collection

The study was carried out in Euclides da Cunha Paulista, Mirante do Paranapanema, Sandovalina and Teodoro Sampaio, located in the Pontal do Paranapanema region, far west of São Paulo state (22°30'35.74"S, 52°18'51.03"W). This region is part of the Atlantic Rainforest biome, and the predominant vegetation is the Semideciduous Seasonal Forest (Oliveira-Filho & Fontes, 2000a) with an average altitude of 350 m above sea level. The climate is continental, Aw-Tropical Humid, which covers a narrow strip along the Paraná River, characterized by a rainy summer season and dry winter, with an average annual temperature of 22-24ºC, and annual rainfall of 1,500 mm, and Cwa-Mesothermal Dry winter, covering most of the region, characterized by annual average temperatures lower than 22ºC, with rainfall concentrated in summer months, typical of tropical climate (Beck et al., 2018). Soils in this region are derived from sedimentary rocks, including the Cuiuá sandstone from the Bauru Group, with increased sand contents, low natural fertility, good permeability, and excessive drainage (Souza, 2021). The soil particle-size distribution of the studied areas is presented in Table 1.

Table 1. Soil textural classificationa in two orders (Oxisol and Ultisol) and six land uses [forest fragment (FF), forest restoration (FR), cassava (CA), grains (GR), pasture (PA), and sugar cane (SC)] in Pontal do Paranapanema, SP, Brazil.

Soil Order[a]	Land Use	Depth	Sand	Silt	Clay
		cm		g kg^{-1}	
Oxisol	FF	0-5	68.24	7.29	24.48
		95-100	66.86	6.53	26.62
	FR	0-5	85.91	1.74	12.35
		95-100	76.55	2.09	21.36
	CA	0-5	82.11	5.52	12.36
		95-100	76.47	4.34	19.19
	GR	0-5	78.28	3.30	18.42
		95-100	71.91	3.54	24.54
	PA	0-5	82.27	4.86	12.88
		95-100	73.90	4.84	21.25
	SC	0-5	71.83	4.61	23.57
		95-100	64.52	5.73	29.75
Ultisol	FF	0-5	82.05	1.39	16.56
		95-100	74.92	1.49	23.59
	FR	0-5	79.23	4.05	16.72
		95-100	67.38	2.94	29.68
	CA	0-5	87.22	2.10	10.68
		95-100	82.80	1.83	15.36
	GR	0-5	79.46	6.32	14.22
		95-100	75.67	3.40	20.93
	PA	0-5	87.82	4.15	8.03
		95-100	80.51	3.93	15.56
	SC	0-5	77.12	4.31	18.57
		95-100	69.51	4.94	25.55

[a] USDA Soil Taxonomy

To identify the soil attributes impacting water resources (i.e., water recharge), six land uses were considered: forest fragment (reference area), forest restoration, pasture, sugarcane, grain cultivation, and cassava, and two predominant soils in the region, Oxisol and Ultisol. The forest fragment area (FF) was selected because the soil under this land use is expected to be of higher quality and, therefore, can be used to contrast with areas of agricultural use. It comprises native vegetation represented by the Atlantic Rainforest and semideciduous forest, i.e. conditioned to a double climatic seasonality: a season with intense summer rains, followed by a dry season. The forest restoration (FR) has a history of use with degraded pasture and abandoned agricultural areas. The forest was recomposed five years ago aiming to improve water recharge in the watersheds, but no practices have been carried out to mitigate soil compaction for planting. The pasture (PA) was converted from native vegetation approximately

50 years ago and is composed of *Urochloa decumbens* (Stapf) R.D. Webster grass, with low animal density (0.8 AU/ha) as well as low investment in soil fertilization and other agricultural inputs. In the sugarcane area (SC), the soil is prepared by plowing and harrowing, with mechanized harvest are mechanized. At the sampling time, the crop was harvested mechanically using harvester and transported by a tractor with a trailer, with fertigation using vinasse. The grains (GR) land use consists of areas with crop rotation between corn (*Zea mays*) and soybean (*Glycine max*) under no-tillage system in the summer, with fallow on winter due insufficient precipitation for a second crop, with this rotation being carried out since 2019. The topsoil was covered with plant residue to maintain temperature and soil moisture. Cassava (CA) was collected in settlement areas, where the soil was manually prepared by digging holes using a hoe and cultivates in the first 120 days in order to avoid competition with weeds, and manually harvested.

2.2 Experimental design and soil analysis

In each soil class, field trials were carried out in randomized block design, with six land uses and three repetitions, comprising 36 sampling points (2 soils x 6 land uses x 3 repetitions). The soil was sampled in January 2023. To determine the physical attributes, disturbed and undisturbed samples were collected using a metallic cylindric core (100 cm^3 volume) from the surface layer (0-5 cm) and subsurface (95-100 cm), with five repetitions in each layer. Depth was not included as a factor in statistical analysis.

Bulk density (BD) and total porosity (TP) were determined through the core method (Dane and Topp, 2002; Teixeira et al., 2017). The available water capacity (AWC) was estimated as the difference between the water content at field capacity (FC) and the permanent wilting point (PWP), estimated at -10 kPa and -1500 kPa, respectively (Silva et al., 2014). WFPS (water-filled porosity space) was obtained by dividing the FC by the TP. The pH, Mehlich-1 extractable K and P were determined according to Dane et al. (2002) and Teixeira et al. (2017). The microbial biomass carbon (MBC) was assessed by the fumigation-extraction method (Vance et al., 1987). The activity of the β-glucosidase enzyme (BG) was determined following the colorimetric method based on estimation of p-nitrophenol (Tabatabai, 1982). Soil organic carbon content (SOC) was determined from 5 g of fine earth (< 2 mm), further grounded in a mortar to pass a 100 mesh (0.149 mm) sieve. Samples were subjected to dry combustion in na elemental analyzer, according to Nelson and Sommers (1996).

2.3 Soil health assessment

The Soil Management Assessment Framework (SMAF) (Andrews et al., 2004) was used to investigate the impacts of land use on soil health in two soil orders (Ultisol and Oxisol). Nine soil indicators, namely soil organic C (SOC), microbial biomass C (MBC), β-glucosidase activity (BG), bulk density (BD), available water capacity (AWC), water filled porosity space (WFPS), pH, and Mehlich-1 extractable K and P, were included in the 0-5 cm minimum data set. As for the 95-100 cm depth, all indicators except for MBC and BG were included in the assessment. This approach agrees with the recommendation of a minimum of five indicators with at least one for representing soil biological, physical and chemical properties and processes (Andrews et al., 2004; Karlen et al., 2008). Individual soil health indicators were converted into scores between 0 and 1 using established algorithms in Excel, with 0 representing the lowest SQ (soil quality) value and 1 indicating the largest SQ value for each indicator. The algorithms, or scoring functions, are modified by factor classes which account for inherent soil properties, climatic factors, site management, and selected analytical methods for soil chemical properties. After conversion, the measured soil properties were plotted against their respective scores. This allows for the visualization of the scoring curves to identify potential adjustments to improve SMAF's sensitivity when used in tropical soils (Amorim et al., 2024). Then, individual scores were integrated into a percentage-based SQ index (SQI).

Specifically, the organic matter factor class "4" (low) was used to modify the SOC, MBC, BG, P, and AWC scores in all soil orders and land uses. Texture classes were "1" for sand and loamy sand soils, "2" for sandy loam and sandy clay loam, and "4" for sandy clay soils, and were used to modify SOC, MBC, BG, BD, P, and AWC. Climate class was "1" (≥ 17°C days and mean annual precipitation ≥ 550 mm) for all soil orders and land uses, and it was used for SOC, MBC, and BG interpretation. The season code modifies MBC scores and was "1" for samples collected before or at planting and "2" for samples collected during the growing season. Mineral class "3" [1:1 clay and Fe- and Al-hydr(oxides), other than smectite and glassy minerals] was used for BD interpretation in all soil orders and land uses. Region code and weathering class "2" refer to humid and highly weathered regions, respectively, and were used to modify AWC and P scores in all soils and land uses. Slope classes were used for P interpretation and were "1", "2", or "3" for soil samples collected at 0-2, 2.1-5, or 5.1-9% slope, respectively. The P method code was "1" for Mehlich-1. Lastly, the current SMAF version does not include crop codes for cassava, sugarcane, and semi-deciduous Atlantic Rainforest; thus, P and pH thresholds were set up based on literature. The optimum P and pH values were: 12 mg dm^{-3} and 5.5 for cassava and Atlantic Rainforest; 13 mg dm^{-3} and 5.5 for pasture; and 16 mg dm^{-3} and 6.0 for sugarcane (Cherubin et al., 2017, 2016a; van Raij et al., 1997). For grains, the SMAF crop code “8” was applied (19 mg kg^{-1} P and 6.3 optimum pH).

2.4 Statistical analysis

Analysis of variance of soil biological, physical, and chemical properties and derived SMAF soil health indices was performed using the R software *fat* and *ExpDes* packages (R Core Team, 2022). The Shapiro-Wilk’s and Bartlett’s tests ($p > 0.05$) were performed to check residue normality and variance homogeneity of the data using the R *base* and *car* packages. Soil order (Ultisol and Oxisol) and land use [cassava (CA), forest fragment (FF), forest restoration (FR), grains (GR), pasture (PA), and sugarcane (SC)] were considered fixed effects in a completely randomized block design, with replication being a random effect ($n = 3$). When main effects of interactions were observed among the explanatory variables ($p < 0.05$), mean separation was performed using Tukey’s test ($p < 0.05$). Depth was not included as a factor in statistical analysis and was not compared.

3. Results and Discussion

3.1 Impacts of land use on soil biological quality

The SMAF biological scores at the 0-5 cm soil depth were affected by the varying land uses in the Oxisol and Ultisol (Table 2), with no effects at the 95-100 cm soil depth (Table 3). In the topsoil, SOC scores were the highest at the forest fragment, pasture, and forest restoration site, with cassava and annual grains showing the lowest SOC score ($p < 0.05$), as a result of the lowest SOC contents (Supplementary Table 1). Specifically, the mean SOC scores in the Oxisol forest fragment and pasture were 3-4 times higher than the cassava and grains, and 2-3 times higher than the sugarcane scores. For the Ultisol, the mean SOC score in the forest restoration was the highest, being 7-times higher than the cassava and 3-times higher than the grains scores. In general, the highest SOC scores in this study (0.72-0.88) were similar or below those reported in the literature for similar soils, cropping systems and environmental conditions (Cherubin et al., 2017; Lisboa et al., 2019; Ruiz et al., 2020), indicating an opportunity to increase C sequestration and soil health through enhanced organic matter management (e.g., straw maintenance, cover crops, manure applications, etc (Amorim et al., 2020). Microbial biomass C and BG scores were mostly unaffected by soil order or land uses (Table 2; $p > 0.05$); however, a trend of low MBC and BG scores was observed for cassava.

3.2 Soil chemical quality as affected by land use

Soil pH scores under sugarcane, pasture, and grains were 34-61% higher than the forest fragment and restoration site (Table 2; $p < 0.05$), likely as a result of higher soil pH and lime application (Supplementary Table 1). Although P scores were not different among land uses ($p > 0.05$), a trend of higher P scores can be observed in the Oxisol annual grains and in the Ultisol sugarcane, while scores near to zero were mostly found in the natural or low-input systems with very low P contents (i.e., cassava, pasture, and forest fragment; 1.33-1.53 mg kg^{-1} P). Mean K scores were the highest in the forest fragment, restoration, and annual grains, owing to the higher K contents (Supplementary Table 1), while near-zero K scores were observed for cassava, pasture, and sugarcane (1.43-5.65 mg kg^{-1} K). Previous SMAF studies in south-central Brazil also reported a similar pattern of low P scores in native vegetation compared to managed pasture and sugarcane plantations (Luz et al., 2019), and lower K scores under pasture and sugarcane and higher scores under native vegetation (Cherubin et al., 2017; Luz et al., 2019). Such pattern is probably linked to increased K availability from parent material (e.g., gneiss) and cycling through litterfall in the native forest. As for pasture and sugarcane, both crops have enhanced K uptake and can lead to soil K depletion with further soil chemical degradation if the nutrient is not replenished to the soil via residue management or proper fertilization.

3.3 Soil physical quality across land uses

The forest fragment and restoration site had the highest BD scores at the 0-5 cm soil depth (Table 2; $p < 0.05$), while the other land uses had BD scores between 0.37 and 0.53, owing to increased BD at the 0-5 cm soil depth (1.56-1.68 Mg m^{-3}). Lower BD scores under pasture and sugarcane compared to native forest were reported previously (Cherubin et al., 2017; Luz et al., 2019; Matos et al., 2022), evidencing the negative impacts of intensive management on soil structure and water storage. Mean WFPS scores of grains, pasture, and sugarcane (0.75-0.87) were higher than the forest fragment and restoration sites ($p < 0.05$; 0.46-0.52), as a result of similar available water contents (Supplemental Table 1) combined with lower total porosity (i.e., increased soil compaction). For plant-available soil water (AWC), no differences ($p > 0.05$) were observed among land uses for both sampling depths.

3.4 Overall soil health across land uses and soil types

As a result of greater biological health, K, and BD scores, the forest fragment had an overall SQI of 61%, greater than cassava (Table 2; $p < 0.05$), with the other land uses showing intermediate values (56-60%), not differing from the forest fragment. Hence, SQI was primarily associated with biological variables in the surface layer, consistent with studies demonstrating their sensitivity in detecting improvements in soil quality after forest restoration or conservation agriculture (Cherubin et al., 2016). Collectively, the lower individual scores under cassava resulted in an overall SQI of 45%, owing to the lack of chemical and biological quality (Figure 3), for 0-5 cm depth. Cassava is cultivated in the region under a nutrient replacement management system and in monoculture for several years in the same area (Reichert et al., 2021). Owing to its relevance as a staple crop, particularly in lower income communities (Burrell, 2003; Yu & Tao, 2009), it is crucial for technicians and extension workers to guide farmers in implementing best management practices that enhance soil conservation, such as vegetative practices like crop rotation.

Table 2. Soil Management Assessment Framework (SMAF) scores measured at the 0-5 cm soil depth in two soil orders (Oxisol and Ultisol) and six land uses [forest fragment (FF), forest restoration (FR), cassava (CA), grains (GR), pasture (PA), and sugar cane (SC)] in Pontal do Paranapanema, SP, Brazil, across soil orders per land use, and per soil order × land use combinations.

Land Use[†]	**Soil Order**	**SMAF Scores**[‡]									
		SOC	**MBC**	**BG**	**pH**	**P**	**K**	**BD**	**AWC**	**WFPS**	**SQI (%)**
FF		0.68 ± 0.1 a	0.99 ± 0.1 a	0.97 ± 0.1 a	0.64 ± 0.05 cd	0.09 ± 0.1 a	0.17 ± 0.04 a	0.99 ± 0.06 a	0.48 ± 0.1 a	0.46 ± 0.07 d	60.9 ± 3.2 a
FR		0.50 ± 0.1 ab	0.86 ± 0.1 a	0.91 ± 0.1 a	0.61 ± 0.05 d	0.24 ± 0.1 a	0.18 ± 0.05 a	0.83 ± 0.06 a	0.47 ± 0.1 a	0.52 ± 0.07 cd	58.6 ± 3.6 ab
CA		0.18 ± 0.1 d[§]	0.72 ± 0.1 a	0.55 ± 0.1 a	0.78 ± 0.05 bc	0.08 ± 0.1 a	0.01 ± 0.04 b	0.53 ± 0.06 b	0.51 ± 0.1 a	0.68 ± 0.07 bc	44.8 ± 3.2 b
GR		0.27 ± 0.1 cd	0.96 ± 0.1 a	0.93 ± 0.1 a	0.86 ± 0.05 ab	0.33 ± 0.1 a	0.17 ± 0.05 a	0.53 ± 0.06 b	0.50 ± 0.1 a	0.75 ± 0.07 ab	58.5 ± 3.6 ab
PA		0.56 ± 0.1 ab	1.00 ± 0.1 a	0.81 ± 0.1 a	0.90 ± 0.05 ab	0.08 ± 0.1 a	0.05 ± 0.04 b	0.50 ± 0.06 b	0.63 ± 0.1 a	0.87 ± 0.07 a	60.0 ± 3.2 ab
SC		0.43 ± 0.1 bc	0.86 ± 0.1 a	0.72 ± 0.1 a	0.98 ± 0.05 a	0.32 ± 0.1 a	0.05 ± 0.04 b	0.37 ± 0.06 b	0.49 ± 0.1 a	0.85 ± 0.07 ab	55.5 ± 3.9 ab
p-value		*< 0.01*	*0.35*	*0.10*	*< 0.01*	*0.46*	*0.01*	*< 0.01*	*0.58*	*< 0.01*	*0.02*
FF	Oxisol	0.88 ± 0.1 a	1.00 ± 0.1 a	1.01 ± 0.2 a	0.62 ± 0.1 a	0.06 ± 0.2 a	0.05 ± 0.06 cde	0.99 ± 0.1 a	0.49 ± 0.1 a	0.55 ± 0.1 a	62.9 ± 4.5 abc
FR		0.29 ± 0.1 cd	0.71 ± 0.1 a	0.85 ± 0.2 a	0.57 ± 0.1 a	0.12 ± 0.2 a	0.14 ± 0.06 bcd	0.88 ± 0.1 a	0.52 ± 0.1 a	0.54 ± 0.1 a	51.2 ± 4.5 bcd
CA		0.25 ± 0.1 cd	0.97 ± 0.1 a	0.71 ± 0.2 a	0.78 ± 0.1 a	0.13 ± 0.2 a	0.00 ± 0.06 e	0.44 ± 0.1 a	0.52 ± 0.1 a	0.77 ± 0.1 a	50.7 ± 4.5 cd
GR		0.27 ± 0.1 cd	1.00 ± 0.1 a	1.00 ± 0.2 a	0.84 ± 0.1 a	0.65 ± 0.2 a	0.28 ± 0.06 a	0.48 ± 0.1 a	0.49 ± 0.1 a	0.76 ± 0.1 a	64.1 ± 4.5 ab
PA		0.74 ± 0.1 ab	1.00 ± 0.1 a	0.77 ± 0.2 a	0.87 ± 0.1 a	0.12 ± 0.2 a	0.09 ± 0.06 bcde	0.51 ± 0.1 a	0.61 ± 0.1 a	0.90 ± 0.1 a	62.2 ± 4.5 abc
SC		0.35 ± 0.1 cd	1.00 ± 0.1 a	0.68 ± 0.2 a	0.99 ± 0.1 a	0.25 ± 0.2 a	0.05 ± 0.06 cde	0.39 ± 0.1 a	0.46 ± 0.1 a	0.85 ± 0.1 a	52.8 ± 5.5 a-d
FF	Ultisol	0.49 ± 0.1 bc	0.98 ± 0.1 a	0.94 ± 0.2 a	0.66 ± 0.1 a	0.12 ± 0.2 a	0.28 ± 0.06 ab	0.99 ± 0.1 a	0.47 ± 0.1 a	0.38 ± 0.1 a	58.9 ± 4.5 abc
FR		0.72 ± 0.1 ab	1.00 ± 0.1 a	0.98 ± 0.2 a	0.65 ± 0.1 a	0.36 ± 0.2 a	0.23 ± 0.07 abc	0.79 ± 0.1 a	0.41 ± 0.1 a	0.51 ± 0.1 a	66.1 ± 5.5 a
CA		0.10 ± 0.1 d	0.47 ± 0.1 a	0.38 ± 0.2 a	0.77 ± 0.1 a	0.04 ± 0.2 a	0.03 ± 0.06 de	0.61 ± 0.1 a	0.50 ± 0.1 a	0.60 ± 0.1 a	38.9 ± 4.5 d
GR		0.26 ± 0.1 cd	0.92 ± 0.1 a	0.86 ± 0.2 a	0.89 ± 0.1 a	0.01 ± 0.2 a	0.06 ± 0.07 de	0.58 ± 0.1 a	0.52 ± 0.1 a	0.75 ± 0.1 a	52.8 ± 5.5 a-d
PA		0.39 ± 0.1 cd	1.00 ± 0.1 a	0.85 ± 0.2 a	0.92 ± 0.1 a	0.04 ± 0.2 a	0.02 ± 0.06 de	0.48 ± 0.1 a	0.65 ± 0.1 a	0.85 ± 0.1 a	57.8 ± 4.5 abc
SC		0.51 ± 0.1 bc	0.72 ± 0.1 a	0.75 ± 0.2 a	0.96 ± 0.1 a	0.39 ± 0.2 a	0.05 ± 0.06 de	0.36 ± 0.1 a	0.51 ± 0.1 a	0.84 ± 0.1 a	58.3 ± 5.5 abc
p-value		*< 0.01*	*0.15*	*0.67*	*0.98*	*0.23*	*0.01*	*0.74*	*0.97*	*0.86*	*0.03*

[†] FF, forest fragment; FR, forest restoration; CA, cassava; GR, grains; PA, pasture; SC, sugar cane;

[‡] SOC, soil organic C; MBC, microbial biomass C; BG, beta-glucosidase; BD, bulk density; AWC, available water capacity; WFPS, water filled porosity space; SQI, soil quality index;

[§] Means followed by the same letter within a column do not differ ($p > 0.05$).

Table 3. Soil Management Assessment Framework (SMAF) scores measured at the 95-100 cm soil depth in two soil orders (Oxisol and Ultisol) and six land uses [forest fragment (FF), forest restoration (FR), cassava (CA), grains (GR), pasture (PA), and sugar cane (SC)] in Pontal do Paranapanema, SP, Brazil, across soil orders per land use, and per soil order × land use combinations.

Land Use†	**Soil Order**	**SMAF Scores‡**							
		SOC	**pH**	**P**	**K**	**BD**	**AWC**	**WFPS**	**SQI (%)**
FF		0.36 ± 0.1 a	0.64 ± 0.1 a	0.01 ± 0.03 a	0.09 ± 0.02 a	0.61 ± 0.1 a	0.38 ± 0.05 a	0.52 ± 0.1 a	38.4 ± 2.3 a
FR		0.27 ± 0.1 a	0.72 ± 0.1 a	0.03 ± 0.03 a	0.05 ± 0.03 abc	0.52 ± 0.1 a	0.34 ± 0.05 a	0.52 ± 0.1 a	36.2 ± 2.3 a
CA		0.22 ± 0.1 a§	0.74 ± 0.1 a	0.00 ± 0.03 a	0.01 ± 0.02 bc	0.42 ± 0.1 a	0.30 ± 0.05 a	0.54 ± 0.1 a	31.9 ± 2.3 a
GR		0.32 ± 0.1 a	0.81 ± 0.1 a	0.08 ± 0.03 a	0.06 ± 0.02 ab	0.57 ± 0.1 a	0.35 ± 0.05 a	0.52 ± 0.1 a	38.8 ± 2.3 a
PA		0.35 ± 0.1 a	0.83 ± 0.1 a	0.00 ± 0.03 a	0.01 ± 0.02 c	0.45 ± 0.1 a	0.48 ± 0.05 a	0.77 ± 0.1 a	41.5 ± 2.3 a
SC		0.32 ± 0.1 a	0.83 ± 0.1 a	0.00 ± 0.03 a	0.03 ± 0.02 bc	0.48 ± 0.1 a	0.38 ± 0.05 a	0.52 ± 0.1 a	36.6 ± 2.3 a
p-value		*0.70*	*0.13*	*0.44*	*0.01*	*0.37*	*0.15*	*0.18*	*0.11*
FF	Oxisol	0.44 ± 0.1 a	0.66 ± 0.1 a	0.00 ± 0.04 a	0.03 ± 0.03 a	0.53 ± 0.1 a	0.45 ± 0.06 a	0.72 ± 0.1 a	42.9 ± 3.2 a
FR		0.25 ± 0.1 a	0.73 ± 0.1 a	0.06 ± 0.04 a	0.03 ± 0.03 a	0.51 ± 0.1 a	0.33 ± 0.06 a	0.56 ± 0.1 a	35.2 ± 3.2 a
CA		0.26 ± 0.1 a	0.71 ± 0.1 a	0.00 ± 0.04 a	0.00 ± 0.03 a	0.43 ± 0.1 a	0.31 ± 0.06 a	0.54 ± 0.1 a	32.2 ± 3.2 a
GR		0.33 ± 0.1 a	0.78 ± 0.1 a	0.14 ± 0.04 a	0.07 ± 0.03 a	0.64 ± 0.1 a	0.30 ± 0.06 a	0.46 ± 0.1 a	39.0 ± 3.2 a
PA		0.49 ± 0.1 a	0.86 ± 0.1 a	0.00 ± 0.04 a	0.01 ± 0.03 a	0.41 ± 0.1 a	0.45 ± 0.06 a	0.77 ± 0.1 a	42.8 ± 3.2 a
SC		0.23 ± 0.1 a	0.89 ± 0.1 a	0.00 ± 0.04 a	0.03 ± 0.03 a	0.51 ± 0.1 a	0.33 ± 0.06 a	0.55 ± 0.1 a	36.2 ± 3.2 a
FF	Ultisol	0.28 ± 0.1 a	0.63 ± 0.1 a	0.02 ± 0.04 a	0.14 ± 0.03 a	0.69 ± 0.1 a	0.30 ± 0.06 a	0.31 ± 0.1 a	33.8 ± 3.2 a
FR		0.29 ± 0.1 a	0.72 ± 0.1 a	0.00 ± 0.04 a	0.07 ± 0.04 a	0.53 ± 0.1 a	0.35 ± 0.06 a	0.48 ± 0.1 a	37.3 ± 3.2 a
CA		0.18 ± 0.1 a	0.76 ± 0.1 a	0.00 ± 0.04 a	0.03 ± 0.03 a	0.41 ± 0.1 a	0.30 ± 0.06 a	0.53 ± 0.1 a	31.5 ± 3.2 a
GR		0.31 ± 0.1 a	0.84 ± 0.1 a	0.02 ± 0.04 a	0.04 ± 0.03 a	0.50 ± 0.1 a	0.41 ± 0.06 a	0.58 ± 0.1 a	38.5 ± 3.2 a
PA		0.21 ± 0.1 a	0.80 ± 0.1 a	0.00 ± 0.04 a	0.00 ± 0.03 a	0.50 ± 0.1 a	0.52 ± 0.06 a	0.77 ± 0.1 a	40.2 ± 3.2 a
SC		0.42 ± 0.1 a	0.77 ± 0.1 a	0.00 ± 0.04 a	0.03 ± 0.03 a	0.45 ± 0.1 a	0.43 ± 0.06 a	0.49 ± 0.1 a	37.1 ± 3.2 a
p-value		*0.25*	*0.84*	*0.58*	*0.07*	*0.68*	*0.36*	*0.29*	*0.56*

† FF, forest fragment; FR, forest restoration; CA, cassava; GR, grains; PA, pasture; SC, sugar cane;

‡ SOC, soil organic C; MBC, microbial biomass C; BG, beta-glucosidase; BD, bulk density; AWC, available water capacity; WFPS, water filled porosity space; SQI, soil quality index;

§ Means followed by the same letter within a column do not differ ($p > 0.05$).

The forest restoration adopted in the region, in general, has shown potential in promoting soil health and bringing the conditions of the forest fragment closer together, which can be seen in the similar SQI values, especially when comparing the averages of the two soils (60.9% for FF and 58.6% for FR, Figure 1). Also, forest fragment and restoration showed the same pattern of increased soil biological quality and mean BD score > 80% (Figure 3). This suggests that areas with greater vegetation cover, such as forest fragment and restoration, favor nutrient cycling and the maintenance of microbial activity, improving the surface soil quality (Cherubin et al., 2016; Karlen et al., 2008; Zinn et al., 2007). The SOC accumulation in soils under forest has been widely documented, showing that forest restoration systems can potentially recover soil quality in degraded areas (Nunes et al., 2021). However, when analyzed separately by soil type, the effectiveness of FR varied. In Ultisol, FR (66.1%) was more effective in approaching FF (58.9%), whereas in Oxisol, FR (51.2%) was less effective, reaching a lower similarity to FF (62.9%). In addition, the forest restoration site in the Ultisol had 30% greater SQI than in the Oxisol. This difference can be mainly attributed to the lower SOC contents under FR in the Ultisol (Table 2; Supplementary Table 1). This may be explained by the origin of areas typically designated for forest restoration, which often include previously degraded pastureland. As a result, organic matter levels are lower due to the removal of part of the surface horizon by erosion (Avanzi et al., 2013; Barros et al., 2018; Santana et al., 2023a), in addition to potentially having higher bulk density (BD) due to overgrazing and compaction. In contrast, Oxisols are considered soils with a greater capacity to accumulate organic matter when compared to Ultisols, which can be explained by the greater inherent structural stability of these soils, which is also consistent with the literature that highlights the resilience of Oxisols in maintaining the biological soil quality, even under different management systems (Amorim et al., 2023). Thus, with appropriate management practices, soil health is expected to improve over time in this environment.

In general, all land uses showed a deficit in chemical quality (i.e., gap in available P and K in Fig. 3), which reflects the natural nutrient depletion of tropical, highly weathered soils coupled to minimal fertility management. However, annual grains and sugarcane had lower physical and biological quality than the forest uses, but greater chemical scores (Fig. 3), which helped to offset the overall SQI (Figure 1). These results are consistent with Cherubin et al. (2017), whose findings indicated significant physical and biological degradation in agricultural soils compared to native forest, with SQI scores from the SMAF showing that soils with native vegetation functioned at 80% of its capacity, while long-term agricultural soil operated at only 64% of its potential.

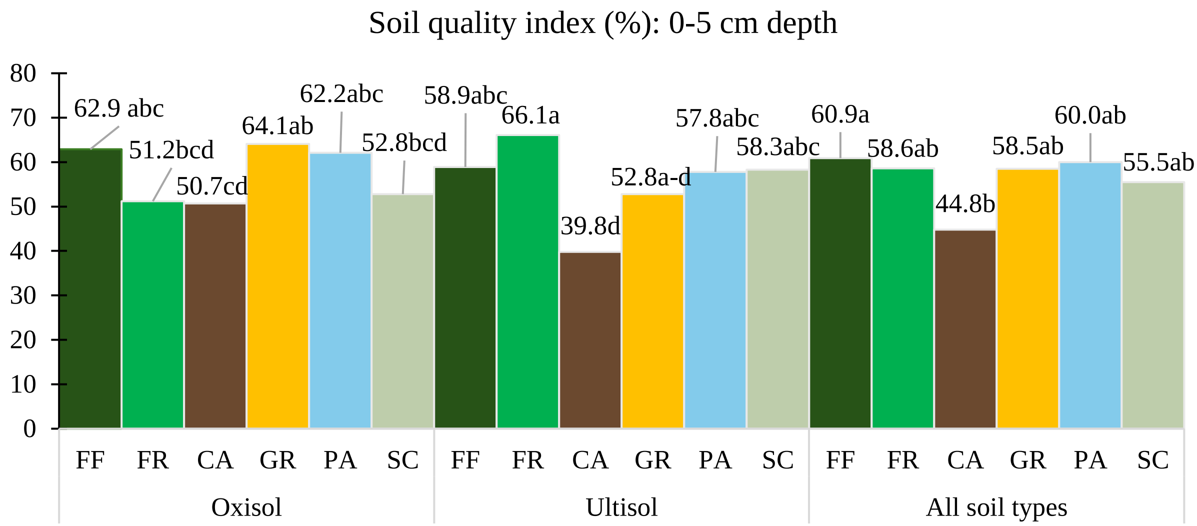

Figure 1. Soil Management Assessment Framework (SMAF) soil quality indices at the 0-5 cm soil depth in Pontal do Paranapanema, SP, Brazil, across soil orders (Oxisol and Ultisol) and average for all soil types per land use. Means followed by the same letter within a column do not differ ($p > 0.05$).

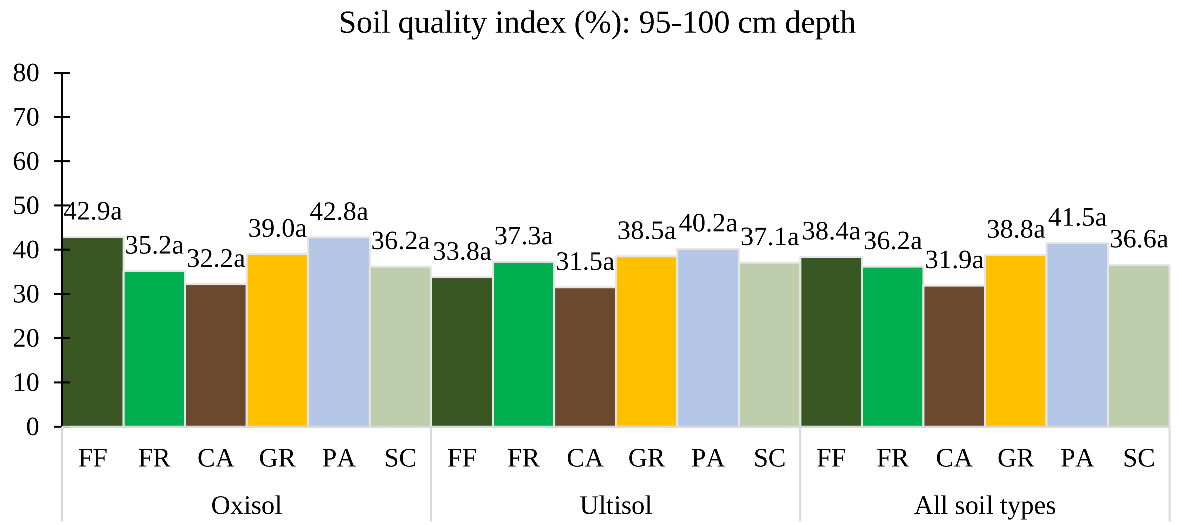

Figure 2. Soil Management Assessment Framework (SMAF) soil quality indices at the 95-100 cm soil depth in Pontal do Paranapanema, SP, Brazil, across soil orders (Oxisol and Ultisol) and average for all soil types per land use. Means followed by the same letter within a column do not differ ($p > 0.05$).

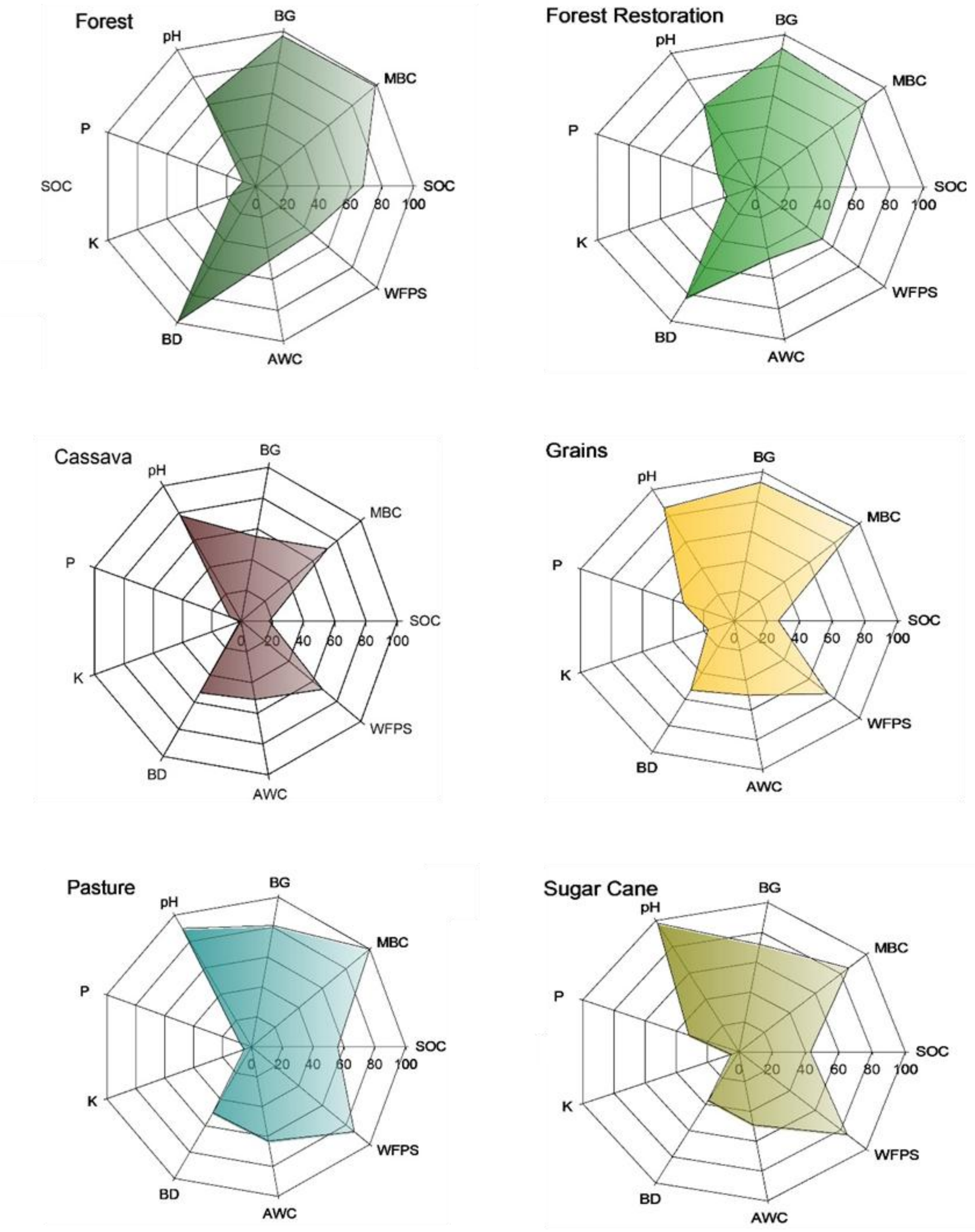

Figure 3. Radar plots of Soil Management Assessment Framework (SMAF) soil quality indices (%) [soil organic C (SOC), microbial biomass C (MBC), beta-glucosidase (BG), Mehlich-1 extractable P and K; bulk density (BD), available water capacity (AWC); water filled porosity space (WFPS)] at the 0-5 cm soil depth in Pontal do Paranapanema, SP, Brazil, across soil orders (Oxisol and Ultisol) per land use.

In turn, pasture had greater MBC and SOC scores than annual grains and sugarcane, likely due to root-C inputs and greater microbial activity, resulting in an overall SQI of 60%. Cherubin et al. (2017) suggest that management strategies to restore soil quality in agricultural areas should primarily focus on increasing soil carbon and alleviating soil compaction. As such, we demonstrated that land uses impacted soil chemical, physical, and biological properties differently, evidencing gaps for management improvements in each land use.

The impacts of land use on soil health differed within soil orders ($p < 0.05$; Table 2) as previously demonstrated for FR and FF. In the Ultisol, the SMAF SQI in the forest fragment, forest restoration, pasture, and sugarcane sites were 50-70% greater than cassava, which had the lowest SQI of all land uses across soils (39%). As for the Oxisol, annual grains, forest fragment, and pasture had 22-25% greater SQI than cassava, owing to enhanced soil fertility and SOC concentration (Table 2). Indeed, the depletion of soil organic matter through conventional tillage in cassava productions systems reduced the SOC score and soil biological quality at the 0-15 cm in a sandy clay loam Oxisol (Cherubin et al., 2017).

Also, our results underscore the role of inherent soil properties, such as soil texture and mineralogy, on SOC retention and nutrient availability, which in turn greatly affect overall soil health in low-input agroecosystems (e.g., cassava and forest restoration). Soil type is considered an intrinsic factor in soil functions, and can interact with land uses and drive change. However, this aspect has been little explored in Brazil, with few studies on soil health addressing soil type as an inherent factor, usually related to texture variation. This analysis provides information on the response of essential soil functions to human activities and their interaction with natural factors in the Pontal do Paranapanema region. In general, the results indicate that both intrinsic factors, such as soil type, and dynamic factors, such as land use and management, have a direct influence on soil health (Santana et al. 2023). In addition, the impact of these practices on the management of soil properties and dynamic functions varies according to location and is conditioned by soil type. Thus, land use and management strategies aimed at improving soil functionality in the Pontal do Paranapanema region must take these intrinsic characteristics into account.

4. Conclusion

Soil health, assessed via SMAF, was affected by land use in the Pontal do Paranapanema region in Brazil. Results indicated that forest fragment areas showed the best soil quality indices, followed by forest restoration areas. This suggests forest restoration not only recovered soil quality, but also contributes to the sustainability of ecosystem services, especially those related to water recharge. However, the effectiveness of forest restoration in improving soil health was directly related to prior land use, highlighting the need for appropriate management strategies to maximize the benefits of restoration in tropical soils.

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Conflict of interest statement

All authors certify that they have no affiliations or involvement with any organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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Supplementary Table 1. Soil physiochemical properties measured at the 0-5 cm soil depth in two soil orders (Oxisol and Ultisol) and six land uses [forest fragment (FF), forest restoration (FR), cassava (CA), grains (GR), pasture (PA), and sugar cane (SC)] in Pontal do Paranapanema, SP, Brazil, across soil orders per land use, and per soil order × land use combinations.

Land Use†	**Soil Order**	**Soil Properties‡**								
		SOC	**MBC**	**BG**	**pH**	**P**	**K**	**BD**	**AWC**	**WFPS**
		%	mg kg^{-1}	μg PNF g^{-1} h^{-1}		mg kg^{-1}		Mg m^{-3}	g g^{-1}	
FF		0.83 ± 0.07 a	475.80 ± 58.7 a	191.81 ± 29.7 a	4.92 ± 0.4 a	1.33 ± 1.7 a	18.95 ± 5.3 a	1.27 ± 0.04 c	0.08 ± 0.01 a	0.18 ± 0.04 b
FR		0.66 ± 0.07 ab	241.95 ± 58.7 bc	134.38 ± 29.7 a	4.82 ± 0.4 a	2.54 ± 1.7 a	20.01 ± 5.8 a	1.42 ± 0.04 b	0.08 ± 0.01 a	0.20 ± 0.04 b
CA		0.37 ± 0.07 c[§]	151.15 ± 58.7 c	82.06 ± 29.7 a	5.37 ± 0.4 a	1.33 ± 1.7 a	1.43 ± 5.3 b	1.59 ± 0.04 a	0.09 ± 0.01 a	0.28 ± 0.04 ab
GR		0.50 ± 0.07 bc	277.61 ± 58.7 bc	147.77 ± 29.7 a	6.10 ± 0.4 a	7.64 ± 1.8 a	20.51 ± 5.8 a	1.56 ± 0.04 a	0.11 ± 0.01 a	0.33 ± 0.04 a
PA		0.70 ± 0.07 ab	391.83 ± 58.7 ab	111.30 ± 29.7 a	5.83 ± 0.4 a	1.53 ± 1.7 a	5.65 ± 5.3 b	1.61 ± 0.04 a	0.12 ± 0.01 a	0.39 ± 0.04 a
SC		0.64 ± 0.07 ab	307.40 ± 58.7 abc	115.78 ± 29.7 a	5.90 ± 0.4 a	4.10 ± 2.0 a	4.88 ± 5.3 b	1.68 ± 0.04 a	0.10 ± 0.01 a	0.36 ± 0.04 a
p-value		*< 0.01*	*0.01*	*0.20*	*0.07*	*0.14*	*0.01*	*< 0.01*	*0.08*	*< 0.01*
FF	Oxisol	1.05 ± 0.1 a	595.56 ± 82.9 a	236.12 ± 41.9 a	4.87 ± 0.5 a	1.49 ± 2.3 a	5.68 ± 7.5 cd	1.27 ± 0.06 a	0.10 ± 0.02 a	0.21 ± 0.05 a
FR		0.46 ± 0.1 cd	178.61 ± 82.9 a	93.97 ± 41.9 a	4.70 ± 0.5 a	1.44 ± 2.3 a	15.31 ± 7.5 bcd	1.41 ± 0.06 a	0.08 ± 0.02 a	0.20 ± 0.05 a
CA		0.47 ± 0.1 cd	203.66 ± 82.9 a	102.19 ± 41.9 a	5.37 ± 0.5 a	1.61 ± 2.3 a	0.00 ± 7.5 cd	1.61 ± 0.06 a	0.10 ± 0.02 a	0.34 ± 0.05 a
GR		0.51 ± 0.1 cd	374.09 ± 82.9 a	194.60 ± 41.9 a	6.07 ± 0.5 a	13.89 ± 2.3 a	34.58 ± 7.5 a	1.58 ± 0.06 a	0.12 ± 0.02 a	0.38 ± 0.05 a
PA		0.85 ± 0.1 ab	480.99 ± 82.9 a	123.91 ± 41.9 a	5.70 ± 0.5 a	1.65 ± 2.3 a	9.00 ± 7.5 bcd	1.59 ± 0.06 a	0.13 ± 0.02 a	0.40 ± 0.05 a
SC		0.59 ± 0.1 bc	377.09 ± 82.9 a	129.99 ± 41.9 a	6.13 ± 0.5 a	3.48 ± 2.9 a	4.93 ± 7.5 cd	1.65 ± 0.06 a	0.11 ± 0.02 a	0.36 ± 0.05 a
FF	Ultisol	0.61 ± 0.1 bc	356.05 ± 82.9 a	147.50 ± 41.9 a	4.97 ± 0.5 a	1.17 ± 2.3 a	32.21 ± 7.5 ab	1.28 ± 0.06 a	0.07 ± 0.02 a	0.15 ± 0.05 a
FR		0.86 ± 0.1 ab	305.29 ± 82.9 a	174.78 ± 41.9 a	4.93 ± 0.5 a	3.63 ± 2.3 a	24.71 ± 8.8 abc	1.43 ± 0.06 a	0.07 ± 0.02 a	0.19 ± 0.05 a
CA		0.28 ± 0.1 d	98.63 ± 82.9 a	61.92 ± 41.9 a	5.37 ± 0.5 a	1.06 ± 2.3 a	2.86 ± 7.5 d	1.57± 0.06 a	0.08 ± 0.02 a	0.22 ± 0.05 a
GR		0.49 ± 0.1 cd	181.14 ± 82.9 a	100.94 ± 41.9 a	6.13 ± 0.5 a	1.38 ± 2.9 a	6.44 ± 8.8 cd	1.54 ± 0.06 a	0.10 ± 0.02 a	0.29 ± 0.05 a
PA		0.54 ± 0.1 cd	302.66 ± 82.9 a	98.69 ± 41.9 a	5.97 ± 0.5 a	1.41 ± 2.3 a	2.31 ± 7.5 d	1.63 ± 0.06 a	0.12 ± 0.02 a	0.39 ± 0.05 a
SC		0.68 ± 0.1 bc	237.71 ± 82.9 a	101.57 ± 41.9 a	5.67 ± 0.5 a	4.72 ± 2.9 a	4.83 ± 7.5 d	1.71 ± 0.06 a	0.10 ± 0.02 a	0.36 ± 0.05 a
p-value		*< 0.01*	*0.33*	*0.37*	*0.98*	*0.09*	*0.01*	*0.93*	*0.97*	*0.86*

† FF, forest fragment; FR, forest restoration; CA, cassava; GR, grains; PA, pasture; SC, sugar cane;

‡ SOC, soil organic C; MBC, microbial biomass C; BG, beta-glucosidase; Mehlich-1 extractable P and K; BD, bulk density; AWC, available water capacity; WFPS, water filled porosity space;

§ Means followed by the same letter do not differ ($p > 0.05$).

Supplementary Table 2. Soil physiochemical properties measured at the 95-100 cm soil depth in two soil orders (Oxisol and Ultisol) and six land uses [forest fragment (FF), forest restoration (FR), cassava (CA), grains (GR), pasture (PA), and sugar cane (SC)] in Pontal do Paranapanema, SP, Brazil, across soil orders per land use, and per soil order × land use combinations.

Land Use†	**Soil Order**	**Soil Properties‡**						
		SOC	**pH**	**P**	**K**	**BD**	**AWC**	**WFPS**
		%		mg kg^{-1}		Mg m^{-3}	g g^{-1}	
FF		0.62 ± 0.1 a	4.92 ± 0.3 a	0.57 ± 0.4 a	8.73 ± 2.5 a	1.46 ± 0.04 a	0.08 ± 0.01 a	0.23 ± 0.04 a
FR		0.52 ± 0.1 a	5.18 ± 0.3 a	0.77 ± 0.4 a	3.93 ± 2.7 abc	1.53 ± 0.04 a	0.07 ± 0.01 a	0.21 ± 0.04 a
CA		0.45 ± 0.1 a§	5.23 ± 0.3 a	0.13 ± 0.4 a	1.41 ± 2.5 bc	1.61 ± 0.04 a	0.06 ± 0.01 a	0.20 ± 0.04 a
GR		0.54 ± 0.1 a	5.25 ± 0.3 a	1.33 ± 0.4 a	5.64 ± 2.5 ab	1.53 ± 0.04 a	0.07 ± 0.01 a	0.20 ± 0.04 a
PA		0.56 ± 0.1 a	5.68 ± 0.3 a	0.28 ± 0.4 a	0.62 ± 2.5 c	1.60 ± 0.04 a	0.10 ± 0.01 a	0.33 ± 0.04 a
SC		0.57 ± 0.1 a	5.15 ± 0.3 a	0.39 ± 0.4 a	3.00 ± 2.5 bc	1.54 ± 0.04 a	0.07 ± 0.01 a	0.21 ± 0.04 a
p-value		*0.69*	*0.44*	*0.47*	*0.02*	*0.14*	*0.11*	*0.11*
FF	Oxisol	0.67 ± 0.1 a	4.97 ± 0.4 a	0.22 ± 0.6 a	3.51 ± 3.6 a	1.54 ± 0.06 a	0.11 ± 0.01 a	0.32 ± 0.05 a
FR		0.46 ± 0.1 a	5.20 ± 0.4 a	1.23 ± 0.6 a	3.32 ± 3.6 a	1.55 ± 0.06 a	0.07 ± 0.01 a	0.21 ± 0.05 a
CA		0.49 ± 0.1 a	5.13 ± 0.4 a	0.11 ± 0.6 a	0.00 ± 3.6 a	1.59 ± 0.06 a	0.07 ± 0.01 a	0.20 ± 0.05 a
GR		0.56 ± 0.1 a	5.20 ± 0.4 a	1.88 ± 0.6 a	7.21 ± 3.6 a	1.48 ± 0.06 a	0.06 ± 0.01 a	0.18 ± 0.05 a
PA		0.71 ± 0.1 a	5.73 ± 0.4 a	0.37 ± 0.6 a	1.24 ± 3.6 a	1.63 ± 0.06 a	0.11 ± 0.01 a	0.35 ± 0.05 a
SC		0.49 ± 0.1 a	5.43 ± 0.4 a	0.48 ± 0.6 a	2.74 ± 3.6 a	1.54 ± 0.06 a	0.07 ± 0.01 a	0.20 ± 0.05 a
FF	Ultisol	0.57 ± 0.1 a	4.87 ± 0.4 a	0.93 ± 0.6 a	13.94 ± 3.6 a	1.39 ± 0.06 a	0.06 ± 0.01 a	0.14 ± 0.05 a
FR		0.58 ± 0.1 a	5.17 ± 0.4 a	0.30 ± 0.6 a	4.53 ± 4.0 a	1.51 ± 0.06 a	0.07 ± 0.01 a	0.20 ± 0.05 a
CA		0.41± 0.1 a	5.33 ± 0.4 a	0.15 ± 0.6 a	2.82 ± 3.6 a	1.63 ± 0.06 a	0.06 ± 0.01 a	0.20 ± 0.05 a
GR		0.52 ± 0.1 a	5.30 ± 0.4 a	0.78 ± 0.6 a	4.06 ± 3.6 a	1.58 ± 0.06 a	0.07 ± 0.01 a	0.22 ± 0.05 a
PA		0.42 ± 0.1 a	5.63 ± 0.4 a	0.19 ± 0.6 a	0.00 ± 3.6 a	1.58 ± 0.06 a	0.10 ± 0.01 a	0.32 ± 0.05 a
SC		0.65 ± 0.1 a	4.87 ± 0.4 a	0.30 ± 0.6 a	3.26 ± 3.6 a	1.55 ± 0.06 a	0.07 ± 0.01 a	0.22 ± 0.05 a
p-value		*0.29*	*0.92*	*0.73*	*0.10*	*0.32*	*0.44*	*0.36*

† FF, forest fragment; FR, forest restoration; CA, cassava; GR, grains; PA, pasture; SC, sugar cane;

‡ SOC, soil organic C; Mehlich-1 extractable P and K; BD, bulk density; AWC, available water capacity; WFPS, water filled porosity space;

§ Means followed by the same letter do not differ ($p > 0.05$).

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PAPER 3 – SOIL PHYSICAL QUALITY AND ECOSYSTEM SERVICES OF BIOMASS PRODUCTION, WATER RECHARGE AND EROSION RESISTANCE IN THE FACE OF AGRICULTURAL EXPANSION AND FOREST RESTORATION IN THE ATLANTIC FOREST

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Abstract

The importance of preserving soil through appropriate management practices lies in the many benefits that soils provide to society, such as those arising from soil ecosystem services. For this reason, the use of soil quality assessment protocols and studies such as water recharge potential are vital for monitoring impacts on environmental quality and ensuring the proper functioning of the soil. Thus, the impact of land use on ecosystem services can be assessed using a minimum set of indicators for calculating additive functions and a soil physical quality index. In this sense, the objective was to evaluate the physical properties associated with the relevant ecosystem services of the soil in Pontal do Paranapanema, considering the different uses, management systems and predominant soil classes in the region. The evaluation considered a combination of six land uses (forest fragment, forest restoration, pasture, sugar cane, grain cultivation and cassava) and two soil classes (Oxisol and Ultisol), predominant in the region. Deformed and undeformed soil samples were collected from the surface layer 0-5 cm and the subsurface layer 95-100 cm to analyze the physical indicators of soil quality and calculate the Soil Physical Quality Index. The intensive use of land for agriculture, particularly in sugarcane and cassava cultivation, led to higher soil compaction, affecting infiltration and root growth. In contrast, forest fragments and restoration areas showed better soil structure, with higher porosity and water retention capacity, reinforcing their role in preserving soil quality. The surface layer (0-5 cm) was more affected than deeper layers (95-100 cm). While restoration improved surface conditions, deeper layers still reflected past land use impacts. Oxisols had better water infiltration and lower resistance to penetration than Ultisols, indicating greater resilience. However, in both soil types, forest fragments demonstrated superior soil quality, serving as reference areas for conservation efforts. Conservation practices in grain cultivation, such as crop rotation and cover maintenance, improved soil conditions compared to conventional systems. Expanding these methods is essential to reducing compaction and erosion, particularly in Ultisols. Degraded areas, including abandoned pastures, should be prioritized for forest restoration with native species and managed to ensure long-term ecosystem recovery. The regional soil quality assessment tool effectively identified areas with degradation and potential for ecosystem services.

Keywords: root development; water for plants; gas exchange; resistance to erosion; groundwater recharge potential

1. Introduction

Soil acts as a dynamic and complex multifunctional ecosystem, supporting three main ecosystem services (ES): provisioning, regulating and supporting services (MEA, 2005b). The concept of soil quality is defined as the ability of the soil to function within the limits of the ecosystem in order to sustain agricultural productivity, maintain environmental quality and ensure human, plant and animal health (Doran & Parkin, 1994). Therefore, it is the soil's ability to perform its functions in nature, acting as a medium for plant growth and food production, maintaining biodiversity, controlling erosion processes, regulating water flows (hydrological cycle), and controlling floods by preventing flooding, contributing to the recharge of aquifers (Vezzani & Mielniczuk, 2009).

Soil quality is strongly influenced by its use and management (Castioni et al., 2019; Richart et al., 2005). When used inappropriately, it can degrade its physical, chemical and biological quality and/or reduce the quantity and quality of ES provided (Luz et al., 2019). Just as good soil uses and management practices improve soil quality (Freitas et al., 2012), compaction, lack of vegetation cover and low soil organic matter content are the main causes of agricultural soil degradation (Melo et al., 2021; Peixoto et al., 2019).

With the increase in global demand to ensure high levels of food production, agricultural activity has been very concerned about the physical degradation of the soil (Cavalcanti et al., 2020b; Cherubin; Bordonal, et al., 2021). Therefore, integrated agricultural and forestry production systems with the adoption of conservation practices such as minimum cultivation, crop rotation, green and cover fertilization and management of cultural remains, can provide ecosystem support and regulation services, such as increased nutrient cycling, greater infiltration of water into the soil and erosion control (Koschke et al., 2013; Lal, 2015; Tamburini et al., 2020). Knowing and monitoring soil quality indicators, their potential and weaknesses, as well as the characteristics of each production system, makes it easier to choose the best forms of land use and management. Thus, this approach makes it possible to pinpoint the production systems with the greatest potential for sustainability and the provision of ecosystem services.

In the Brazilian context, the suppression of native vegetation and the fragmentation of biomes, such as the Atlantic Forest, have been increasingly intensified. Originally, the Atlantic Forest covered around 15% of Brazil's territory, which corresponded to approximately 1.3 million km² spread over 17 states (SOS Mata Atlântica Foundation, 2017). Today, after decades of suppression and fragmentation, around 12.4% of its original cover remains, which is equivalent to approximately 160,000 km² (SOS Mata Atlântica Foundation, 2017). Most of these remnants are highly fragmented, with small isolated fragments, mainly in environmental protection areas. Even though they are reduced and fragmented, forest areas have a direct influence on climate protection, regulating infiltration processes and mitigating erosion events and therefore soil loss.

The Pontal do Paranapanema region, located in the Atlantic Forest in the far west of the state of São Paulo, was once considered one of the best preserved areas in the interior of the state. Since the mid-1856s, occupation in this region has been characterized by the most violent land conflicts in the country (Leite, 1998). Conversely, the process of land grabbing and illegal occupation characterized by the suppression of the natural environment, on the other hand, the claiming of these lands through occupations and encampments (squatters) pressuring the government for the implementation of settlements (Costa Neto, 2018). The strategy adopted by these groups basically consisted of eliminating the forest and forming pasture areas, on the presumption of demarcating and guaranteeing land ownership (Ditt, 2002). Also, as a result of the agrarian conflicts, part of the pasture areas was transformed into settlements, corresponding to areas of 20ha, and another part of these pasture areas was leased to sugarcane mills for the sugar and biofuel market (Souza, 2021).

With forest fragmentation and susceptibility to erosion processes, there is evidence of a reduction in soil functions and the economic value associated with it, as it reduces its productive capacity. This context points to an urgent need to restore degraded areas and preserve fragments of the Atlantic Forest, which is a major challenge for maintaining the capacity of these ecosystems to provide goods and services. Evaluating soil quality using indicators in biomes such as the Atlantic Forest is of the utmost importance, since it is home to large sugar-alcohol enterprises that seek to meet the demand for biofuels and major agricultural expansion.

A relevant approach in studies on the condition of soil in different land uses is the quantitative assessment of its quality. However, soil quality is not directly measured, but inferred based on the selection of a minimum set of relevant indicators (Cherubin et al., 2016a; Karlen et al., 1997; Rinot et al., 2019). Through these, it is possible to estimate a soil physical quality index (SPQI) and integrate multiple functions associated with groundwater recharge, through soil water infiltration indicators (bulk density, hydraulic conductivity and macroporosity) (Alvarenga et al., 2012), for example. The SPQI has also been used to assess the impacts of land use succession associated with sugarcane expansion in Brazil (Cherubin et al., 2016a) and to evaluate the dynamics and inherent soil factors that impact soil physical properties and the processes that drive water recharge potential, biomass production and water erosion control (Santana et al., 2023).

In the context of making water reservoirs more durable for cleaner electricity generation, as well as contributing to improving/maintaining the provision of ecosystem services, we tested the hypotheses: (i) forest restoration in degraded areas improves soil physical quality and water recharge potential; (ii) land use change from Atlantic forest to food and energy production (pasture, sugarcane; and more recently cassava and soybean) reduces soil quality and increases soil susceptibility to erosion, which can lead to increased siltation of water reservoirs; and (iii) soil type influences soil quality and ecosystem services for the same land use. Thus, our objectives were: (i) evaluate the physical properties linked to ecosystem services - provision of water, energy, food and erosion control - as a function of the main land uses (Atlantic forest, pasture, sugar cane, grain cultivation, cassava cultivation and forest restoration) and soil types (Oxisol and Ultisol) in the Pontal Paranapanema region; (ii) to access soil quality by means of the Soil Physical Quality Index (SPQI) and by multivariate analysis of soil physical and water properties; and (iii) to develop a tool/map to extrapolate the SQI and soil functions associated with the potential for water recharge and erosion control, with a view to enabling the monitoring of areas of agricultural expansion in the Atlantic Forest biome.

2. Material and Methods

2.1 Study area

The Pontal do Paranapanema region is located in the far west of the state of São Paulo, Brazil, between the important Paraná and Paranapanema rivers, covering more than 245,000 hectares. It is home to the municipality of Teodoro Sampaio, one of the largest in the state in terms of land area, which has the largest environmental preservation area in the interior of the state and the largest population on the planet of one of the most endangered primates, the black lion tamarin (Souza, 2021). This region is also home to the largest reforested forest ecological corridor in the country (Souza, 2021), between the cities of Teodoro Sampaio and Euclides da Cunha Paulista. The biome is Atlantic Forest and the original forest is classified as semideciduous seasonal (Oliveira-Filho & Fontes, 2000b), one of the most threatened of the global biodiversity hotspots (Myers et al., 2000). The predominant relief is flat or gently undulating, with an average altitude of 350 m. The geology of the region is made up of sedimentary rocks from the Cretaceous period, belonging to the Paraná Basin and composed mainly of sandstones, siltstones and claystones forming part of the Bauru Group (L. A. Fernandes & Coimbra, 2000). According to the Köppen classification, the climate is divided into continental type *Aw,* tropical humid with dry winters - the second most prevalent (25.8% of the country) - and *Cfa,* subtropical humid with hot summers - the fourth most prevalent (6.5%) - with an average annual temperature of between 22 and 24 ºC and annual rainfall of around 1500 mm (Alvares et al., 2013).

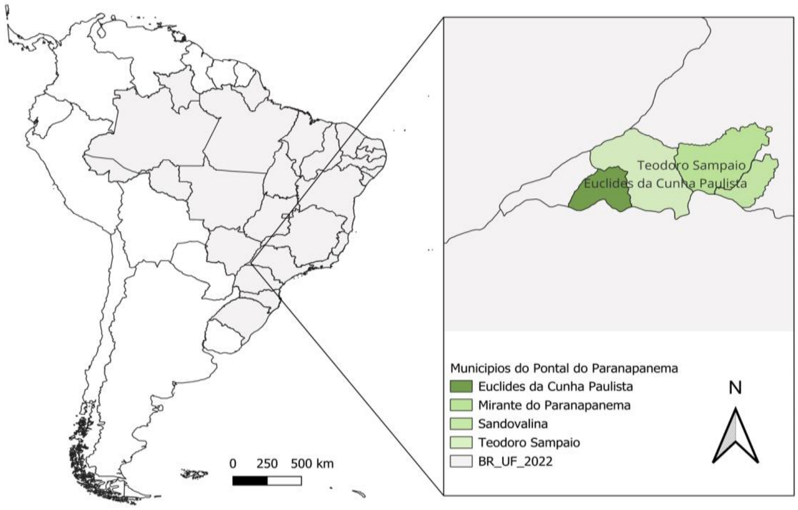

Figure 1. Geographic location of the Pontal do Paranapanema and study sites.

2.2 Sampling sites and soil characterization

In order to analyze and interpret soil quality and its impact on ecosystem services related to water resources (biomass production, water recharge, erosion resistance, flow regulation and sediment production), a combination of six land uses and two soil classes, predominant in the region, were studied: forest fragment as a reference area (FF), forest restoration (FR), pasture (PA), sugarcane (SC), grain cultivation (GR) and cassava (CA), and the soil classes Ultisol and Oxisol.

The FF area of native vegetation is represented by the Atlantic Forest and semideciduous forest. The FR has a history of use with degraded pasture and abandoned agricultural areas. Current forest recompositing started 5 years ago, no soil compaction mitigation practices were carried out during the establishment of the new plants. The PA area was converted from native forest 50 years ago for territorial demarcation purposes, being characterized by low animal density, around 0.8 animal unit/ha, and *Brachiaria decumbens* (Syn. *Urochloa decumbens*) is the main grass. For SC, soil is conventionally tilled with plowing and harrowing. Fertilization and irrigation were conducted through fertigation with vinasse to complement conventional amendments. The sugarcane was harvested mechanically, and the crop was transported by trailer. The GR cultivation area operates under no-till and a crop rotation system between corn and soybeans in summer, with a fallow period in autumn-winter. Surface soil cover is maintained with plant residues. The cassava (*Manihot esculenta* Crantz) area is manually prepared, with soil preparation involving the opening of planting holes after plowing and harrowing, followed by clearing the cultivation area during the first 120 days with a hoe to prevent competition with weeds.

The selected areas had similar management conditions and 3 replications were evaluated, totaling 36 sampling points (2 soils x 6 land uses x 3 replications). In each soil x land use combination, deformed and undeformed soil samples were collected to analyze the physical attributes in the surface layer 0-5 cm and subsurface layer 95-100 cm, using five replicates in each layer. In addition to the surface layer, a subsurface analysis was carried out on the pedogenetic horizon, which best represents the intrinsic conditions of the soil classes and is more representative of the vadose zone, influencing processes related to water recharge from the soil, and which may or may not be impacted by changes in land use and management practices. To collect the soil with preserved structure, undeformed samples were extracted using an Uhland sampler in volumetric steel cylinders 2.5 cm high and 6.3 cm in diameter. These samples were used to determine: bulk density, macroporosity, microporosity, total porosity, water capacity, aeration capacity, relative field capacity and drainable porosity. In addition to these, two undeformed samples using volumetric steel cylinders 8.0 cm high and 6.3 cm in diameter were taken to determine saturated hydraulic conductivity. Samples were also taken to analyze aggregate stability in the surface horizon. In the same locations, deformed samples were taken for textural analysis and determination of the organic matter content in the two horizons to characterize the soil (Table 1). Water infiltration and soil resistance to penetration tests were carried out in the field.

Table 1. Classification and information about land use and management history for forest fragment (FF), forest restoration (FR), pasture (PA), sugar cane (SC), grain cultivation (GR) and cassava (CA) in the study sites.

Soil classification[a]	Land use	Depth	Sand	Silt	Clay	SOM[b]
		--------- cm		---------- g kg^{-1} ----------		
Ultisol	FF	0-20	82.05	1.39	16.56	1.60
		80-100	74.92	1.49	23.59	0.71
	FR	0-20	79.23	4.05	16.72	1.55
		80-100	67.38	2.94	29.68	0.47
	PA	0-20	87.82	4.15	8.03	0.82
		80-100	80.51	3.93	15.56	0.30
	SC	0-20	77.12	4.31	18.57	1.30
		80-100	69.51	4.94	25.55	0.57
	GR	0-20	79.46	6.32	14.22	1.27
		80-100	75.67	3.40	20.93	0.52
	CA	0-20	87.22	2.10	10.68	0.73
		80-100	82.80	1.83	15.36	0.34
Oxisol	FF	0-20	68.24	7.29	24.48	1.34
		80-100	66.86	6.53	26.62	0.81
	FR	0-20	85.91	1.74	12.35	1.08
		80-100	76.55	2.09	21.36	0.28
	PA	0-20	82.27	4.86	12.88	1.42
		80-100	73.90	4.84	21.25	0.62
	SC	0-20	71.83	4.61	23.57	1.26
		80-100	64.52	5.73	29.75	0.52
	GR	0-20	78.28	3.30	18.42	1.96
		80-100	71.91	3.54	24.54	0.92
	CA	0-20	82.11	5.52	12.36	0.71
		80-100	76.47	4.34	19.19	0.33

[a] Soil classification according to Soil Taxonomy [b] SOM: soil organic matter determined with potassium dichromate.
[c] soil particle distribution determined by pipette method with NaOH 1M (Teixeira et al., 2017).

2.3 Analyses carried out in the field

Soil penetration resistance (PR) was measured in the field using a Stolf dynamic impact penetrometer with a conical tip (30º) (Stolf, 1991; Vaz et al., 2011) to calculate the cone index. The PR was determined to a depth of 0.60 m at 10 points along a 22.6 m transect. The PR data was discretized into depths of every 10 cm using a spreadsheet from Stolf et al. (2014). To assess soil water content (θ) using the thermogravimetric method, five samples were collected at depths of 0-20, 20-40, 40-60 cm, resulting in 15 samples per transect.

Unsaturated hydraulic conductivity was estimated using the method proposed by Zhang et al. (1997) using the Mini Disk Infiltrometer, which was positioned on the soil surface for measurements. Readings were taken every thirty seconds, starting at time 0 (zero) corresponding to the initial volume. This method requires the measurement of cumulative infiltration versus time, adjusting the results with the following equation:

$$I = C_1 t + C_2 \sqrt{t}, \qquad (1)$$

Where I (m) is the accumulated infiltration, t (s) is time, C_1 (m s^{-1}) is an adjustment parameter related to soil sorptivity, and C_2 (m s$^{-1/2}$) is related to hydraulic conductivity.

The unsaturated hydraulic conductivity of the soil (K) was calculated from:

$$K = \frac{C_1}{A}, \qquad (2)$$

Where C_1 is the slope of the cumulative infiltration curve in relation to the square root of time (1), and A is a value that relates the parameters of the van Genuchten (1980) equation to the suction rate applied to the infiltrometer during the test and the radius of the infiltrometer disk.

We calculated$A$ using the following equations:

$$A = \frac{11{,}65\,(n^{0{,}1}-1)exp[2{,}92(n-1{,}9)\alpha h_0]}{(\alpha r_0)^{0{,}91}} \qquad n \geq 1{,}9\,, \qquad (3)$$

$$A = \frac{11{,}65\,(n^{0{,}1}-1)exp[7{,}5(n-1{,}9)\alpha h_0]}{(\alpha r_0)^{0{,}91}} \qquad n < 1{,}9, \qquad (4)$$

n and ∝ are the parameters of the van Genuchten (1980) for soil obtained for the loamy sand textural class according to Carsel & Parrish (1988), r_0 is the radius of the disk (2.25 cm) and h_0 is the suction on the surface of the disk (2.0 cm).

Considering that the soil water infiltration test was conducted until the infiltrated volume reached a constant volume over time, achieved through 3 equal consecutive readings, the calculated hydraulic conductivity value was used as an estimate of the basic infiltration rate (BIR).

2.4 Laboratory analyses

For the physical and chemical analysis, the procedures recommended by Teixeira et al. (2017) were adopted. The undeformed soil samples were saturated with water for 24 hours by capillary action and then weighed. Bulk density (BD) was determined using the volumetric ring method, as was total porosity (Pt), estimated using the soil's water content at saturation. Macroporosity (Mac) was calculated as the difference between the soil water content at saturation and the soil water content at the water potential of -6 kPa corresponding to microporosity.

The available water capacity (AWC) was estimated as the difference between the water content at field capacity (FC) and at the permanent wilting point (PWP), estimated at -10 kPa and -1500 kPa, respectively (Silva et al., 2014). The soil's total aeration capacity (AC) and relative field capacity (RFC) were determined as described by Reynolds et al. (2009, 2002), according to the following equations 5 and 6, respectively:

$$CA = \theta_{sat} - \theta_{10kPa} \tag{5}$$

$$RFC = \left(\frac{\theta_{10kPa}}{\theta_{sat}}\right) = \left[1 - \left(\frac{CA}{\theta_{sat}}\right)\right] \tag{6}$$

where θ_{10kPa} e θ_{sat} correspond to the water content retained at the matric potential of -10kPa (m^3 m^{-3}) and at saturation, respectively.

To determine the saturated hydraulic conductivity (Ksat), the samples were saturated for 48 hours with water at 2/3 of the height of the ring. The method used was the constant load permeameter as described in Klute (1986). The Ksat value was estimated using the Darcy equation (equation 7) and corrected for a temperature of 20 ºC using equation 08.

$$Ks = \frac{(V*L)}{(A*H*t)} \tag{7}$$

$$K_{20} = K_t * \left(\frac{\mu_T}{\mu_{20}}\right) \tag{8}$$

where Ks: saturated hydraulic conductivity (cm/h); V: volume of water collected (mL); L: height of test specimen (cm); A: area of test specimen (cm²); H: height of test specimen + height of water column (cm); t: water percolation time (h); K_{20}: saturated hydraulic conductivity at 20 ºC; K_t: saturated hydraulic conductivity at T ºC; μ_T : water viscosity at T ºC;μ_{20}: water viscosity at 20 ºC.

Aggregate stability was measured using the methodology proposed by Yoder (1936) with the considerations proposed by Grohmann (1960). The samples collected on the surface were sieved through 8 and 4 mm meshes and, for the analysis, 50 g of dry aggregates retained on the 4 mm sieve were weighed. The aggregates were subjected to slow wetting by capillarity and taken to a set of sieves with diameters of 4.76 mm, 2.00, 1.00, 0.5, 0.25 and 0.105 mm for sieving in water. After 15 minutes of vertical movements at 45 oscillations per minute, the material retained on each sieve was dried in an oven at 105-110 °C for 48 hours to determine the dry mass and calculate the percentage of aggregates in each size class. The geometric mean diameter (GMD) was calculated using equations 9:

$$GMD = exp\frac{\sum Wi}{W} ln(Di), \qquad (9)$$

where, GMD is the geometric mean diameter (mm);Wi : i is the weight of the sample of each aggregate size class (g), and Di is the mean diameter of thei_{th} class of aggregates (mm).

Drainable porosity (DP, m^3 m^3), also known as effective porosity, was defined as the fraction of total porosity in which water moves freely under the action of gravity (Beltran, 1986; Pizarro, 1985). DP was calculated according to Otto (1988) by equation 10, with θ_{FC} estimated by θ_{10kPa} (Alvarenga et al., 2009; Santana et al., 2023).

$$DP = \theta_s - \theta_{FC} \qquad (10)$$

The structural stability index (SSI %) was calculated according to that presented by Reynolds et al. (2009b) using equation 11:

$$SSI = \frac{(1.724 \text{ x } SOC)}{(Silt+Clay)} \text{x}100 \qquad (11)$$

where, SOC is the organic carbon content of the soil (g kg^{-1}). The van Bemmelen factor (1.724) was used to convert SOC into soil organic matter (SOM) (Cambardella et al., 2001).

2.5 Evaluation of physical functions and soil physical quality index

The soil physical quality index (SPQI) was calculated as described by Karlen and Stott (1994), Cherubin et al. (2016) and Santana et al. (2023). The first stage consisted of selecting indicators, which make it possible to establish relationships with ecosystem services, ranging from diagnosis (one-off assessments) to monitoring of five physical soil functions related to biomass production, resistance to erosive processes and water provisioning: f(i) supporting root development; f(ii): water availability for plants; f(iii): allowing gas exchange between soil and atmosphere; f(iv): ability to resist erosion and f(v) groundwater recharge potential. To determine the SPQI, a set of ten soil physical indicators was selected based on the literature and the experience of experts (Cherubin et al., 2016; Alvarenga et al., 2012; Santana et al., 2023). For supporting root development f(i), bulk density (BD) and penetration resistance (PR) were used; for f(ii), saturated hydraulic conductivity (ksat), available water capacity (AWC) and relative field capacity (RFC); for f(iii), macroporosity (Mac) and structural stability index (SSI); for f(iv), soil water infiltration rate (BIR), geometric mean diameter (GWD) and structural stability index (SSI); and for f(v) drainable porosity (DP), soil water infiltration rate (BIR), and saturated hydraulic conductivity (ksat).

The next stage consisted of interpreting the indicator using the linear technique described by Andrews et al. (2002), transforming each observed value into a dimensionless value, ranging from 0 to 1, in which 0 was assigned to the worst quality condition of the soil and 1 to the best. The indicators were ranked in ascending or descending order, depending on whether a higher value was considered "good" or "bad" in terms of soil function. For 'more is better' indicators (Mac, Ksat, SSI, BIR, GMD and DP) each observation was divided by the highest value observed, so that this received a score of 1. For 'less is better' indicators (BD and PR) the lowest value observed (in the numerator) was divided by each observation (in the denominator) so that the lowest value observed received a score of 1. For 'ideal' indicators (AWC and RFC), observations were scored as "higher is better" up to a threshold value and then "lower is better" above the threshold (Reynolds et al., 2008, 2009b).

The strategy of integrating weight additives (Rinot et al., 2019) was used to calculate individual scores for each soil physical function. Based on the literature, certain indicators that have the greatest influence on each function were assigned the following weights (BD and PR were assigned a weight of 0.50; Ksat, AWC, RFC, MAC, SSI, GMD, BIR and DP were assigned a weight of 0.33 each. These weighted scores were added together to calculate the SPQI.

To help land use planners, a map was created by integrating information on land use, soil classes and the values of physical functions and SPQI. The soil class maps of Pontal de Paranapanema, extracted from Rossi (2017) at a scale of 1:250,000, were filtered to include only the *Argissolo* (Ultisol) and *Latossolo* (Oxisol) classes. To analyze land use, the map from the "MapBiomas Collection 8" of 2023 (MapBiomas, 2023) on a scale of 1:250,000 was used, considering the categories "Forest Formation", "Pasture", "Soybean" and "Sugarcane" present in the collection. Using the QGIS Desktop program, version 3.28.13 (QGIS Development Team, 2024) with Universal Transverse Mercator (UTM) projection, zone 22S (central meridian -51°), WGS-84 datum, the maps were overlaid and the attributes associated by location. Thus, a new overlay map was created, containing information on the class and land use for each polygon. For each combination of class and land use, the average values of f(i), f(ii), f(iii), f(iv), f(v) and SPQI were assigned to the respective areas studied. The values from the two depths of soil sampling evaluated were averaged.

2.6 Statistical analysis

The data on soil physical attributes, soil functions and SPQI were subjected to analysis of variance (ANOVA) followed by the Tukey test ($p<0.05$) to assess differences between depths and uses using the means of the factorial scheme. Principal Component Analysis (PCA) was carried out in order to correlate the soil quality indicators and ecosystem services of interest, as well as to distinguish environments. Pearson's correlation coefficient was used to measure the linear correlation between variables (Benesty et al., 2009). The data was processed using SISVAR software (Ferreira, 2011) and R software (R Core Team, 2022) using the RStudio platform (RStudio Team, 2018).

3. Results

3.1 Soil physical properties in the main land uses and predominant soils

The analysis of variance revealed a significant interaction for bulk density ($p < 0.05$) between depths and land uses (Fig. 2). The conversion of FF to the other land uses increased BD in both soil classes, especially at 0-5 cm (Fig. 2A). At this depth, the variation between FF and the other land uses was around 30% for Oxisol and 33% for Ultisol, with SC having the greatest difference in BD (1.26 to 1.64 Mg m^{-3}). Forest restoration (FR) was the only land use that did not differ statistically from FF. At 95 cm, only CA use on Ultisol significantly increased BD compared to FF, while no changes were observed for Oxisol

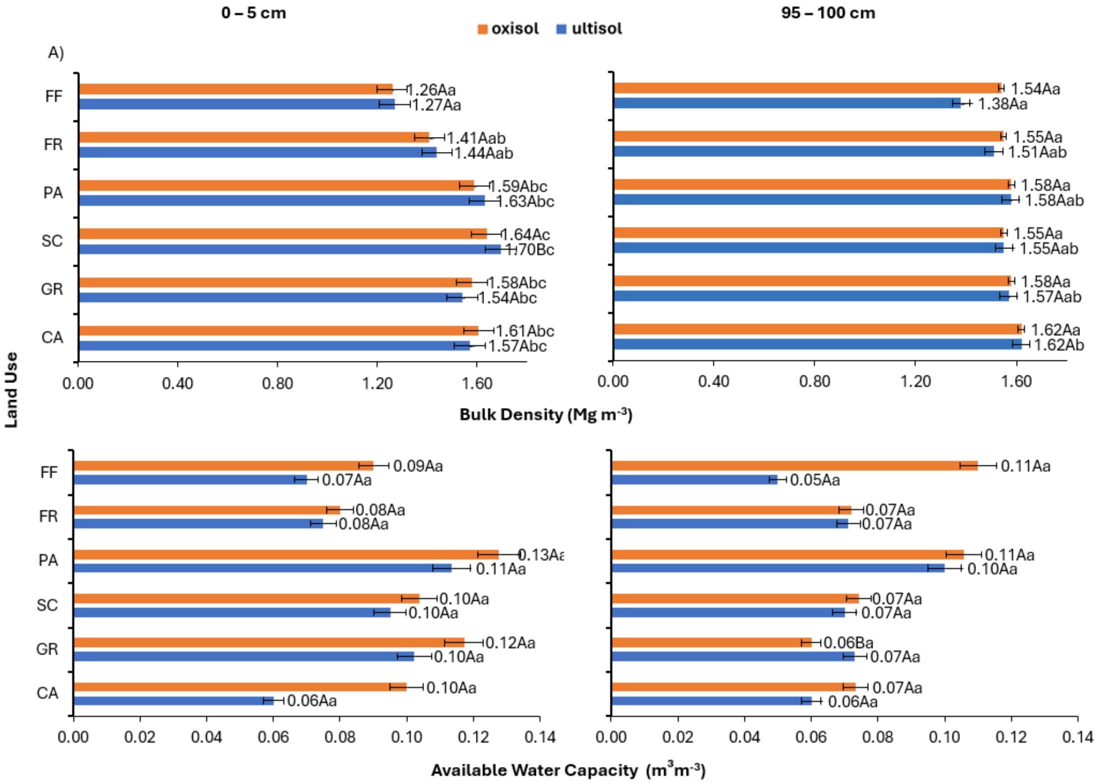

Figure 2. Bulk density - BD (A) and available water capacity - AWC (B) at depths of 0-5 and 95-100 cm under forest fragment (FF), forest restoration (FR), pasture (PA), sugar cane (SC), annual crop (GR) and cassava (CA). Averages followed by the same uppercase letter do not differ between depths for the same land use, and averages followed by the same lowercase letter do not differ between land uses for the same depth by Tukey's test ($p < 0.05$). Error bars denote standard deviation of the mea.

For AWC, no significant differences were observed between the uses for both soils within each depth assessed. At 0-5 cm, values ranged from 0.08 in FR to 0.13 m^3m^{-3} in PA for Oxisol, and from 0.06 in CA to 0.11 m^3m^{-3} in PA for Ultisol. At 95-100 cm, there was a variation from 0.06 m^3m^{-3} in GR to 0.11 m^3m^{-3} in FF and PA for Oxisol and from 0.05 in FF to 0.10 in PA for Ultisol. It was also observed that AWC was higher in the subsurface only when the Oxisol was cultivated with grain, and did not differ between depths for the other treatments.

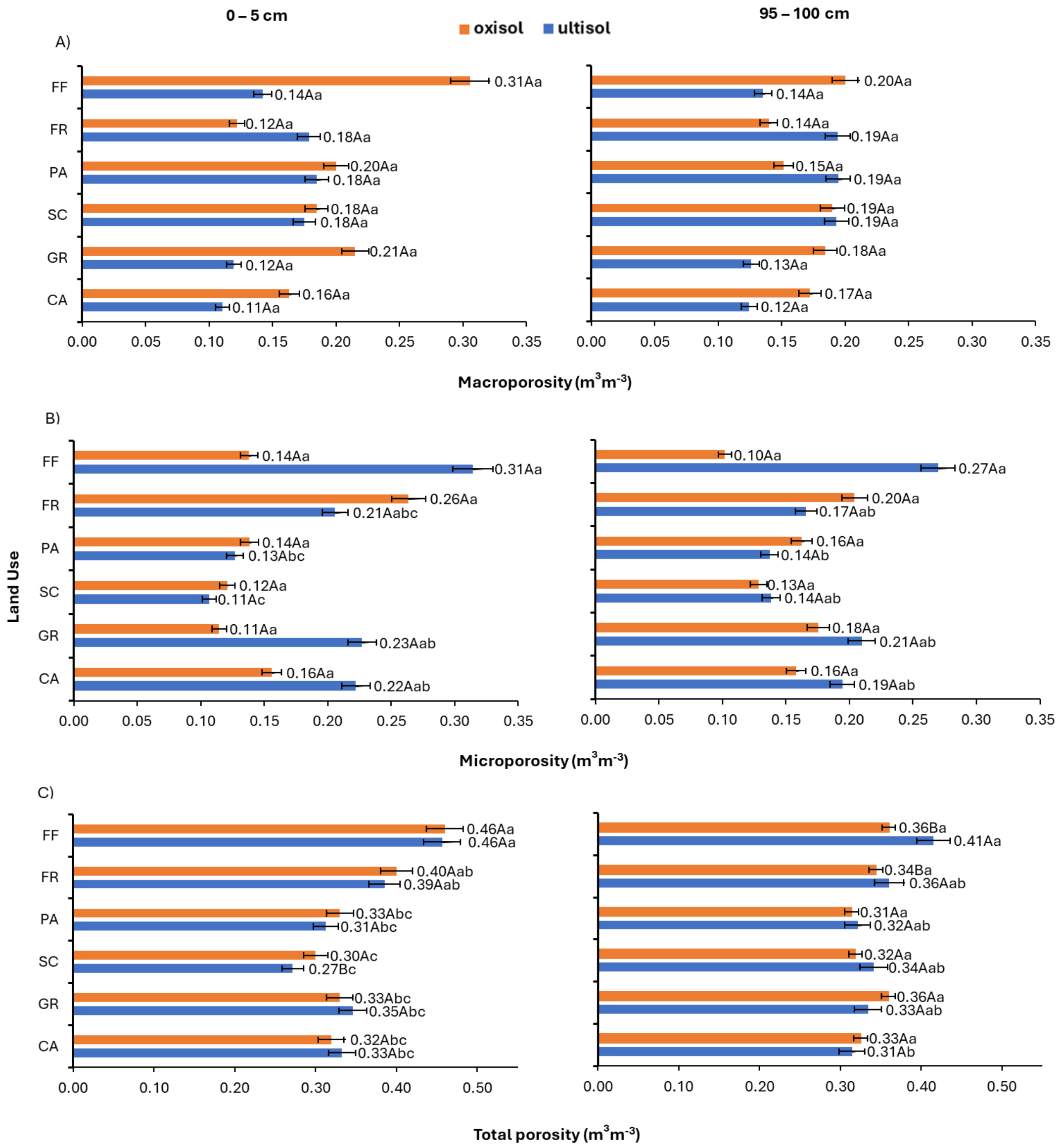

Figure 3. Macroporosity - MaC (A), microporosity - MiC (B) and total porosity - TP (C) at depths of 0-5 and 95-100 cm under forest fragment (FF), forest restoration (FR), pasture (PA), sugar cane (SC), annual crop (GR) and cassava (CA). Averages followed by the same uppercase letter do not differ between depths and averages followed by the same lowercase letter do not differ between land uses by Tukey's test ($p < 0.05$). Error bars denote standard deviation of the mean.

MaC did not differ between land uses, for either Oxisol or Ultisol, regardless of the depth assessed (Fig. 3A). High Mac values were observed in FF for Oxisol, both on the surface (0.31 m^3m^{-3}) and in the subsurface (0.27 m^3m^{-3}). As for MiC, there was a significant difference in FF, with a reduction in PA and SC uses in the surface layer and in the subsurface for PA use, only for the Ultisol (Fig. 3B). The forest areas (FF and FR) showed higher TP in both soil types, regardless of depth (Fig. 3C). In relation to the treatments, TP decreased by around 34% for Oxisol and 41% for Ultisol in the surface layer with the change from FF to agricultural uses. At a depth of 95-100 cm there was a 24% reduction in TP when converting FF to CA for Ultisol areas, but for Oxisol the uses did not differ statistically.

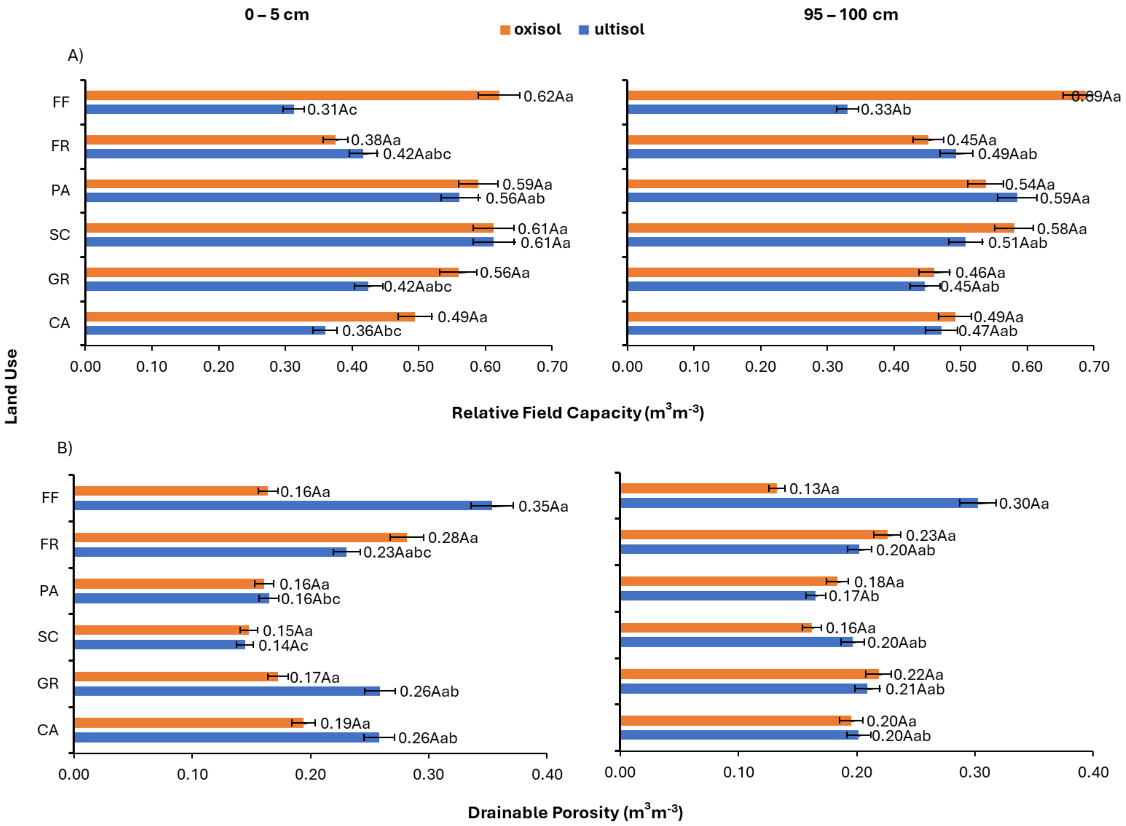

Figure 4. Relative field capacity - RFC (A) and drainable porosity - DP (B) at depths of 0-5 and 95-100 cm under forest fragment (FF), forest restoration (FR), pasture (PA), sugar cane (SC), annual crop (GR) and cassava (CA). Averages followed by the same uppercase letter do not differ between depths and averages followed by the same lowercase letter do not differ between land uses by Tukey's test ($p < 0.05$). Error bars denote standard deviation of the mean.

For RFC, there was no significant interaction ($p < 0.05$) for uses between depths in both soils (Fig. 4A). For the Ultisol, RFC was lower in FF compared to PA and SC at 0-5 cm and PA at 95-100 cm. As for DP, there was no difference uses for Oxisol (Fig. 4B). For Ultisol, there was greater DP on the surface under FF use = FR=CA=GR in relation to PA=SC. The variation in this indicator between the uses observed at this depth was 43% for Oxisol and 60% for Ultisol. At depth, DP was significantly reduced by 43% when transforming FF into PA under Ultisol.

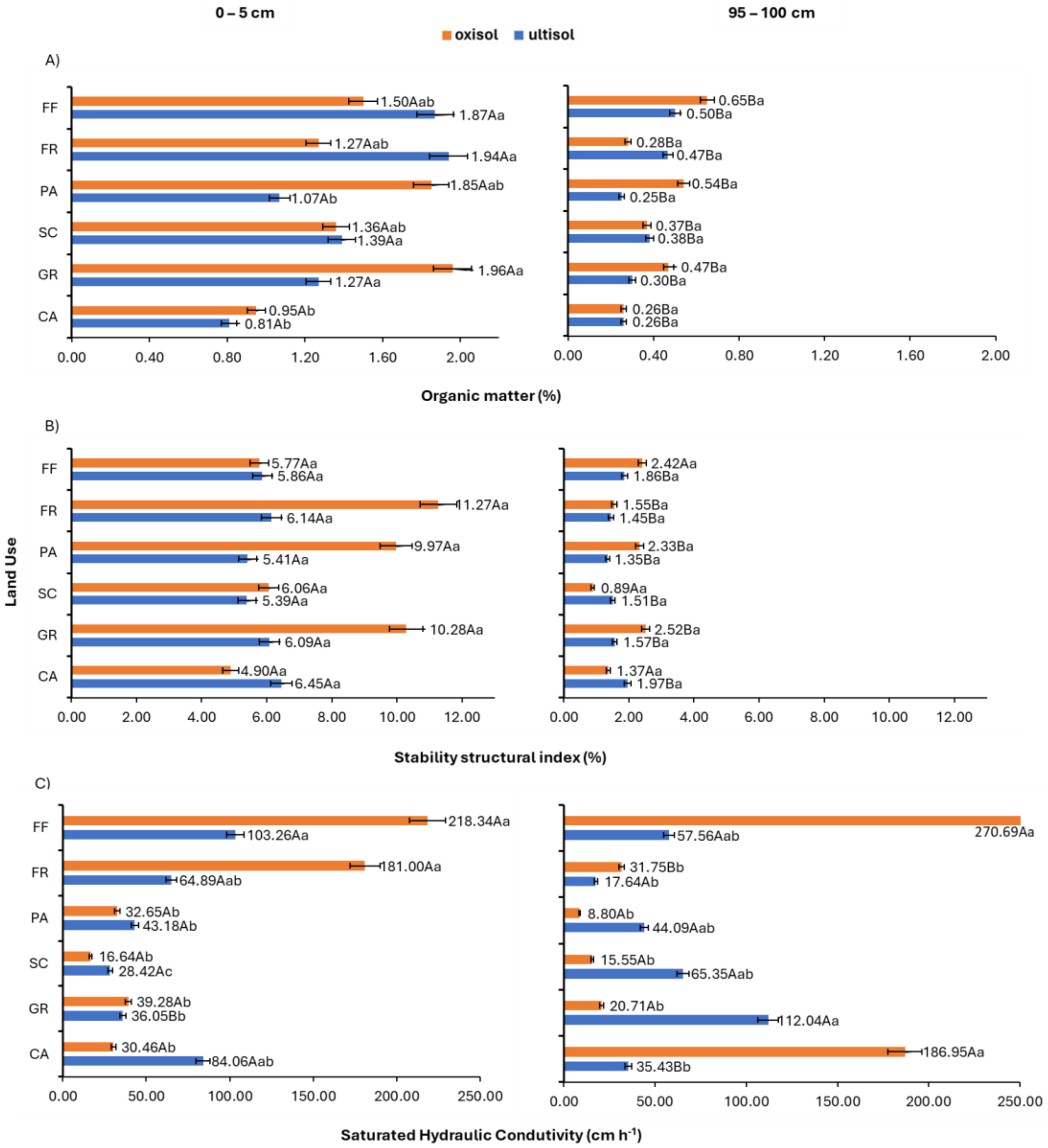

Figure 5. Organic matter - OM (A), stability structural index - SSI (B) and saturated hydraulic conductivity - Ksat (C) at depths of 0-5 and 95-100 cm under forest fragment (FF), forest restoration (FR), pasture (PA), sugar cane (SC), annual crop (GR) and cassava (CA). Averages followed by the same uppercase letter do not differ between depths and averages followed by the same lowercase letter do not differ between land uses by Tukey's test ($p < 0.05$). Error bars denote standard deviation of the mean.

OM content differed between uses only on the surface. For the Ultisol, CA and PA differed from the other uses with lower OM. For the Oxisol, GR had higher OM than CA, and did not differ from the other land uses (Fig. 5A). For the SSI indicator, there was no statistical difference between uses (Fig. 5B). Among the depths assessed, in the Ultisol all the uses had higher SSI on the surface. For Oxisol, FR, PA and GR showed higher SSI on the surface.

For Ksat, at the 0-5cm depth, FR was equal to FF, and was followed by the other uses for the Oxisol. For the Ultisol, FF also showed the highest Ksat, which did not differ from FR, while SC cultivation showed the lowest Ksat (Fig. 5C). The impacts of land use were also significant in the subsurface, with FF and CA showing higher Ksat in Oxisol. For the Ultisol, GR showed the highest Ksat, which did not differ statistically from FF.

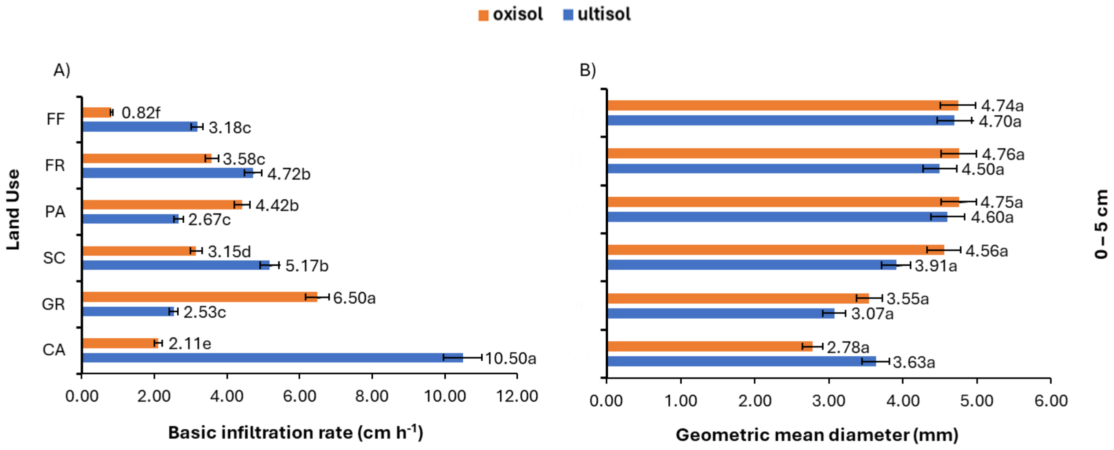

Figure 6. Basic Infiltration Rate - BIR (A) and Geometric Mean Diameter - GMD (B) at a depth of 0-5 cm under forest fragment (FF), forest restoration (FR), pasture (PA), sugar cane (SC), annual crop (GR) and cassava (CA). Averages followed by the same uppercase letter do not differ between depths and averages followed by the same lowercase letter do not differ between land uses by Tukey's test ($p < 0.05$). Error bars denote standard deviation of the mean.

Significant differences in BIR were observed between the land uses and they are quite distinct for the soils studied (Fig. 6A). In Oxisol, BIR decreased in the order GR>PA>FR>SC>CA>FF. On the other hand, for Ultisol, the decreasing order was: CA>SC= FR> FF=PA=GR. Of particular note for Oxisol was the 70% increase in BIR when GR was cultivated (6.50 cm h^{-1}) compared to FF (0.82 cm h^{-1}). Conversely, in the Ultisol, there was a 20% reduction in BIR in GR (2.53 cm $h^{-1)}$ compared to FF (3.18 cm h^{-1}), while CA (10.5 cm h^{-1}) increased by 230% compared to FF. GMD did not differ statistically between uses for the Oxisol and also for the Ultisol (Fig. 6B). Even though the average GMD values for the Ultisol tended to be lower for both soils, the FF, FR and PA uses showed values higher than 4.5 mm.

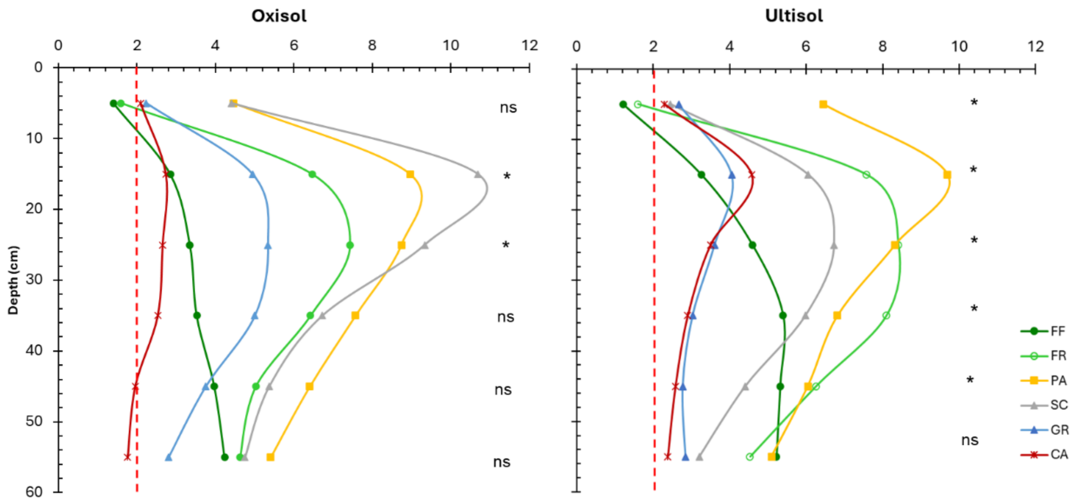

Figure 7. Soil penetration resistance evaluated in the field in the 0 to 60 cm layers for Oxisol and Ultisol under forest fragment (FF), forest restoration (FR), pasture (PA), sugar cane (SC), annual crop (GR) and cassava (CA). The red dashed line indicates the critical limit for plant root development of 2 MPa according to Bengough et al. (2011). * Denotes statistical difference, ns: not significant.

Table 2. Gravimetric soil water content (%mass/mass) in the 0-20, 20-40 and 40-60 cm layers depending on the use and type of soil evaluated at the time of the field analysis of soil resistance to penetration.

Depth (cm)	Oxisol						Ultisol					
	FF	FR	PA	SC	GR	CA	FF	FR	PA	SC	GR	CA
	Gravimetric water content (%)											
0-20	8d	19a	15b	14b	21a	14c	12c	20a	16b	21a	8d	11c
20-40	8c	15b	20a	15b	14b	15b	12b	15a	15a	13a	11b	13b
40-60	9c	16b	18a	15b	14b	14b	15bc	26a	17b	15bc	13d	12cd

Average values of each land use for the same depth and soil class followed by the same letter do not differ by Tukey's test ($p < 0.05$).

Under the conditions evaluated in the field soil moisture (Table 2), soil resistance to penetration (RP) was lower than the critical limit for root development of (2 MPa) in Oxisol for all uses up to a depth of 5 cm, with values ranging from 0.69 MPa in FF to 1.95 MPa in PA (Fig. 7). However, values above 2 MPa are found from this depth for all uses. In general, up to the first 20 cm of the profile, all uses show an increasing increase in PR, while from this depth onwards, PR decreases. The highest PR value was observed for SC (>10 MPa) between 10 cm and 30 cm depth, followed by PA>FR>GR and finally FF and CA.

In Ultisol, it is possible to see a significant difference between uses up to a depth of 50 cm, with a tendency for PR to increase for all land uses up to 15 cm. In the surface layer, PA showed high PR (>6 MPa), differing from the other uses, as well as in the 15 cm layer (>9 MPa), followed by FR, SC, CA, GR and finally FF. FF showed a tendency to increase RP with increasing depth up to 40 cm, and then maintain high values (> 4 MPa) in the 40-60 cm layer, which is due to the very nature of Ultisol, which has an accumulation of clay at depth, implying densification of the structure.

3.2 Soil quality functions and indices

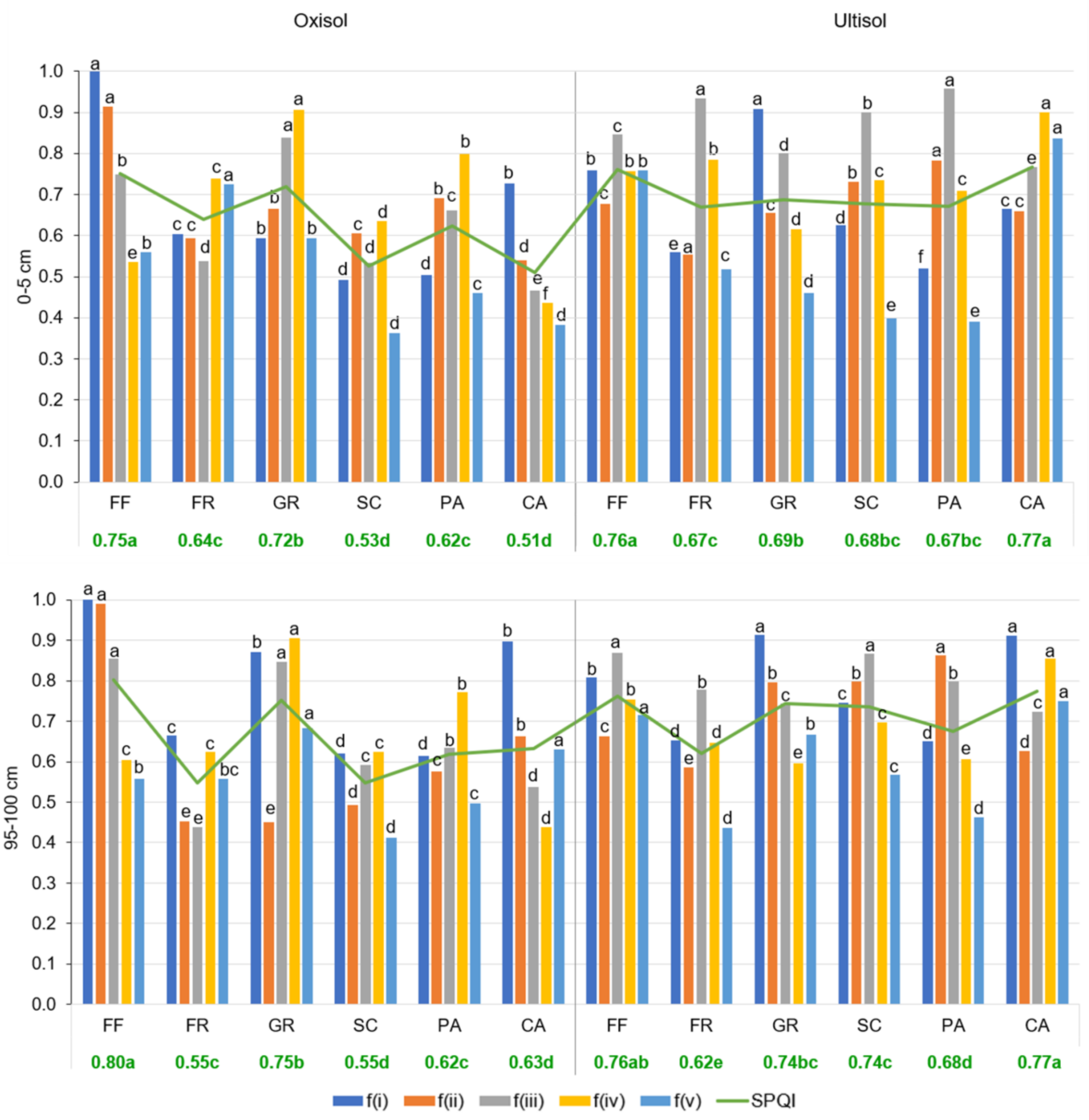

Figure 8. Soil physical functions and soil physical quality index (SPQI) in the 0-5 cm and 95-100 cm in the forest fragment (FF), forest restoration (FR), sugarcane (SC), pasture (PA), cassava (CA) and grain cultivation (GR). *f(i): support roots growth; f(ii): supply water for plants and edaphic fauna; f(iii): allow gases exchange between soil and atmosphere (soil aeration); f(iv): ability resist erosion and physical degradation and f(v) groundwater recharge potential. **Values for SPQI mean values within each soil function followed by the same letter do not differ among themselves according to Tukey's test ($p < 0.05$) are shown in green font.

Figure 8 shows the results of the functions provided by the soil and the soil physical quality index (SPQI), integrated from the functions, for comparisons between the main land uses, for the two predominant soils in the Pontal do Paranapanema region, evaluated in the surface layer (0-5cm) and subsurface layer (95-100cm). For the root growth support function f(i), the highest values were observed in FF for Oxisol and GR for Ultisol for both layers, while PA showed the lowest values for both soils at both depths for this function, equaling SC in Oxisol. With regard to the support function for plants and edaphic fauna f(ii), the highest value occurred in FF in Oxisol and PA in Ultisol, and the same was observed in the subsurface layer. With the exception of the Oxisol on the surface, FR was lower than the other uses for this function, regardless of depth.

With regard to the gas exchange function f(iii), GR stood out in Oxisol in the 0-5 cm layer, and in the subsurface layer it was equal to FF. The lowest values were observed for CA and FR in Oxisol, at 0-5 and 95-100 cm, respectively. PA use showed the highest values in Ultisol, which was not statistically different from FR in the surface layer, and in depth FF was higher and equal to SC. In turn, CA differed from the other uses, showing the highest values for the erosion resistance function (iv) and water recharge potential (v) in Ultisol, followed by FF at both depths. For Oxisol, GR followed by PA showed the highest values for the i(v) function in general and for f(v) at depth. GR use also stood out on the surface along with FF preceded by FR.

In general, in the surface layer of the Oxisol, the FF use had the highest values for the f(i), f(ii) and f(v) functions, while the GR use was better in the f(iii) and f(iv) functions. In the subsurface, FF stood out in the f(i), f(ii) and f(iii) functions, and GR was better in the f(iv) and f(v) functions. As for the Ultisol, in the surface layer, the PA use showed higher values for the f(ii) and f(iii) functions, with no significant difference in FR f(iii). The CA use was better in the f(iv) and f(v) functions. In the subsurface, the use of CA followed by FF stood out in the functions f(iv) and f(v). On the other hand, the lowest f(v) function values were observed in the surface layer, with SC in Oxisol (0.36) followed by PA in Ultisol (0.40). It is noteworthy that, for f(iv) related to resistance capacity to erosion and soil degradation, the regional trend of land use change from PA to GR has been beneficial in Oxisol. However, this same use had the lowest score in Ultisol, which did not differ from PA. It is also worth noting that FR showed a reduction in all the functions evaluated in the subsurface for both soils compared to the other uses, and therefore more attention should be paid to forest restoration processes, considering soil quality.

For SPQI, in the surface layer, in Oxisol the highest values were found in FF, followed by GR and FR = PA, and finally SC and CA which did not differ. In Ultisol, FF and CA differed from the other uses, followed by GR= SC> PA> FR. At a depth of 95-100 cm, for Oxisol the highest values were found for FF, followed by GR and CA = PA. For Ultisol, the highest SPQI values were found in CA and FF areas, but FF did not differ statistically from GR. On the other hand, the lowest SPQI values occurred in areas of FR for Ultisol in the subsurface, repeating what happened for Oxisol and for the surface layer of Ultisol.

3.3 Relationships between quality indicators

Figure 9 shows the results of the linear correlations between the soil properties used as soil quality indicators the 0-5 cm (Fig. 9A) and 95-100 cm (Fig. 9B) layers. In the surface layer, the AC and DP indicators correlated negatively with BD (r = -0.52), AWC (r = -0.61), RFC (r = -0.94) and MaC (r = -0.62). A strong positive correlation was observed between AWC and RFC (r = 0.70), between AWC and MaC (r = 0.42), and RFC and Mac (r = 0.73), showing the importance of maintaining large pores also for plant water availability. Ksat correlated significantly with Ds (r = -0.64) and RP (= -0.42), and GMD correlated negatively with Ds (-0.45), indicating soil degradation due to compaction, implying increased susceptibility to erosion

As on the surface, in the subsurface AC and DP were the indicators that correlated most with other indicators, negatively with RFC (r = -0.94), AWC (r = -0.78), Mac (r = -0.56) and Bd (r = -0.64). The indicators of water availability showed a strong positive correlation, AWC and RFC (r = 0.85). Mac correlated directly with AWC (r = 0.51) and RFC (r = 0.71), as was observed in the subsurface layer.

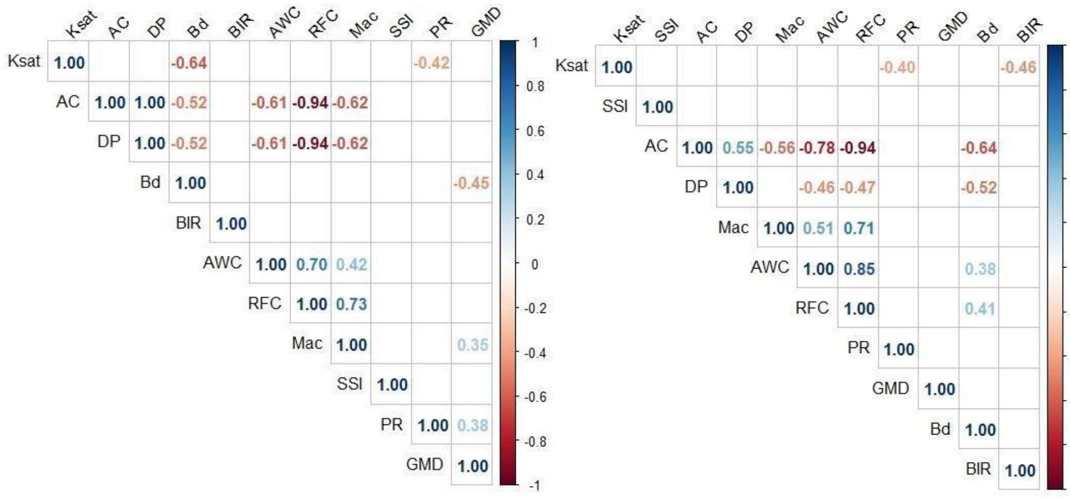

Figure 9. Pearson's correlation coefficients for Oxisol and Ultisol at 0-5 cm (A) and 95-100 cm (B) among soil physical properties in forest fragment (FF), forest restoration (FR), sugarcane (SC), pasture (PA), cassava (CA) and grain cultivation (YE). BD: bulk density; AC: aeration capacity; AWC: available water capacity; RFC: relative field capacity; MiP: microporosity; DP: drainable porosity; MaC: macroporosity; BIR: basic infiltration rate; GMD: geometric mean diameter; PR: soil resistance to penetration; Ksat: saturated hydraulic conductivity; SAND: sand; SILT: silt; CLAY: clay; DP: drainable porosity; SOC: soil organic carbon. Red values represent a negative correlation while blue values represent a positive correlation. Blank boxes did not show a significant Pearson correlation coefficient (p-value< 0.05).

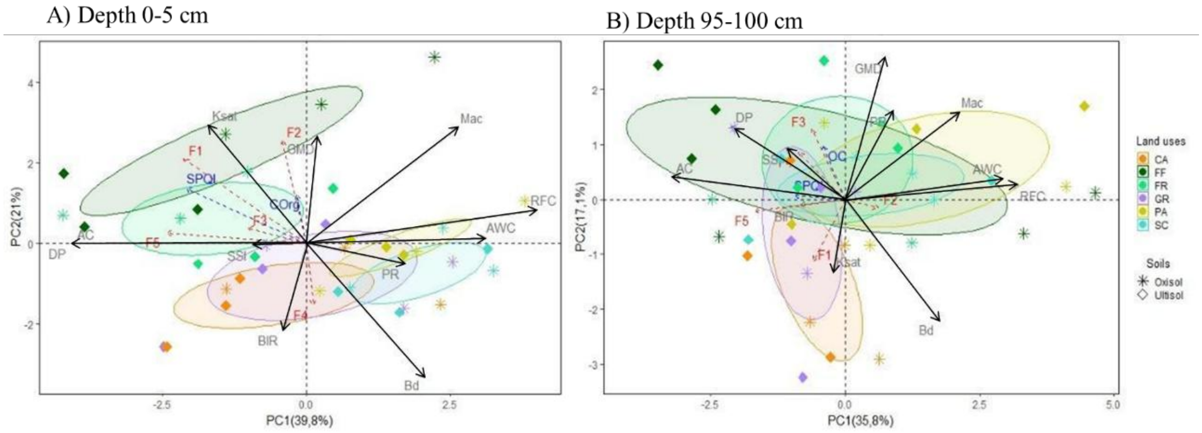

Figure 10. Principal component analysis for Oxisol and Ultisol at 0-5 cm (A) and 95-100 cm (B) among soil physical properties in forest fragment (FF), forest restoration (FR), sugarcane (SC), pasture (PA), cassava (CA) and grain cultivation (GR). BD: bulk density; AC: soil aeration capacity; AWC: available water capacity; RFC: relative field capacity; MiP: microporosity; TP: total porosity; MaP: macroporosity; BIR: basic infiltration rate; GMD: geometric mean diameter; PR: soil resistance to penetration; ksat: saturated hydraulic conductivity; SAND: sand; SILT: silt; CLAY: clay; DP: drainable porosity; SOC: soil organic carbon. Soil functions: f(i) support root growth; f(ii) supply water for plants; f(iii) allow gas exchange between soil and atmosphere; f(iv) resistance to erosion; f(v) groundwater recharge potential.

The principal component analysis (PCA) carried out for the physical properties of the soil in Oxisol and Ultisol showed that the environments differed between the sampling depths. The PCA explained 60.9% and 52.9% of the total variance at depths of 0-5 cm (Fig. 10A) and 95-100 cm (Fig. 10B), respectively. At a depth of 0-5 cm (Fig. 10A), regardless of soil class, there was a separation into two groups, one composed of FF and FR uses and the other of SC, PA, GR and CA agricultural uses. The first group was separated by the highest values of the Ksat, GMD, AC and SSI properties. The second group was separated mainly by the highest BD and PR values. Therefore, the grouping of FF and FR suggests that the forest restoration process has the potential to improve soil quality, while agricultural and livestock uses show signs of soil compaction. It should also be noted that the increase in the values of functions i, ii, iii, v and SPQI, as well as CO, are in the same direction as the definition of the first group, indicating synergy between the results of the PCA and the SPQI index, as well as an increase in soil organic matter. Only f(iv) was favored by the second group. As for soil classes, when analyzing the FF native vegetation environment, Oxisol was separated mainly by Mac, while Ultisol was separated by AC and DP.

For the 95-100 cm depth (Fig. 10B), it was not possible to differentiate between land uses, since all the ellipses defining the variability of each land use crossed each other. However, only CA was allocated to the lower quadrant for both soil classes, defined mainly by the increase in BD.

3.4 Map of physical functions and soil quality

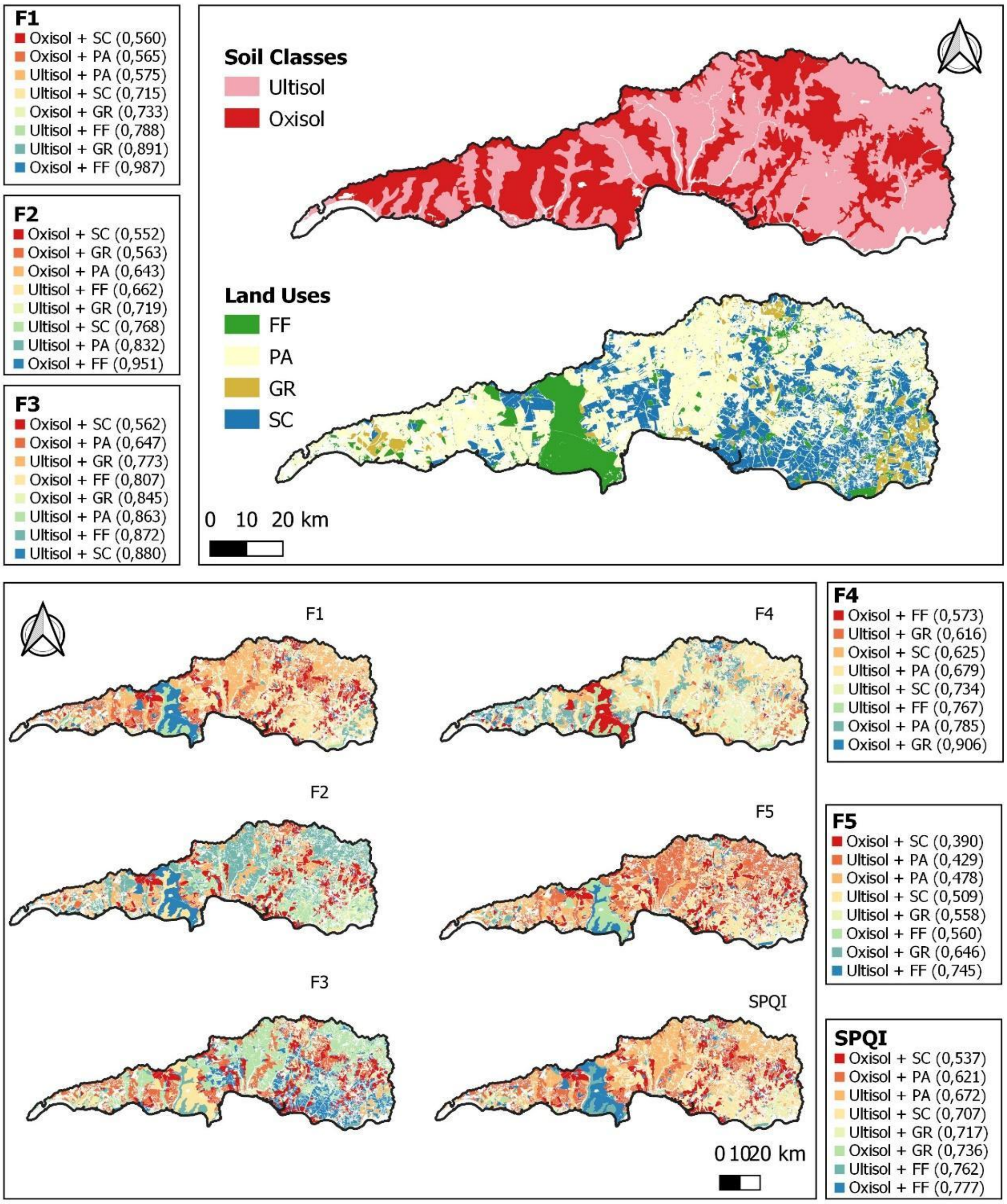

Figure 11. Map of functions for different soil types and their uses, f(i): support roots growth; f(ii): supply water for plants and edaphic fauna; f(iii): allow gases exchange between soil and atmosphere (soil aeration); f(iv): ability resist erosion and physical degradation and f(v) groundwater recharge potential and soil physical functions and soil physical quality index (SPQI) in the 0-5 cm and 95-100 cm for Ultisol and Oxisol in the forest fragment (FF), sugarcane (SC), pasture (PA), and grain cultivation (GR).

Figure 11 shows the map of soil functions and the soil physical quality index resulting from the interaction between the main land uses for the predominant soils in the region, with the exception of the FR and CA uses, which were below the minimum threshold of representativeness for the scale adopted and were therefore not used in this figure. The soil quality index (SPQI) shows that the combination of Oxisol or Ultisol with FF had the highest values (0.777 and 0.762 respectively), followed by the use of GR (0.736 in Oxisol and 0.717 in Ultisol), while the combination of Oxisol with SC had the lowest value (0.537). Therefore, among the agricultural uses, the one that has best maintained the soil's physical quality is GR, which occurs mainly in the eastern region, but has also expanded in the western portion. On the other hand, the areas of SC in Oxisol and PA (0.621 and 0.672) occur predominantly in the west, the region where the main water reservoirs for electricity generation are located.

The root growth and support function f(i) varied significantly between soil classes and land uses. The combination of Oxisol with FF had the highest index (0.987), while the combination of Oxisol with SC had the lowest index (0.560). Regardless of soil type, the uses that stood out most for this function were GR, followed by FF and the lowest SC. The water availability function for plants f(ii) was highest in the combination of Oxisol with FF (0.951) followed by PA in Ultisol and lowest in the combination of Oxisol with SC (0.552), as were the GR (0.563) and PA (0.643) uses for the same type of soil. For the soil aeration function (F3), the SC use had the highest index (0.880), followed by the FF (0.872) and PA (0.863) uses for the Ultisol. However, the lowest index was found for the combination of Oxisol and SC (0.562). The erosion resistance function f(iv) was highest in the combination of Oxisol with GR (0.906) and lowest in the combination of Oxisol with FF (0.573). Water recharge potential f(v) was highest in the combination of Ultisol with FF (0.745) and lowest in the combination of Oxisol with SC (0.390). It is worth noting that the combination of Oxisol with SC had the lowest indices in the f(i), f(ii), f(iii) and f(v) functions, which occur in a well-distributed way across the region.

4. Discussion

4.1 Effect of forest restoration on soil physical properties

In the Oxisol environment, which has a more homogeneous profile with no textural gradient, the SSI was better on the surface only for the FR, PA and GR uses. Despite being in a lower humidity condition, FF still had lower PR values compared to the other uses, especially in Oxisol. This lower PR is due to the greater presence of litter and the greater contribution of organic matter in these preserved areas (Brito et al., 2019; Reynolds et al., 2009b). In addition, the absence of management contributes to this behavior, which means that these areas are used as a reference for soil quality under different conditions of use and management. The increase in PR at depth in the FF areas can possibly be attributed to the obvious increase in root growth in this layer, as justified by Goulart et al. (2020), Pires et al. (2017) and Reichert et al. (2007) who suggested that there may be a compression of the soil between the roots and, consequently, generate compaction due to the mechanical forces applied by them to the soil.

With the exception of the FF area, the greatest PR occurred between 5 and 30 cm depth for all uses and soils, which is related to the frequent use of agricultural implements in this range, resulting in increased soil compaction. Below this depth, there was a decrease in PR, which is a factor associated with the absence of soil tillage when the crop was planted and the higher moisture content at depth, which contributes to the reduction in PR.

However, it is also important to note that the soils studied contain a large amount of sand (>64%), which explains the high bulk densities and PR. This predominance of the sand fraction is probably linked to the lithology, since its source material is sandstone. In general, average bulk density values for sandy soils range from 1.2 to 1.9 g cm^3 (Reinert; Reichert, 2006). Bulk densities of around 1.65 g cm^{-3} for soils with a high sand content have been associated with a high probability of restrictions on plant root growth (Reinert; Reichert, 2006). Despite the differences between soil classes, the mineral fractions were consistent with weathered tropical soils for both Ultisol and Oxisol (Table 1). The clay fraction was typically < 20 g kg^{-1} in the surface layer, consistent with the sandstone parent material. Clay contents increased with depth in the Ultisols, an intrinsic characteristic of this soil class, which has a textural B horizon. The Oxisol, although it has a typical Bw diagnostic horizon, showed a tendency for the clay content to increase in depth, although this was less pronounced than that of the Ultisol.

4.2 Effect of agricultural uses on soil physical properties

The results showed that, in general, the conversion of preserved areas, represented here by the forest fragment (FF), to agricultural use should be thoroughly studied, considering the impacts of this expansion on the physical properties and associated soil functions. Agricultural uses (PA, SC, GR and CA) generally led to an increase in bulk density (BD) and a reduction in total porosity (TP) and hydraulic conductivity (Ksat), especially in the surface layer of both soil classes. Soil degradation, especially on the surface, leads to a loss of fertility, as it removes the surface layer where the nutrients essential for plant development are concentrated, thus reducing the potential for agricultural productivity (Benevenute et al., 2020; Peixoto et al., 2019), which can lead to pressure to incorporate new preserved areas for agriculture. In addition, degraded soils become more susceptible to erosion (Avanzi et al., 2013; Barros et al., 2018), especially in uncovered areas, which impacts the infiltration and redistribution of water, the reduction of biodiversity and the loss of organic matter (Santana et al., 2023b; Silva et al., 2023).On the other hand, in the subsurface, root development is limited, which is an extremely important factor for the survival of the crop, in terms of support and absorption of water and nutrients during periods of drought (Leal et al., 2013).

Among the agricultural uses, PA and SC showed a considerable reduction in surface drainable porosity (DP). Both the excessive animal load on pastures (Benevenute et al., 2020; Kunz et al., 2013) and the intense traffic of agricultural machinery have the potential to increase the degree of soil compaction and compromise the physical quality of the soil (Keller et al., 2019; Lima et al., 2017). Animal density has a major influence on soil degradation in pasture areas. The average animal stocking rate in pasture areas is approximately 1 AU ha^{-1} day^{-1}, but in the PA areas evaluated, animal density was close to 0.8 AU ha^{-1} day^{-1}, so pasture utilization was at adequate levels of load-bearing capacity (Kunz et al., 2013). Thus, the levels of soil degradation observed may be related to another factor, such as the absence of soil and vegetation conservation practices, which are visible in these areas. Previous studies have reported that well-fertilized brachiaria pastures or the practice of intercropping with legumes are able to improve soil structure and resist compaction more (Vasques et al. 2019), practices that have not been reported in the region studied.

The land uses with SC and PA in Oxisol and PA in Ultisol also showed PR in the evaluation condition above the critical limit of 2 MPa (Bengough et al., 2006, 2011), indicating restrictions on root growth starting at the soil surface and more pronounced in the 15-35 cm layer, attributed to the effects of changes in the soil resulting from the compaction process (Rabot et al., 2018; Reichert et al., 2016a). For SC cultivation areas, soil compaction is often associated with intense machine traffic during agricultural operations, especially the cane transshipment operation during mechanized harvesting, and is well documented in the literature as increasing PR and B (Barbosa et al., 2019; Castioni et al., 2018; Cavalcanti et al., 2020b; Cherubin et al., 2016b; Santos et al., 2021; Benevenute et al., 2020; DeArmond et al., 2019; Peixoto et al., 2019) D

The CA and GR uses showed lower PR in relation to the other agricultural uses, which can be attributed to soil preparation and the contribution of organic matter, respectively. GR was equal to the forest fragment (FF) in terms of surface OM content in both soil classes, and showed higher BIR in the Oxisol, which is explained by the combination of straw from previous crops and reduced soil preparation for planting in these areas. These practices that make up the no-till system have been responsible for increasing water infiltration (Cortez et al., 2017; Nunes et al., 2015; Peixoto et al., 2019; Wang et al., 2014), and improving soil quality in sandy soils (Głąb et al., 2016; Ozores-Hampton et al., 2011; Silva et al., 2021). The higher OM contents on the surface for all uses positively influenced the quality indices in this part of the soil profile, contributing to an improvement in the SSI (Brito et al., 2019; Reynolds et al., 2009b; Santana et al., 2023), which is clearly visible for the Ultisol (Fig. 5A).

The area with CA under Ultisol not only showed low PR in relation to the other agricultural uses, but also higher BIR, which can be explained by the vertical growth of the roots, which reach depths of between 0.50 m and 1.00 m (Reichert et al., 2021). It is a plant adaptable to different climatic and soil conditions (Burrell, 2003; Yu and Tao, 2009), with sandy and medium-textured soils being the most suitable for its cultivation, as they favor adequate root growth, good drainage and facilitate the harvesting process (Silva et al., 2008b). During harvesting, the soil is disturbed to remove the roots and then the stems are cut to produce new seedlings. Although this temporary disturbance provides better aeration conditions, it also leads to greater exposure of organic matter waste, resulting in rapid oxidation by the action of microorganisms, reducing the levels of organic matter in the soil (Fig. 5A) (Albuquerque et al., 2005). However, in this crop there is greater exposure of the soil surface due to low plant density and biomass production, factors which can contribute to compaction, loss of soil structural stability (Silva et al., 2008a) and susceptibility to erosion, as observed in the GMD values (Fig. 6B).

Soil aggregation is directly influenced by the presence of organic matter (Fernandes et al., 2023; Ologunde et al., 2024; Loss et al., 2015; Salton et al., 2008), but varies with soil texture and mineralogy (Andrade et al., 2009; Dufranc et al., 2004; Stefanoski et al., 2013). Clay content has a strong influence on soil aggregation due to its high specific surface area and surface charges (Dufranc et al., 2004). The structural stability index (SSI) indicates that the ecological complexity of the different land uses played a major role in stabilizing the aggregates (Vezzani; Mielniczuk, 2009). Although there were no differences between uses and depths, the areas under agricultural uses were similar to the forest areas (FF and FR) in SSI and OM, indicating good stability and the presence of macroaggregates (Abreu et al., 2004; Cavalieri et al., 2009; Fabrizzi et al., 2005; Reichert et al., 2016b), possibly due to the plant residues left on the soil surface between harvests (Cavalieri et al., 2009; Moraes et al., 2016). In general, these conditions favor an increase in organic matter levels and, thus, greater soil aggregation (Bonini; Alves, 2012).

4.3 Physical functions and soil quality

It is important to use a combination of indicators to obtain a more holistic view of soil quality, allowing for a more assertive and reliable assessment that makes it possible to identify the potential and limitations of soil functions in each land use to help decision-makers. In this context, in order to understand the impacts of land use on soil functions and ecosystem services, we opted to compare protocols based on statistical techniques, through principal component analysis (Fig. 10), and on the knowledge and experience of experts that can be expressed by an index, such as the SPQI (Fig. 8), calculated from simple additive or weighted additive functions (Karlen; Stott, 1994), which have already been widely used in Brazil, but mainly for biomass production, and as far as we know, with only three records for water recharge potential (Alvarenga et al., 2009; Santana et al., 2023).

Overall, the highest SPQI was found in soils under FF (Fig. 8), indicating a state of equilibrium in ecosystems, where the various components interact harmoniously, preserving the health and functioning of the environment, which is essential to ensure the survival and development of various forms of life, as well as sustaining fundamental ecosystem services (Costanza, 2008; Fisher et al., 2009; MEA, 2005a). Among the agricultural uses, GR stood out from the rest with the highest SPQI in general, which illustrates that even in systems with high cropping intensity and plant productivity, in addition to biomass production, ecosystem services associated with the functions f(i) - highlighted in Ultisol f (iii) - highlighted in Oxisol, this land use performed well in the functions associated with resistance to erosive processes, f(iv) - highlighted for Oxisol and water recharge potential f(v) - highlighted for Oxisol, suggesting that conservation management practices can reconcile plant production with environmental benefits, which was also reported in a wide-ranging study carried out on 65 no-till farms in reasonably similar soil and climate conditions (Serafim et al., 2019). In agreement, the PCA shows that GR was the agricultural use with the greatest tendency to approach FF (Fig. 10A), with the same tendency to increase SPQI and CO, ksat and decrease BD, found for the subsurface layer. Therefore, the contribution and stock of carbon in the soil is fundamental for these benefits to be achieved (Totti et al., 2025).

Considering the efforts made for ecological restoration (FR), according to the SPQI (Fig. 8) FR points to a more challenging scenario than PCA (Fig. 10). In the surface layer, the PCA suggests a trend of similarity with FF due to the increase in ksat, GMD and DP, as well as fi and fv, implying an increase in physical quality. However, it can be seen that, especially in the subsurface, FR showed a reduction in the potential for water recharge and functions associated with biomass production, root growth support, plant support and edaphic fauna (Fig. 8). Although adopting restorative practices is challenging and requires considerable investment of time, resources and effort, the long-term environmental, social and economic benefits justify these efforts. The conversion of degraded pasture areas and abandoned agricultural areas to forest restoration reflected a history of use without the adoption of conservation measures, especially in depth. It is worth noting that these areas still can withstand the impacts of past land use and that forest restoration efforts were undertaken without sufficient practices to mitigate soil compaction. It is known that the efficiency of the restoration process is achieved when the ecosystem has species characteristic of the reference, has resources to maintain populations and has connectivity with the ecological matrix (Fiore et al., 2019; Rodrigues et al., 2015; Souza et al., 2024). However, the diagnosis carried out in this study shows that, even in the face of disturbances and degradation of land use over the years, the areas of FR show resilience at normal levels of disturbance and natural regeneration, being able to maintain and evolve, showing tendencies to resemble forest fragment areas in the surface layer (Fig. 10A).

Based on Bünemann et al. (2018), it is possible to establish a relationship between the threats to the soil present in the region studied - compaction, erosion, decline in organic matter, loss of biodiversity and siltation - with the soil-based ecosystem services of biomass production, erosion control, water supply and biodiversity conservation, through the soil functions evaluated here. It can therefore be seen that maintaining soil structure is essential to guarantee the continuity of the ecosystem services mentioned. And this is achieved through FR strategies, which are more similar to FF and, in the context of agricultural uses, to GR. Therefore, FR strategies should be encouraged and improved, while the other agricultural uses in the region, especially SC and PA, need more attention in terms of adopting conservation management practices.

4.4 Proposal for a tool to support the definition of vulnerable and priority areas for recovery action

The soil function map (Fig. 11) made it possible to spatially assess the region's environmental vulnerabilities, considering the main land uses and predominant soils. Considering the importance of the region for the production of electricity from large water reservoirs, the erosion resistance function f(iv) shows the importance of keeping the FF preserved, especially in Oxisols, as they are fragile environments in terms of erosion, while they are highly important for water recharge potential f(v). Also, in Oxisol, areas of SC showed low resistance to erosion associated with low capacity to support root growth f(i), probably compacted, which, when combined with areas of PA in Ultisol are possibly responsible for the greater generation of sediment with the potential to silt up water reservoirs in the eastern part of the region. Ultisol areas under PA also showed low water recharge potential and are widely distributed in the eastern part of the region. Unfortunately, erosion, especially laminar erosion, is common in Brazilian pastures on Ultisol (Alves et al., 2023; Lense et al., 2019; Rocha Junior et al., 2017), which is associated with reduced soil permeability in the B horizon that facilitates rapid saturation of the more sandy A horizon (in this case with a B/A clay textural gradient close to 2, Table 1), and consequent reduced infiltration (Fig. 6A) and increased surface runoff, as previously reported.

Conversely, in the western part there were more erosion-resistant areas, greater recharge potential and intermediate capacity to support root growth f(i) and allow gas exchange f(iii). This is due to the presence of GR in Oxisol, which has been expanding in the region in former PA areas (Souza, 2021). This change is beneficial compared to previous land use, especially in the context of mitigating sediment generation and maintaining the useful life of reservoirs. However, GR areas on Ultisol still need management adjustments, incorporating conservation practices such as crop rotation using plants that produce higher C:N ratio mulches and compaction management to improve the provision of ecosystem services (Amorim et al., 2023).

Areas cultivated with sugarcane on Oxisol showed the lowest indices for the f(i), f(ii) and f(iii) functions associated with biomass production, occupying a significant area spread across the entire region evaluated, which is possibly due to soil compaction caused by the intensive management intrinsic to this crop with heavy machinery traffic in cultivation operations (Esteban et al., 2019; Barzegar et al., 2000; Cherubin, et al., 2021). In this sense, management practices such as crop rotation, such as peanuts or sorghum associated with no-till farming can be beneficial in relieving the compaction installed (Farhate et al., 2022) and preventive measures such as the adoption of load-bearing capacity models to define the best time for machinery to enter the soil without compaction occurring according to the method described by Dias Junior; Pierce (1995) and Severiano (2007) can be suggested by land use planners.

The water recharge potential f(v) and the soil physical quality index (SPQI) corroborate the superiority of forest fragments on Ultisols in promoting the sustainability of water resources.

It is clear that the soil structure under native vegetation provided the porosity and water dynamics conditions necessary for water recharge, associated with higher ksat, DP, GMD and CO, as well as lower BD, which also occurred for the forest restoration areas, as can also be observed in the literature (Alvarenga et al., 2012; Santana et al., 2023a). This highlights the importance of native vegetation and forest restoration efforts in maintaining the hydrological cycle, especially in soils that are more vulnerable to water loss, such as Ultisols.

5. Conclusions

Land use, especially in intensive agricultural areas such as sugar cane and cassava cultivation, is associated with greater soil compaction, as evidenced by the high values of penetration resistance (PR) and bulk density at depth, compromising the physical quality of the soil, negatively affecting its ability to infiltrate water and support root growth. In contrast, areas of forest fragment (FF) and forest restoration (FR) showed better soil physical quality, with greater macroporosity, structural stability index and water retention capacity, highlighting the role of native vegetation and restored areas in preserving soil health.

The soil's physical functions were more impacted in surface layers (0-5 cm) than at greater depths (95-100 cm), with evidence of greater compaction and a reduction in the capacity to support root growth in areas under intensive agricultural management. In soils under restoration, despite the improvement on the surface, the historical impacts of land use are still evident in the deeper layers.

The Oxisol showed better water infiltration capacity and lower penetration resistance compared to the Ultisol, suggesting greater resilience to intensive management practices. However, in both soil types, the forest fragments showed higher physical soil quality, standing out as a reference for the preservation of ecosystem services.

Agricultural systems, such as grain cultivation, which adopt conservation practices, including crop rotation and maintenance of vegetation cover, showed higher soil quality compared to areas under conventional management, as cassava. The expansion of these practices, such as the use of green manure and minimal tillage, is fundamental to reducing compaction and improving water infiltration, especially in soils that are more susceptible to erosive processes, such as Ultisol.

In areas of intensive cultivation, such as sugar cane, it is essential to implement strategies to mitigate soil compaction, such as reducing heavy machinery traffic, using lighter machinery and adopting conservation tillage techniques. These measures are important for maintaining soil structure and improving its infiltration capacity and support for plant growth.

Areas with a history of degradation, such as abandoned pastures and areas of intensive cultivation, should be prioritized for forest restoration, associated with practices that reduce compaction and increase the retention of organic matter. Restoration with native species must be accompanied by appropriate management to ensure the long-term recovery of ecosystem functions.

The proposal of a tool for regional assessment of soil quality according to the main land uses in the dominant soils, considering the predominant soils, was effective in showing areas with the greatest environmental degradation and also the greatest potential for providing ecosystem services. Land use planners will be able to effectively visualize where priority actions should be allocated. In the present study, it was identified that areas of pasture in Ultisol and sugar cane in Oxisol have impacted erosion processes and water recharge, potentially with greater production of sediment that could silt up water reservoirs for electricity generation. Soil conservation practices should be more effectively promoted and disseminated in order to improve soil quality and maintain ecosystem services.

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Conflict of interest statement

All authors certify that they have no affiliations or involvement with any organization or entity with a financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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FINAL CONSIDERATIONS

The research carried out in this thesis reinforces the importance of forest restoration in improving the physical quality of the soil and conserving ecosystem services related to water recharge. The results obtained validate the hypotheses raised, demonstrating that forest restoration contributes significantly to improving water infiltration and retention in the soil, mitigating the negative impacts of intensive land use.

The first article revealed that scientific production on forest restoration and water recharge has grown globally, with a greater concentration of publications in developed countries, where there are more investments and resources for research. On the other hand, emerging countries such as Brazil are relevant to the subject, but still face challenges in increasing their visibility and international collaboration. These findings reinforce the need to strengthen research networks and increase funding for studies applied to forest restoration and water conservation in tropical regions.

The second article assessed the sensitivity of the Soil Management Assessment Framework (SMAF) in measuring soil quality in tropical environments. The results indicated that although the tool is useful for monitoring physical, chemical and biological soil attributes, its calibration for tropical soils is still limited. Forest restoration was found to have significantly improved soil quality, especially compared to areas under intensive management. However, the response of the soil to restoration was conditioned by the history of land use and the type of soil, highlighting the need for specific strategies for each edaphoclimatic context.

The third article took a closer look at the physical quality of the soil, considering different land uses and soil types. The results showed that forest fragment (FF) and forest restoration (FR) areas had better soil quality indices compared to agricultural areas, especially those under intensive cultivation of sugar cane and cassava. The Argissolo showed greater sensitivity to changes in land use, while the Latossolo showed greater resilience to compaction and better water infiltration capacity. The spatial distribution of ecosystem services indicated that areas under conventional cultivation presented a greater risk of erosion and soil loss, compromising water recharge and increasing the silting up of reservoirs.

Overall, the findings of this thesis highlight the importance of forest restoration as an essential strategy for mitigating the impacts of soil degradation and promoting water conservation. The implementation of conservation practices, such as maintaining vegetation cover, reducing heavy machinery traffic and using sustainable management techniques, is fundamental to guaranteeing soil functionality and the sustainability of ecosystems. In addition, the soil quality indicators developed in this research can serve as decision-making support tools, helping managers and public policy makers to define priority areas for restoration and implement strategies for water and soil conservation.

In this way, this thesis contributes not only to the advancement of scientific knowledge on forest restoration and soil quality, but also provides technical support for the formulation of environmental policies aimed at recovering degraded areas and promoting more sustainable land use systems. Further research in this area should focus on improving soil quality assessment methodologies, adapting indices for tropical soils and long-term monitoring of the impacts of forest restoration on water resource conservation.