UNIVERSIDADE ESTADUALDE SANTA CRUZ – UESC PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA E CONSERVAÇÃO DA BIODIVERSIDADE – PPGECB

MARINA GOMES DE FIGUEIREDO

DIVERSIDADE DE ÁRVORES, ESTOQUE DE CARBONO E MANEJO LOCAL: IMPACTOS NA CONSERVAÇÃO DA BIODIVERSIDADE E PRODUTIVIDADE DA LAVOURA CACAUEIRA

ILHÉUS - BAHIA

2024

MARINA GOMES DE FIGUEIREDO

DIVERSIDADE DE ÁRVORES, ESTOQUE DE CARBONO E MANEJO LOCAL: IMPACTOS NA CONSERVAÇÃO DA BIODIVERSIDADE E PRODUTIVIDADE DA LAVOURA CACAUEIRA

Tese apresentada à Universidade Estadual de Santa Cruz, como parte das exigências para obtenção do título de Doutor em Ecologia e Conservação da Biodiversidade. Área de concentração: Ecologia e Conservação da Biodiversidade

Discente: Marina Gomes de Figueiredo
Orientadora: Profª. Drª Deborah Faria

Co-orientadora: Profª. Drª Larissa Rocha-Santos

ILHÉUS – BAHIA

2024

F475 Figueiredo, Marina Gomes de.
Diversidade de árvores, estoque de carbono e manejo local: impactos na conservação da biodiversidade e produtividade da lavoura cacaueira / Marina Gomes de Figueiredo. – Ilhéus, BA: UESC, 2024.
72f.: il.

Orientadora: Deborah Faria
Tese (Doutorado) – Universidade Estadual de Santa Cruz. Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade – PPGECB.
Inclui referências.

1. Sistemas agroflorestais. 2. Agrossilvicultura. 3. Pagamentos por serviços ambientais. 4. Mercado de emissão de carbono. 5. Agricultura sustentável. I. Título.

CDD 634.99

AGRADECIMENTOS

Eu agradeço primeiramente aos produtores rurais e coletivos de agroecologia que tive contato nos últimos anos, que mudaram radicalmente a minha leitura de mundo e me ensinaram tanto. Gostaria de agradecer à minha fiel companheira Cacildis, que depois de 15 anos de convivência conseguiu me acompanhar até a minha defesa do segundo doutorado e 15 dias depois não resistiu e fez a passagem. Muito obrigada por tudo, sou uma pessoa melhor por ter tido você na minha vida.

Também queria agradecer à minha família, especialmente a minha mãe, pelo amor e suporte, a minha irmã, pelas trocas e presença e cunhado por todo apoio. Agradeço aos parentes mais distantes que também me apoiaram como puderam, desde comprar rifas do laboratório, até visitas calorosas.

Agradeço à Deborah pela orientação, liberdade, confiança e esforço para estar presente, mesmo em momentos que eu sabia que isso era extremamente difícil, meu muito obrigada! Agradeço à Larissa pelos ensinamentos de campo, ajuda nas identificações de plantas e coorientação durante todo o doutorado. Gostaria de agradecer imensamente ao Lukas Daneo pelo auxilio no campo, profissionalismo, generosidade com seu vasto conhecimento, amizade e respeito. Você tornou inúmeras campanhas de campo mais leves!

Eu agradeço a todos os produtores que abriram suas porteiras para a nossa pesquisa, e foram sempre tão acolhedores e gentis conosco. Gostaria de agradecer ao pessoal do LEAC pelas muitas trocas, auxilio e aprendizado durante esse processo. Especialmente a todas as pessoas que me acompanharam no campo, vocês ajudaram a tornar esse trabalho possível.

Agradeço aos muitos amigos que ganhei e mantive nessa jornada! Especialmente àqueles que foram minha rede de apoio nos últimos anos, me ajudando desde problemas de casa, até análises estatísticas. Sou muito agradecida também aos meus colegas de pós graduação, em um cenário mal remunerado, com perspectivas de mercado precárias e altas cobranças, é extremamente importante o quanto nos ajudamos nesse período.

Meu muito obrigado à equipe que me acompanha e me ajudou com meu diagnóstico tardio de TDAH e TEA, vocês me ajudaram a me entender melhor e respeitar meus limites e capacidade.

E por fim, eu agradeço às instituições de fomento de pesquisa que tornaram esse trabalho possível, fornecendo verba ou materiais para campo, CAPES, CNPq, Fapesb e a Idea Wild. Assim como à UESC e ao Programa de Pós Graduação em Ecologia e Conservação da Biodiversidade.

DIVERSIDADE DE ÁRVORES, ESTOQUE DE CARBONO E MANEJO LOCAL: IMPACTOS NA CONSERVAÇÃO DA BIODIVERSIDADE E PRODUTIVIDADE DA LAVOURA CACAUEIRA

RESUMO

O cacau (*Theobroma cacao*) é uma espécie de árvore nativa da bacia Amazônica, cujo cultivo começou há cerca de 2.000 anos na América Central. Ao longo dos séculos, o cultivo de cacau foi estabelecido no sub-bosque das florestas tropicais, transformando significativamente as paisagens das planícies de regiões da América Latina, África e Ásia. Atualmente, o cacau, juntamente com o café, é uma das principais commodities produzidas em sistemas agroflorestais, sendo cultivado principalmente por pequenos agricultores em regiões tropicais ricas em biodiversidade, chamadas de hotspots. Além disso, a produção de cacau é um fator determinante nas mudanças climáticas e altamente vulnerável aos seus impactos. Devido a esses fatores, associados à crescente demanda mundial por cacau, o principal desafio é encontrar sistemas de cultivo que aumentem a produtividade e, ao mesmo tempo, proporcionem benefícios sociais e ambientais. O cultivo do cacau pode ocorrer no sub-bosque de florestas, denominado agrofloresta rústica, ou em monocultivo, sombra especializada, sombra comercial, sombra mista e agrofloresta sucessional de cacau. No primeiro capítulo desta tese, revisamos os principais estudos publicados sobre agroflorestas sucessionais de cacau, comparando-as com outros tipos de cultivo e discutindo os principais desafios para sua implementação. A agrofloresta sucessional (S-AFS) imita florestas naturais, conservando a biodiversidade, os serviços ecossistêmicos e os meios de subsistência dos agricultores. Ao mesmo tempo, esse sistema aumenta a resiliência às mudanças climáticas, o sequestro de carbono e a ciclagem de nutrientes. Apesar das suas vantagens, o sistema demanda amplo conhecimento sobre as espécies e suas interações, além de manejo intenso e constante, o que consome muitas horas de trabalho. Há necessidade de políticas públicas que promovam assistência técnica, organização entre produtores e financiamento adequado.

No segundo capítulo, avaliamos os principais fatores que afetam a produtividade do cacau e o estoque de carbono em sistemas agroflorestais de cacau no sul da Bahia, Brasil, com o objetivo de identificar cenários vantajosos tanto do ponto de vista socioeconômico quanto ambiental. As agroflorestas de cacau dessa região foram criadas pela substituição do sub-bosque da floresta natural por cacaueiros, em uma área crítica de biodiversidade no *hotspot* da Mata Atlântica. Amostramos 47 fazendas em diferentes contextos de paisagem e avaliamos a resposta da produtividade do cacau à cobertura florestal da paisagem, estrutura da vegetação, nível de sombra, estoque de carbono e práticas de manejo, com base em pesquisas e entrevistas in situ. Também analisamos a relação entre cobertura florestal, níveis de sombra e práticas de manejo com o estoque de carbono. Nossos resultados não indicaram nenhuma relação entre produtividade e sombreamento local, embora a frequência das práticas de manejo tenha afetado positivamente os rendimentos de cacau. Por outro lado, as árvores de sombra desempenharam um papel fundamental no armazenamento de carbono (93% do valor total), indicando um alto potencial para o mercado de carbono, além de proteger espécies ameaçadas. Nosso estudo também mostra que a intensificação sustentável da produção de cacau envolve priorizar práticas de manejo como controle de ervas daninhas, poda de cacaueiros, ajuste do número total de cacaueiros por hectare e aplicação de fertilizantes minerais e/ou orgânicos.

A região sul da Bahia tem cerca de dois terços do estoque de carbono nas cabrucas, o que tem despertado interesse em Pagamentos por Serviços Ambientais (PSA) nessa área. Devido aos limites orçamentários globais, é fundamental buscar soluções que abordem simultaneamente a conservação da diversidade florística e o estoque de carbono. No terceiro capítulo desta tese, avaliamos como aspectos específicos do cultivo de cacau, como produtividade, práticas de manejo e cobertura florestal da paisagem, afetam a diversidade de árvores em 54 fazendas da zona de produção de cacau do sul da Bahia, Brasil. Para avaliar a diversidade de árvores, utilizamos uma abordagem abrangente que inclui diversidade taxonômica (TD), diversidade filogenética (PD e sesPD), diversidade funcional (FD e sesFD) e valor de conservação, com foco em espécies ameaçadas e endêmicas. Também investigamos a relação entre essas métricas de diversidade e o armazenamento de carbono. Nossas descobertas revelaram que as cabrucas hospedam um conjunto diverso de árvores e que nem as práticas de manejo nem a cobertura florestal influenciaram significativamente a diversidade de árvores. Apesar do impacto negativo da diversidade taxonômica na produtividade, algumas fazendas mantiveram altos níveis de produtividade e diversidade por meio de práticas seletivas de manejo. Embora as cabrucas sirvam como habitats vitais para espécies endêmicas e ameaçadas, além de armazenarem grandes quantidades de carbono acima do solo, nossa análise não encontrou correlação entre as métricas de diversidade de árvores e o armazenamento de carbono. A exclusão da biodiversidade dos esquemas de PSA pode levar à substituição de espécies ameaçadas e endêmicas, que armazenam menos carbono, por espécies mais eficientes no sequestro de carbono. Assim, as políticas públicas devem integrar ambos os serviços ecossistêmicos para maximizar os benefícios à biodiversidade e à conservação de carbono. Portanto, é imperativo que as estratégias de conservação de carbono incluam a biodiversidade para garantir uma abordagem mais abrangente e eficaz no planejamento de conservação.

ABSTRACT

Cocoa (*Theobroma cacao*) is a tree species native to the Amazon basin, whose cultivation began about 2,000 years ago in Central America. Over the centuries, cocoa cultivation was established in the understory of tropical forests, significantly transforming lowland landscapes in regions of Latin America, Africa, and Asia. Today, cocoa, along with coffee, is one of the main commodities produced in agroforestry systems, mainly cultivated by small farmers in tropical regions rich in biodiversity, known as hotspots. Moreover, cocoa production is a key factor in climate change and highly vulnerable to its impacts. Due to these factors, along with the growing global demand for cocoa, the main challenge is to find farming systems that increase productivity while providing social and environmental benefits. Cocoa can be cultivated in forest understory systems, called rustic agroforestry, or in monoculture, specialized shade, commercial shade, mixed shade, and successional agroforestry systems. In the first chapter of this thesis, we reviewed the main published studies on successional cocoa agroforestry systems, comparing them with other types of cultivation and discussing the main challenges for their implementation. Successional agroforestry (S-AFS) mimics natural forests, conserving biodiversity, ecosystem services, and farmers' livelihoods. At the same time, this system increases resilience to climate change, carbon sequestration, and nutrient cycling. Despite its advantages, this system requires extensive knowledge of species and their interactions, as well as intensive and constant management, which consumes many hours of labor. Public policies are needed to promote technical assistance, organization among producers, and adequate financing.

In the second chapter, we evaluated the main factors affecting cocoa productivity and carbon stocks in cocoa agroforestry systems in southern Bahia, Brazil, to identify advantageous scenarios from both socioeconomic and environmental perspectives. The cocoa agroforests in this region were created by replacing the natural forest understory with cacao trees, in a critical biodiversity area within the Atlantic Forest hotspot. Based on in situ surveys and interviews, we sampled 47 farms in different landscape contexts and evaluated cocoa productivity responses to forest cover, vegetation structure, shade levels, carbon stocks, and management practices. We also analyzed the relationship between forest cover, shade levels, and management practices with carbon stocks. Our results did not indicate any relationship between productivity and local shading, although the frequency of management practices positively affected cocoa yields. On the other hand, shade trees played a key role in overall carbon storage (93% of the total value), indicating high potential for the carbon market, as well as protecting endangered species. Our study also shows that achieving sustainable intensification in cocoa production involves prioritizing management practices such as weed control, cacao tree pruning, adjusting the total number of cacao trees per hectare, and applying mineral and/or organic fertilizers.

The southern Bahia region holds about two-thirds of the carbon stock in *cabrucas*, which has led to increased interest in Payments for Environmental Services (PES) in this area. Due to global budgetary limits, it is crucial to seek solutions that address both the conservation of floristic diversity and carbon stocks. In the third chapter of this thesis, we evaluated how specific aspects of cocoa cultivation—such as productivity, management practices, and forest cover—affect tree diversity in 54 farms in the cocoa production zone of southern Bahia, Brazil. To assess tree diversity, we used a comprehensive approach that includes taxonomic diversity (TD), phylogenetic diversity (PD and sesPD), functional diversity (FD and sesFD), and conservation value, with a specific focus on threatened and endemic species. We further investigated the relationship between these diversity metrics and carbon storage. Our findings revealed that *cabrucas* host diverse trees and that neither management practices nor forest cover significantly influenced tree diversity. Despite the negative impact of taxonomic diversity on productivity, some farms maintained high levels of both productivity and diversity through selective management practices chosen by smallholder farmers. Although *cabrucas* serve as vital habitats for endemic and threatened tree species, as well as store substantial amounts of aboveground carbon, our analysis found no correlation between community tree diversity metrics and carbon storage. Excluding biodiversity from PES schemes may lead to the displacement of threatened and endemic species, which store less carbon, by more carbon-efficient species. Public policies must integrate both ecosystem services to maximize biodiversity and carbon conservation benefits. Therefore, it is imperative to incorporate biodiversity considerations into carbon conservation strategies to ensure a more comprehensive and effective approach to conservation planning.

Sumário

INTRODUÇÃO

Atender às demandas de produção nos sistemas agrícolas, minimizando impactos no meio ambiente, tornou-se um grande desafio para governos e agricultores, principalmente no Antropoceno. Este setor é especialmente vulnerável às mudanças ambientais, incluindo as alterações climáticas globais (Foley et al. 2005; IPCC 2014; Tilman et al. 2011). Nas últimas décadas, as discussões sobre a intensificação sustentável (SI) na agricultura ganharam destaque, enfatizando o desenvolvimento de práticas que aumentem a produtividade enquanto oferecem benefícios sociais e ambientais (Rockström et al. 2017; Tilman et al. 2001, 2011). Entre essas práticas, os sistemas agroflorestais, que integram árvores e culturas, são reconhecidos como uma estratégia eficaz para gerenciar recursos naturais, equilibrando o desenvolvimento agrícola e a preservação dos serviços ecossistêmicos (Addo-Danso et al. 2024; Mortimer, Saj, and David 2018).

O cacau (*Theobroma cacao* L.) é uma espécie de árvore nativa da bacia Amazônica e foi cultivado pela primeira vez na América Central há mais de 2.000 anos (Zarrillo et al. 2018). Ao longo dos séculos, o cultivo do cacau transformou significativamente as paisagens das florestas tropicais de planície na América Latina, África e Ásia, e continua moldando essas regiões até hoje (Schroth and Harvey 2007). Atualmente, é cultivada em aproximadamente 60 países e é uma das culturas agroflorestais mais difundidas, juntamente com o café, cobrindo milhões de hectares em áreas tropicais (FAOSTAT 2024). A maioria das plantações de cacau é estabelecida no sub-bosque das florestas tropicais, onde as plantas jovens de cacau se beneficiam da sombra natural, solos férteis e competição reduzida com ervas daninhas, mitigando o estresse causado pela luz solar direta (Clough, Dwi Putra, et al. 2009; Rice and Greenberg 2000). Essa abordagem pode gerar benefícios econômicos significativos, um conceito conhecido como "renda da floresta", que impulsionou a conversão de *hotspots* de floresta tropical (Clough, Faust, and Tscharntke 2009; Ruf and Schroth 2004). No entanto, à medida que as plantações envelhecem e entram em seu segundo ciclo (cerca de 30 a 40 anos), os benefícios associados à renda da floresta diminuem, levando à redução da fertilidade do solo, aumento de pragas e doenças e estagnação na produção (Clough et al. 2011; Ruf, Schroth, and Doffangui 2015).

Entre 2000 e 2020, a produção global de cacau aumentou cerca de 33%, enquanto os rendimentos médios por hectare permaneceram estáveis em aproximadamente 440–550 kg de grãos secos fermentados em todas as regiões de produção (FAOSTAT 2024). Esse aumento na produção geralmente resulta da conversão de terras agrícolas usadas por agricultores de subsistência em áreas de cultivo de cacau (Ajagun et al. 2022) e da invasão de florestas protegidas e parques nacionais (Asare et al. 2014). Consequentemente, o cacau tornou-se o quarto maior impulsionador do desmatamento global, contribuindo para a perda de 2,3 milhões de hectares entre 2001 e 2015 (Dow Goldman et al. 2020). Pequenos agricultores frequentemente simplificam os sistemas agroflorestais para aumentar os rendimentos, reduzindo as árvores de sombra e mudando para a produção em monocultura (Rice and Greenberg 2000). Embora essa abordagem inicialmente impulsione a produção, geralmente leva a rendimentos reduzidos após cerca de quinze anos (Ahenkorah et al. 1987), menor resiliência (Jacobi et al. 2015), perda de serviços ecossistêmicos (Clough, Faust, et al. 2009) e aumento da densidade de pragas (Tscharntke et al. 2011).

Cerca de 80–90% do cacau é produzido por pequenos agricultores em todo o mundo, envolvendo aproximadamente 5–6 milhões de agricultores (Beg et al. 2017). Esses agricultores, que dependem fortemente do cacau para sua subsistência, são economicamente vulneráveis e enfrentam insegurança alimentar devido à volatilidade dos preços do cacau e ao impacto devastador das doenças nas colheitas (Ajagun et al. 2022). Além disso, a produção de cacau contribui para as mudanças climáticas e é altamente suscetível aos seus efeitos (Parra-Paitan et al. 2024a). Como resultado, a indústria do cacau enfrenta o desafio de aumentar a produção enquanto mantém a sustentabilidade (Mattalia et al. 2022). Para enfrentar esses desafios, os sistemas agroflorestais baseados no cacau são frequentemente recomendados como uma solução viável. Esses sistemas têm o potencial de fornecer rendimentos sustentáveis a longo prazo, oferecer múltiplos benefícios e conservar a biodiversidade (Maney, Sassen, and Hill 2022; Olwig, Bosselmann, and Owusu 2023).

No sul da Bahia, as agroflorestas de cacau são chamadas 'cabrucas', elas formam uma matriz permeável nessa paisagem essencial para a conservação da biodiversidade, funcionando como corredores ecológicos e habitats adicionais (Faria 2006; Sambuichi et al., 2012). Juntamente com o norte do Espírito Santo, essa região é um centro de endemismo e um *hotspot* de biodiversidade na Mata Atlântica, abrigando muitas espécies endêmicas de mamíferos, aves, formigas e plantas (Martini et al., 2007; Thomas et al., 1998). Apesar de não possuírem a mesma riqueza de espécies das florestas intactas, as cabrucas sustentam quase 2/3 das espécies florestais, incluindo algumas ameaçadas (Faria et al., 2006; Faria & Baumgarten, 2007). Além disso, as árvores de sombra nas cabrucas armazenam 59% do carbono da vegetação arbórea do sul da Bahia, com a intensificação dos sistemas representando uma ameaça a esse armazenamento de carbono (Schroth et al., 2015).

Nas décadas de 1960 e 1970, o Comitê Executivo do Plano de Cultivo do Cacau (CEPLAC) promoveu a remoção de árvores no sul da Bahia para aumentar a produtividade do cacau com menos sombra e mais uso de fertilizantes (Cabala Rosand et al., 1976; Johns, 1998). Embora houvesse um aumento de rendimento a curto prazo, a redução da sombra era questionável devido aos benefícios ecológicos e econômicos proporcionados por ela (Beer, 1987). Atualmente, uma lei estadual define que para ser caracterizado como cabruca, uma agrofloresta de cacau deve manter pelo menos 20 árvores nativas por hectare (Decreto Estadual nº 15.180/2014, Bahia), um valor bem abaixo do encontrado em as cabrucas tradicionais, que abrigavam cerca de 200 árvores/ha (Sambuichi et al., 2012; Schroth et al., 2016).

Posteriormente, no final da década de 1980, a chegada da vassoura-de-bruxa, uma doença causada pelo fungo *Moniliophthora perniciosa* causou grande declínio da produtividade (Filho et al., 2023). Mesmo após a recuperação parcial das lavouras, a produtividade no sul da Bahia, majoritariamente no sistema cabruca, varia entre 230 a 300 kg/ha^{-1} de grãos secos de cacau, ainda bem abaixo da média global (cerca de 450-500 kg/ha^{-1}) (FAOSTAT, 2022; IBGE, 2019). Isso destaca a importância de equilibrar produção com serviços ecossistêmicos, como o armazenamento de carbono, a biodiversidade e a resiliência socioeconômica (Mortimer et al., 2018). Nesse contexto, fomentar uma copa diversificada de árvores de sombra torna-se fundamental, pois contribui para a conservação dessas áreas, além de melhorar serviços como polinização e controle de pragas, o que, por sua vez, aumenta a produtividade agroflorestal (Maza-Villalobos et al., 2024).

Alinhar a conservação com a produção de cacau dos pequenos agricultores exige maiores esforços da indústria para reduzir os ciclos do cacau e aproveitar oportunidades de sustentabilidade (Girardello et al., 2019; Sanial et al., 2023). Para melhorar os serviços ecossistêmicos e aumentar a produtividade do cacau no sul da Bahia, é essencial adotar uma gestão eficaz das agroflorestas de cacau, incluindo o uso de fertilizantes. Isso pode elevar os rendimentos, atualmente abaixo da média mundial (585 kg/ha), e manter altos estoques de carbono (65 Mg/ha) e níveis de sombra (55%) (Schroth et al., 2016).

Nesta tese, apresento três capítulos que exploram a otimização e valorização dos serviços ecossistêmicos junto à produção de cacau. O primeiro capítulo revisa as agroflorestas sucessionais como uma solução sustentável frente ao aumento da demanda por cacau. O segundo capítulo discute estratégias para elevar a produtividade do cacau, preservando ao máximo os estoques de carbono. Já no terceiro capítulo, analiso a viabilidade de obter co-benefícios por meio do pagamento por serviços ambientais (PSA), focado no estoque de carbono e na conservação de espécies ameaçadas e endêmicas da região.

Capítulo 1: Successional agroforestry system as a sustainable alternative for cocoa (*Theobroma cacao*) production: a review.

A ser submetido à *Agroforestry Systems.*

Capítulo 2: “Management practices can improve yields of carbon-rich cocoa agroforests in Brazil”

A ser submetido à *Agricultural Systems*.

Capítulo 3: “Assessment of co-benefits between carbon storage and biodiversity conservation in cocoa agroforests in southern Bahia, Brazil”

A ser submetido à *Agriculture*, *Ecosystems & Environment*.

REFERÊNCIAS BIBLIOGRÁFICAS

Addo-Danso, Shalom D., Richard Asare, Abigail Tettey, Jennifer E. Schmidt, Marie Sauvadet, Mathieu Coulis, Nelly Belliard, and Marney E. Isaac. 2024. “Shade Tree Functional Traits Drive Critical Ecosystem Services in Cocoa Agroforestry Systems.” *Agriculture, Ecosystems and Environment* 372(May):109090. doi: 10.1016/j.agee.2024.109090.

Ahenkorah, Y., BJ Halm, MR Appiah, GS Akrofi, and JEK Yirenkyi. 1987. “TWENTY YEARS ’ RESULTS FROM A SHADE AND FERTILIZER TRIAL ON AMAZON COCOA { THEOBROMA CACAO) IN GHANA Cocoa Research Institute of Ghana (CRIG), PO Box 8 , New Tafo-Akim , Ghana (Accepted 27 March 1986) Following the Success of the Earlier Amelonado Co.” *Experimental Agriculture* 23:31–39.

Ajagun, Ebunoluwa O., George Ashiagbor, Winston A. Asante, Benjamin A. Gyampoh, Kwasi A. Obirikorang, and Emmanuel Acheampong. 2022. “Cocoa Eats the Food: Expansion of Cocoa into Food Croplands in the Juabeso District, Ghana.” *Food Security* 14(2):451–70. doi: 10.1007/s12571-021-01227-y.

Andres, Christian, Hermann Comoé, Anna Beerli, Monika Schneider, Stephan Rist, and Johanna Jacobi. 2016. *Cocoa in Monoculture and Dynamic Agroforestry*.

Ariza-Salamanca, Antonio Jesús, Rafael Mª Navarro-Cerrillo, Jayne Crozier, Clare Stirling, Agnese Mancini, Wilma Blaser-Hart, and Pablo González-Moreno. 2024. “Drivers of Cocoa Yield and Growth in Young Monoculture and Agroforestry Systems.” *Agricultural Systems* 219(June). doi: 10.1016/j.agsy.2024.104044.

Asare, Richard, Victor Afari-Sefa, Yaw Osei-Owusu, and Opoku Pabi. 2014. “Cocoa Agroforestry for Increasing Forest Connectivity in a Fragmented Landscape in Ghana.” *Agroforestry Systems* 88(6):1143–56. doi: 10.1007/s10457-014-9688-3.

Beg, Mohd Shavez, Sameer Ahmad, Kulsum Jan, and Khalid Bashir. 2017. “Status, Supply Chain and Processing of Cocoa - A Review.” *Trends in Food Science and Technology* 66:108–16. doi: 10.1016/j.tifs.2017.06.007.

Blaser, W. J., J. Oppong, S. P. Hart, J. Landolt, E. Yeboah, and J. Six. 2018. “Climate-Smart Sustainable Agriculture in Low-to-Intermediate Shade Agroforests.” *Nature Sustainability* 1(5):234–39. doi: 10.1038/s41893-018-0062-8.

Clough, Yann, Jan Barkmann, Jana Juhrbandt, Michael Kessler, Thomas Cherico Wanger, Alam Anshary, Damayanti Buchori, Daniele Cicuzza, Kevin Darras, Dadang Dwi Putra, Stefan Erasmi, Ramadhanil Pitopang, Carsten Schmidt, Christian H. Schulze, Dominik Seidel, Ingolf Steffan-Dewenter, Kathrin Stenchly, Stefan Vidal, Maria Weist, Arno Christian Wielgoss, and Teja Tscharntke. 2011. “Combining High Biodiversity with High Yields in Tropical Agroforests.” *Proceedings of the National Academy of Sciences* 108(20):8311–16. doi: 10.1073/PNAS.1016799108.

Clough, Yann, Dadang Dwi Putra, Ramadhanil Pitopang, and Teja Tscharntke. 2009. “Local and Landscape Factors Determine Functional Bird Diversity in Indonesian Cacao Agroforestry.” *Biological Conservation* 142(5):1032–41. doi: https://doi.org/10.1016/j.biocon.2008.12.027.

Clough, Yann, Heiko Faust, and Teja Tscharntke. 2009. “Cacao Boom and Bust: Sustainability of Agroforests and Opportunities for Biodiversity Conservation.” *Conservation Letters* 2(5):197–205. doi: 10.1111/j.1755-263x.2009.00072.x.

Dow Goldman, Elizabeth, Mikaela Weisse, Nancy Harris, and Martina Schneider. 2020. “Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber.” *World Resources Institute* (October):1–22. doi: 10.46830/writn.na.00001.

FAOSTAT. 2024. “FAOSTAT_data_en_8-21-2024.”

Faria, Deborah, Rudi Ricardo Laps, Julio Baumgarten, and Maurício Cetra. 2006. “Bat and Bird Assemblages from Forests and Shade Cacao Plantations in Two Contrasting Landscapes in the Atlantic Forest of Southern Bahia, Brazil.” *Biodiversity and Conservation* 15(2):587–612. doi:

10.1007/s10531-005-2089-1.

Foley, Jonathan A., Ruth DeFries, Gregory P. Asner, Carol Barford, Gordon Bonan, Stephen R. Carpenter, F. Stuart Chapin, Michael T. Coe, Gretchen C. Daily, Holly K. Gibbs, Joseph H. Helkowski, Tracey Holloway, Erica A. Howard, Christopher J. Kucharik, Chad Monfreda, Jonathan A. Patz, I. Colin Prentice, Navin Ramankutty, and Peter K. Snyder. 2005. “Global Consequences of Land Use.” *Science* 309(5734):570–74. doi: 10.1126/science.1111772.

FORCLIME. 2013. “Introducing Successional Agroforestry for Cocoa Production in the Heart of Borneo.” *Module Briefing Note* (9):2.

ICCO. 2023. “(Thousand Tonnes).” *Supply & Demand_QBCS* L(2):2023.

IPCC. 2014. *Climate Change 2014 Part A: Global and Sectoral Aspects*.

Jacobi, Johanna, Monika Schneider, Patrick Bottazzi, Maria Pillco, Patricia Calizaya, and Stephan Rist. 2015. “Agroecosystem Resilience and Farmers’ Perceptions of Climate Change Impacts on Cocoa Farms in Alto Beni, Bolivia.” *Renewable Agriculture and Food Systems* 30(2):170–83. doi: 10.1017/S174217051300029X.

Koog, Ivanoé. 2020. “Biophysical State of Cocoa Dynamic Agroforestry Systems in Ghana: A Chronosequence.” ETH Zurich.

Maney, Calum, Marieke Sassen, and Samantha L. L. Hill. 2022. “Modelling Biodiversity Responses to Land Use in Areas of Cocoa Cultivation.” *Agriculture, Ecosystems and Environment* 324(October 2021):107712. doi: 10.1016/j.agee.2021.107712.

Mattalia, Giulia, Alexander Wezel, Pierre Costet, Patrick Jagoret, Olivier Deheuvels, Paola Migliorini, and Christophe David. 2022. “Contribution of Cacao Agroforestry versus Mono-Cropping Systems for Enhanced Sustainability. A Review with a Focus on Yield.” *Agroforestry Systems* 96(7):1077–89. doi: 10.1007/s10457-022-00765-4.

Mortimer, Róisín, Stéphane Saj, and Christophe David. 2018. “Supporting and Regulating Ecosystem Services in Cacao Agroforestry Systems.” *Agroforestry Systems* 92(6):1639–57. doi: 10.1007/s10457-017-0113-6.

Niether, Wiebke, Johanna Jacobi, Wilma J. Blaser, Christian Andres, and Laura Armengot. 2020. “Cocoa Agroforestry Systems versus Monocultures: A Multi-Dimensional Meta-Analysis.” *Environmental Research Letters* 15(10). doi: 10.1088/1748-9326/abb053.

Olwig, Mette Fog, Aske Skovmand Bosselmann, and Kwadwo Owusu. 2023. *Agroforestry as Climate Change Adaptation: The Case of Cocoa Farming in Ghana*.

Parra-Paitan, Claudia, Patrick Meyfroidt, Peter H. Verburg, and Erasmus K. H. J. zu Ermgassen. 2024a. “Deforestation and Climate Risk Hotspots in the Global Cocoa Value Chain.” *Environmental Science and Policy* 158(December 2023):103796. doi: 10.1016/j.envsci.2024.103796.

Parra-Paitan, Claudia, Patrick Meyfroidt, Peter H. Verburg, and Erasmus K. H. J. zu Ermgassen. 2024b. “Deforestation and Climate Risk Hotspots in the Global Cocoa Value Chain.” *Environmental Science and Policy* 158(June):103796. doi: 10.1016/j.envsci.2024.103796.

Rebello, José Fernando dos Santos, and Daniela Ghiringhello Sakamoto. 2021. *Agricultura Sintrópica Segundo Ernst Götsch*.

Rice, Robert A., and Russell Greenberg. 2000. “Cacao Cultivation and the Conservation of Biological Diversity.” *Ambio* 29(3):167–73. doi: 10.1579/0044-7447-29.3.167.

Rockström, Johan, John Williams, Gretchen Daily, Andrew Noble, Nathanial Matthews, Line Gordon, Hanna Wetterstrand, Fabrice DeClerck, Mihir Shah, Pasquale Steduto, Charlotte de Fraiture, Nuhu Hatibu, Olcay Unver, Jeremy Bird, Lindiwe Sibanda, and Jimmy Smith. 2017. “Sustainable Intensification of Agriculture for Human Prosperity and Global Sustainability.” *Ambio* 46(1):4–17. doi: 10.1007/s13280-016-0793-6.

Ruf, François, and Götz Schroth. 2004. “Chocolate Forests and Monocultures: A Historical Review of Cocoa Growing and Its Conflicting Role in Tropical Deforestation and Forest Conservation.” *Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press, Washington* 107–34.

Ruf, François, Götz Schroth, and Kone Doffangui. 2015. “Climate Change, Cocoa Migrations and

Deforestation in West Africa: What Does the Past Tell Us about the Future?” *Sustainability Science* 10(1):101–11. doi: 10.1007/s11625-014-0282-4.

Sambuichi, Regina Helena Rosa, and Mundayatan Haridasan. 2007. “Recovery of Species Richness and Conservation of Native Atlantic Forest Trees in the Cacao Plantations of Southern Bahia in Brazil.” *Biodiversity and Conservation* 16(13):3681–3701. doi: 10.1007/s10531-006-9017-x.

Schneider, M., C. Andres, G. Trujillo, F. Alcon, P. Amurrio, E. Perez, F. Weibel, and J. Milz. 2017. “COCOA and TOTAL SYSTEM YIELDS of ORGANIC and CONVENTIONAL AGROFORESTRY VS. MONOCULTURE SYSTEMS in A LONG-TERM FIELD TRIAL in BOLIVIA.” *Experimental Agriculture* 53(3):351–74. doi: 10.1017/S0014479716000417.

Schroth, Götz, and Celia A. Harvey. 2007. “Biodiversity Conservation in Cocoa Production Landscapes: An Overview.” *Biodiversity and Conservation* 16(8):2237–44. doi: 10.1007/s10531-007-9195-1.

Schulz, B., B. Becker, and E. Götsch. 1994. “Indigenous Knowledge in a ‘modern’ Sustainable Agroforestry System-a Case Study from Eastern Brazil.” *Agroforestry Systems* 25(1):59–69. doi: 10.1007/BF00705706.

Sonwa, Denis J., Bernard A. Nkongmeneck, Stephan F. Weise, Maturin Tchatat, Akin A. Adesina, and Marc J. J. Janssens. 2007. “Diversity of Plants in Cocoa Agroforests in the Humid Forest Zone of Southern Cameroon.” *Biodiversity and Conservation* 16(8):2385–2400. doi: 10.1007/s10531-007-9187-1.

Steinfeld, Jonas P., Felix J.J.A. Bianchi, Jorge Luiz Locatelli, Rodnei Rizzo, Maria Eduarda Bispo de Resende, Maria V. Ramos Ballester, Carlos E. P. Cerri, Alberto C. C. Bernardi, and Rachel E. Creamer. 2023. “Increasing Complexity of Agroforestry Systems Benefits Nutrient Cycling and Mineral-Associated Organic Carbon Storage, in South-Eastern Brazil.” *Geoderma* 440(November):116726. doi: 10.1016/j.geoderma.2023.116726.

Steinfeld, Jonas P., Massimiliano Miatton, Rachel E. Creamer, Martin Ehbrecht, Vivian Valencia, Maria Victoria Ramos Ballester, and Felix J. J. A. Bianchi. 2024. “Identifying Agroforestry Characteristics for Enhanced Nutrient Cycling Potential in Brazil.” *Agriculture, Ecosystems and Environment* 362(October 2023):108828. doi: 10.1016/j.agee.2023.108828.

Tancara, Ariel Luis Arragan. 2014. “Efecto de La Poda y Raleo Se Árboles, En Un Sustema Agrofroestal Sucesionalen La Producción de Cacao (Theobroma Cacao), Del Alto Beni.”

Tilman, D., J. Fargione, B. Wolff, C. D’Antonio, A. Dobson, R. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. “Forecasting Agriculturally Driven Global Environmental Change.” *Science* 292(5515):281–84. doi: 10.1126/science.1057544.

Tilman, David, Christian Balzer, Jason Hill, and Belinda L. Befort. 2011. “Global Food Demand and the Sustainable Intensification of Agriculture.” *Proceedings of the National Academy of Sciences* 108(50):20260–64.

Tscharntke, Teja, Yann Clough, Shonil A. Bhagwat, Damayanti Buchori, Heiko Faust, Dietrich Hertel, Dirk Hölscher, Jana Juhrbandt, Michael Kessler, Ivette Perfecto, Christoph Scherber, Götz Schroth, Edzo Veldkamp, and Thomas C. Wanger. 2011. “Multifunctional Shade-Tree Management in Tropical Agroforestry Landscapes - A Review.” *Journal of Applied Ecology* 48(3):619–29. doi: 10.1111/j.1365-2664.2010.01939.x.

Vieira, Daniel L. M., Karen D. Holl, and Fabiana M. Peneireiro. 2009. “Agro-Successional Restoration as a Strategy to Facilitate Tropical Forest Recovery.” *Restoration Ecology* 17(4):451–59. doi: 10.1111/j.1526-100X.2009.00570.x.

Young, Katherine J. 2017. *Mimicking Nature: A Review of Successional Agroforestry Systems as an Analogue to Natural Regeneration of Secondary Forest Stands*.

Zarrillo, Sonia, Nilesh Gaikwad, Claire Lanaud, Terry Powis, Christopher Viot, Isabelle Lesur, Olivier Fouet, Xavier Argout, Erwan Guichoux, Franck Salin, Rey Loor Solorzano, Olivier Bouchez, Hélène Vignes, Patrick Severts, Julio Hurtado, Alexandra Yepez, Louis Grivetti, Michael Blake, and Francisco Valdez. 2018. “The Use and Domestication of Theobroma Cacao during the Mid-Holocene in the Upper Amazon.” *Nature Ecology and Evolution* 2(12):1879–88. doi: 10.1038/s41559-018-0697-x.

CAPITULO I

SUCCESSIONAL AGROFORESTRY SYSTEM AS A SUSTAINABLE ALTERNATIVE FOR COCOA (*THEOBROMA CACAO*) PRODUCTION: A REVIEW

Successional Agroforestry System as A Sustainable Alternative for Cocoa (*Theobroma Cacao*) Production: A Review

Abstract

Successional cocoa agroforestry systems are complex agroecosystems based on a set of strategies to simulate the successional stages and the structure of natural ecosystems. These systems are designed considering four dimensions: width, length, height (multi-strata), and time (species lifetime: pioneer, secondary and primary). Therefore, successional agroforestry includes coordinated practices such as (i) high-density, diversified, and stratified planting, and (ii) management interventions such as pruning and selective thinning (of cocoa and shade trees). Herein we present a systematic review addressing several topics regarding the classification, definitions, and contribution of such systems. Published studies that involve cocoa successional agroforestry practices are scarce, however, this review identified documents that address these practices, compared to other farming systems or fallow. Results obtained demonstrate the potential for high cocoa productivity in agroforestry. Shade trees and periodic management practices (pruning and thinning) helped producers achieve better results in addition to diversifying income and increasing economic and food security for family farmers. This review presents a compilation of these data and possible suggestions for agroforestry cocoa plantations that can help in planning and optimizing social, economic, and environmental outcomes.

Keywords: dynamic agroforestry, climate-smart agriculture, syntropic, sustainable agriculture.

1. Introduction

Cocoa (*Theobroma cacao* L.), native to the Amazon basin and first cultivated in Central America over 2,000 years ago (Zarrillo et al. 2018), has significantly transformed tropical forest landscapes across Latin America, Africa, and Asia (Schroth and Harvey 2007). Initially grown in the understory of tropical forests, cocoa plants benefit from natural shade, fertile soils, and reduced weed competition, which alleviates stress from direct sunlight (Clough, Faust, and Tscharntke 2009; Rice and Greenberg 2000). This practice, known as "forest rent," has driven the conversion of tropical forests, however, these benefits diminish as plantations age, leading to reduced soil fertility, increased pests, and stagnating production (Clough et al. 2011; Ruf et al. 2015). To counter these challenges, smallholder farmers often simplify agroforestry systems by reducing shade trees and shifting to monoculture practices, which initially boosts yields but ultimately results in lower productivity, decreased resilience, loss of ecosystem services, and higher pest densities over time (Rice and Greenberg 2000; Ahenkorah et al. 1987; Clough et al. 2009; Jacobi et al. 2015; Tscharntke et al. 2011).

Current cocoa production systems include (1) unshaded monocultures; (2) plantations with specialized or mixed shade trees, including species such as *Inga*, *Erythrina*, *Gliricidia*, and *Albizia*; (3) commercial polycultures where cocoa is intercropped with crops like *Hevea brasiliensis*, *Cocos nucifera*, bananas, or *Elaeis guineensis*; (4) rustic plantations under sparse forest cover, known as *cabrucas* in Brazil and "jungle cocoa" in Central and West Africa (Faria et al. 2006; Sambuichi and Haridasan 2007; Sonwa et al. 2007); and (5) successional agroforestry systems, which do not require "forest rent," and can be established in areas of recovery or degradation, mimicking natural forest succession (Vieira, Holl, and Peneireiro 2009; Young 2017). Successional agroforestry (S–AFS) is the most complex and sustainable system, designed to mimic natural forest ecosystems. It includes high planting densities and diversity, stratification, and high energy flow, typically without external inputs, and involves management practices such as various pruning interventions, weeding, selective grafting, and the selection of healthy planting material (Rebello and Sakamoto 2021).

Given the dual role of cocoa production as both a contributor to and highly vulnerable to climate change effects (Parra-Paitan et al. 2024b), climate-smart solutions are essential to meet the growing global demand for cocoa (Blaser et al. 2018). Successional agroforestry offers a win-win solution by enhancing biodiversity, promoting ecosystem services, and improving farmer livelihoods. It mitigates risks from pests and diseases, increases resilience to climate change, and contributes to carbon sequestration, soil health, and habitat connectivity (Andres et al. 2016; FORCLIME 2013). The presence of multiple species in this system also improves nutrient cycling and water retention, reducing the need for chemical inputs (Steinfeld et al. 2023, 2024). These multi-strata SAFs are designed with a diverse array of functionally distinct species, thus maximizing the use of nutrients, solar energy, and water (Rebello and Sakamoto 2021). Moreover, the inclusion of various crops diversifies farmers' income sources, providing food security and economic stability during periods of market volatility (Jacobi et al. 2015).

With the increasing need to boost cocoa production in the coming years (ICCO 2023), S-AFS offers a promising approach for cultivation on abandoned agricultural lands and degraded soils (Steinfeld et al. 2023; Vieira et al. 2009). Furthermore, S-AFS supports high biodiversity and has been proposed as an effective tool for forest restoration (Vieira et al. 2009), contrasting with other agroforestry systems that incorporate only a limited number of shade trees (Ariza-Salamanca et al. 2024). Despite these advantages, the adoption of cocoa successional agroforestry systems remains limited, with documented and effective implementation primarily observed in Brazil (Schulz, Becker, and Götsch 1994) and Bolivia (Tancara 2014), where it has been established for decades, and more recently piloted on a smaller scale in Côte d'Ivoire (Andres et al. 2016) and Ghana (Koog 2020).

Although some reviews have addressed cocoa agroforestry (Ariza-Salamanca et al. 2024; Mattalia et al. 2022; Niether et al. 2020; Schneider et al. 2017), a specific focus on successional agroforestry systems (S-AFS) compared to other systems has been lacking. This review aims to provide a comprehensive analysis of published data on the comparative performance of cocoa in successional agroforestry systems, cocoa monocultures (both conventional and organic), other cocoa agroforestry systems (including rustic, simple, or complex systems in both conventional and organic forms), and natural fallow as a control for biological aspects. We seek to enhance the understanding of this complex system by synthesizing these findings and have also surveyed the main challenges faced in the implementation and expansion of S-AFS.

2. Methods

A literature search before August 2024 was carried out about cocoa successional SAF in contrast to other farming systems or fallow. A systematic review was conducted within ISI Web of Science (www.isiwebofknowledge.com), SCOPUS (www.scopus.com), and Google Scholar, using the following 'title', 'keywords' or 'abstract' search terms: "Cacao agroforestry" OR "cocoa-based* agroforestry" OR "Cocoa* agroforestry" OR "agroforestry cocoa" OR "agroforestry cacao" OR "cocoa tree" OR "Cocoa farm" AND “Successional” OR “dynamic” OR “Syntropy*” OR "Agro-successional" OR "regenerative analog agroforestry" OR “climate-smart”. The search was limited to English-, Spanish-, and Portuguese-language documents, and also combined the keywords in these languages.

The database search produced 48 published documents. After removing articles without original data and duplicates. The criteria for selecting documents from the database query results were focused on studies that compared different attributes between successional agroforestry systems (AFS) of cocoa and other AFS, monocultures, or fallow. Additionally, the “snowball” referencing technique was employed, whereby studies cited within the initially identified articles were also selected. To broaden the scope of the review and provide a more comprehensive overview of all available evidence, gray literature was also included. 13 documents from these databases and 6 with the snowball method were considered within the scope of this study, totaling 19 articles with a time range from 1994 to 2023. Only four countries carried out studies combining cocoa with this type of agroforestry: Bolivia, Brazil, Ghana, and Côte d’Ivoire.

After retrieving and filtering the articles, they were categorized based on the attributes examined in their results: **(1)** cocoa productivity and quality**; (2)** biomass production and c-stock; **(3)** Soil quality; **(4)** Pest and disease control; **(5)** Biodiversity conservation; **(6)** Microclimate.

3. Results

Finally, of the 15 documents identified (Table S1), 21 attributes were assessed, 24% related to soil quality and cocoa or total production, 19% related to biomass production, 14% related to biodiversity conservation, 9% assessed estimated pests and disease control, and 5% evaluated the microclimate, C stock, and quality of cocoa beans.

In terms of productivity, SAF achieves cocoa yields without external inputs, matching levels that other agroforestry systems or monocultures can only reach with substantial amounts of fertilizers and pesticides (Jacobi et al., 2015; B. Schulz et al., 1994). Other studies found that conventional monocultures had significantly higher dry cocoa bean yields, while SAF had lower yields compared to other systems. However, total system yields were significantly higher in agroforestry systems compared to monocultures (Andres et al., 2016; Niether et al., 2019; Schneider et al., 2017). Effective management practices are crucial for SAFs; systems with pruning and thinning of shade trees produced 7,138 pods per hectare, compared to 1,953 pods per hectare in the control plot (Tancara, 2014). Additionally, element concentrations (N, Mg, S, Fe, Mn, Na, and Zn) were higher in beans produced in agroforestry systems compared to monocultures (Niether, Smit, et al., 2017).

Regarding biomass and carbon stock, SAFs produced significantly higher stocks than monoculture and traditional agroforests (Jacobi et al., 2014; Rivero & Mérida, 2009; B. Schulz et al., 1994). The soil in the SAF area had significantly higher phosphorus levels and less base saturation compared to the fallow area. Additionally, the SAF area had a more advanced successional stage of soil macrofauna, dominated by saprophytes, while the fallow area was dominated by predators (Peneireiro, 1999). The litter in SAFs had a higher nutrient content compared to traditional and fallow agroforests (Koog, 2020; Peneireiro, 1999; Rivero & Mérida, 2009). Furthermore, the uppermost soil layer in the agroforestry systems had higher soil (Niether, Schneidewind, et al., 2017). Cocoa in successional agroforestry systems exhibited significantly fewer incidences of witches' broom, *Moniliophthora perniciosa*, compared to monocultures and simple agroforests in Bolivia (Andres et al., 2016; Jacobi et al., 2015).

Bird species number and visit frequency were positively related to plant structure complexity and tree diversity, decreasing from fallow to SAFs, agroforestry systems, and monocultures ($\beta 1 = -0.149 \pm 0.046$ for species number, $\beta 1 = -0.167 \pm 0.078$ for visit frequency) (Naoki et al., 2017). SAF areas had greater diversity and equity than fallow, showing faster growth and lower mortality rates compared to conventional systems (Peneireiro, 1999). This allowed them to quickly host biodiversity comparable to tropical forests, regenerate soil, and improve early cocoa growth conditions (Koog, 2020). While agroforestry systems buffered temperature fluctuations better than monocultures, they reduced light and throughfall. High and closed-shade tree canopies had low spatial variability in throughfall and transmitted light, and although shade tree pruning increased canopy openness, light transmittance, and throughfall, it reduced the systems' buffering capacity against temperature and humidity fluctuations (Niether et al., 2018).

4. Discussion

The adoption of cocoa successional agroforestry systems remains restricted, with documented and effective implementation observed primarily in Brazil (Götsch, 1997; B. Schulz et al., 1994), Bolivia (Tancara, 2014), where it has been established for decades, and recently piloted on a smaller scale in Côte d'Ivoire (Andres et al., 2016) and Ghana (Koog, 2020). The key characteristics of successional SAFs are (i) plantings at high densities and diversity, vertical stratification, and a high internal energy flow; (ii) management practices such as different types of pruning interventions, e.g. rehabilitation, selective weeding or grafting and selection of healthy and productive planting material (ANDRES *et al.*, 2016; GOETSCH, 1992; SCHULZ, 2011). For the successional SAF implementation, planting or sowing is done with all species from different life cycles (pioneers, secondary, and primary) at the same time, and non-agricultural species (native and exotic) are also included, increasing the accumulation of biomass (Andres et al., 2016). Several pruning interventions are taken to increase the amount of light entering the system and make the biomass available in the soil providing nutrients and helping moisture retain (Götsch, 1994, 1997; Young, 2017a).

Pruning is essential for the success of this system, it has several functions such as: rejuvenating mature plants, using pruned biomass in the soil (for protection and fertilization), increasing the entry of light into the system, accelerating and directing the succession process and extending the life cycle of pioneer species, optimizing the soil improvement they provide (Goetsch, 1992). The succession process is hastened by actions such as introducing plants from the next stage of succession and regular pruning. This pruning generates organic matter, a key driver of succession dynamics that supports vegetation growth in degraded soils. Pioneer plants are thus densely planted because of their rapid growth and ability to thrive with minimal soil nutrients. They accumulate biomass, recycle nutrients, and enhance soil conditions for subsequent stages of succession (J. Schulz, 2011).

4.1 Cocoa successional agroforestry performance compared to the other management

Cocoa SAF showed superior results regarding biomass production, c-stock, soil quality, pest and disease control, biodiversity conservation, and microclimate compared to monoculture, other SAF management, and fallow. Only one study showed SAF with significantly less cocoa production than different cocoa production systems; however, this result was offset by a significantly higher total yield (cocoa and other fruits) in SAF than in monoculture (Schneider et al., 2017). Other studies addressing cocoa productivity indicated better results for successional SAF due to design (B. Schulz et al., 1994), farmers' enhanced knowledge (Jacobi et al., 2015), applied management such as pruning (Tancara, 2014), and lower incidences of pests and diseases (Andres et al., 2016; Jacobi et al., 2015). Furthermore, SAF showed higher cocoa bean nutrient concentration, contributing to variations in cocoa bean quality (Niether, Smit, et al., 2017).

Farmers expect yield reductions for cash crops like cocoa in agroforestry systems compared to monocultures due to competition for resources such as nutrients and water (Niether et al., 2019). However, species complementarities in resource use can enhance efficiency and improve overall system performance (Niether et al., 2019). SAFs were statistically superior for nutrient concentration, without external fertilizers input (Koog, 2020; Peneireiro, 1999; Rivero & Mérida, 2009). The moisture detected in the successional

SAFs was also higher, indicating the importance of shading in reducing surface water loss, where 80% of the fine roots of cacao trees are concentrated (Niether, Schneidewind, et al., 2017). Additionally, meeting the agricultural production demands, successional SAFs host greater floristic (Jacobi et al., 2014; Koog, 2020; Peneireiro, 1999), and bird (Naoki et al., 2017) diversity than other systems and fallows. This complex agroecosystem also contributes to climate change mitigation with the highest total carbon stocks in the system (Jacobi et al., 2014), and protection from climate extremes (Niether et al., 2018).

By selecting species based on life expectancy and strata (pioneer, secondary, primary; low, medium, high, emerging), SAFs transformed dystrophic soil into a fertile, productive area within 12 years (Peneireiro, 1999). This cultivation system mimics and accelerates natural succession by planting locally adapted edible plants with similar functional characteristics to those in the local ecosystem. Initially, the focus is on increasing organic material to integrate higher successional level plants (Young, 2017b). As the system develops, greater plant diversity with varied functional and structural characteristics leads to shorter nutrient and water cycles. This method has regenerated highly degraded areas, resulting in a four-fold increase in agricultural production compared to previous annual cropping systems, while also reducing drought-related harvest loss risk through crop diversification and the use of perennial plants (J. Schulz, 2011).

4.2 Obstacles to Cocoa Successional Agroforestry Implementation

Mimicking natural ecosystems in agroecosystems requires knowledge of species-specific traits to select multi-functional species and develop ideal spatial arrangements. Agroforestry managers need an understanding of natural successional development and tropical forest dynamics. Despite their complexity and labor intensity, particularly in the first 5-10 years, quantitative data on socio-economic and ecological benefits are lacking, limiting adoption by local farmers (Young, 2017b).

Farmers in Bolivia perceive the disadvantages of implementing SAF as difficulties in pruning trees, high humidity promoting fungal diseases, and challenging market access for diverse produce. In Côte d'Ivoire, farmers find managing by-crops labor-intensive and time-consuming. Local experts in both countries highlight issues such as knowledge intensity, difficulty obtaining plants and seeds, by-crop failures, challenges in sharing dynamic agroforestry knowledge, and neglect of unfamiliar by-crops (Andres et al., 2016).

This process of diversification reduces risks related to markets and the environment and empowers farmers to adapt independently. Supporting this approach includes providing access to planting materials and financial resources (Läderach et al., 2013). Interested farmers also need to understand the foundational principles of these methods and receive technical support, assistance in establishing farmer-to-farmer knowledge exchange networks, and fair pricing for their agricultural products (Andres et al., 2016). The success of SAF implementation relies on dual capacity building: experts with agroecological knowledge drive change, complemented by local insights that inform adapted cultivation techniques and enhance expert training. NGOs and public policies can play crucial roles in knowledge dissemination and motivating farmers to adopt new methods. Training local leaders to showcase practical benefits fosters networks for knowledge exchange and formal farmer associations. This organizational support empowers smallholders and promotes local organic product chains. Farmers also benefit by reconnecting with their local environments, learning from ecosystem processes, and establishing tree nurseries to meet the growing demand for local species, potentially aiding landscape restoration (J. Schulz, 2011).

5. Conclusion

Integrating species combinations and appropriate management practices can optimize resource utilization, enhance biomass production, facilitate high cocoa productivity, increase soil nutrient concentration, and promote fine root production. Findings from this review indicate that cocoa successional agroforestry systems (SAFs) hold promises for sustainably enhancing productivity, capable of rehabilitating low-productivity and degraded areas while improving soil fertility. While successional SAF offers great potential, it remains challenging to make it a widespread practice. Producers claim that they need in-depth knowledge of applied techniques and plant life cycles, management practices are intense and frequent, need large seed banks, difficulties in understanding and applying different types of pruning, and lack of market for diversified production (Andres et al. 2016). These problems can be minimized through adequate public policies that ensure periodical specialized technical assistance and courses in the first years of implementation, organization of joint effort groups for collective management, creation of associations or cooperatives of producers for the commercialization of products, and promotion of the exchange of seeds.

6. References

Addo-Danso, Shalom D., Richard Asare, Abigail Tettey, Jennifer E. Schmidt, Marie Sauvadet, Mathieu Coulis, Nelly Belliard, and Marney E. Isaac. 2024. "Shade Tree Functional Traits Drive Critical Ecosystem Services in Cocoa Agroforestry Systems." *Agriculture, Ecosystems and Environment* 372(May):109090. doi: 10.1016/j.agee.2024.109090.

Ahenkorah, Y., BJ Halm, MR Appiah, GS Akrofi, and JEK Yirenkyi. 1987. "TWENTY YEARS ' RESULTS FROM A SHADE AND FERTILIZER TRIAL ON AMAZON COCOA { THEOBROMA CACAO) IN GHANA Cocoa Research Institute of Ghana (CRIG), PO Box 8 , New Tafo-Akim , Ghana (Accepted 27 March 1986) Following the Success of the Earlier Amelonado Co." *Experimental Agriculture* 23:31–39.

Ajagun, Ebunoluwa O., George Ashiagbor, Winston A. Asante, Benjamin A. Gyampoh, Kwasi A. Obirikorang, and Emmanuel Acheampong. 2022. "Cocoa Eats the Food: Expansion of Cocoa into Food Croplands in the Juabeso District, Ghana." *Food Security* 14(2):451–70. doi: 10.1007/s12571-021-01227-y.

Andres, Christian, Hermann Comoé, Anna Beerli, Monika Schneider, Stephan Rist, and Johanna Jacobi. 2016. *Cocoa in Monoculture and Dynamic Agroforestry*.

Ariza-Salamanca, Antonio Jesús, Rafael Mª Navarro-Cerrillo, Jayne Crozier, Clare Stirling, Agnese Mancini, Wilma Blaser-Hart, and Pablo González-Moreno. 2024. "Drivers of Cocoa Yield and Growth in Young Monoculture and Agroforestry Systems." *Agricultural Systems* 219(June). doi: 10.1016/j.agsy.2024.104044.

Asare, Richard, Victor Afari-Sefa, Yaw Osei-Owusu, and Opoku Pabi. 2014. "Cocoa Agroforestry for Increasing Forest Connectivity in a Fragmented Landscape in Ghana." *Agroforestry Systems* 88(6):1143–56. doi: 10.1007/s10457-014-9688-3.

Beg, Mohd Shavez, Sameer Ahmad, Kulsum Jan, and Khalid Bashir. 2017. "Status, Supply Chain and Processing of Cocoa - A Review." *Trends in Food Science and Technology* 66:108–16. doi: 10.1016/j.tifs.2017.06.007.

Blaser, W. J., J. Oppong, S. P. Hart, J. Landolt, E. Yeboah, and J. Six. 2018. "Climate-Smart Sustainable Agriculture in Low-to-Intermediate Shade Agroforests." *Nature Sustainability* 1(5):234–39. doi: 10.1038/s41893-018-0062-8.

Clough, Yann, Jan Barkmann, Jana Juhrbandt, Michael Kessler, Thomas Cherico Wanger, Alam Anshary, Damayanti Buchori, Daniele Cicuzza, Kevin Darras, Dadang Dwi Putra, Stefan Erasmi, Ramadhanil Pitopang, Carsten Schmidt, Christian H. Schulze, Dominik Seidel, Ingolf Steffan-Dewenter, Kathrin Stenchly, Stefan Vidal, Maria Weist, Arno Christian Wielgoss, and Teja Tscharntke. 2011. "Combining High Biodiversity with High Yields in Tropical Agroforests." *Proceedings of the National Academy of Sciences* 108(20):8311–

16. doi: 10.1073/PNAS.1016799108.

Clough, Yann, Dadang Dwi Putra, Ramadhanil Pitopang, and Teja Tscharntke. 2009. “Local and Landscape Factors Determine Functional Bird Diversity in Indonesian Cacao Agroforestry.” *Biological Conservation* 142(5):1032–41. doi: https://doi.org/10.1016/j.biocon.2008.12.027.

Clough, Yann, Heiko Faust, and Teja Tscharntke. 2009. “Cacao Boom and Bust: Sustainability of Agroforests and Opportunities for Biodiversity Conservation.” *Conservation Letters* 2(5):197–205. doi: 10.1111/j.1755-263x.2009.00072.x.

Dow Goldman, Elizabeth, Mikaela Weisse, Nancy Harris, and Martina Schneider. 2020. “Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber.” *World Resources Institute* (October):1–22. doi: 10.46830/writn.na.00001.

FAOSTAT. 2024. “FAOSTAT_data_en_8-21-2024.”

Faria, Deborah, Rudi Ricardo Laps, Julio Baumgarten, and Maurício Cetra. 2006. “Bat and Bird Assemblages from Forests and Shade Cacao Plantations in Two Contrasting Landscapes in the Atlantic Forest of Southern Bahia, Brazil.” *Biodiversity and Conservation* 15(2):587–612. doi: 10.1007/s10531-005-2089-1.

Foley, Jonathan A., Ruth DeFries, Gregory P. Asner, Carol Barford, Gordon Bonan, Stephen R. Carpenter, F. Stuart Chapin, Michael T. Coe, Gretchen C. Daily, Holly K. Gibbs, Joseph H. Helkowski, Tracey Holloway, Erica A. Howard, Christopher J. Kucharik, Chad Monfreda, Jonathan A. Patz, I. Colin Prentice, Navin Ramankutty, and Peter K. Snyder. 2005. “Global Consequences of Land Use.” *Science* 309(5734):570–74. doi: 10.1126/science.1111772.

FORCLIME. 2013. “Introducing Successional Agroforestry for Cocoa Production in the Heart of Borneo.” *Module Briefing Note* (9):2.

ICCO. 2023. “(Thousand Tonnes).” *Supply & Demand_QBCS* L(2):2023.

IPCC. 2014. *Climate Change 2014 Part A: Global and Sectoral Aspects*.

Jacobi, Johanna, Monika Schneider, Patrick Bottazzi, Maria Pillco, Patricia Calizaya, and Stephan Rist. 2015. “Agroecosystem Resilience and Farmers’ Perceptions of Climate Change Impacts on Cocoa Farms in Alto Beni, Bolivia.” *Renewable Agriculture and Food Systems* 30(2):170–83. doi: 10.1017/S174217051300029X.

Koog, Ivanoé. 2020. “Biophysical State of Cocoa Dynamic Agroforestry Systems in Ghana: A Chronosequence.” ETH Zurich.

Maney, Calum, Marieke Sassen, and Samantha L. L. Hill. 2022. “Modelling Biodiversity Responses to Land Use in Areas of Cocoa Cultivation.” *Agriculture, Ecosystems and Environment* 324(October 2021):107712. doi: 10.1016/j.agee.2021.107712.

Mattalia, Giulia, Alexander Wezel, Pierre Costet, Patrick Jagoret, Olivier Deheuvels, Paola Migliorini, and Christophe David. 2022. “Contribution of Cacao Agroforestry versus Mono-Cropping Systems for Enhanced Sustainability. A Review with a Focus on Yield.” *Agroforestry Systems* 96(7):1077–89. doi: 10.1007/s10457-022-00765-4.

Mortimer, Róisín, Stéphane Saj, and Christophe David. 2018. “Supporting and Regulating Ecosystem Services in Cacao Agroforestry Systems.” *Agroforestry Systems* 92(6):1639–57. doi: 10.1007/s10457-017-0113-6.

Niether, Wiebke, Johanna Jacobi, Wilma J. Blaser, Christian Andres, and Laura Armengot. 2020. “Cocoa Agroforestry Systems versus Monocultures: A Multi-Dimensional Meta-Analysis.” *Environmental Research Letters* 15(10). doi: 10.1088/1748-9326/abb053.

Olwig, Mette Fog, Aske Skovmand Bosselmann, and Kwadwo Owusu. 2023. *Agroforestry as Climate Change Adaptation: The Case of Cocoa Farming in Ghana*.

Parra-Paitan, Claudia, Patrick Meyfroidt, Peter H. Verburg, and Erasmus K. H. J. zu Ermgassen. 2024a. “Deforestation and Climate Risk Hotspots in the Global Cocoa Value Chain.” *Environmental Science and Policy* 158(December 2023):103796. doi: 10.1016/j.envsci.2024.103796.

Parra-Paitan, Claudia, Patrick Meyfroidt, Peter H. Verburg, and Erasmus K. H. J. zu Ermgassen. 2024b. “Deforestation and Climate Risk Hotspots in the Global Cocoa Value Chain.” *Environmental Science and Policy* 158(June):103796. doi: 10.1016/j.envsci.2024.103796.

Rebello, José Fernando dos Santos, and Daniela Ghiringhello Sakamoto. 2021. *Agricultura Sintrópica Segundo Ernst Götsch*.

Rice, Robert A., and Russell Greenberg. 2000. “Cacao Cultivation and the Conservation of Biological Diversity.” *Ambio* 29(3):167–73. doi: 10.1579/0044-7447-29.3.167.

Rockström, Johan, John Williams, Gretchen Daily, Andrew Noble, Nathanial Matthews, Line Gordon, Hanna Wetterstrand, Fabrice DeClerck, Mihir Shah, Pasquale Steduto, Charlotte de Fraiture, Nuhu Hatibu, Olcay Unver, Jeremy Bird, Lindiwe Sibanda, and Jimmy Smith. 2017. “Sustainable Intensification of Agriculture for Human Prosperity and Global Sustainability.” *Ambio* 46(1):4–17. doi: 10.1007/s13280-016-0793-6.

Ruf, François, and Götz Schroth. 2004. “Chocolate Forests and Monocultures: A Historical Review of Cocoa Growing and Its Conflicting Role in Tropical Deforestation and Forest Conservation.” *Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press, Washington* 107–34.

Ruf, François, Götz Schroth, and Kone Doffangui. 2015. “Climate Change, Cocoa Migrations and Deforestation in West Africa: What Does the Past Tell Us about the Future?” *Sustainability Science* 10(1):101–11. doi: 10.1007/s11625-014-0282-4.

Sambuichi, Regina Helena Rosa, and Mundayatan Haridasan. 2007. “Recovery of Species Richness and Conservation of Native Atlantic Forest Trees in the Cacao Plantations of Southern Bahia in Brazil.” *Biodiversity and Conservation* 16(13):3681–3701. doi: 10.1007/s10531-006-9017-x.

Schneider, M., C. Andres, G. Trujillo, F. Alcon, P. Amurrio, E. Perez, F. Weibel, and J. Milz. 2017. “COCOA and TOTAL SYSTEM YIELDS of ORGANIC and CONVENTIONAL AGROFORESTRY VS. MONOCULTURE SYSTEMS in A LONG-TERM FIELD TRIAL in BOLIVIA.” *Experimental Agriculture* 53(3):351–74. doi: 10.1017/S0014479716000417.

Schroth, Götz, and Celia A. Harvey. 2007. “Biodiversity Conservation in Cocoa Production Landscapes: An Overview.” *Biodiversity and Conservation* 16(8):2237–44. doi: 10.1007/s10531-007-9195-1.

Schulz, B., B. Becker, and E. Götsch. 1994. “Indigenous Knowledge in a ‘modern’ Sustainable Agroforestry System-a Case Study from Eastern Brazil.” *Agroforestry Systems* 25(1):59–69. doi: 10.1007/BF00705706.

Sonwa, Denis J., Bernard A. Nkongmeneck, Stephan F. Weise, Maturin Tchatat, Akin A. Adesina, and Marc J. J. Janssens. 2007. “Diversity of Plants in Cocoa Agroforests in the Humid Forest Zone of Southern Cameroon.” *Biodiversity and Conservation* 16(8):2385–2400. doi: 10.1007/s10531-007-9187-1.

Steinfeld, Jonas P., Felix J.J.A. Bianchi, Jorge Luiz Locatelli, Rodnei Rizzo, Maria Eduarda Bispo de Resende, Maria V. Ramos Ballester, Carlos E. P. Cerri, Alberto C. C. Bernardi, and Rachel E. Creamer. 2023. “Increasing Complexity of Agroforestry Systems Benefits Nutrient Cycling and Mineral-Associated Organic Carbon Storage, in South-Eastern Brazil.” *Geoderma* 440(November):116726. doi: 10.1016/j.geoderma.2023.116726.

Steinfeld, Jonas P., Massimiliano Miatton, Rachel E. Creamer, Martin Ehbrecht, Vivian Valencia, Maria Victoria Ramos Ballester, and Felix J. J. A. Bianchi. 2024. “Identifying Agroforestry Characteristics for Enhanced Nutrient Cycling Potential in Brazil.” *Agriculture, Ecosystems and Environment* 362(October 2023):108828. doi: 10.1016/j.agee.2023.108828.

Tancara, Ariel Luis Arragan. 2014. “Efecto de La Poda y Raleo Se Árboles, En Un Sustema Agrofroestal Sucesionalen La Producción de Cacao (Theobroma Cacao), Del Alto Beni.”

Tilman, D., J. Fargione, B. Wolff, C. D’Antonio, A. Dobson, R. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. “Forecasting Agriculturally Driven Global Environmental Change.” *Science* 292(5515):281–84. doi: 10.1126/science.1057544.

Tilman, David, Christian Balzer, Jason Hill, and Belinda L. Befort. 2011. “Global Food Demand and the Sustainable Intensification of Agriculture.” *Proceedings of the National Academy of Sciences* 108(50):20260–64.

Tscharntke, Teja, Yann Clough, Shonil A. Bhagwat, Damayanti Buchori, Heiko Faust, Dietrich Hertel, Dirk Hölscher, Jana Juhrbandt, Michael Kessler, Ivette Perfecto, Christoph Scherber, Götz Schroth, Edzo Veldkamp, and Thomas C. Wanger. 2011. “Multifunctional Shade-Tree Management in Tropical Agroforestry Landscapes - A Review.” *Journal of Applied Ecology* 48(3):619–29. doi: 10.1111/j.1365-2664.2010.01939.x.

Vieira, Daniel L. M., Karen D. Holl, and Fabiana M. Peneireiro. 2009. “Agro-Successional Restoration as a Strategy to Facilitate Tropical Forest Recovery.” *Restoration Ecology* 17(4):451–59. doi: 10.1111/j.1526-100X.2009.00570.x.

Young, Katherine J. 2017. *Mimicking Nature: A Review of Successional Agroforestry Systems as an Analogue to Natural Regeneration of Secondary Forest Stands*.

Zarrillo, Sonia, Nilesh Gaikwad, Claire Lanaud, Terry Powis, Christopher Viot, Isabelle Lesur, Olivier Fouet, Xavier Argout, Erwan Guichoux, Franck Salin, Rey Loor Solorzano, Olivier Bouchez, Hélène Vignes, Patrick Severts, Julio Hurtado, Alexandra Yepez, Louis Grivetti, Michael Blake, and Francisco Valdez. 2018. “The Use and Domestication of Theobroma Cacao during the Mid-Holocene in the Upper Amazon.” *Nature Ecology and Evolution* 2(12):1879–88. doi: 10.1038/s41559-018-0697-x.

Supplementary material

TableS1. Species selection for cocoa successional agroforestry, classified by lifespan and canopy strata using species described in the sampled publications.

Lifespan Stratification	% of shade	0-6 months	1-3 years	3-10 years	10-20 years	20-50 years	Over 50 years
Emerging	15%	Corn, Sorghum	Papaya, Castor bean	Cecropia	African mahogany	Caja-mirim	Ipê
High	35%	Cowpea	Cassava, Pigeon pea	Açaí, Juçara	Soursop, Jackfruit	Ingá	Copaíba
Medium	45%	Eggplant	Heliconias, Banana	Cupuaçu	Avocado	Jambo, Carambola	Pitomba, Jabuticaba
Low	80%	Pumpkin	Yam, Ginger	Cocoa	Cocoa	Cocoa	Cocoa

Species list: Corn - *Zea mays;* Sorgum - *Sorghum bicolor*; Cowpea - *Vigna unguiculata*; Eggplant - *Solanum melongena*; Pumpkin - *Cucurbita sp*.; Papaya - *Carica papaya*; Castor bean - *Ricinus communis*; Cassava – *Manihot sp*.; Pigeon pea - *Cajanus cajan*; Heliconias – *Heliconia sp*.; Banana – *Musa sp*.; Yam - *Dioscorea sp*; Ginger - *Zingiber officinale*; Cecropia - *Cecropia pachystachya*; Açaí - *Euterpe oleracea*; Juçara – *Euterpe edulis*; Cupuaçu - *Theobroma grandiflorum*; Cocoa – *Theobroma cacao*; African mahogany - *Khaya grandifoliola*; Soursop - *Annona muricata*; Jackfruit - *Artocarpus heterophyllus*; Avocado - *Persea americana*; Caja-mirim - *Spondias mombin*; Ingá – *Inga sp*.; Jambo - *Syzygium jambos*; Carambola - *Averrhoa carambola*; Ipê - *Handroanthus sp*.; Copaíba – *Copaifera sp.* ; Pitomba - *Talis esculenta*; Jabuticaba – *Plinia cauliflora*.

TableS2. Selected documents on cocoa successional agroforestry systems 1994-2020.

Citation	Country	Years of experiment	Category analyzed	Attribute	Successional AgroForestry	Monoculture	Traditional Agroforestry	Fallow
Schulz B; et al. (1994)	Brazil	6	Biomass production	Dry matter/ mulch [t/ha/a]	8–16	1.5-5		
			Productivity	Cocoa yield [kg/ha]	110–370	225[1]		
Peneireiro FM (1999)	Brazil	12	Biodiversity conservation	Floristic diversity [Shannon and Jaccard indices]	(H') 3.363 (J) 0,855			(H') 3.010 (J) 0,702
			Soil quality	Relative average values [V%], the sum of bases [mmolc/Kg]	83%, 195			41%, 73
Rivero G; Mérida AL (2009)	Bolivia	5 - 12	Biomass production	Aerial biomass [t/ha]	82-107^{a}		19-44^{b}	
			Soil quality	Nutrients concentrattion [N, P, K - Kg/ha]	79.96 – 156, 0.04 – 0.11, 36.80 – 77.7		35.68 – 101, 0.02 – 0.06, 22.34 – 82.79	
Jacobi J; et al. (2013)	Bolivia	9.5 - 14	Productivity	Cocoa yield [kg/ha]	510±55.2	350±124.2	423±78.2	
			Pest and disease control	Moniliophthora	0.5±0.1^{a}	2.5±0.1^{b}	1.3±0.2^{c}	
Jacobi J; et al. (2014)	Bolivia	5 - 17	C - Stock	Total C	143.7 ± 5.3^{a}	86.3 ± 4.0^{b}	128.4 ± 20^{a}	125.2 ± 10^{a}
Tancara LAA (2014)	Bolivia	-	Productivity	Cocoa beans [unit/ha]	7138 ^{a}		1953 ^{b}[2]	

Alfaro-Flores A; et al. (2015)	Bolivia	3	Soil quality	Microbial biomass [µg C/g], Microbial biomass [µg N/g] cellulase activity [µg glucose/ g*24h]	395 – 580^{a}, 45 – 75^{ab}, 140 – 220	300 – 430^{a}, 40 – 55^{a}, 100 – 180	490 – 790^{a}, 55 – 110^{ab}, 150 – 190	585 – 750^{b}, 65 – 75^{b}, 150 – 190
Schneider M; et al. (2016)	Bolivia	4	Productivity	Total system yields [kg/ha]	8392	3424 -5837	10610 – 13592	
Andres C; et al. (2016)	Bolivia	2	Pest and disease control	Pods, Mirids, Witches broom, Black pod rot	15.5, 0.40^{a}, 1.32^{b}, 2.58	20.1, 1.00^{b}, 2.58^{c}, 0.65		
	Côte d’Ivoire	1	Productivity	Pod counts, Cocoa yield [kg/ha]	12747, 478	11965, 426		
Naoki K; et al. (2017)	Bolivia	3	Biodiversity conservation	Number of bird species, visitation frequency	19, 46	20-16, 53-26	14, 37-21	27, 56
Niether W; et al. (2017b)	Bolivia	1.5	Soil quality	Soil temperature [°C], volumetric water content	24.4 - 25.5, 14.4 – 25.6	24.6 - 27.3, 18.2 – 77.1	24.4 - 25.6, 20 – 36.6	23.7 - 24.4, 10.8 – 37.1
Niether W; et al. (2017a)	Bolivia	6	Cocoa beans quality	Nutrients concentrattion [N (mg g $^{-1}$), P (µg g $^{-1}$), K (µg g $^{-1}$)] Stress indicators [polyamines (µg g $^{-1}$) and total phenolic content (mg g $^{-1}$)]	22.4 – 23, 4478 – 4496, 8088 – 8716 5.61 – 6.72, 5.26 – 7.76	22.9 – 24.4, 3672 – 4706, 8310 – 9016 8.2 – 10.3, 4.23 – 7.53	23.4, 4268 – 4548, 7866 – 9133 7.75 – 10.59, 5.10 – 7.76	
Niether W; et al.	Bolivia	2	Microclimate	Temperature amplitude [°C],	15.4 - 21.9^{bc},	18.1 - 22.3^{ac},	15.7 - 23.6^{bc},	14.7 - 18.3^{ba},

(2018)				Relative humidity [%], Vapor pressure deficit [kPa]	82.4 – 93.7^{bcde}, 0.18 – 0.88^{bcd}	81 – 92.4^{ad}, 0.24 - 0.94^{ac}	81.9 – 95^{bd}, 0.14 - 0.95^{bc}	84.4 – 96.3^{ce}, 0.10 – 0.69^{bd}
Niether W; et al. (2019)	Bolivia	7	Biomass production	Fine root biomass density	0.35 – 0.56	0.22 – 0.39	0.22 – 0.43	
Koog I (2020)	Ghana	1-3	Biodiversity conservation	Floristic diversity [Shannon indices]	(H’) 3.78		(H’) 1.94	
			Soil quality	Nutrients concentrattion [N, P, K, C – mg Kg/ha]	0.1 – 0.32^{a}, 172.8 – 266.6^{a}, 142.4 – 231.1^{a}, 1.03 – 3.22^{a}		0.07 – 0.21^{b}, 122.4 – 197.8^{ab}, 114.4 – 173.3^{b}, 0.78 – 2.27^{b}	

^{abcde} Different lowercase letters indicate that the authors found significance among treatments.

[1] CEPLAC (Commissao Executiva do Plano da Lavoura Cacaueira), the Brazilian Cocoa Research Center

[2] Dynamic Agroforestry without pruning or thinning.

[3] 5- and 10-year multi-strata successional agroforestry systems respectively

CAPÍTULO II

“MANAGEMENT PRACTICES CAN IMPROVE YIELDS OF CARBON-RICH COCOA AGROFORESTS IN BRAZIL”

Management Practices Can Improve Yields of Carbon-Rich Cocoa Agroforests in Brazil

Abstract

CONTEXT: Solutions to enhance agricultural productivity, along with delivering social and environmental benefits, stand as major challenges in this century. Cocoa, the third most traded commodity worldwide, is primarily cultivated by small-holding producers in biodiversity-rich, conservation-priority tropical regions. This raises questions regarding optimal management practices that maximize agricultural yields, diversify producers' income, and ensure biodiversity maintenance and ecosystem services.

OBJECTIVE: We evaluate the main factors affecting cocoa productivity and carbon stock in cocoa agroforestry systems in southern Bahia, Brazil, aiming to identify win-win scenarios for both socioeconomic and environmental.

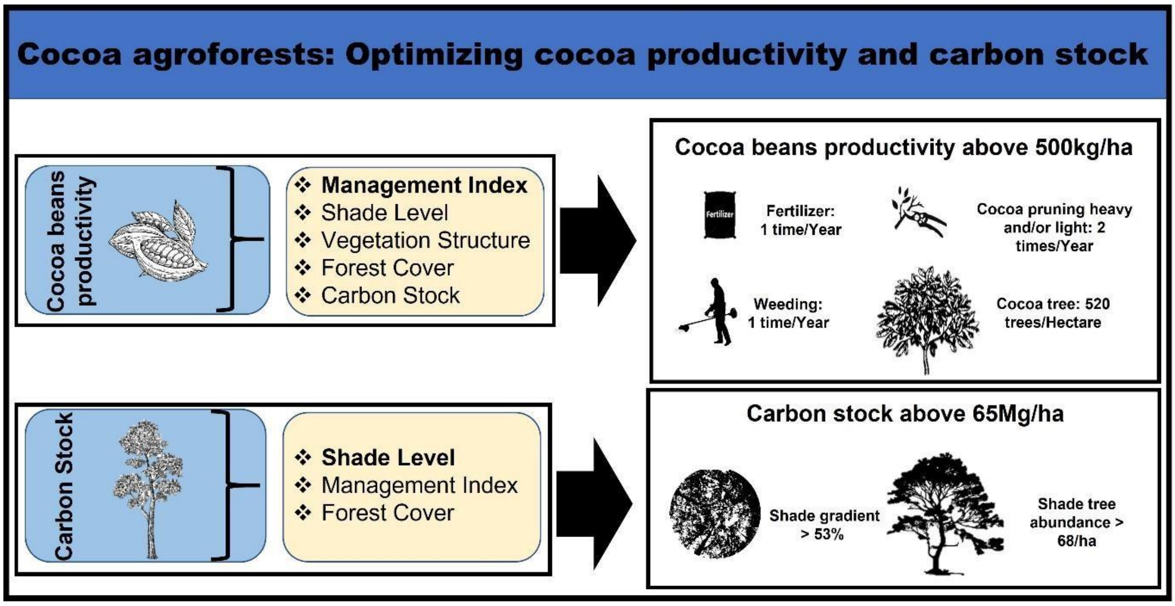
METHODS: We carefully selected and sampled 47 agroforest farms embedded within different landscape contexts, and evaluated the response of cocoa productivity to landscape forest cover, vegetation structure, shade level, carbon stock, and management practices, based on *in-situ* surveys and interviews. We also assessed the relationship between landscape forest cover, shade levels, and management practices to carbon stock.

CONCLUSION: Our results indicate no relationship between productivity and local shading, although the frequency of management practices positively affected cocoa yields. Conversely, shade trees played a key role in overall carbon storage (93% of the total amount), indicating a high potential for the carbon market in addition to safeguarding threatened species.

SIGNIFICANCE: our study also shows that achieving sustainable intensification in cocoa production involves prioritizing management practices such as weed control, pruning cocoa trees, adjusting the total number of cocoa trees per hectare, and applying mineral and organic fertilizer. We therefore provide guidelines on effectively managing trade-offs between cocoa productivity, biodiversity conservation, and the delivery of key ecosystem services in tropical forest landscapes.

Keywords: *Theobroma cacao*, sustainable intensification, ecosystem services, management index, cocoa productivity

Graphical Abstract



1. Introduction

In the Anthropocene, meeting production demands through agriculture systems has been a primary challenge for governmental sectors and farmers, especially given that this comprises the most adversely affected sector by environmental changes including global climate change (Foley et al., 2005; IPCC, 2014; Tilman et al., 2011). Therefore, discussions on the concept of sustainable intensification (SI) in agriculture have significantly expanded in recent decades, especially focusing on prioritizing the development of practices that boost productivity while providing social and environmental benefits (Rockström et al., 2017; Tilman et al., 2002, 2011). In particular, cocoa (*Theobroma cacao*) is a key crop able to offer SI benefits when cultivated under climate-friendly agroforestry systems, given that canopy trees are maintained in the property to provide shade for cocoa tree development (Niether et al., 2020; Street & Legon, 2014). As a result, cocoa agroforests can store significant amounts of carbon, depending on the management practices adopted by the farmer. In addition, it comprises the third most worldwide traded agricultural product, with millions of smallholder farmers involved in its production (Ariza-Salamanca et al., 2023). Cocoa naturally thrives in shaded environments, given that it comprises a shade-tolerant Amazonian tree, yet shade requirements for optimal growth are debated among scientists and producers to date (Asare et al., 2017, 2019; Cabala Rosand et al., 1976). While reduction of shade level in established cocoa plantations has initially shown significant yield increases, long-term trials highlight various detrimental effects such as decreased lifespan of the cocoa trees, increased pest and disease damage, and greater demand for agrochemical inputs (Ahenkorah et al., 1974, 1987). However, growing global demand for cocoa beans has driven the expansion of cocoa-producing regions through deforestation, and a shift from agroforestry to full-sun monocultures in many production areas, involving significant use of agrochemicals and, at times, of irrigation to increase productivity (Andres et al., 2016; Schneider et al., 2017).

Traditional cocoa agroforest transitions to low-shade plantations became prominent in the mid-1980s, with the widespread assumption among farmers that local shading is negatively associated with production (Asare et al., 2010). The removal of shade trees is particularly alarming in biodiversity-rich regions, where the structurally complex agroforests are known to host many native species and deliver various ecosystem services (Harvey et al., 2006; Schroth & Harvey, 2007). This is the case of southern Bahia, in Brazil, where cocoa agroforests (locally known as "cabrucas") provide habitat for native and threatened biota of the Atlantic Forest biome, one of the global biodiversity hotspots (Cassano et al., 2011; Faria et al., 2023; Faria & Baumgarten, 2007; Schroth et al., 2011). Cabrucas covers approximately 6,000 km² in southern Bahia, surpassing the native forests in extent (Landau & Hirsch, 2008), and contributing to curb deforestation in several municipalities. As a result, approximately two-thirds of the regional above-ground carbon stock in southern Bahia is estimated to be stored by cabrucas (Schroth et al., 2015).

In the 1960s and 1970s, the Executive Committee of the Cocoa Farming Plan (CEPLAC), the government agency responsible for promoting cocoa production in Brazil, initiated an extensive program of tree removal in southern Bahia, aiming to maximize cocoa yields with minimal shading and encouraging fertilizer application (Cabala Rosand et al., 1976; Johns, 1998). Despite short-term yield boosts, the economic reason for reducing shade in cocoa systems was questionable, given the wide range of ecological and economic benefits provided by shade that are lost or minimized, particularly in sustainable agriculture contexts (Beer, 1987). Currently, this local intensification is supported by a state law stating that each cabruca must maintain a minimum of 20 native trees per hectare (State Decree No. 15180/2014, Bahia), a significant reduction in tree abundance compared to the traditional cabrucas that typically harbor ~ 200 trees/ha (Sambuichi et al., 2012; Schroth et al., 2016). Nevertheless, the Bahia region has maintained a mean cocoa productivity ranging between 230-300 kg/ha^{-1} of dried cocoa beans since the 2000s (IBGE, 2019), which is significantly lower than the global average of approximately 450-500 kg/ha^{-1} (FAOSTAT, 2024).

High levels of shade are often identified as significant contributors to low regional cocoa productivity in southern Bahia. Nonetheless, research indicates that it is feasible to surpass the below-average yield levels (585 kg/ha^{-1}) while maintaining relatively high above-ground carbon stocks (e.g., 65 Mg/ha) and shade levels (e.g., 55% shade) through effective management practices, including the application of fertilizers (Schroth et al., 2016). Meanwhile, the absence of technical assistance (for instance, 75% of producers in southern Bahia received no technical support between 2011 and 2017) leads to limited input usage and inadequate management practices (Chiapetti et al., 2020). Regarding management in the Bahia region, the most common practices include weed control and both heavy and light pruning of the cocoa trees, whereas 53% of farmers never used any type of fertilizer on their property (Chiapetti et al., 2020). Therefore, understanding the synergy between production, carbon storage, and shading becomes crucial to ensure the adoption of appropriate management practices that optimize a wide range of ecosystem services, including carbon sequestration, and simultaneously maintaining shade trees and stocking high levels of carbon.

Here, we intend to contribute to the design of a sustainable intensification maximizing biodiversity conservation, while benefiting the livelihoods of cocoa producers in agroforests of southern Bahia. For this, we (i) investigated the main determinants of cocoa productivity, including, key landscape and local factors (i.e., landscape forest cover, local vegetation structure, aboveground carbon stock, shade levels, and management practices) aiming to identify how producers can optimize yields; (ii) estimated aboveground carbon stocks in surveyed cabrucas and subsequently assessed the influence of landscape and local factors on such reservoirs. We hypothesized that sustainable intensification would be possible, as management practices would emerge as the primary factor affecting cocoa productivity. We finally hypothesized that cabrucas have the potential to achieve higher productivity of cocoa than the world average productivity of 585 kg/ha^{-1}, while also maintaining shade trees and carbon stocks above the regional average in southern Bahia.

2. Materials and methods

2.1. Study area and farm selection

We carried out this study in the Central-South and Southern mesoregions of the state of Bahia, located in northeastern Brazil. The climate in these mesoregions is predominantly characterized as tropical rainforest, according to the Köppen classification (Alvares et al., 2013), with an annual average temperature of 25°C and an annual rainfall ranging from 1000 to 1900 mm. This region currently presents heterogeneous human-modified landscapes, encompassing different land-use types, including Atlantic Forest remnants under different successional stages, urban areas, plantations of shade cacao, rubber and eucalyptus, and cattle pastures (Faria et al., 2023). In particular, more than 2,100 km^2 of the region is covered by cocoa cultivation (37% of overall land-use types), surpassing the native forest coverage (MapBiomas Cacau, 2020).

We randomly selected 47 independently managed farms (Fig. 1) that initiated cocoa cultivation many decades or even a century ago by replacing the native understory of the Atlantic Forest while retaining native shade trees, following the traditional agroforestry practice known as 'cabruca' (Araujo et al., 1998). Currently, cocoa farms employ different types of management approaches, including rustic (without the use of fertilizers), conventional (utilizing chemical fertilizers), organic (employing organic fertilizers), or agroecological (incorporating organic fertilizers, biofertilizer blends, and agroecological practices), among other practices such as pruning. Sampling was conducted between 2021 and 2023.

2.2. Aboveground biomass (AGB) and aboveground carbon storage (AGC)

We established four 1-ha plots (50 x 50 m) within each cabruca, ensuring a minimum distance of 30 m between plots. On each plot, we measured all shade trees (including arboreal palms) presenting a diameter at breast height (DBH = 1.30 m above the ground) ≥ 10 cm. For each tree, we measured the diameter and height, and identified it at the lowest taxonomic level possible, with the assistance of an experienced botanist. Non-identified individuals had branches collected to further proceed with taxonomic identification at virtual herbarium and herbarium collections located in the state of Bahia, including CEPEC/Ceplac and HUESC/UESC. In addition, we established a 25 x 25-m subplot within each plot where we counted all cocoa trees, and measured the diameter of 10 individuals randomly selected. These calculations were performed to obtain biomass per tree, including native and exotic trees, using the BIOMASS package for R (Réjou- Méchain et al., 2017), by using wood density values from a freely available dataset (Chave et al., 2014). In those cases where assigning a wood density value at the species level was unfeasible (4.5% of all sampled individuals), we used the average value at the genus or family level, considering only species from South America. For unidentified individuals (1.3 %), we used the average wood density value of all other species in the plot. Lastly, we derived carbon stocks by assuming that 50% of each tree's above-ground biomass is carbon (Malhi et al., 2004).

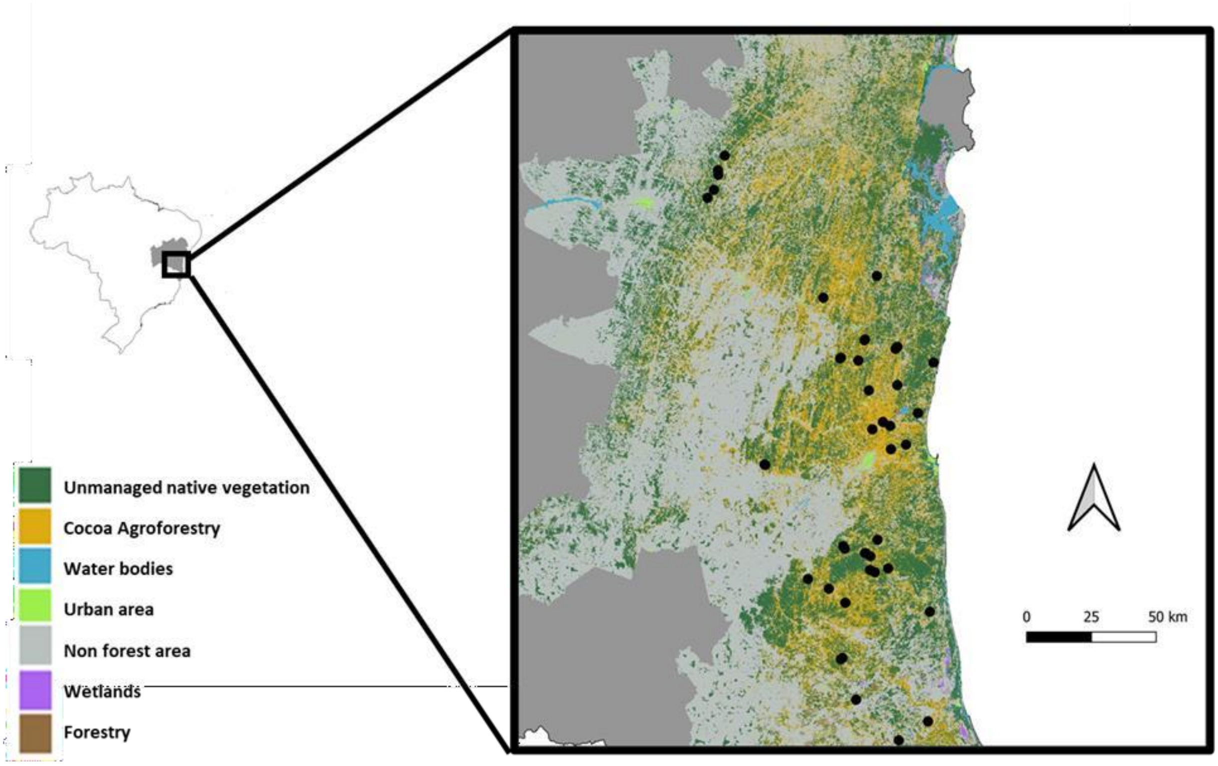


Figure 1. Map of the study area in southern Bahia, northeastern Brazil, displaying the 47 sampled cocoa agroforestry farms (black dots).

2.3. Vegetation structure and shade gradient

To characterize the vegetation structure in each sampling cabruca, we assessed five variables measured in each sampling plot, which included (i) the average height of shade trees (DBH ≥ 10 cm), (ii) the mean DBH of shade trees, (iii) shade tree diversity (species richness, encompassing individuals of both native and exotic species), (iv) average height, and (v) diameter of cocoa trees.

We evaluated the shade tree coverage by taking nine photographs using hemispherical lenses (NOOT products) attached to the digital camera of a Redmi cell phone on each plot. In particular, eight photos were taken along the plot vertices, spaced at 25-meter intervals, and one at the plot's center (Fig. 2A). To capture these images, the cell phone was affixed to an extension pole, raising it to a height of 5 m, above the central region of the cocoa tree canopy. These photos were taken during two specific time windows, to obtain the best contrast and avoid overexposure: either from 6 am to 8 am or from 5 pm to 6 pm. Then, we analyzed the images using the Gap Light Analyzer 2.0 software, which quantifies the extent of canopy open spaces within a hemispherical photograph and uses the mean value to obtain the percentage of shading per farm.

2.4. Cocoa productivity and management index

We gathered data on both productivity and management practices through semi-structured interviews conducted with each cocoa owner or manager, in both 2021 and 2023. We first requested information from their overall cocoa production in the two years preceding the interviews (i.e., 2019 and 2022). Subsequently, we obtained the cocoa production per area by dividing the two-year average value by the reported size of the cabruca area.

We thus obtained data on management practices to obtain a ‘Management Intensity Index’ (MI) for each farm, by adapting existing indices used in coffee studies (Mas & Dietsch, 2003), and standardizing values of frequency of management practices per year. In particular, as five specific management practices are commonly used on cabrucas, we estimated them as follows: 1) weed control (frequency per year); 2) frequency of organic fertilization and/or liming (per year); 3) frequency of chemical fertilization and/or liming (per year); 4) frequency of cocoa tree pruning, in which they often remove excess shoots and rarely conduct heavy pruning of branches and larger stems (per year); 5) the total number of cocoa trees in the established vegetation plot. We assigned equal weights to each variable, ranging from 0 to 1, with 0 representing the least intensive and 1 representing the most intensive management (Table S2). For each farm, we obtained standardized frequency values, by normalizing the variables by dividing them by the highest value observed on all farms for that variable. Subsequently, the values for each variable were summed to create an overall management index (MI) for each farm, where 0 denotes minimal management and a maximum score of 4 indicates intensive management practices.

2.5. Landscape forest cover

We used Landsat satellite images from the latest available regional mapping resource, the free-accessible "MapBiomas Cacau" (https://mapbiomas.org/mapbiomas_cacau_download), to estimate the amount of native forest cover surrounding each sampling cabruca. We established four landscape sizes (0.5, 1, 5, and 10 km in radius), starting from the central area between the four sampled plots on each farm (Fig. 2B), to assess forest cover, employing the QGIS software.

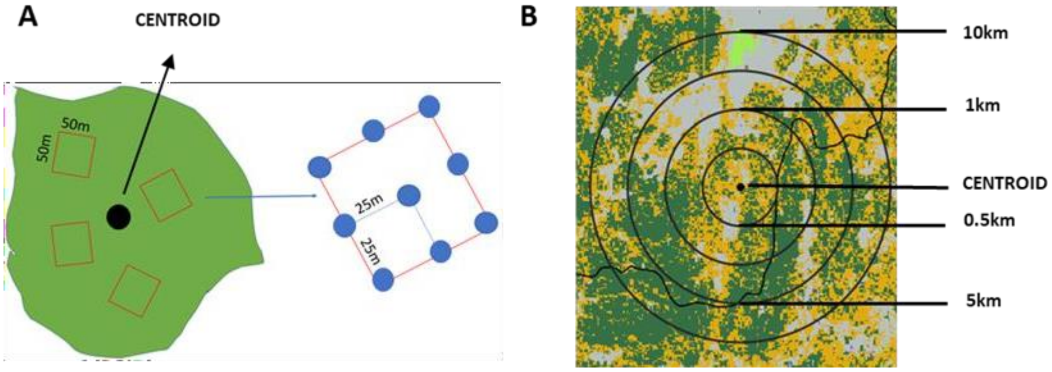


Figure 2. Schematic representation of **A.** the position of the four 50 x 50m plots (red squares) inserted in each sampling

farm, highlighting one plot composed of nine points used to take shade-tree photos (blue circles). **B.** Sampled landscape, evidencing the different radii sizes (0.5, 1, 5, and 10 km) used to estimate native forest cover surrounding each farm.

2.6. Statistical analysis

Given that we obtained data on five vegetation structure variables (i.e., average tree height, mean DBH of shade trees and cocoa trees, and diversity of shade trees), we performed a Principal Component Analysis (PCA) to synthesize vegetation structure of each cabruca, and subsequently used the first two axes in data analyses. To identify the suitable scale of landscape forest cover to be used in our data analyses, we performed the Spearman rank test (r) across this predictor considering our predefined landscape scales (i.e., 0.5, 1, 5, and 10 km in radius) against both cocoa productivity and carbon stock. Our analyses indicated that the 10 and 5 km scales presented the most significant coefficient values for productivity and carbon stocks, respectively, and were therefore chosen as the optimal scale.

We assessed the influence of local (i.e., management index, the two PCA axes as a proxy of vegetation structure, shade levels, and carbon stock) and landscape predictors (i.e., landscape forest cover) on cocoa productivity, through Generalized Least Squares (GLS) models. In addition, we also used the same predictors but removed the vegetation structure variables, to assess the main factors explaining carbon stock. We first verified the normality assumptions by scrutinizing residuals through Quantile-Quantile Normal plots. Importantly, no correlations ($r > 0.73$) were observed among the predictor variables in any of the tested models, and we standardized the environmental variables using the ‘‘standardize’’ method of the vegan package.

Spatial autocorrelation in ecological data can inflate Type I errors in statistical analyses (Diniz-Filho et al., 2003). Therefore, we checked the autocorrelation with Moran’s I test in the “ape” package, and the results showed significant spatial autocorrelation in the observed environmental variables ($p< 0.05$ for both productivity and carbon stock). To determine the most suitable autocorrelation structure (which is unknown a priori), we built alternative models with different correlation structures: spherical (corSpher), linear (corLin), rational quadratic (corRatio), gaussian (corGaus), and exponential (corExp). Models included correlation structure with the form = ~ longitude + latitude, as implemented in the R package “nlme” (Bates & Pinheiro, 1998).

We adopted a multi-model inference approach in which we identified Gaussian models as the model that provided the most comprehensive explanations for each response variable (i.e., productivity and carbon stock). This selection process was guided by the Akaike Information Criterion (AICc), which we considered as parsimonious those models presenting AICc values lower than 2 units (denoted as ΔAICc), with ΔAICc of 0 indicating the model with the greatest explanatory potential. We calculated average model parameters from the selected models and assessed the importance of predictor variables using Akaike weights (Anderson & Burnham, 2004). All statistical analyses were performed using R software version 4.2.2 (R Core Team, 2021).

3. Results

Our survey resulted in a total of 4,750 shade trees (DBH ≥10 cm, including exotic and native species) across 47 sampled hectares within cocoa agroforests in southern Bahia. On average, each plot of 1 ha included 101 (±SD = 48.7) shade trees. Native species represented 61% of the total species sampled. Although four farms had less than 20 native tree species/ha, turning them ineligible for the classification as cabrucas, they were retained in our analyses. We identified twelve threatened tree species: one Critically Endangered (*Acanthosyris paulo-alvinii*), five Endangered (*Cariniana legalis*, *Pleroma elegans*, *Swartzia micrantha*, *Sloanea obtusifolia*, *Croton sapiifolius*) and six Vulnerable tree species (*Cedrela fissilis*, *Dalbergia nigra*, *Euterpe edulis*, *Melanoxylon brauna*, *Moldenhawera blanchetiana* and *Swartzia riedelii*) in sampled cabrucas. The presence of at least one individual from a threatened species was observed in 77% of the sampled farms.

The shade level above the cocoa trees varied from 31% to 78%. Vegetation structure, as evaluated by PCA, showed that the first axis explaining 36% of total variation represented an increasing gradient of tree DBH and height, while the second axis (25% of total variation) depicted increasing values in tree diversity (Fig. S1). We estimated an average carbon stock of 55 Mg C/ha-1 (SD ± 25), with shade trees contributing 93%, whereas cocoa trees accounted for 7% of our total carbon estimates. The farms exhibited considerable variability in productivity, with an average yield of 337 kg/ha-1 (SD ± 300). In general, the farms had a low management index value, which ranged from 0.6 to 3.6 and averaged 1.56 (SD ± 0.86). For carbon stock assessment, we utilized the value of 65 Mg/ha of above-ground carbon stocks that had been established in a previous study as the maximum carbon stock that still allowed cocoa yields above the (relatively low) regional average yield in our study region (Schroth et al., 2016). Farms sampled in the present study that exhibited carbon stocks exceeding 65 Mg/ha displayed specific local characteristics, such as shade level > 53% and shade tree abundance > 68 individuals per hectare (Fig. 3E-F).

We found a considerable variation in management practices among the surveyed farms. Weeding emerged as the predominant practice, occurring in all sampled farms, yet in different ways, including the backpack mower, a type of local machete (biscó), or by use of herbicides. Approximately 89% of farms engaged in pruning activity, with frequency varying from monthly to annually across different properties. Chemical or organic fertilization was less common, but the majority (55%) of farms employed it. Of these, 65% used solely chemical fertilization, 27% used only organic fertilization, and around 8% utilized both types. Cocoa tree density also varied substantially among farms, ranging from 336 to 1,036 trees per hectare, reflecting therefore substantial productivity levels. For productivity, we used the global average of 500 kg/ha as a benchmark. Farms surpassing this figure adhered to specific minimum management practices: annual fertilization, biannual pruning, yearly weeding, and a minimum of 520 cocoa trees per hectare (Fig. 3A-D).

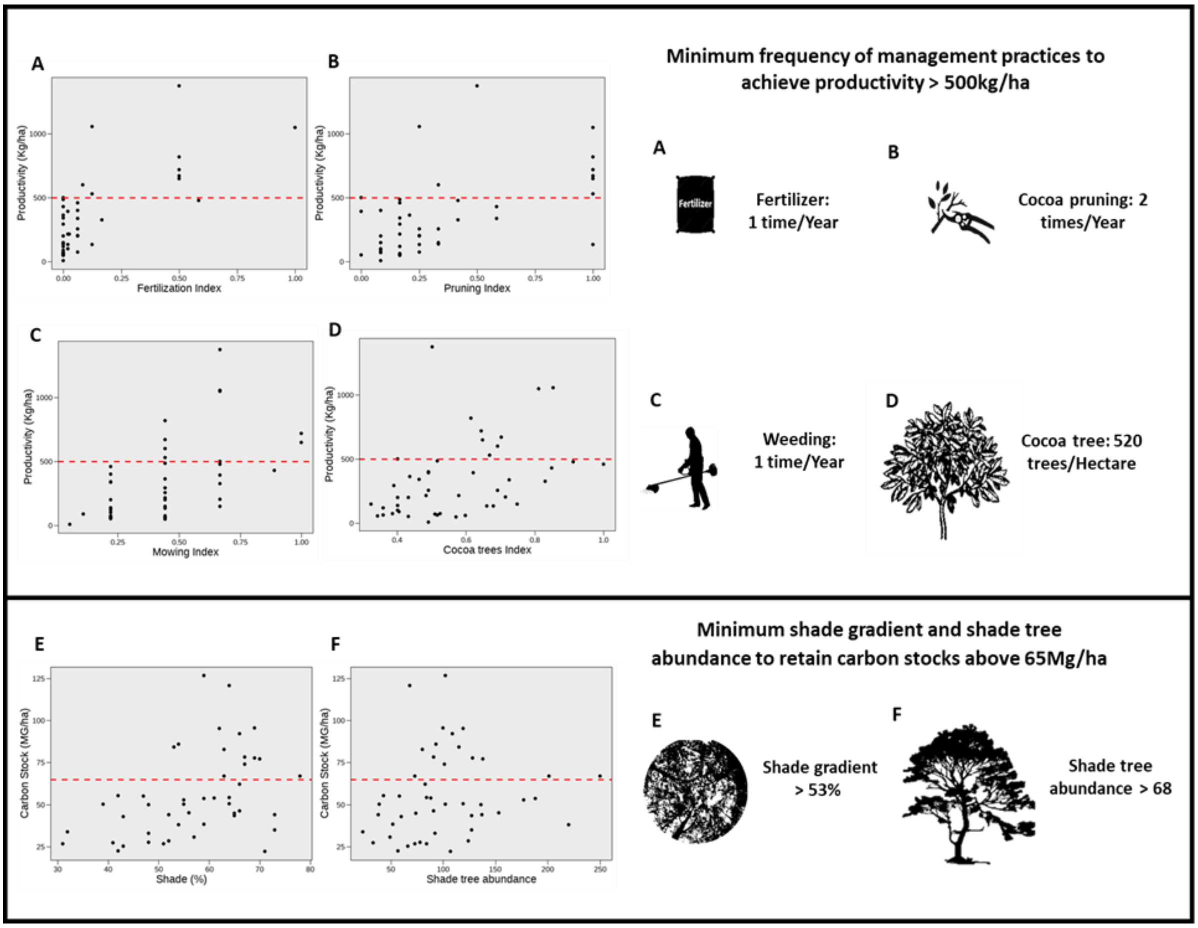


Figure 3. Graphics A-D represents the relationship between management practices and cocoa productivity in traditional cocoa agroforests (cabrucas). The world average cocoa yield of 500 kg ha^{-1} is indicated by a dashed red line. Graphics E-F represents the relationship between shade gradient and shade tree abundance to retain carbon stocks above 65 Mg/ha (represented by a dashed red line).

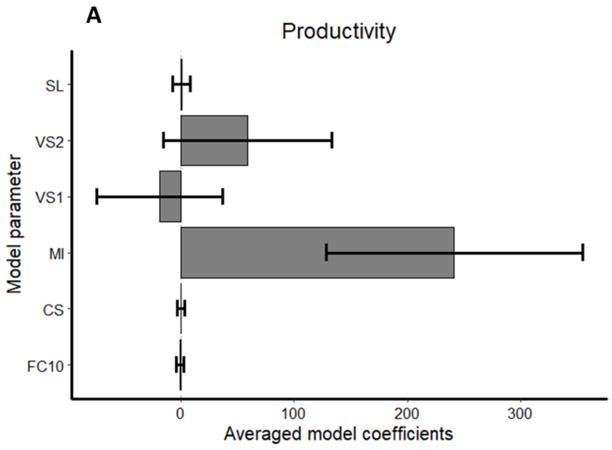


Figure 4. Averaged model coefficients for productivity within DAICc < 2. FC10 – Forest Cover estimated in 10 km in radius; CS –Carbon Stock; MI – Management Index; VS1 – PC1 Vegetation Structure; VS2 – PC2 Vegetation Structure; SL– Shade Level.

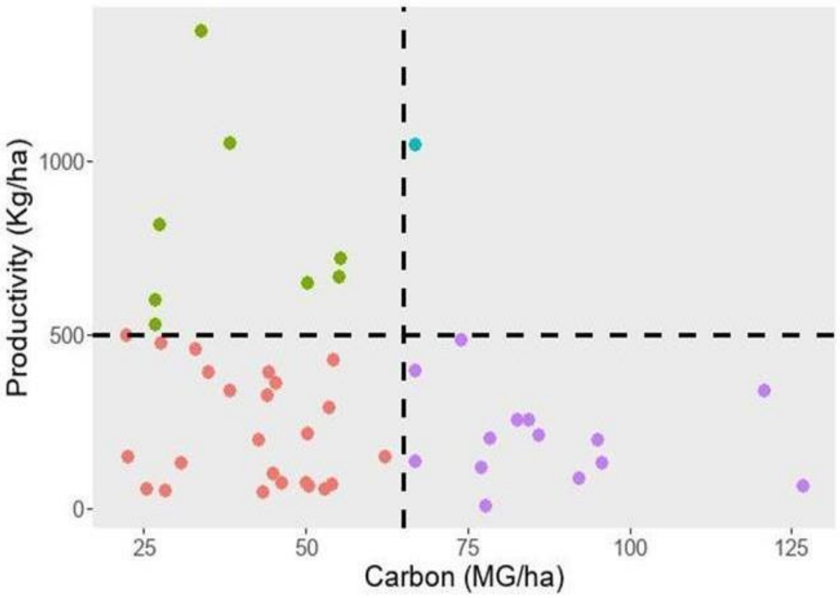


Figure 5. Relationship between cocoa productivity and aboveground carbon stock in 47 cocoa agroforests (cabrucas) located in southern Bahia, Brazil. Dashed lines represent the world average cocoa yield (500 kg/ha^{-1}) and C-stocks above regional recommendation (65Mg/ha).

We detected a significant positive influence of management over cacao productivity, while carbon stock was best explained by shade level. In particular, the best model predicting cocoa productivity contained landscape forest cover, management intensity, the two axes of PCA, and shade level, with a positive and significant effect of management index (*P*–value < 0.001; Table S3 and Fig. 4). In addition, both management index and shade level were included in the best (and single) model explaining carbon storage, with the latter being significant (*P*–value < 0.001; Table S3). These findings imply that sustainable intensification management strategies enable the region to achieve cocoa production levels surpassing the global average while maintaining substantial carbon reserves (Fig. 5).

4. Discussion

Our research has underscored the significant impact of management practices on cocoa yield, enabling the attainment of productivity levels surpassing the global average. Furthermore, our findings indicate no trade-off between local shade and cocoa productivity, demonstrating the feasibility of harmonizing increased productivity with the preservation of shade trees, thereby maintaining substantial carbon stocks. Consequently, we have explored strategies aimed at fostering the sustainable intensification of cabrucas in southern Bahia. These strategies encompass optimizing the ecosystem services provided by shade trees and enhancing productivity to yield economic and consequently result in social advantages, all while adhering to principles of environmental conservation. In addition, given its status as a hotspot within a larger hotspot, we underscore the pivotal role of cabrucas in conserving tree species, including threatened ones.

4.1. Productivity and management practices

The escalating demand for cocoa, combined with globally low average productivity, constitutes a significant threat to forest maintenance, as it fosters the expansion of agricultural frontiers. Consequently, deciphering sustainable methods to enhance productivity remains one of the main challenges in the coming decades. Our findings underscore the impact of management practices in determining cocoa productivity. Notably, fertilization emerges as a key limiting factor, with only 53% of surveyed farmers engaging in this practice. Indeed, all properties that produce more than the global median (500 kg/ha) carry out fertilization at least annually. This result aligns with other studies that highlighted the potential of fertilization to significantly improve the yield of cocoa crops (Schroth et al. 2016; Afrifa et al., 2007; Appiah et al., 2000; Snoeck et al., 2016; van Vliet et al., 2015). The necessity for fertilization arises due to nutrient depletion and soil degradation within cocoa systems, which contributes to the globally low average cocoa productivity. Considering the continuous fruit extraction from the agroecosystem, the "natural income" derived from the soil's inherent fertility where cocoa was planted is no longer sufficient to sustain high productivity (Ruf & Schroth, 2004). Therefore, fertilization emerges as a central concern for the future of cocoa cultivation and the well-being of cocoa farmers (Snoeck et al., 2016). However, a substantial challenge faced by farmers is the lack of information about the management conditions under which fertilizer application can result in improved yields. Fertilizer recommendations for cocoa production vary greatly in both quantity and composition, and the basis for these recommendations is often unclear (van Vliet et al., 2015). This knowledge gap can result in the application of significant fertilizer inputs in situations where other management measures (such as excessive shade or disease levels, or poor management of the cocoa trees) prevent yield increases so that fertilizer is wasted (Schroth et al., 2016). Additionally, socioeconomic factors impact fertilizer usage. Households with lower incomes per person per day tend to have lower cocoa yields, more household members, smaller land sizes, and rely more on cocoa income compared to higher-income households. The poorest families encounter various obstacles to investing in cocoa production, including purchasing inputs (van Vliet et al., 2015; Chiapetti et al., 2020).

Our models did not detect any shade effects on cocoa productivity within the range of shade levels studied (31 to 78%), which aligns with evidence from a previous study in the same region (Schroth et al., 2016). We found that it is possible to achieve productivity above the global average with a shade level of up to 63%. Meanwhile, the impact of shade on the response to fertilization has been debated for decades. Previous experiments have shown conflicting results: some found a negative interaction between shade and fertilizer on yields (Ahenkorah et al., 1974; Cabala Rosand et al., 1976), while others indicated increased productivity with a 30% increase in shade levels (Asare et al., 2017, 2019; Blaser et al., 2018). Although higher productivity has been observed in monocultures, such as 3,000 - 4,000 kg/ha, the absence of shade has led to a rise in disease prevalence, making the cocoa trees unable to sustain high yields (exceeding 1000 kg of dry cocoa per hectare) beyond 15 years of intensive cultivation (Ahenkorah et al., 1974). Furthermore, there are risks associated with shade removal and the importance of associated factors such as pest control, weed incidence, nutrient cycling, biodiversity maintenance, carbon stock, wood provision, mitigation of adverse effects during dry seasons, soil degradation, and food security for farmer families (Cassano et al., 2009; Clough et al., 2011; Mortimer et al., 2018; Niether et al., 2017, 2020; Tscharntke et al., 2011).

Among the sampled farms, approximately 60% of those interviewed received some form of technical assistance, or the owner possessed technical training. This figure exceeds both the Brazilian average of ~15% and the Southern region of Bahia itself, where 25% of properties receive some type of assistance (Chiapetti et al., 2020; IBGE, 2019). However, the annual fertilization practice is not widespread, even among owners who receive or have access to such assistance.

4.2. Shade tree diversity, aboveground carbon stock, and shade level

The transition from shaded agroforests to unshaded monocultures poses a threat to the resilience of tropical landscapes (Middendorp et al., 2018). Cocoa agroforests are pivotal in delivery key ecosystem services, including a wide range of native forest species (Cassano et al., 2009; Faria & Baumgarten, 2007; Pardini et al., 2009; Schroth et al., 2011), seed dispersal (Araújo-Santos et al., 2021) and carbon storage, acting therefore as a valuable tool for climate change mitigation (Boeckx et al., 2020; Jacobi et al., 2014). We observed an average carbon stock of 55 Mg C/ha-1, consistent with earlier findings in the studied region (Schroth et al., 2016). This figure is comparable to cocoa agroforests in Panama and Costa Rica (Somarriba et al., 2013). Despite this, previous studies have demonstrated that this region has the potential to store 65 Mg C/ha, maintaining productivity above the global average (Schroth et al., 2016). According to our results, to achieve these carbon stock values, cabrucas should maintain at least 53% of shade and 68 shade trees. Indeed, shade trees accounted for over 90% of the carbon stock per hectare in the cabrucas, with over 60% of these composed of native trees from the Atlantic Forest. Thus, cocoa agroforests also contribute to tree species conservation, as evidenced by the high diversity and great number of threatened tree species observed, which has also been observed in cocoa farms elsewhere (Clough et al., 2011; Mortimer et al., 2018; Niether et al., 2017, 2020; Tscharntke et al., 2011). Specifically, among the twelve species identified as threatened in our study, *Cariniana legalis*, *Croton sapiifolius*, *Dalbergia nigra*, *Pleroma elegans*, *Acanthosyris paulo-alvinii*, *Swartzia riedelii*, *Swartzia micrantha*, and *Moldenhawera blanchetiana* are all endemic to the Atlantic Forest, with the three latter being endemic to the Bahia state. *Cedrela fissilis* emerged as the most frequently endangered species, present on 77% of the sampled farms. Additionally, we recorded a palm tree, *Euterpe edulis*, threatened due to the overexploitation to its palm hearts, and *Sloanea obtusifolia* and *Melanoxylon brauna*, both threatened primarily due to extensive timber use. Collectively, these species accounted for approximately 376 Mg C/ha-1 of the total carbon stock, with *Cariniana legalis*, *Moldenhawera blanchetiana*, *Cedrela fissilis,* and *Sloanea obtusifolia* being the primary contributors.

Conclusions

Our results indicate that sustainable intensification of cocoa in cabrucas is viable. Shade did not significantly influence productivity, and high levels of productivity were achieved within this agroecosystem. Even with 63% shading, it was possible to achieve a cocoa yield of 1050 kg/ha, in addition to the yield from the shade trees. Consistent management practices, including organic fertilization and regular pruning, were key to these high productivity levels. Notably, a quarter of the sampled farms, despite having less than 60% shade, had productivity levels below the regional average (280 kg/ha). We identified a negative relationship between shading and the frequency of management practices. High shade is a reflection of poorly managed farms and consequently low production. Increasing productivity will not only be achieved by reducing shade but also by appropriate management, such as increased fertilization.

In regions like southern Bahia, unsustainable practices like full-sun cultivation have been used to boost productivity. However, low productivity in agroforests is not solely due to shade levels but also to inadequate farm management practices. Proper pruning and weeding protocols, along with fertilization, are likely to enhance productivity in traditional cocoa farms.

We demonstrate the feasibility of achieving cocoa production levels significantly above the regional and global average while maintaining high carbon stocks and supporting diverse species, confirming earlier research in the region. Addressing local obstacles that impede the adoption of sustainable management practices is crucial. These barriers may include insufficient knowledge among farmers, limited access to technical support, economic challenges in acquiring fertilizers, and lack of supportive public policies. Effective public policies are crucial, including comprehensive rural technical assistance and incentives for sustainable intensification. Linking rural credit to environmental performance and providing subsidies for positive environmental and social impacts can foster a more sustainable approach to cocoa production in southern Bahia.

Funding

This work was supported by the Pró-Reitoria de Pesquisa e Pós Graduação of the Universidade Estadual de Santa Cruz (grant number 22011001867), PROPP/UESC (073.6764.2020.0000065-80); and the Instituto Nacional de Ciência e Tecnologia em Estudos Interdisciplinares e Transdisciplinares em Ecologia e Evolução - INCT IN-TREE (INC0006/2019). J.C.M-F. (303302/2022-4), M.B. (304189/2022-7)
and D.F (307990/2018-4) received a productivity grant from CNPq.

Credit authorship contribution statement

Marina Gomes de Figueiredo: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Larissa Rocha-Santos:** Investigation, Methodology, Writing - original draft, Writing - review & editing. **Eduardo Mariano-Neto:** Formal analysis, Methodology, Writing - original draft. **Goetz Schroth:** Conceptualization, Writing - original draft, Writing - review & editing. **Maíra Benchimol:** Investigation, Methodology, Writing - original draft, Writing - review & editing. **José Carlos Morante-Filho:** Investigation, Methodology, Writing - original draft, Writing - review & editing. **Deborah Faria:** Conceptualization, Supervision, Funding acquisition, Investigation, Methodology, Writing - original draft, Writing - review & editing.

Acknowledgements

MGF received funding from the National Council for Scientific and Technological Development (CNPq). Special thanks to Lukas Daneu for his invaluable assistance in the field and species identification. We extend our appreciation to the generous farm owners and administrators for permitting us to research their properties. We are grateful to the members of the Applied Ecology & Conservation Lab for their scientific and field contributions and to the reviewers for their interesting comments. This study is part of the 'Eco-nomia das cabrucas' project (publication number 12), funded by the Brazilian Council for Research and Technology (CNPq) and the Research Support Foundation of the State of Bahia (FAPESB, grant number INC0006/2019), which support the National Institute of Science and Technology in Interdisciplinary and Transdisciplinary Studies in Ecology and Evolution (INCT IN-TREE).

5. References

Afrifa, A. A., Ofori-Frimpong, K., Appiah, M. R., Acquaye, S., & Snoeck, D. (2007). Nitrogen, Phosphorus and Potassium Budget Under the Cocoa Ecosystem: Produce Harvesting Phase. *Proceedings of the 15th International Cocoa Research Conference, May 2015*, 395–404. file:///D:/Documents and Settings/cocoa literature resources/Conference No Tag Proceedings/COPAL ICRC/15 ICRC Costa Rica/individual papers/ICRC15AFR07A.pdf

Ahenkorah, Y., Akrofi, G. S., & Adri, A. K. (1974). The end of the first cocoa shade and manurial experiment at the Cocoa Research Institute of Ghana. *Journal of Horticultural Science*, *49*(1), 43–51. https://doi.org/10.1080/00221589.1974.11514550

Ahenkorah, Y., Halm, B., Appiah, M., Akrofi, G., & Yirenkyi, J. (1987). TWENTY YEARS ' RESULTS FROM A SHADE AND FERTILIZER TRIAL ON AMAZON COCOA { THEOBROMA CACAO) IN GHANA Cocoa Research Institute of Ghana (CRIG), PO Box 8 , New Tafo-Akim , Ghana (Accepted 27 March 1986) Following the success of the earlier Amelonado co. *Experimental Agriculture*, *23*, 31–39.

Alvares, C. A., Stape, J. L., Sentelhas, P. C., De Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711– 728. https://doi.org/10.1127/0941-2948/2013/0507

Anderson, D., & Burnham, K. (2004). Model selection and multi-model inference. *Second. NY: Springer-Verlag*, *63*(2020), 10.

Andres, C., Comoé, H., Beerli, A., Schneider, M., Rist, S., & Jacobi, J. (2016). *Cocoa in Monoculture and Dynamic Agroforestry*. https://doi.org/10.1007/978-3-319-26777-7_3

Appiah, M., Ofori-Frimpong, K. ., & Afrifa, A. (2000). Evaluation of fertilizer application on some peasant cocoa farms in Ghana. *Ghana Journal of Agricultural Science*, *33*, 183–190.

Araújo-Santos, I., Morante-Filho, J. C., Oliveira, S., Cabral, J. P., Rocha-Santos, L., Cassano, C. R., Faria, D., & Benchimol, M. (2021). Seed rain in cocoa agroforests is induced by effects of forest loss on frugivorous birds and management intensity. *Agriculture, Ecosystems and Environment*, *313*(February). https://doi.org/10.1016/j.agee.2021.107380

Araujo, M., Alger, K., Rocha, R., & Mesquita, C. A. (1998). A mata atlântica do sul da bahia. *Série Cadernos Da Reserva Da Biosfera Da Mata Atlântica*, *8*, 20.

Ariza-Salamanca, A. J., Navarro-Cerrillo, R. M., Quero-Pérez, J. L., Gallardo-Armas, B., Crozier, J., Stirling, C., de Sousa, K., & González-Moreno, P. (2023). Vulnerability of cocoa-based agroforestry systems to climate change in West Africa. *Scientific Reports*, *13*(1), 1–12. https://doi.org/10.1038/s41598-023-37180-3

Asare, R., Afari-sefa, V., Gyamfi, I., Okafor, C., & Mva, J. M. (2010). *The Sustainable Tree Crops Program (STCP) STCP Working Paper Series Issue 11 Cocoa seed multiplication : an assessment of seed gardens in By : International Institute of Tropical Agriculture*. *11*.

Asare, R., Asare, R. A., Asante, W. A., Markussen, B., & RÆbild, A. (2017). INFLUENCES of SHADING and FERTILIZATION on ON-FARM YIELDS of COCOA in GHANA. *Experimental Agriculture*, *53*(3), 416–431. https://doi.org/10.1017/S0014479716000466

Asare, R., Markussen, B., Asare, R. A., Anim-Kwapong, G., & Ræbild, A. (2019). On-farm cocoa yields increase with canopy cover of shade trees in two agro-ecological zones in Ghana. *Climate and Development*, *11*(5), 435–445. https://doi.org/10.1080/17565529.2018.1442805

Bates, D. M., & Pinheiro, J. C. (1998). Linear and Nonlinear Mixed-Effects Models. *Conference on Applied Statistics in Agriculture*. https://doi.org/10.4148/2475-7772.1273

Beer, J. (1987). Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. *Agroforestry Systems*, *5*(1), 3–13.

Blaser, W. J., Oppong, J., Hart, S. P., Landolt, J., Yeboah, E., & Six, J. (2018). Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nature Sustainability*, *1*(5), 234–239. https://doi.org/10.1038/s41893-018-0062-8

Boeckx, P., Bauters, M., & Dewettinck, K. (2020). Poverty and climate change challenges for sustainable intensification of cocoa systems. *Current Opinion in Environmental Sustainability*, *47*, 106–111.

Cabala Rosand, P., de Santana, C. J. L., & de Miranda, E. R. (1976). Respuesta del cacaotero al abonamiento en el sur de Bahia, Brasil. *Boletim Técnico-Comissao Executiva Do Plano Da Lavoura Cacaueira (Brasil)(No. 43) 24 P.*

Cassano, C. R., Kierulff, M. C. M., & Chiarello, A. G. (2011). The cacao agroforests of the Brazilian Atlantic forest as habitat for the endangered maned sloth Bradypus torquatus. *Mammalian Biology*, *76*(3), 243–250.

Cassano, C. R., Schroth, G., Faria, D., Delabie, J. H. C., & Bede, L. (2009). Landscape and farm scale management to enhance biodiversity conservation in the cocoa producing region of southern Bahia, Brazil. *Biodiversity and Conservation*, *18*(3), 577–603. https://doi.org/10.1007/s10531-008-9526-x

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., Duque, A., Eid, T., Fearnside, P. M., Goodman, R. C., Henry, M., Martínez-Yrízar, A., Mugasha, W. A., Muller-Landau, H. C., Mencuccini, M., Nelson, B. W., Ngomanda, A., Nogueira, E. M., Ortiz-Malavassi, E., … Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, *20*(10), 3177–3190. https://doi.org/10.1111/gcb.12629

Chiapetti, J., Rocha, R. B. da, Conceição, A. S. da, & Baiardi, A. (2020). Panorama da Cacauicultura no Território Litoral Sul da Bahia (2015-2019). *Revelando Desafios e Oportunidades Sociais, Econômicas, e Ecológicas Para Restauração de Florestas Em Propriedades Rurais Na Mata Atlântica Do Sul Da Bahia*, 1–110. https://www.worldcocoafoundation.org/wp-content/uploads/2020/05/Panorama-da-cacauicultura-TILSB-Versao-final-Web.pdf

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T. C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Putra, D. D., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C. H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., … Tscharntke, T. (2011). Combining high biodiversity with high yields in tropical agroforests. *Proceedings of the National Academy of Sciences*, *108*(20), 8311–8316. https://doi.org/10.1073/PNAS.1016799108

Diniz-Filho, J. A. F., Bini, L. M., & Hawkins, B. A. (2003). Spatial autocorrelation and red herrings in geographical ecology. *Global Ecology and Biogeography*, *12*(1), 53–64. https://doi.org/10.1046/j.1466-822X.2003.00322.x

Faria, D., & Baumgarten, J. (2007). Shade cacao plantations (Theobroma cacao) and bat conservation in southern Bahia, Brazil. *Biodiversity and Conservation*, *16*(2), 291–312. https://doi.org/10.1007/s10531-005-8346-5

Faria, D., Morante-Filho, J. C., Baumgarten, J., Bovendorp, R. S., Cazetta, E., Gaiotto, F. A., Mariano-Neto, E., Mielke, M. S., Pessoa, M. S., Rocha-Santos, L., Santos, A. S., Soares, L. A. S. S., Talora, D. C., Vieira, E. M., & Benchimol, M. (2023). The breakdown of ecosystem functionality driven by deforestation in a global biodiversity hotspot. *Biological Conservation*, *283*(April). https://doi.org/10.1016/j.biocon.2023.110126

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570–574. https://doi.org/10.1126/science.1111772

Harvey, C. A., Medina, A., Sánchez, D. M., Vílchez, S., Hernández, B., Saenz, J. C., Maes, J. M., Casanoves, F., & Sinclair, F. L. (2006). Patterns of animal diversity in different forms of tree cover in agricultural landscapes. *Ecological Applications*, *16*(5), 1986–1999. https://doi.org/10.1890/1051-0761(2006)016[1986:POADID]2.0.CO;2

IBGE. (2019). Censo agropecuário 2017: resultados definitivos. *Censo Agropecuário*, *8*, 1–105.

IPCC. (2014). Climate Change 2014 Part A: Global and Sectoral Aspects. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. papers2://publication/uuid/B8BF5043-C873-4AFD-97F9-A630782E590D

Jacobi, J., Andres, C., Schneider, M., Pillco, M., Calizaya, P., & Rist, S. (2014). Carbon stocks, tree diversity, and the role of organic certification in different cocoa production systems in Alto Beni, Bolivia. *Agroforestry Systems*, *88*(6), 1117–1132. https://doi.org/10.1007/s10457-013-9643-8

Johns, N. D. (1998). Conservation in Brazil’s chocolate forest: The unlikely persistence of the traditional cocoa agroecosystem. *Environmental Management*, *23*(1), 31–47. https://doi.org/10.1007/s002679900166

Landau, E. C., & Hirsch, A. (2008). *Vegetation cover and land use in the Atlantic Coastal Forest of Southern Bahia, Brazil, based on satellite imagery: a comparison among municipalities BDGEOPRIM-Database of Georeferenced Localities for Neotropical Primates View project. January*. https://www.researchgate.net/publication/280311639

Malhi, Y., Baker, T. R., Phillips, O. L., Almeida, S., Alvarez, E., Arroyo, L., Chave, J., Czimczik, C. I., Di Fiore, A., Higuchi, N., Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L., Montoya, L. M. M., Monteagudo, A., Neill, D. A., Vargas, P. N., Patino, S., … Lloyd, J. (2004). The above-ground coarse wood productivity of 104 Neotropical forest plots. *Global Change Biology*, *10*(5), 563–591. https://doi.org/10.1111/j.1529-8817.2003.00778.x

Mas, A. H., & Dietsch, T. V. (2003). An index of management intensity for coffee agroecosystems to evaluate butterfly species richness. *Ecological Applications*, *13*(5), 1491–1501. https://doi.org/10.1890/01-5229

Middendorp, R. S., Vanacker, V., & Lambin, E. F. (2018). Impacts of shaded agroforestry management on carbon sequestration, biodiversity and farmers income in cocoa production landscapes. *Landscape Ecology*, *33*(11), 1953–1974. https://doi.org/10.1007/s10980-018-0714-0

Mortimer, R., Saj, S., & David, C. (2018). Supporting and regulating ecosystem services in cacao agroforestry systems. *Agroforestry Systems*, *92*(6), 1639–1657. https://doi.org/10.1007/s10457-017-0113-6

Niether, W., Jacobi, J., Blaser, W. J., Andres, C., & Armengot, L. (2020). *Cocoa agroforestry systems versus monocultures : OPEN ACCESS Cocoa agroforestry systems versus monocultures : a multi-dimensional meta-analysis*.

Niether, W., Schneidewind, U., Armengot, L., Adamtey, N., Schneider, M., & Gerold, G. (2017). Spatial-temporal soil moisture dynamics under different cocoa production systems. *Catena*, *158*(July), 340–349. https://doi.org/10.1016/j.catena.2017.07.011

Pardini, R., Faria, D., Accacio, G. M., Laps, R. R., Mariano-Neto, E., Paciencia, M. L. B., Dixo, M., & Baumgarten, J. (2009). The challenge of maintaining Atlantic forest biodiversity: A multi-taxa conservation assessment of specialist and generalist species in an agro-forestry mosaic in southern Bahia. *Biological Conservation*, *142*(6), 1178–1190. https://doi.org/10.1016/j.biocon.2009.02.010

Réjou-Méchain, M., Tanguy, A., Piponiot, C., Chave, J., & Hérault, B. (2017). Methods Ecol Evol - 2017 - R jou-M chain - biomass an r package for estimating above-ground biomass and its uncertainty in(1).pdf. In *Methods in Ecology and Evolution* (Issue 8, pp. 1163–1167).

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*(1), 4–17. https://doi.org/10.1007/s13280-016-0793-6

Ruf, F., & Schroth, G. (2004). Chocolate forests and monocultures: a historical review of cocoa growing and its conflicting role in tropical deforestation and forest conservation. *Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press, Washington*, 107–134.

Sambuichi, R. H. R., Vidal, D. B., Piasentin, F. B., Jardim, J. G., Viana, T. G., Menezes, A. A., Mello, D. L. N., Ahnert, D., & Baligar, V. C. (2012). Cabruca agroforests in southern Bahia, Brazil: Tree component, management practices and tree species conservation. *Biodiversity and Conservation*, *21*(4), 1055–1077. https://doi.org/10.1007/s10531-012-0240-3

Schneider, M., Andres, C., Trujillo, G., Alcon, F., Amurrio, P., Perez, E., Weibel, F., & Milz, J. (2017). COCOA and TOTAL SYSTEM YIELDS of ORGANIC and CONVENTIONAL AGROFORESTRY VS. MONOCULTURE SYSTEMS in A LONG-TERM FIELD TRIAL in BOLIVIA. *Experimental Agriculture*, *53*(3), 351–374. https://doi.org/10.1017/S0014479716000417

Schroth, G., Bede, L. C., Paiva, A. O., Cassano, C. R., Amorim, A. M., Faria, D., Mariano-Neto, E., Martini, A. M. Z., Sambuichi, R. H. R., & Lôbo, R. N. (2015). Contribution of agroforests to landscape carbon storage. *Mitigation and Adaptation Strategies for Global Change*, *20*(7), 1175–1190. https://doi.org/10.1007/s11027-013-9530-7

Schroth, G., Faria, D., Araujo, M., Bede, L., van Bael, S. A., Cassano, C. R., Oliveira, L. C., & Delabie, J. H. C. (2011). Conservation in tropical landscape mosaics: The case of the cacao landscape of southern Bahia, Brazil. *Biodiversity and Conservation*, *20*(8), 1635–1654. https://doi.org/10.1007/s10531-011-0052-x

Schroth, G., & Harvey, C. A. (2007). Biodiversity conservation in cocoa production landscapes: An overview. *Biodiversity and Conservation*, *16*(8), 2237–2244. https://doi.org/10.1007/s10531-007-9195-1

Schroth, G., Jeusset, A., Gomes, A. da S., Florence, C. T., Coelho, N. A. P., Faria, D., & Läderach, P. (2016). Climate friendliness of cocoa agroforests is compatible with productivity increase. *Mitigation and Adaptation Strategies for Global Change*, *21*(1), 67–80. https://doi.org/10.1007/s11027-014-9570-7

Snoeck, D., Koko, L., Joffre, J., Bastide, P., & Jagoret, P. (2016). *Cacao Nutrition and Fertilization*. https://doi.org/10.1007/978-3-319-26777-7_4

Somarriba, E., Cerda, R., Orozco, L., Cifuentes, M., Dávila, H., Espin, T., Mavisoy, H., Ávila, G., Alvarado, E., Poveda, V., Astorga, C., Say, E., & Deheuvels, O. (2013). Carbon stocks and cocoa yields in agroforestry systems of Central America. *Agriculture, Ecosystems and Environment*, *173*, 46–57. https://doi.org/10.1016/j.agee.2013.04.013

Street, B., & Legon, E. (2014). *Cocoa Market Update*. *4*, 1–11.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260–20264.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*(6898), 671–677.

Tscharntke, T., Clough, Y., Bhagwat, S. A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., & Wanger, T. C. (2011). Multifunctional shade-tree management in tropical agroforestry landscapes - A review. *Journal of Applied Ecology*, *48*(3), 619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x

van Vliet, J. A., Slingerland, M., & Giller, K. E. (2015). Mineral nutrition of cocoa. In *Advances in Agronomy* (Issue July). https://doi.org/10.1016/bs.agron.2016.10.017%0Ahttp://arohatgi.info/WebPlotDigitizer/ app/

CAPITULO III

ASSESSMENT OF POTENTIAL CO-BENEFITS BETWEEN CARBON STORAGE AND CONSERVATION OF TREE DIVERSITY IN COCOA AGROFORESTS IN SOUTHERN BAHIA, BRAZIL

Assessment Of Potential Co-Benefits Between Carbon Storage and Conservation of Tree Diversity in Cocoa Agroforests In Southern Bahia, Brazil

Abstract

In the Southern Bahia region, northeastern Brazil, cocoa agroforests have been established through the process of thinning and replacing the natural forest understory with cocoa trees. This area is recognized as a crucial zone for biodiversity conservation within the Atlantic Forest hotspot, particularly due to their potential to host tree assemblages in addition to an important c-stock landscape reservoir. To better understand such a topic, here we evaluate how specific aspects of cocoa cultivation, namely productivity, management practices, and landscape forest cover, on the diversity of trees in 54 farms in the cocoa-production zone growing region of southern Bahia, Brazil. To assess community tree diversity, we utilized a comprehensive approach that includes taxonomic diversity (TD), phylogenetic diversity (PD and sesPD), functional diversity (FD and sesFD), and conservation value, specifically focusing on endangered and endemic species. We further investigated the relationship between these diversity metrics and carbon storage. Our findings revealed that cabrucas, host a diverse tree assemblage and that neither management practices nor forest cover significantly influenced the tree diversity. Despite the negative impact of DT on productivity, certain farms have managed to maintain high levels of both productivity and diversity through selective management practices chosen by smallholders. Despite serving as vital habitats for endemic and threatened tree species, as well as storing substantial amounts of aboveground carbon, our analysis did not uncover any correlation between community tree diversity metrics and carbon storage. Failure to include biodiversity in PES could lead to the displacement of threatened and endemic species that store less carbon by species more efficient in carbon sequestration. Policy frameworks must integrate both ecosystem services to maximize benefits for biodiversity and carbon conservation. Thus, it is imperative to integrate biodiversity considerations into carbon conservation strategies to ensure a more comprehensive and effective approach to conservation planning.

1. Introduction

Mitigating climate change through carbon offset strategies, like conserving and restoring ecosystems, is critical (Phelps, Friess, et al., 2012; Phelps, Webb, et al., 2012). However, limited carbon-based payments for ecosystem services (PES) highlight the need to integrate solutions for both climate change and biodiversity conservation (Venter et al., 2009). Economic pressures often prioritize maximizing carbon gains at minimal cost, making areas with high carbon density and conservation priorities vital for achieving dual benefits (Girardello et al., 2019). The alignment of high carbon stocks with Red-listed and endemic species and biodiversity richness demonstrates significant co-benefits, helping to prevent diversity loss in tropical rainforests through c-stock PES (Magnago et al., 2015; Matos et al., 2020). Achieving these benefits, however, involves significant trade-offs that are not fully recognized (Phelps, Friess, et al., 2012). Focusing solely on carbon sequestration risks losing many species (Ferreira et al., 2018; Reside et al., 2017). Therefore, it is essential to integrate biodiversity conservation into carbon conservation planning.

Agroforestry systems, where crops and trees are integrated, are recognized as a natural resource management strategy that distinguishes from other agricultural practices by balancing agricultural development with the preservation of ecosystem services (Addo-Danso et al., 2024; Mortimer et al., 2018; Schroth et al., 2004). Cocoa agroforests in Southern Bahia were established by thinning the canopy of native forests and selecting some canopy trees to shade the cocoa plants that replace the entire native understory, closely mimicking natural forest ecosystems (Rice & Greenberg, 2000, Michon & de Foresta, 1996; Schroth et al., 2004, 2011). This resulting crop system is known as 'cabrucas', and still maintains a complex structure with a shade canopy that stores ~60% of the total tree-dominated vegetation aboveground carbon stocks in this region. While not equaling undisturbed forests in tree species richness, these plantations provide habitat for nearly 2/3 of the forest species of various biological groups (Faria et al., 2006; Faria & Baumgarten, 2007; Pardini et al., 2009), including endangered species (Cassano et al., 2009; Raboy et al., 2004). South Bahia together with the northern region of Espírito Santo state, Brazil, forms a center of species endemism being a hot point for biodiversity conservation in the Atlantic Forest hotspot (Martini et al., 2007; Thomas et al., 1998). This region represents exceptional biological importance, harboring several endemic species of mammals, birds (Bencke et al., 2006; Cassano et al., 2011), ants (Delabie et al., 2007; Lacau et al., 2004), some of the highest levels of woody species richness, and very high rates of plant endemism in the world.

Cabrucas exhibit high tree diversity and varied structures, with forest specialist trees dominating (63.9%) (Sambuichi et al., 2012). However, endangered and endemic species are not effectively preserved (Sambuichi et al., 2008). Despite this, cabrucas are crucial for conserving forest species in human-altered landscapes by enhancing heterogeneity and serving as ecological corridors, habitats, and buffer zones (Cassano et al., 2009; Faria et al., 2006; Sambuichi et al., 2012). The growing global demand for cocoa beans and the push to maximize yields have driven traditional cocoa agroforests towards low-shade plantations, despite controversies over the trade-offs between shade tree effects and agricultural intensification (Clough, Faust, et al., 2009; Jacobi et al., 2015; Tscharntke et al., 2011). Participating in PES schemes should incentivize traditional cocoa agroforests to adopt climate-friendly practices and recognize their role in biodiversity conservation and carbon sequestration (Schroth et al., 2016).

A win-win scenario for cocoa agroforests in Southern Bahia should enhance ecosystem services and increase cocoa yields. While conservation can align with smallholder cacao production, achieving this necessitates heightened industry efforts to curb cacao cycles and capitalize on opportunities for integrating sustainability (Sanial et al., 2023). Payment for ecosystem services (PES) targeting the carbon stock in this region would aid in conserving native species; however, it is crucial to ensure that endemic and threatened species are also prioritized.

In this study, we examine the impact of cocoa productivity, management practices, and landscape forest cover on community tree diversity metrics. Furthermore, we aim to investigate the relationship between tree diversity metrics and carbon storage. We utilize taxonomic diversity (TD), phylogenetic diversity (PD and sesPD), functional diversity (FD and sesFD), and conservation value (endangered and endemic species) to assess community tree diversity. We hypothesize that it is possible to optimize productivity (exceeding the world average) and management practices while conserving ecosystem services, and we anticipate co-benefits between carbon storage and biodiversity.

2. Materials and Methods

2.1. Study Area

We carried out this study in the southeastern region of Bahia in northeastern Brazil. According to the Köppen classification (Alvares et al., 2013), the climate of this region is predominantly characterized by humid tropical forests, with an average annual temperature of 25 °C and annual precipitation of 1000-1900 mm. The area is currently characterized by a diverse, human-modified landscape, encompassing various types of land use. This mosaic includes remnants of the Atlantic Forest in different stages of succession, occupying around 35% of the landscape, with the remainder consisting of urban areas, cocoa, rubber, and eucalyptus plantations under shade, as well as pastures for livestock (MapBiomas).

We randomly selected 54 independent farms that began cultivating cocoa decades and even a century ago. These farms replaced the native Atlantic Forest understory while maintaining native shade trees (Araujo et al., 1998). Four farms had fewer than 20 native tree species per hectare, and under the law, they were not considered cabrucas. However, they were included in our sampling as we used a traditional definition of cabruca, which considers plantations in which cocoa trees are cultivated under a thinned native forest. Currently, cocoa farms employ different management practices like rustic (no use of fertilizers), conventional (using chemical fertilizers), organic (employing organic fertilizers), or agroecological (using organic fertilizers, blends of biofertilizers, and agroecological techniques like pruning). Sampling was carried out between 2021 and 2023.

2.2. Tree Sampling and Aboveground Biomass (AGB)

We sampled 1 hectare, in four plots of 50 x 50 m within each farm, ensuring a minimum distance of 30 m between plots. We recorded all shade trees (including arboreal palms) with a diameter at breast height (DBH; measured at 1.30 m above the ground) of 10 cm or more. Trees were measured (DBH and height) and identified at the lowest possible taxonomic level, with the assistance of an experienced botanist. For those individuals that couldn't be identified in the field, we collected branches to facilitate taxonomic identification through virtual herbarium resources and herbarium collections in Bahia: CEPEC/Ceplac and HUESC/UESC. Additionally, within each plot, we established a 25 x 25 m subplot to count all cocoa trees and measure the diameter of 10 randomly selected individuals. These data were used to estimate biomass per tree, covering both native and exotic species, using the BIOMASS package for R (Réjou-Méchain et al., 2017) along with wood density values from an openly accessible dataset (Chave et al., 2014). We included native and exotic shade tree species collected and used average values at the genus or family level when species-level wood density values were unavailable. For unidentified trees (5.2%), we used the average wood density value of all other species in the plot. Finally, we calculated carbon stocks by assuming that 50% of each tree's above-ground biomass constitutes carbon (Malhi et al., 2004).

2.3. Cocoa Productivity and Management Index

We collected data on both productivity and management practices through semi-structured interviews with each cocoa owner or manager in 2021 and 2023. Initially, we requested information about their overall cocoa production for the two years preceding each interview (i.e., 2019 and 2022). We then estimated cocoa production per unit area by dividing the two-year average production by the reported size of the cabruca area.

We gathered data on management practices to derive a 'Management Intensity Index' (MI) for each farm. This index was adapted from existing indices used in coffee studies (Mas & Dietsch, 2003) and standardized based on the frequency of management practices per year. Specifically, we focused on five common management practices in cabrucas: 1) weed control (frequency per year); 2) organic fertilization and/or liming (frequency per year); 3) chemical fertilization and/or liming (frequency per year); 4) cocoa tree pruning (frequency per year), which includes the removal of excess shoots and occasional heavy pruning of branches and larger stems; and 5) the total number of cocoa trees in the established vegetation plot. Each variable was assigned equal weight, ranging from 0.0 to 1.0, with 0 indicating the least intensive and 1 indicating the most intensive management. For each farm, we normalized the frequency values by dividing them by the highest value observed across all farms for that variable. The values for each variable were then summed to create an overall management index (MI) for each farm, with 0 representing minimal management and a maximum score of 5 indicating intensive management practices.

2.4. Landscape Forest Cover

We used Landsat satellite images from the latest available regional mapping resource, the free-access "MapBiomas Cacau" (https://mapbiomas.org/mapbiomas_cacau_download), to estimate the amount of native forest cover surrounding each sampled cabruca. Four landscape sizes (0.5, 1, 5, and 10 km in radius) were established, starting from the central area between the four sampled plots on each farm, to assess forest cover, using QGIS software.

2.5. Phylogeny Reconstruction

We generated a phylogenetic tree for the 158 species using the V.PhyloMaker package (Jin & Qian, 2019) in the R programming language and environment (R Core Team, 2018). This package links the species names in our dataset with those in the time-calibrated mega tree (GBOTB.extended.tre), which includes the largest dated phylogeny for seed plants as a backbone for phylogenetic reconstruction. We used the default argument scenario 3 approach to add missing taxa (e.g., genus or species) to the phylogeny by binding them to the crown node of their corresponding genus (Qian & Jin, 2016), an approach implemented in the PHYLOCOM software package.

2.6. Tree Community Metrics

2.6.1. Taxonomic Diversity

To assess taxonomic diversity (TD), we included all morphospecies sampled in the four plots of each farm. This measure serves as an indicator of alpha diversity for each cocoa agroforest sampled.

2.6.2. Phylogenetic Diversity

We calculated the phylogenetic diversity based on Faith's Phylogenetic Diversity index (PD) which consists of the summed lengths of the phylogenetic branches of a species set (Faith, 1992). Because phylogenetic diversity (PD) is sensitive to species richness (SR), showing a strong correlation even with a moderate gradient in SR, several issues arise. For instance, if a researcher reports that two communities have significantly different phylogenetic diversity (PD) values, it becomes challenging to determine whether this difference is merely due to the variation in their SR values or if there is an underlying factor related to the significant phylogenetic information (Swenson, 2014). To deal with differences in species richness, we determined the standardized effect size (ses). This involved calculating the difference between the observed metric value and the mean value of null communities with the same species richness, divided by the standard deviation of 999 randomized values. Communities with sesPD values near 1 (i.e., high quantiles) suggest that co- occurring species have greater phylogenetic distances than what would be expected by chance. Conversely, communities with sesPD values near 0 (i.e., low quantiles) indicate that co-occurring species have smaller phylogenetic distances than expected by chance.

2.6.3. Functional Diversity

We evaluated three functional traits across 192 species associated with (i) fruit type - categorized into fleshy or non-fleshy fruits; (ii) fruit dispersal syndrome, categorized into zoochoric or non-zoochoric dispersion; and (iii) carbon storage measured as wood density in dry weight (g/cm^3). These functional characteristics demonstrate the availability of resources for fauna, as well as regenerative traits and reproductive strategies (Pérez-Harguindeguy et al., 2013). These metrics were obtained from field observations, the SpeciesLink database (for more details, see: http://splink.cria.org.br/), and specialized literature (Pott and Pott, 1994; Lorenzi, 1998; Barroso et al., 2000; Pérez-Harguindeguy et al., 2016).

We built a functional dendrogram from a species × functional traits matrix transformed into a distance matrix to calculate the Functional Diversity Index (FD). We used Gower distance to treat categorical (dispersal syndrome and fruit type) and quantitative data (wood density) in the ade4 (Dray et al., 2007) and ape packages (Paradis et al., 2004) and the UPGMA clustering method. We converted the dendrogram output to a tree using the as.phylo() function available on the ape package.

Species traits (and phylogenetic diversity) can be integrated at both large and local spatial scales to uncover the historical, deterministic, and stochastic processes affecting local community compositions (Pavoine & Bonsall, 2011). We assess functional diversity (FD) by calculating the total branch length of a functional dendrogram, which is particularly useful for understanding the connection between functional diversity and ecosystem functioning (Petchey & Gaston, 2002). Additionally, we measured the standardized effect size of functional diversity (sesFD) because species richness can influence FD similarly to how it influences PD. All metrics were calculated using the picante package in R software version 3.2.1 (R Development Core Team 2015).

2.6.4. Endemism and Threatened Species

We define (i) endemic species as those recorded exclusively in the Atlantic Forest domain, based on the Flora do Brazil database (https://bit.ly/2G1W2D2). Additionally, we classify (ii) threatened species as those identified with any level of extinction risk (CR - critically endangered, VU - vulnerable, and EN - endangered) according to the Ministry of the Environment's classification (MMA - ORDER Nº 148, OF JUNE 7, 2022). We identified twelve threatened tree species: one critically endangered (*Acanthosyris paulo-alvinii*), five endangered (*Cariniana legalis, Pleroma elegans, Swartzia micrantha, Sloanea obtusifolia, Croton sapiifolius*), and six vulnerable (*Cedrela fissilis, Dalbergia nigra, Euterpe edulis, Melanoxylon brauna, Moldenhawera blanchetiana, Swartzia riedelii*) in the sampled cabrucas. At least one individual from a vulnerable or threatened species was found in 85% of the sampled farms. *Cedrela fisssilis* was the most common species, being found on 70% of the farms sampled.

2.7. Statistical analyses

To determine the appropriate scale of landscape forest cover for our data analyses, we conducted the Spearman rank test (r) for this predictor variable across our predefined landscape scales (i.e., 0.5, 1, 5, and 10 km radii) against the community metrics. Our analyses revealed that a 0.5 km scale was most suitable for FD and sesFD, while the 10 km scale showed the most significant coefficient values for TD, PD, sesPD, and both endemic and threatened species. Consequently, these were respectively selected as the optimal scales. We found no correlations ($r > 0.73$) among the predictor variables (forest cover, management index, productivity, and carbon stock) in any of the tested models. We analyzed the effect of each set of them on community metrics.

We used the "simulateResiduals" function from the "DHARMa" package to assess overdispersion. We applied GLMs with Gaussian distributions, as the Shapiro–Wilk test confirmed the normal distribution of residuals. For the count data on conservation value (questions: iv and v), we applied negative binomial distributions with log link functions after rejecting the Poisson model. We implemented GLMs using the 'glm/glm.nb' function from the MASS package. We select the model guided by the Akaike Information Criterion (AICc), as implemented in the R package "nlme" (Bates & Pinheiro, 1998).

We adopted a binomial distribution family for all variables. Subsequently, we used selection using the Akaike Information Criterion (AICc), considering models with AICc values lower than 4 units (denoted as ΔAICc) as the most parsimonious, with ΔAICc of 0 indicating the best explanatory model. We calculated average model parameters from the selected models and assessed the importance of predictor variables using Akaike weights (Anderson & Burnham, 2004). All statistical analyses were performed using R software version 4.2.2 (R Core Team, 2021).

3. Results

3.1. Impacts of Productivity, Management Index, and Landscape Forest Cover on Tree Community Metrics

We collected a total of 5,492 individuals and identified 97.9% (5,381 individuals) at the species level, 1% (54 individuals) at the genus level, 0.6% (31 individuals) at the family level, and 0.5% (26 individuals) remained unidentified (Table S1). In the sampled area of 54 ha (1 ha per farm), we detected 64 families, 149 genera, and 192 species. Among these individuals, 38% (2,070) were exotic species, 1% (63) were endemic and threatened species of the Atlantic Forest, 1% (54) were threatened species, and 4% (234) were endemic to the Atlantic Forest. Of the Atlantic Forest endemics, 11 species are restricted to the Bahia-Espírito Santo hot point, with 5 of these facing some level of threat (Table S1). The remaining 56% (3,071) were native species that were neither threatened nor endemic.

No significant correlations were identified among the predictor variables ($p > 0.73$). Productivity was the only variable that had a significant influence in any of the tested models, indicating the negative effect on taxonomic diversity ($\beta = -3.1426 \pm 0.881$ SE, $z = 3.567$, $p < 0.001$; Figure 2).

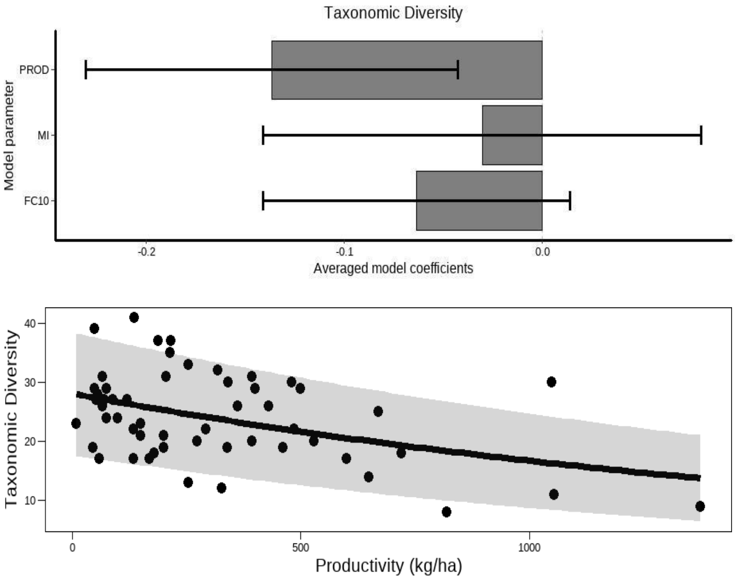


Figure 1. Impact of productivity, Management Index, and landscape forest cover on Taxonomic Diversity. The analysis of average models was performed considering all the models with values of ΔAICc ≤ 4. Graph of Taxonomic Diversity relationship with productivity.

According to the averaged model coefficients (ΔAICc ≤ 4), forest cover and management index did not affect tree community metrics.

3.2. Impacts Tree Community Metrics on Carbon Stock

We did not observe a significant impact on any of the tree community metrics variables on carbon stock. We estimated that the carbon stock comprised 20.4% exotic species, 4% species that are both threatened and endemic to the Atlantic Forest, 3.8% endemic species, 3.8% threatened species, and 67.9% other native species.

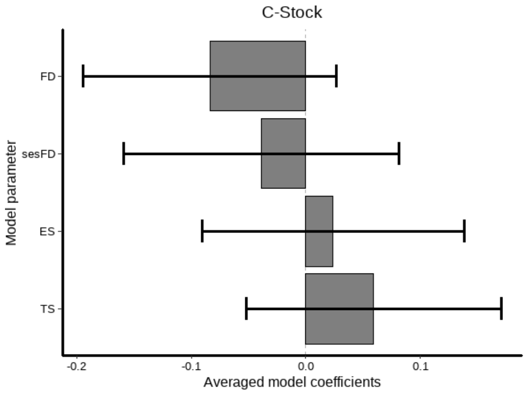


Figure 3. Averaged model coefficients for Carbon Stock and community tree metrics. The analysis of average models was performed considering all the models with values of ΔAICc ≤ 4. **FD** – Functional Diversity, **sesFD** – Standardized effect size Functional Diversity, **TS** - threatened species, and **ES** - endemic species

4. Discussion

Promoting a diverse canopy of shade trees is essential for enhancing the conservation value of cocoa plantations and their ecosystem services, such as soil enrichment, pollination, and pest control, thereby boosting agroforestry productivity (Maza-Villalobos et al., 2024). Strengthening payment-for-ecosystem services and certification schemes is crucial to incentivize smallholders to maintain non-cocoa tree cover, improving their economic potential and food security (Middendorp et al., 2018). Additionally, promoting climate-friendly intensification with technical assistance that integrates biodiversity-rich agroforests into incentive programs will reward environmental contributions and support landscape-level biomass and diversity (Chiapetti et al., 2020; Schroth et al., 2016).

Forest cover and management index did not show any influence on tree community metrics in our study. In contrast, productivity exhibited a significant negative impact on taxonomic diversity. It's noteworthy that one farm maintained high taxonomic diversity (~30 species of shade trees/ha) despite achieving productivity exceeding 1000 kg/ha. This suggests that the relationship between productivity and diversity may hinge on the specific types and quantities of management practices implemented.

Moreover, we observed an inverse correlation between productivity and the frequency of management practices, indicating a prevalent tendency among producers to reduce shade trees in pursuit of higher productivity. This highlights that high shading levels reflect poor farm management practices, which in turn lead to lower productivity. Thus, this study demonstrates the feasibility of simultaneously enhancing cocoa yields, conserving carbon stocks, and preserving tree diversity. It also underscores the necessity of an integrated planning framework to ensure the conservation of the most ecologically valuable forests.

Given the limited financial resources available to address climate change and biodiversity loss, it is imperative to identify actions that effectively tackle both issues simultaneously (Gilroy et al., 2014; Venter et al., 2009). However, if prioritization centers only on carbon sequestration potential, numerous areas vital for biodiversity would be overlooked (Ferreira et al., 2018; Phelps, Friess, et al., 2012; Reside et al., 2017). Although cabrucas play a crucial role as habitats for endemic and threatened tree species (Sambuichi et al., 2008), as well as storing significant amounts of aboveground carbon (Schroth et al., 2015), our analysis did not find any correlation between community tree diversity metrics and carbon storage. These findings suggest that while cabrucas are important for conserving native species and maintaining landscape ecosystem services, implementing carbon-based Payments for Ecosystem Services (PES) without considering biodiversity may fail to protect many threatened and endemic species.

Most threatened species have very restricted geographic distributions, with low frequency and density in the field. These results indicate that these species are not being effectively preserved in the cabrucas. Nonetheless, their presence in human-altered landscapes is crucial for conservation, increasing overall heterogeneity, and can serve as ecological corridors, additional habitats, and buffer zones (Sambuichi et al., 2008, 2012). If biodiversity is not incorporated into PES, threatened and endemic species that do not accumulate significant carbon may be displaced by species that are more effective at sequestering and storing carbon. It is crucial to incorporate both ecosystem services into policy frameworks to ensure benefits for both biodiversity and carbon conservation.

Studies consistently demonstrate that landowners significantly influence tree diversity in shade plantations (Sambuichi et al., 2012; Maza-Villalobos et al., 2024), highlighting the impact of their decisions on species composition. Promoting tree biodiversity could involve encouraging farmers to diversify shade tree species, particularly those with high conservation value. Strengthening policy frameworks to facilitate landowner participation in carbon storage projects that also benefit biodiversity, and ensuring additional gains in both carbon and biodiversity, is crucial (Reside et al., 2017). Prioritizing biodiversity in land-based carbon sequestration and storage efforts in this region promises significant benefits for both biodiversity conservation and carbon mitigation.

5. Conclusion

In the contexts where our findings are relevant, the metrics of tree diversity were not significantly influenced by productivity and management practices. This observation suggests a potential to cultivate a shade tree layer with high diversity. Such outcomes hold particular significance in the South Bahia region, renowned for its high levels of endemism and the threatened plant diversity characteristic of the Atlantic Forest biome. However, an exclusive focus on land prioritization based on carbon sequestration potential might lead to inadequate protection of numerous species within the most species-rich forests. The data indicate that increased carbon levels do not necessarily correspond with higher biodiversity. Consequently, biodiversity considerations must be integrated into carbon conservation strategies to ensure a more comprehensive and effective approach to conservation planning.

6. References

Addo-Danso, S. D., Asare, R., Tettey, A., Schmidt, J. E., Sauvadet, M., Coulis, M., Belliard, N., & Isaac, M. E. (2024). Shade tree functional traits drive critical ecosystem services in cocoa agroforestry systems. *Agriculture, Ecosystems and Environment*, *372*(May), 109090. https://doi.org/10.1016/j.agee.2024.109090

Ahenkorah, Y., Halm, B., Appiah, M., Akrofi, G., & Yirenkyi, J. (1987). TWENTY YEARS' RESULTS FROM A SHADE AND FERTILIZER TRIAL ON AMAZON COCOA {THEOBROMA CACAO) IN GHANA Cocoa Research Institute of Ghana (CRIG), PO Box 8 , New Tafo-Akim , Ghana (Accepted 27 March 1986) Following the success of the earlier Amelonado co. *Experimental Agriculture*, *23*, 31–39.

Andres, C., Comoé, H., Beerli, A., Schneider, M., Rist, S., & Jacobi, J. (2016). *Cocoa in Monoculture and Dynamic Agroforestry*. https://doi.org/10.1007/978-3-319-26777-7_3

Beer, J. (1987). Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. *Agroforestry Systems*, *5*(1), 3–13.

Bencke, A. G., Mauricio, G. ., Develey, P.F, & Goerck, J. G. (2006). Áreas Importantes para a Conservação das Aves no Brasil- estados do dominínio da Mata Atlântica. In *Bird Life Internacional*.

Blaser, W. J., Oppong, J., Hart, S. P., Landolt, J., Yeboah, E., & Six, J. (2018). Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nature Sustainability*, *1*(5), 234–239. https://doi.org/10.1038/s41893-018-0062-8

Cabala Rosand, P., de Santana, C. J. L., & de Miranda, E. R. (1976). Respuesta del cacaotero al abonamiento en el sur de Bahia, Brasil. *Boletim Técnico-Comissao Executiva Do Plano Da Lavoura Cacaueira (Brasil)(No. 43) 24 P.*

Cassano, C. R., Kierulff, M. C. M., & Chiarello, A. G. (2011). The cacao agroforests of the Brazilian Atlantic forest as habitat for the endangered maned sloth Bradypus torquatus. *Mammalian Biology*, *76*(3), 243–250.

Cassano, C. R., Schroth, G., Faria, D., Delabie, J. H. C., & Bede, L. (2009). Landscape and farm scale management to enhance biodiversity conservation in the cocoa producing region of southern Bahia, Brazil. *Biodiversity and Conservation*, *18*(3), 577–603. https://doi.org/10.1007/s10531-008-9526-x

Chiapetti, J., Rocha, R. B. da, Conceição, A. S. da, & Baiardi, A. (2020). Panorama da Cacauicultura no Território Litoral Sul da Bahia (2015-2019). *Revelando Desafios e Oportunidades Sociais, Econômicas, e Ecológicas Para Restauração de Florestas Em Propriedades Rurais Na Mata Atlântica Do Sul Da Bahia*, 1–110. https://www.worldcocoafoundation.org/wp-content/uploads/2020/05/Panorama-da-cacauicultura-TILSB-Versao-final-Web.pdf

Clough, Y., Dwi Putra, D., Pitopang, R., & Tscharntke, T. (2009). Local and landscape factors determine functional bird diversity in Indonesian cacao agroforestry. *Biological Conservation*, *142*(5), 1032–1041. https://doi.org/https://doi.org/10.1016/j.biocon.2008.12.027

Clough, Y., Faust, H., & Tscharntke, T. (2009). Cacao boom and bust: sustainability of agroforests and opportunities for biodiversity conservation. *Conservation Letters*, *2*(5), 197–205. https://doi.org/10.1111/j.1755-263x.2009.00072.x

Delabie, J. H. C., Jahyny, B., Do Nascimento, I. C., Mariano, C. S. F., Lacau, S., Campiolo, S., Philpott, S. M., & Leponce, M. (2007). Contribution of cocoa plantations to the conservation of native ants (Insecta: Hymenoptera: Formicidae) with a special emphasis on the Atlantic Forest fauna of southern Bahia, Brazil. *Biodiversity and Conservation*, *16*(8), 2359–2384. https://doi.org/10.1007/s10531-007-9190-6

FAOSTAT. (2022). *No Title*. Production; Cocoa, Beans; West Africa; South America;Centre Amrica; Asia.

Faria, D., & Baumgarten, J. (2007). Shade cacao plantations (Theobroma cacao) and bat conservation in southern Bahia, Brazil. *Biodiversity and Conservation*, *16*(2), 291–312. https://doi.org/10.1007/s10531-005-8346-5

Faria, D., Laps, R. R., Baumgarten, J., & Cetra, M. (2006). Bat and bird assemblages from forests and shade cacao plantations in two contrasting landscapes in the Atlantic Forest of southern Bahia, Brazil. *Biodiversity and Conservation*, *15*(2), 587–612. https://doi.org/10.1007/s10531-005-2089-1

Ferreira, J., Lennox, G. D., Gardner, T. A., Thomson, J. R., Berenguer, E., Lees, A. C., Mac Nally, R., Aragão, L. E. O. C., Ferraz, S. F. B., Louzada, J., Moura, N. G., Oliveira, V. H. F., Pardini, R., Solar, R. R. C., Vieira, I. C. G., & Barlow, J. (2018). Carbon-focused conservation may fail to protect the most biodiverse tropical forests. *Nature Climate Change*, *8*(8), 744–749. https://doi.org/10.1038/s41558-018-0225-7

Filho, H. R. S., Bezerra, M. de A., Jesus, R. M. de, & Chiapetti, J. (2023). *Cocoa Production and Distribution in Bahia (Brazil) after the Witch's Broom* (S. O. Agele & O. S. Ibiremo (eds.); p. Ch. 4). IntechOpen. https://doi.org/10.5772/intechopen.112199

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570–574. https://doi.org/10.1126/science.1111772

Gilroy, J. J., Woodcock, P., Edwards, F. A., Wheeler, C., Baptiste, B. L. G., Medina Uribe, C. A., Haugaasen, T., & Edwards, D. P. (2014). Cheap carbon and biodiversity co-benefits from forest regeneration in a hotspot of endemism. *Nature Climate Change*, *4*(6), 503–507. https://doi.org/10.1038/nclimate2200

Girardello, M., Santangeli, A., Mori, E., Chapman, A., Fattorini, S., Naidoo, R., Bertolino, S., & Svenning, J. C. (2019). Global synergies and trade-offs between multiple dimensions of biodiversity and ecosystem services. *Scientific Reports*, *9*(1), 1–8. https://doi.org/10.1038/s41598-019-41342-7

Goetsch, E. (1992). *Natural Succession of Species in Agroforestry and in Soil Recovery*. 1–19.

Götsch, E. (1994). Break-Through in Agriculture. *Analysis*, 1–15.

Götsch, E. (1997). *Homem e natureza-cultura e sociedade.pdf*. 12.

IBGE. (2019). Censo agropecuário 2017: resultados definitivos. *Censo Agropecuário*, *8*, 1–105.

IPCC. (2014). Climate Change 2014 Part A: Global and Sectoral Aspects. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change. papers2://publication/uuid/B8BF5043-C873-4AFD-97F9-A630782E590D

Jacobi, J., Andres, C., Schneider, M., Pillco, M., Calizaya, P., & Rist, S. (2014). Carbon stocks, tree diversity, and the role of organic certification in different cocoa production systems in Alto Beni, Bolivia. *Agroforestry Systems*, *88*(6), 1117–1132. https://doi.org/10.1007/s10457-013-9643-8

Jacobi, J., Schneider, M., Bottazzi, P., Pillco, M., Calizaya, P., & Rist, S. (2015). Agroecosystem resilience and farmers' perceptions of climate change impacts on cocoa farms in Alto Beni, Bolivia. *Renewable Agriculture and Food Systems*, *30*(2), 170–183. https://doi.org/10.1017/S174217051300029X

Johns, N. D. (1998). Conservation in Brazil's chocolate forest: The unlikely persistence of the traditional cocoa agroecosystem. *Environmental Management*, *23*(1), 31–47. https://doi.org/10.1007/s002679900166

Koog, I. (2020). Biophysical state of cocoa dynamic agroforestry systems in Ghana: a chronosequence. In *Master thesis* (Issue march). ETH Zurich.

Lacau, S., Villemant, C., & Delabie, J. H. C. (2004). Typhlomyrmex meire, a remarkable new species endemic to Southern Bahia, Brazil (Formicidae: Ectatomminae). *Zootaxa*, *678*(1), 1. https://doi.org/10.11646/zootaxa678.1.1

Läderach, P., Martinez-Valle, A., Schroth, G., & Castro, N. (2013). Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. *Climatic Change*, *119*(3–4), 841–854. https://doi.org/10.1007/s10584-013-0774-8

Magnago, L. F. S., Magrach, A., Laurance, W. F., Martins, S. V., Meira-Neto, J. A. A., Simonelli, M., & Edwards, D. P. (2015). Would protecting tropical forest fragments provide carbon and biodiversity cobenefits under REDD+? *Global Change Biology*, *21*(9), 3455–3468. https://doi.org/10.1111/gcb.12937

Martini, A. M. Z., Fiaschi, P., Amorim, A. M., Paixão, J. L. Da, & Da Paixão, J. L. (2007). A hot-point within a hot-spot: a high diversity site in Brazil's Atlantic Forest. *Biodiversity and Conservation*, *16*(11), 3111–3128. https://doi.org/10.1007/s10531-007-9166-6

Matos, F. A. R., Magnago, L. F. S., Aquila Chan Miranda, C., de Menezes, L. F. T., Gastauer, M., Safar, N. V. H., Schaefer, C. E. G. R., da Silva, M. P., Simonelli, M., Edwards, F. A., Martins, S. V., Meira-Neto, J. A. A., & Edwards, D. P. (2020). Secondary forest fragments offer important carbon and biodiversity cobenefits. *Global Change Biology*, *26*(2), 509–522. https://doi.org/10.1111/gcb.14824

Maza-Villalobos, S., Nicasio-Arzeta, S., Benitez-Malvido, J., Ramírez-Marcial, N., Alvarado-Sosa, E., & Rincón-Arreola, D. (2024). Effect of land-use history on tree taxonomic and functional diversity in cocoa agroforestry plantations. *Agriculture, Ecosystems and Environment*, *367*(May 2024). https://doi.org/10.1016/j.agee.2024.108952

Michon, G., & de Foresta, H. (1996). Agroforests as an alternative to pure plantations for the domestication and commercialization of NTFPs. *Domestication and Commercialization of Non-Timber Forest Products in Agroforestry Systems, Non-Wood Forest Products*, *9*, 160–175.

Middendorp, R. S., Vanacker, V., & Lambin, E. F. (2018). Impacts of shaded agroforestry management on carbon sequestration, biodiversity and farmers income in cocoa production landscapes. *Landscape Ecology*, *33*(11), 1953–1974.

https://doi.org/10.1007/s10980-018-0714-0

Mortimer, R., Saj, S., & David, C. (2018). Supporting and regulating ecosystem services in cacao agroforestry systems. *Agroforestry Systems*, *92*(6), 1639–1657. https://doi.org/10.1007/s10457-017-0113-6

Naoki, K., Isabel Gómez, M., & Schneider, M. (2017). *Selection of different cacao (Theobroma cacao, Malvaceae) production systems by birds in Alto Beni, Bolivia - a cafeteria experiment in the field*. *52*(2), 100–115.

Niether, W., Armengot, L., Andres, C., Schneider, M., & Gerold, G. (2018). Shade trees and tree pruning alter throughfall and microclimate in cocoa (Theobroma cacao L.) production systems. *Annals of Forest Science*, *75*(2). https://doi.org/10.1007/s13595-018-0723-9

Niether, W., Jacobi, J., Blaser, W. J., Andres, C., & Armengot, L. (2020). Cocoa agroforestry systems versus monocultures: A multi-dimensional meta-analysis. *Environmental Research Letters*, *15*(10). https://doi.org/10.1088/1748-9326/abb053

Niether, W., Schneidewind, U., Armengot, L., Adamtey, N., Schneider, M., & Gerold, G. (2017). Spatial-temporal soil moisture dynamics under different cocoa production systems. *Catena*, *158*(July), 340–349. https://doi.org/10.1016/j.catena.2017.07.011

Niether, W., Schneidewind, U., Fuchs, M., Schneider, M., & Armengot, L. (2019). Below- and aboveground production in cocoa monocultures and agroforestry systems. *Science of the Total Environment*, *657*, 558–567. https://doi.org/10.1016/j.scitotenv.2018.12.050

Niether, W., Smit, I., Armengot, L., Schneider, M., Gerold, G., & Pawelzik, E. (2017). Environmental Growing Conditions in Five Production Systems Induce Stress Response and Affect Chemical Composition of Cocoa (Theobroma cacao L.) Beans. *Journal of Agricultural and Food Chemistry*, *65*(47), 10165–10173. https://doi.org/10.1021/acs.jafc.7b04490

Pardini, R., Faria, D., Accacio, G. M., Laps, R. R., Mariano-Neto, E., Paciencia, M. L. B., Dixo, M., & Baumgarten, J. (2009). The challenge of maintaining Atlantic forest biodiversity: A multi-taxa conservation assessment of specialist and generalist species in an agro-forestry mosaic in southern Bahia. *Biological Conservation*, *142*(6), 1178–1190. https://doi.org/10.1016/j.biocon.2009.02.010

Pavoine, S., & Bonsall, M. B. (2011). Measuring biodiversity to explain community assembly: A unified approach. *Biological Reviews*, *86*(4), 792–812. https://doi.org/10.1111/j.1469-185X.2010.00171.x

Peneireiro, F. M. (1999). *<Tese_Fabiana_Peneireiro.Pdf>*.

Petchey, O. L., & Gaston, K. J. (2002). Functional diversity (FD), species richness and community composition. *Ecology Letters*, *5*(3), 402–411. https://doi.org/10.1046/j.1461-0248.2002.00339.x

Phelps, J., Friess, D. A., & Webb, E. L. (2012). Win-win REDD+ approaches belie carbon-biodiversity trade-offs. *Biological Conservation*, *154*, 53–60. https://doi.org/10.1016/j.biocon.2011.12.031

Phelps, J., Webb, E. L., & Adams, W. M. (2012). Biodiversity co-benefits of policies to reduce forest-carbon emissions. *Nature Climate Change*, *2*(7), 497–503. https://doi.org/10.1038/nclimate1462

Raboy, B. E., Christman, M. C., & Dietz, J. M. (2004). The use of degraded and shade cocoa forests by Endangered golden-headed lion tamarins Leontopithecus chrysomelas. *Oryx*, *38*(1), 75–83. https://doi.org/10.1017/S0030605304000122

Reside, A. E., Vanderwal, J., & Moran, C. (2017). Trade-offs in carbon storage and biodiversity conservation under climate change reveal risk to endemic species. *Biological Conservation*, *207*, 9–16. https://doi.org/10.1016/j.biocon.2017.01.004

Rice, R. A., & Greenberg, R. (2000). Cacao cultivation and the conservation of biological diversity. *Ambio*, *29*(3), 167–173. https://doi.org/10.1579/0044-7447-29.3.167

Rivero, G., & Mérida, A. (2009). Producción de biomasa y nutrientes que genera la poda en sistemas agroforestales sucesionales y tradicionales con cacao, Alto Beni, Bolivia. *ACTA NOVA (Número Especial: 1er*, *4*(2–3), 263–280. http://www.censalud.ues.edu.sv/CDOC-Deployment/documentos/Producción_de_biomasa_y_nutrientes_que_genera_poda_en_sistemas.....pdf

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*(1), 4–17. https://doi.org/10.1007/s13280-016-0793-6

Ruf, F. O., & Schroth, G. (2004). Chocolate forests and monocultures: A historical review of cocoa growing and its conflicting role in tropical deforestation and forest conservation. *Agroforestry and Biodiversity Conservation in Tropical Landscapes*, *06*, 107–134.

Sambuichi, R. H. R., De Oliveira, R. M., Neto, E. M., Thévenin, J. M. R., De Jesus, C. P., De Oliveira, R. L., & Pelição, M. C. (2008). Conservation status of ten endemic trees from the Atlantic Forest in the south of Bahia - Brazil. *Natureza a Conservacao*, *6*(1), 208–225.

Sambuichi, R. H. R., Vidal, D. B., Piasentin, F. B., Jardim, J. G., Viana, T. G., Menezes, A. A., Mello, D. L. N., Ahnert, D., & Baligar, V. C. (2012). Cabruca agroforests in southern Bahia, Brazil: Tree component, management practices and tree species conservation. *Biodiversity and Conservation*, *21*(4), 1055–1077. https://doi.org/10.1007/s10531-012-0240-3

Sanial, E., Ruf, F., Louppe, D., Mietton, M., & Hérault, B. (2023). Local farmers shape ecosystem service provisioning in West African cocoa agroforests. *Agroforestry Systems*, *97*(3), 401–414. https://doi.org/10.1007/s10457-021-00723-6

Schneider, M., Andres, C., Trujillo, G., Alcon, F., Amurrio, P., Perez, E., Weibel, F., & Milz, J. (2017). COCOA and TOTAL SYSTEM YIELDS of ORGANIC and CONVENTIONAL AGROFORESTRY VS. MONOCULTURE SYSTEMS in A LONG-TERM FIELD TRIAL in BOLIVIA. *Experimental Agriculture*, *53*(3), 351–374. https://doi.org/10.1017/S0014479716000417

Schroth, G., Bede, L. C., Paiva, A. O., Cassano, C. R., Amorim, A. M., Faria, D., Mariano-Neto, E., Martini, A. M. Z., Sambuichi, R. H. R., & Lôbo, R. N. (2015). Contribution of agroforests to landscape carbon storage. *Mitigation and Adaptation Strategies for Global Change*, *20*(7), 1175–1190. https://doi.org/10.1007/s11027-013-9530-7

Schroth, G., Faria, D., Araujo, M., Bede, L., van Bael, S. A., Cassano, C. R., Oliveira, L. C., & Delabie, J. H. C. (2011). Conservation in tropical landscape mosaics: The case of the cacao landscape of southern Bahia, Brazil. *Biodiversity and Conservation*, *20*(8), 1635–1654. https://doi.org/10.1007/s10531-011-0052-x

Schroth, G., & Harvey, C. A. (2007). Biodiversity conservation in cocoa production landscapes: An overview. *Biodiversity and Conservation*, *16*(8), 2237–2244. https://doi.org/10.1007/s10531-007-9195-1

Schroth, G., Izac, A.-M. N., Vasconcelos, H. L., Gascon, C., da Fonseca, G. A. B., & Harvey, C. A. (2004). *Agroforestry and biodiversity conservation in tropical landscapes*. Island Press.

Schroth, G., Jeusset, A., Gomes, A. da S., Florence, C. T., Coelho, N. A. P., Faria, D., & Läderach, P. (2016). Climate friendliness of cocoa agroforests is compatible with productivity increase. *Mitigation and Adaptation Strategies for Global Change*, *21*(1), 67–80. https://doi.org/10.1007/s11027-014-9570-7

Schulz, B., Becker, B., & Götsch, E. (1994). Indigenous knowledge in a “modern” sustainable agroforestry system-a case study from eastern Brazil. *Agroforestry Systems*, *25*(1), 59–69. https://doi.org/10.1007/BF00705706

Schulz, J. (2011). Agroforestry as a tool for landscape restoration. In *Agroforestry as a tool for landscape restoration* (p. 201).

Schulz, J. J., & Weckenbrock, P. (2016). *Complex Agroforestry Systems for Europe : Inspiration From Successional Agroforestry*. *1*, 2016. https://doi.org/10.13140/RG.2.2.25747.32808

Street, B., & Legon, E. (2014). *Cocoa Market Update*. *4*, 1–11.

Swenson, N. G. (2014). Functional and Phylogenetic Ecology in R. In *Use R!*

Tancara, A. L. A. (2014). *Efecto de la poda y raleo se árboles, en un sustema agrofroestal sucesionalen la producción de cacao (Theobroma cacao), del alto Beni*.

Thomas, W. M. W., Carvalho, A. M. V. D. E., Amorim, A. M. A., Garrison, J., Arbela´ez, & L, A. (1998). Plant endemism in two forests in southern Bahia, Brazil. *Biodiversity & Conservation*, *7*(3), 311–322. https://doi.org/10.1023/A:1008825627656

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260–20264.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*(6898), 671–677.

Tscharntke, T., Clough, Y., Bhagwat, S. A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., & Wanger, T. C. (2011). Multifunctional shade-tree management in tropical agroforestry landscapes - A review. *Journal of Applied Ecology*, *48*(3), 619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x

Venter, O., Laurance, W. F., Iwamura, T., Wilson, K. A., Fuller, R. A., & Possingham, H. P. (2009). Harnessing carbon payments to protect biodiversity. *Science*, *326*(5958), 1368. https://doi.org/10.1126/science.1180289

Young, K. J. (2017a). *Mimicking Nature: A Review of Successional Agroforestry Systems as an Analogue to Natural Regeneration of Secondary Forest Stands* (Issue January 2017). https://doi.org/10.1007/978-3-319-69371-2_8

Young, K. J. (2017b). *Mimicking Nature: A Review of Successional Agroforestry Systems as an Analogue to Natural Regeneration of Secondary Forest Stands* (Issue January). https://doi.org/10.1007/978-3-319-69371-2_8

Supplementary Material

Table S1. List of species collected in the 54 cabrucas sampled in the southern region of Bahia. **DP** – Dispersion Syndrome – (1) zoochoric or (2) non-zoochoric dispersion; **FT** – Fruit Type – (1) fleshy or (2) non-fleshy fruits; **WD** – Wood Density; **END** – Endemic species – (1) endemic species from the Atlantic Forest, (2) endemic species from Bahia and Espirito Santo States or (0) non-endemic species; **THR** – Threatened species – (1) for species classified as CR (critically endangered), VU (vulnerable), or EN (endangered) according to the Ministry of the Environment, and (0) for not threatened species; **CLASS** – species establishment classified as native for Atlantic Forest species or exotic for species that do not occur naturally in this biome.

Family	Species	DS	FT	WD	END	THR	CLASS
Santalaceae	*Acanthosyris paulo-alvinii*	1	1	0.62275	2	1	native
Lamiaceae	*Aegiphila integrifolia*	1	1	0.86	0	0	native
Fabaceae	*Albizia pedicellaris*	2	2	0.5563	0	0	native
Fabaceae	*Albizia polycephala*	2	2	0.5563	0	0	native
Euphorbiaceae	*Alchornea glandulosa*	1	1	0.378	0	0	native
Euphorbiaceae	*Alchornea triplinervia*	1	1	0.4667	0	0	native
Arecaceae	*Allagoptera caudescens*	1	1	0.5153	1	0	native
Phyllanthaceae	*Amanoa guianensis*	2	2	0.843	0	0	native
Anacardiaceae	*Anacardium occidentale*	1	2	0.4465	0	0	native
Fabaceae	*Andira fraxinifolia*	1	1	0.92	0	0	native
Fabaceae	*Andira vermifuga*	1	1	0.7739	0	0	native
Lauraceae	*Aniba intermedia*	1	1	0.5908	0	0	native
Annonaceae	*Annona dolabripetala*	1	1	0.5188	1	0	native
Annonaceae	*Annona mucosa*	1	1	0.5188	0	0	native
Annonaceae	*Annona muricata*	1	1	0.36	0	0	exotic
Euphorbiaceae	*Aparisthmium cordatum*	1	1	0.39	0	0	native
Malvaceae	*Apeiba tibourbou*	2	2	0.2	0	0	native
Fabaceae	*Arapatiella psilophylla*	1	2	0.5153	2	1	native
Moraceae	*Artocarpus altilis*	1	1	0.4325	0	0	exotic
Moraceae	*Artocarpus heterophyllus*	1	1	0.4917	0	0	exotic
Anacardiaceae	*Astronium fraxinifolium*	1	1	0.85	0	0	native
Arecaceae	*Attalea burretiana*	1	1	0.326	2	0	native
Oxalidaceae	*Averrhoa carambola*	1	1	0.5768	0	0	exotic
Fabaceae	*Bauhinia forficata*	2	2	0.7553	0	0	native
Fabaceae	*Bowdichia virgilioides*	2	2	0.91	0	0	native
Moraceae	*Brosimum gaudichaudii*	1	1	0.64	0	0	native
Moraceae	*Brosimum guianense*	1	1	0.5153	0	0	native
Malpighiaceae	*Byrsonima sericea*	1	1	0.78	0	0	native
Myrtaceae	*Campomanesia guaviroba*	1	1	0.8174	0	0	native
Myrtaceae	*Campomanesia viatoris*	1	1	0.5153	0	0	native
Caricaceae	*Carica papaya*	1	1	0.1875	0	0	exotic
Lecythidaceae	*Cariniana estrellensis*	2	2	0.6367	0	0	native
Lecythidaceae	*Cariniana legalis*	2	2	0.495	1	1	native
Salicaceae	*Casearia javitensis*	1	2	0.753	0	0	native
Salicaceae	*Casearia sylvestris*	1	2	0.705	0	0	native
Urticaceae	*Cecropia pachystachya*	1	2	0.41	0	0	native
Meliaceae	*Cedrela fissilis*	2	2	0.4666	0	1	native
Fabaceae	*Centrolobium tomentosum*	2	2	0.665	0	0	native

Solanaceae	*Cestrum intermedium*	1	1	0.5153	1	0	native
Fabaceae	*Chamaecrista duartei*	2	2	0.9035	2	0	native
Sapotaceae	*Chrysophyllum splendens*	1	1	0.5153	1	0	native
Verbenaceae	*Citharexylum myrianthum*	1	1	0.66675	0	0	native
Clusiaceae	*Clusia nemorosa*	1	2	0.6764	0	0	native
Euphorbiaceae	*Cnidoscolus oligandrus*	1	1	0.4267	0	0	native
Arecaceae	*Cocos nucifera*	2	2	0.5153	0	0	exotic
Fabaceae	*Copaifera langsdorffii*	1	2	0.65	0	0	native
Fabaceae	*Copaifera lucens*	1	2	0.6083	1	0	native
Boraginaceae	*Cordia ecalyculata*	1	1	1.076	0	0	native
Boraginaceae	*Cordia glabrifolia*	1	1	0.5425	2	0	native
Urticaceae	*Coussapoa microcarpa*	1	1	0.59	0	0	native
Euphorbiaceae	*Croton sapiifolius*	1	1	0.5104	2	1	native
Euphorbiaceae	*Croton sellowii*	1	1	0.5104	1	0	native
Euphorbiaceae	*Croton urucurana*	1	1	0.528	0	0	native
Sapindaceae	*Cupania impressinervia*	1	1	0.6084	1	0	native
Fabaceae	*Dalbergia nigra*	2	2	0.8124	1	1	native
Fabaceae	*Delonix regia*	2	2	0.57875	0	0	exotic
Fabaceae	*Dialium guianense*	1	1	0.8124	0	0	native
Rutaceae	*Dictyoloma vandellianum*	2	2	0.5153	0	0	native
Araliaceae	*Didymopanax morototoni*	1	1	0.575	0	0	native
Ebenaceae	*Diospyros lasiocalyx*	1	1	0.6833	0	0	native
Fabaceae	*Diplotropis incexis*	2	2	0.6976	1	0	native
Arecaceae	*Elaeis guineensis*	1	1	0.5153	0	0	exotic
Malvaceae	*Eriotheca globosa*	2	2	0.41	0	0	native
Malvaceae	*Eriotheca macrophylla*	2	2	0.4376	1	0	native
Fabaceae	*Erythrina poeppigiana*	1	2	0.305	0	0	exotic
Fabaceae	*Erythrina speciosa*	1	2	0.289	0	0	exotic
Lecythidaceae	*Eschweilera ovata*	1	2	0.9	0	0	native
Myrtaceae	*Eugenia involucrata*	1	1	0.7228	0	0	native
Myrtaceae	*Eugenia uniflora*	1	1	0.8285	0	0	native
Arecaceae	*Euterpe edulis*	1	1	0.3877	0	1	native
Arecaceae	*Euterpe oleracea*	1	1	0.3877	0	0	exotic
Moraceae	*Ficus bahiensis*	1	1	0.4055	0	0	native
Moraceae	*Ficus broadwayi*	1	1	0.4055	0	0	native
Moraceae	*Ficus clusiifolia*	1	1	0.4055	0	0	native
Moraceae	*Ficus eximia*	1	1	0.455	0	0	native
Moraceae	*Ficus gomelleira*	1	1	0.4055	0	0	native
Moraceae	*Ficus mariae*	1	1	0.4055	1	0	native
Moraceae	*Ficus nymphaeifolia*	1	1	0.415	0	0	native
Moraceae	*Ficus pulchella*	1	1	0.4055	0	0	native
Moraceae	*Ficus trigona*	1	1	0.4055	0	0	native
Phytolaccaceae	*Gallesia integrifolia*	2	2	0.51	0	0	native
Rubiaceace	*Genipa americana*	1	1	0.6338	0	0	native
Fabaceae	*Gliricidia sepium*	2	2	0.6175	0	0	exotic
Nyctaginaceae	*Guapira opposita*	1	2	0.83	0	0	native
Meliaceae	*Guarea guidonia*	1	2	0.5651	0	0	native
Bignoniaceae	*Handroanthus chrysotrichus*	2	2	0.5153	0	0	native

Bignoniaceae	*Handroanthus impetiginosus*	2	2	0.5153	0	0	native
Bignoniaceae	*Handroanthus serratifolius*	2	2	0.5153	0	0	native
Moraceae	*Helicostylis tomentosa*	1	1	0.6147	0	0	native
Melastomaceae	*Henriettea succosa*	1	1	0.69	0	0	native
Euphorbiaceae	*Hevea brasiliensis*	2	2	0.46625	0	0	exotic
Apocynaceae	*Himatanthus bracteatus*	2	2	0.53	1	0	native
Malvaceae	*Hydrogaster trinervis*	1	1	0.63	2	0	native
Phyllanthaceae	*Hyeronima alchorneoides*	1	1	0.5153	0	0	native
Fabaceae	*Inga edulis*	1	2	0.5874	0	0	native
Fabaceae	*Inga laurina*	1	2	0.665	0	0	native
Bignoniaceae	*Jacaranda macrantha*	2	2	0.4725	0	0	native
Bignoniaceae	*Jacaranda obovata*	2	2	0.4725	0	0	native
Bignoniaceae	*Jacaranda puberula*	2	2	0.58	0	0	native
Caricaceae	*Jacaratia heptaphylla*	1	1	0.265	1	0	native
Caricaceae	*Jacaratia spinosa*	1	1	0.265	0	0	native
Euphorbiaceae	*Joannesia princeps*	1	1	0.5107	0	0	native
Meliaceae	*Khaya grandifoliola*	2	2	0.5342	0	0	exotic
Apocynaceae	*Lacmellea aculeata*	2	2	0.5131	0	0	native
Lythracea	*Lafoensia pacari*	2	2	0.8	0	0	native
Lecythidaceae	*Lecythis lurida*	1	2	0.8633	0	0	native
Lecythidaceae	*Lecythis pisonis*	1	2	0.857	0	0	native
Lauraceae	*Licaria bahiana*	1	1	0.7868	1	0	native
Fabaceae	*Lonchocarpus cultratus*	2	2	0.761	0	0	native
Malvaceae	*Luehea divaricata*	2	2	0.563	0	0	native
Moraceae	*Maclura tinctoria*	1	2	0.7945	0	0	native
Fabaceae	*Macrolobium latifolium*	1	1	0.5153	1	0	native
Anacardiaceae	*Mangifera indica*	1	1	0.5525	0	0	exotic
Sapotaceae	*Manilkara salzmannii*	1	1	1.03	0	0	native
Phyllanthaceae	*Margaritaria nobilis*	1	2	0.6223	0	0	native
Fabaceae	*Melanoxylon brauna*	2	2	1.038	0	1	native
Melastomaceae	*Miconia ligustroides*	1	1	0.6292	0	0	native
Melastomaceae	*Miconia mirabilis*	1	1	0.603	0	0	native
Melastomaceae	*Miconia prasina*	1	1	0.705	0	0	native
Fabaceae	*Mimosa schomburgkii*	2	2	0.8409	0	0	native
Fabaceae	*Moldenhawera blanchetiana*	2	2	0.81	2	1	native
Chrysobalanaceae	*Moquilea tomentosa*	1	1	0.5153	1	0	native
Myrtaceae	*Myrcia splendens*	1	1	0.8	0	0	native
Primulaceae	*Myrsine coriacea*	1	1	0.647	0	0	native
Lauraceae	*Nectandra cissiflora*	1	1	0.59	0	0	native
Lauraceae	*Nectandra globosa*	1	1	0.39	0	0	native
Lauraceae	*Nectandra membranacea*	1	1	0.5625	0	0	native
Lauraceae	*Nectandra puberula*	1	1	0.5625	0	0	native
Sapindaceae	*Nephelium lappaceum*	1	1	0.7102	0	0	exotic
Lauraceae	*Ocotea canaliculata*	1	1	0.4793	0	0	native
Lauraceae	*Ocotea puberula*	1	1	0.4325	0	0	native
Peraceae	*Pera glabrata*	1	2	0.67	0	0	native
Lauraceae	*Persea americana*	1	1	0.5487	0	0	exotic
Fabaceae	*Piptadenia adiantoides*	2	2	0.799	0	0	native

Fabaceae	*Piptadenia gonoacantha*	2	2	0.799	0	0	native
Fabaceae	*Piptadenia paniculata*	2	2	0.799	0	0	native
Fabaceae	*Plathymenia reticulata*	2	2	0.4967	0	0	native
Melastomaceae	*Pleroma elegans*	2	2	0.5153	1	1	native
Melastomaceae	*Pleroma mutabile*	2	2	0.5153	0	0	native
Myrtaceae	*Plinia peruviana*	1	1	0.95	1	0	native
Fabaceae	*Poecilanthe ulei*	2	2	0.805	0	0	native
Sapotaceae	*Pouteria bangii*	1	1	0.6907	0	0	native
Sapotaceae	*Pouteria durlandii*	1	1	0.6907	0	0	native
Sapotaceae	*Pouteria oxypetala*	1	1	0.6907	1	0	native
Sapotaceae	*Pouteria procera*	1	1	0.6907	0	0	native
Burseraceae	*Protium heptaphyllum*	1	1	0.6907	0	0	native
Myrtaceae	*Psidium guajava*	1	1	0.5153	0	0	exotic
Rubiaceace	*Psychotria pedunculosa*	1	1	0.652	0	0	native
Fabaceae	*Pterocarpus rohrii*	2	2	0.4558	0	0	native
Fabaceae	*Pterodon emarginatus*	2	2	0.91	0	0	native
Euphorbiaceae	*Sapium glandulosum*	1	1	0.4152	0	0	native
Anacardiaceae	*Schinus terebinthifolia*	1	1	0.5153	0	0	native
Fabaceae	*Schizolobium parahyba*	2	2	0.3465	0	0	native
Fabaceae	*Senna macranthera*	1	2	0.6029	0	0	native
Fabaceae	*Senna multijuga*	2	2	0.5153	0	0	native
Simaroubaceae	*Simarouba amara*	1	1	0.3833	0	0	native
Simaroubaceae	*Simarouba versicolor*	1	1	0.5153	0	0	native
Elaeocarpaceae	*Sloanea garckeana*	1	2	0.6095	0	0	native
Elaeocarpaceae	*Sloanea guianensis*	1	2	0.8212	0	0	native
Elaeocarpaceae	*Sloanea obtusifolia*	1	2	0.6095	1	1	native
Solanaceae	*Solanum mauritianum*	1	1	0.5153	0	0	native
Solanaceae	*Solanum swartzianum*	1	1	0.4119	0	0	native
Anacardiaceae	*Spondias macrocarpa*	1	1	0.3526	1	0	native
Anacardiaceae	*Spondias mombin*	1	1	0.3914	0	0	native
Anacardiaceae	*Spondias purpurea*	1	1	0.33	0	0	exotic
Malvaceae	*Sterculia excelsa*	1	2	0.51	0	0	native
Loganiaceae	*Strychnos erichsonii*	1	2	0.5153	0	0	native
Fabaceae	*Stryphnodendron adstringens*	1	2	1.19	0	0	native
Fabaceae	*Swartzia macrostachya*	1	2	0.92	0	0	native
Fabaceae	*Swartzia micrantha*	1	2	0.8486	2	1	native
Fabaceae	*Swartzia riedelii*	1	2	0.8486	2	1	native
Clusiaceae	*Symphonia globulifera*	1	1	0.6727	0	0	native
Myrtaceae	*Syzygium aromaticum*	1	1	0.6644	0	0	exotic
Myrtaceae	*Syzygium cumini*	1	1	0.6727	0	0	exotic
Myrtaceae	*Syzygium jambos*	1	1	0.7	0	0	exotic
Bignoniaceae	*Tabebuia elliptica*	2	2	0.7623	0	0	native
Apocynaceae	*Tabernaemontana salzmannii*	1	2	0.5261	0	0	native
Anacardiaceae	*Tapirira guianensis*	1	1	0.457	0	0	native
Combretaceae	*Terminalia catappa*	2	2	0.5153	0	0	native
Combretaceae	*Terminalia dichotoma*	2	2	0.7077	0	0	native
Combretaceae	*Terminalia glabrescens*	2	2	0.6305	0	0	native
Combretaceae	*Terminalia hoehneana*	2	2	0.6305	0	0	native

Combretaceae	*Terminalia mameluco*	2	2	0.6305	0	0	native
Euphorbiaceae	*Tetrorchidium rubrivenium*	1	2	0.4545	0	0	native
Malvaceae	*Theobroma grandiflorum*	1	1	0.5316	0	0	exotic
Cannabaceae	*Trema micrantha*	1	1	0.319	0	0	native
Fabaceae	*Vatairea heteroptera*	2	2	0.6727	1	0	native
Fabaceae	*Vatairea macrocarpa*	2	2	0.785	0	0	native
Myristicaceae	*Virola officinalis*	1	2	0.4838	1	0	native
Hypericaceae	*Vismia atlantica*	1	1	0.4931	2	0	native
Rutaceae	*Zanthoxylum rhoifolium*	1	2	0.56925	0	0	native
Anacardiaceae	*Anacardiaceae sp1*	NA	NA	0.515793	NA	NA	native
Anacardiaceae	*Astronium sp.*	NA	NA	0.8727	NA	NA	native
Annonaceae	*Annona sp.*	NA	NA	0.51877	NA	NA	native
Annonaceae	*Annonaceae sp1*	NA	NA	0.51579	NA	NA	native
Annonaceae	*Annonaceae sp2*	NA	NA	0.51579	NA	NA	native
Annonaceae	*Guatteria sp.*	NA	NA	0.57709	NA	NA	native
Araliaceae	*Oreopanax sp*	NA	NA	0.52	NA	NA	native
Asteraceae	*Vernonanthura sp.*	NA	NA	0.54	NA	NA	native
Bignoniaceae	*Bignoniaceae sp1*	NA	NA	0.51579	NA	NA	native
Bignoniaceae	*Bignoniaceae sp2*	NA	NA	0.51579	NA	NA	native
Bignoniaceae	*Bignoniaceae sp4*	NA	NA	0.51579	NA	NA	native
Bignoniaceae	*Handroanthus sp.*	NA	NA	0.51579	NA	NA	native
Bignoniaceae	*Handroanthus sp.2*	NA	NA	0.51579	NA	NA	native
Bignoniaceae	*Tabebuia sp.*	NA	NA	0.76232	NA	NA	native
Boraginaceae	*Cordia sp.*	NA	NA	0.54247	NA	NA	native
Caricaceae	*Jacaratia sp.*	NA	NA	0.265	NA	NA	native
Ebenaceae	*Diospyros sp.*	NA	NA	0.7728	NA	NA	native
Elaeocarpaceae	*Sloanea sp1*	NA	NA	0.60945	NA	NA	native
Euphorbiaceae	*Croton sp.*	NA	NA	0.5104	NA	NA	native
Euphorbiaceae	*Euphorbiaceae sp*	NA	NA	0.515793	NA	NA	native
Euphorbiaceae	*Sapium sp.*	NA	NA	0.417141	NA	NA	native
Fabaceae	*Chamaecrista sp.*	NA	NA	0.9035	NA	NA	native
Fabaceae	*Clitoria sp.*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Dalbergia sp.*	NA	NA	0.786836	NA	NA	native
Fabaceae	*Fabaceae sp10*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Fabaceae sp2*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Fabaceae sp4*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Fabaceae sp5*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Fabaceae sp6*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Fabaceae sp7*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Fabaceae sp9*	NA	NA	0.515793	NA	NA	native
Fabaceae	*Inga sp.*	NA	NA	0.57808	NA	NA	native
Fabaceae	*Inga sp1*	NA	NA	0.57808	NA	NA	native
Fabaceae	*Mimosa sp.*	NA	NA	0.840888	NA	NA	native
Fabaceae	*Piptadenia sp.*	NA	NA	0.79883	NA	NA	native
Fabaceae	*Plathymenia sp.*	NA	NA	0.4966	NA	NA	native
Fabaceae	*Platimiscium sp.*	NA	NA	0.51579	NA	NA	native
Fabaceae	*Senna sp.*	NA	NA	0.602857	NA	NA	native
Fabaceae	*Stryphnodendron sp.*	NA	NA	0.64166	NA	NA	native

Fabaceae	*Tachigali sp*	NA	NA	0.57669	NA	NA	native
Lamiaceae	*Aegiphila sp.*	NA	NA	0.65666	NA	NA	native
Lauraceae	*Aniba sp.*	NA	NA	0.5908	NA	NA	native
Lauraceae	*Licaria sp.*	NA	NA	0.78684	NA	NA	native
Lauraceae	*Lauraceae sp1*	NA	NA	0.51579	NA	NA	native
Lauraceae	*Lauraceae sp2*	NA	NA	0.51579	NA	NA	native
Lauraceae	*Nectandra sp.*	NA	NA	0.562449	NA	NA	native
Lauraceae	*Ocotea sp.*	NA	NA	0.4325	NA	NA	native
Lythracea	*Lafoensia sp.*	NA	NA	0.821666	NA	NA	native
Malvaceae	*Eriotheca sp.*	NA	NA	0.43762	NA	NA	native
Meliaceae	*Trichilia sp.*	NA	NA	0.69	NA	NA	native
Moraceae	*Ficus sp.*	NA	NA	0.405535	NA	NA	native
Moraceae	*Ficus sp1*	NA	NA	0.405535	NA	NA	native
Moraceae	*Ficus sp2*	NA	NA	0.405535	NA	NA	native
Moraceae	*Ficus sp3*	NA	NA	0.405535	NA	NA	native
Moraceae	*Ficus sp4*	NA	NA	0.405535	NA	NA	native
Moraceae	*Moraceae sp1*	NA	NA	0.515793	NA	NA	native
Moraceae	*Moraceae sp2*	NA	NA	0.515793	NA	NA	native
Musaceae	*Musa sp.*	1	1	0.51579	0	0	exotic
Myrsinaceae	*Myrsinaceae sp1*	NA	NA	0.741037	NA	NA	native
Myrtaceae	*Myrtaceae sp1*	NA	NA	0.515793	NA	NA	native
Myrtaceae	*Myrtaceae sp2*	NA	NA	0.515793	NA	NA	native
Myrtaceae	*Myrtaceae sp3*	NA	NA	0.515793	NA	NA	native
Myrtaceae	*Plinia sp.*	1	1	0.95	0	0	exotic
Nyctaginaceae	*Guapira sp.*	NA	NA	0.670778	NA	NA	native
Nyctaginaceae	*Nyctaginaceae sp1*	NA	NA	0.51579	NA	NA	native
Rubiaceace	*Guetarda sp.*	NA	NA	0.7275	NA	NA	native
Rutaceae	*Citrus sp.*	1	1	0.74	0	0	exotic
Rutaceae	*Citrus sp1*	1	1	0.74	0	0	exotic
Rutaceae	*Citrus sp2*	1	1	0.74	0	0	exotic
Rutaceae	*Citrus sp3*	1	1	0.74	0	0	exotic
Rutaceae	*Citrus sp4*	1	1	0.74	0	0	exotic
Rutaceae	*Citrus sp5*	1	1	0.74	0	0	exotic
Salicaceae	*Salicaceae sp1*	NA	NA	0.51579	NA	NA	native
Sapindaceae	*Alophilus sp.*	NA	NA	0.51579	NA	NA	native
Sapindaceae	*Talisia sp.*	NA	NA	0.833068	NA	NA	native
Sapotaceae	*Pouteria sp.*	NA	NA	0.690657	NA	NA	native
Sapotaceae	*Pradosia sp.*	NA	NA	0.723833	NA	NA	native
Solanaceae	*Cestrum sp.*	NA	NA	0.515793	NA	NA	native

NA – missing information.

Table S2. Model-averaged coefficients for the Impacts of productivity, Management Index, and landscape forest cover on TD, PD, sesPD, threatened species, and endemic species, among 54 sampled cabrucas. The analysis of average models was performed considering all the models with values of ΔAICc ≤ 4.

Response	Parameters	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)
Taxonomic Diversity	Intercept	23.3333	0.8455	0.8661	26.940	<2e-16 ***
	Forest Cover	-3.1426	0.8600	0.8809	3.567	0.777633
	Management Index	-1.5780	0.9739	0.9979	1.581	0.113791
	Productivity	-0.3279	1.1374	1.1609	0.282	0.000361 ***
Functional Diversity	Intercept	3.044e-16	1.348e-01	1.380e-01	0.000	1.000
	Forest Cover	-1.001e-01	1.516e-01	1.527e-01	0.655	0.512
	Management Index	6.433e-03	4.397e-02	4.47e-02	0.144	0.886
ses Functional diversity	Intercept	2.234e-17	1.357e-01	1.389e-01	0.000	1.000
	Forest Cover	-2.2166e-01	1.354e-01	1.386e-01	1.563	0.118
	Management Index	1.269e-01	1.376e-01	1.408e-01	0.901	0.367
	Productivity	8.826e-02	1.381e-01	1.414e-01	0.624	0.533
Threatened species	Intercept	-8.505e-17	1.361e-01	1.393e-01	0.000	1.000
	Forest Cover	-1.525e-01	1.371e-01	1.403e-01	1.087	0.277
	Management index	-1.047e-01	1.379e-01	1.412e-01	0.741	0.459
Endemic species	Intercept	2.4921	0.4243	0.4299	5.796	1e-08***
	Management Index	-0.3518	0.2361	0.2417	1.455	0.146

ses – standardized effect size, ****p*≤0.001, ***p*≤0.01, and **p*≤0.05

Table S3. Generalized Least Square (*GLS*) model results for the impact of productivity, Management Index, and landscape forest cover.

Response	Parameters	Value	Std. Error	t-value	p-value
Phylogenetic Diversity	Intercept	1220.9463	42.74833	28.561262	0.0000
	Forest Cover	-80.0153	43.50076	-1.839399	0.0718
	Management Index	-10.9351	55.87539	-0.195705	0.8456
	Productivity	-56.4906	56.01138	-1.008556	0.3180
ses Phylogenetic Diversity	Intercept	1210.3862	41.28381	29.318666	0.0000
	Productivity	-46.5227	54.09248	-0.860058	0.3939
	Management Index	-20.4737	53.96114	-0.0379416	0.7060
	Forest Cover	-94.7948	42.01046	-2.256456	0.0684

ses – standardized effect size, ****p*≤0.001, ***p*≤0.01, and **p*≤0.05

Table S4. Model-averaged coefficients for the Impacts of **TD** – Taxonomic Diversity, **PD** – Phylogenetic Diversity, **sesPD** – standardized effect size Phylogenetic Diversity, **FD** – Functional Diversity, **sesFD** – Standardized effect size Functional Diversity, **THR** - threatened species, and **END** - endemic species on carbon stock, among 54 sampled cabrucas. The analysis of average models was performed considering all the models with values of ΔAICc ≤ 4.

Response	Parameters	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)
Carbon Stock	Intercept	74.3728	23.9332	24.5185	3.033	0.00242**
	TD	0.8085	0.4477	0.4578	1.766	0.07738
	FD	-42.1098	29.9758	30.7091	1.371	0.17030
	sesFD	-1.2299	2.4146	2.4752	0.497	0.61926
	THR	1.1249	3.2783	3.3578	0.335	0.73763
	END	-1.9531	2.4146	2.4752	1.371	0.17030

ses – standardized effect size, ***$p \leq 0.001$, **$p \leq 0.01$, and *$p \leq 0.05$

CONSIDERAÇÕES FINAIS

Os resultados encontrados no presente estudo indicam que a intensificação sustentável do cacau em cabrucas é viável, com aumento de produtividade acima da média mundial concomitante com a manutenção das árvores sombreadoras, utilizando práticas de manejo adequadas. Observou-se que fazendas com alta sombra e baixa produção refletem uma gestão inadequada, enquanto o aumento da produtividade depende mais de uma boa gestão do que da redução do sombreamento. Além disso, as métricas da diversidade das árvores não foram significativamente influenciadas pela produtividade e pelas práticas de manejo.

Garantir uma gestão eficaz das agroflorestas de cacau é essencial para atender à crescente demanda por cacau, conservar a biodiversidade, estoques de carbono e outros serviços ecossistêmicos associados. Identificar e superar obstáculos locais que impedem a adoção de práticas sustentáveis é crucial, como, a falta de conhecimento, acesso limitado a apoio técnico, dificuldades econômicas para adquirir fertilizantes e ausência de políticas públicas de apoio. Nossa pesquisa destaca a necessidade de reabastecer solos esgotados por meio de fertilização, dado o cultivo prolongado, sendo que apenas 55% das fazendas realizam fertilização conforme o calendário recomendado.

Tais resultados têm particular importância na região Sul da Bahia, conhecida por seus altos níveis de endemismo e pela diversidade vegetal ameaçada característica do bioma Mata Atlântica. Contudo, os dados indicam que o aumento dos níveis de carbono não corresponde necessariamente a uma maior biodiversidade, por isso um foco exclusivo na priorização de terras com base no potencial de sequestro de carbono pode levar a uma proteção inadequada de numerosas espécies nas florestas mais ricas em espécies. Consequentemente, as considerações sobre a biodiversidade devem ser integradas nas estratégias de conservação do carbono para garantir uma abordagem mais abrangente e eficaz ao planeamento da conservação.

Além disso, os sistemas agroflorestais (SAFs) da sucessão cacaueira são promissores para recuperar áreas degradadas, aumentar a produtividade e garantir segurança alimentar e econômica aos pequenos produtores. No entanto, sua aplicação ainda é limitada devido à complexidade do sistema.

Políticas públicas eficazes devem oferecer assistência técnica rural e promover a intensificação sustentável, vinculando crédito rural ao desempenho ambiental e oferecendo subsídios para impactos ambientais e sociais positivos. Implementando essas políticas, podemos promover uma produção de cacau mais sustentável, equilibrando viabilidade econômica e gestão ambiental no *hotspot* de biodiversidade do sul da Bahia. É fundamental desenvolver opções de comercialização e processamento da produção diversificada. A participação de ONGs, formação de cooperativas, criação de bancos de sementes e grupos de trabalho pode aumentar as oportunidades para os pequenos agricultores.