UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS

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Departamento de Biologia

Valorização, impactos e utilizações dos recursos florestais da província da Huíla (Angola): O caso do carvão e dos produtos alimentares

Documento Definitivo

Doutoramento em Biologia e Ecologia das Alterações Globais
Especialidade de Biologia e Ecologia Tropical

Raquel Kissanga Vicente da Silva Firmino

Tese orientada por:
Luís Catarino
Cristina Máguas Hanson
Ana I. R. Cabral

Documento especialmente elaborado para a obtenção do grau de doutor

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“A verdade nasce … com dores e tribulações e
cada nova verdade é recebida a contragosto.”

Alfred Russel Wallace (1823-1913)

Índice

NOTA PRÉVIA

A presente tese apresenta seis capítulos, dentre os quais, quatro correspondem artigos já publicados (capítulos 2, 3, 4 e 5), de acordo com o previsto no Artigo 3, alínea 5 do Regulamento do Ciclo de Estudos Conducente ao Grau de Doutor da Faculdade de Ciências da Universidade de Lisboa. Tendo os trabalhos sido realizados em colaboração, o candidato esclarece que participou integralmente na conceção dos trabalhos, obtenção dos dados, análise e discussão dos resultados, bem como na redação dos manuscritos.

Raquel Kissanga

RESUMO

Na África Austral, mais da metade da sua superfície é ocupada por floresta aberta e savana arborizada. As florestas de Miombo e de Mopane são das mais representativas em África e cobrem mais de 80% do território angolano. Inúmeros produtos florestais lenhosos (i.e., madeira, carvão e lenha) e não lenhosos (i.e., medicamentos, alimentos, fibras, óleos e resinas) em diversos países africanos são extraídos e valorizados pelas comunidades rurais e urbanas, com um impacto socioecómico na economia e, sobretudo, na renda das famílias mais pobres.

A população africana está a crescer exponencialmente, particularmente nas zonas urbanas, mas não acompanhado com o desenvolvimento económico, uma vez que aumenta o índice de desemprego, baixando o poder de compra. Grande parte das pessoas que vivem nas comunidades rurais recorrem à exploração de produtos florestais para subsistência, vendendo os mesmos aos habitantes das zonas urbanas, para a obtenção da renda familiar. Esses produtos são vendidos nos mercados dos centros urbanos, periferias e ao longo das estradas. A valorização dos produtos florestais, sobretudo em África, é uma mais-valia, mas a sustentabilidade e o impacto decorrente da utilização desses recursos tem sido palco para muitas discussões, ao nível global. Neste contexto, a presente tese, dividida em seis capítulos, abordou um conjunto de questões relacionadas com a valorização e impacto da utilização dos produtos florestais lenhosos e produtos florestais não lenhosos alimentares no sudoeste de Angola.

O capítulo 1, introdutório, apresenta o estado da arte, caracterização da área de estudo e os objectivos da tese. Os capítulos 2 e 3, debruçaram-se sobre a dinâmica do uso do solo e do impacto da utilização dos produtos florestais lenhosos, na evolução das florestas, sobretudo do carvão. Analisaram-se as tendências das mudanças na cobertura do solo no sudoeste de Angola nas últimas décadas (1990-2019), que podem estar relacionadas com a dinâmica social e demográfica nesta região. As principais transições da cobertura do solo ocorreram no sentido de floresta (floresta de Miombo e floresta de Mopane) para savana, de savana para agricultura e solo nu, significando desflorestação e degradação florestal. A tendência inversa também ocorreu, principalmente no período da guerra civil (1990-2000). Taxas de desflorestação anual muito altas foram obtidas, em particular na última década (2009-2019) no município de Cacula. As cidades cresceram exponencialmente, triplicando a área urbana, principalmente a cidade do Lubango, enquanto o município de Cacula cresceu a área agrícola. Zonas reflorestadas, para além do êxodo rural durante o período de guerra, podem indicar maior fiscalização governamental e latifúndios, enquanto as zonas severamente desflorestadas podem estar ligadas a um aumento das vias de comunicção, infraestruturas e centros urbanos. O carvão é um dos produtos florestais mais consumidos pela população urbana na região, sendo que cada família rural produtora de carvão pode usar 17 a 26 hectares de floresta por ano. Outros resultados importantes obtidos foram em relação à evolução das florestas. A floresta de Mopane pode levar mais tempo para a regeneração quando comparada com a floresta de Miombo, uma vez que desenvolve em zonas de clima e solo menos favoráveis. No entanto, o corte selectivo das espécies carbonizáveis nas duas formações não afecta significativamente a biodiversidade, ao contrário da actividade agrícola, uma vez que uma parte do caule e da raiz das árvores abatidas permanece no solo e todas as espécies regeneram por toiças.

Nos capítulos 4 e 5, são referidas alternativas de utilização dos produtos florestais mais sustentáveis, em particular através da valorização dos produtos florestais não lenhosos alimentares. Foram estudados dois tipos de produtos dentre os mais comercializados ao longo do ano na região sudoeste de Angola, nomeadamente folhas de plantas silvestres, denominadas "*lombi*" e cogumelos selvagens, respectivamente. Como resultado, foi possível caracterizar morfologicamente as espécies, as técnicas de colheitas, de armazenamento e de venda dos produtos alimentares pelas comunidades. Foi também possível identificar as propriedades nutricionais e bioativas importantes, inclusive o perfil molecular no caso dos cogumelos, quase todos pela primeira vez em Angola.

Os estudos sobre as alterações do coberto do solo, e o efeito da exploração das espécies lenhosas na estrutura e composição das florestas, podem auxiliar nas medidas de gestão dos recursos florestais. Além disso, uma maior valorização dos recursos florestais não lenhosos pelas populações de Angola é uma mais-valia na mitigação dos impactos que advêm da exploração dos recursos florestais.

Palavras-chave: Biomassa, Degradação Florestal, Desflorestação, Produtos Florestais Não Lenhosos, Segurança Alimentar.

ABSTRACT

More than half of the Southern Africa’ surface is occupied by woodland and savanna wodland. The Miombo and Mopane forests are among the most representative in Africa and cover more than 80 per cent of Angola's territory. Numerous timber (e.g. wood, charcoal and firewood) and non-timber (e.g. medicines, food, fibres, oils and resins) forest products are extracted in various African countries and valued by rural and urban communities, with a socio-economic impact on the economy and, above all, on the income of the poorest families.

Africa's population is growing exponentially, particularly in urban areas, but not in tandem with economic development, as the unemployment rate rises, lowering purchasing power. Many people living in rural communities use forestry products for subsistence, selling them to urban dwellers to earn a family income. These products are sold in markets in urban centres, on the outskirts and along roadsides. The valorisation of forest products, especially in Africa, is an asset, but the sustainability and impact of using these resources has been the subject of much global discussion. In this context, this thesis, divided into six chapters, has addressed a number of issues related to the valorisation and impact of the use of wood forest products and edible non-wood forest products in southwestern Angola.

Chapter 1 introduces the state of the art, characterises the study area and sets out the objectives of the thesis. Chapters 2 and 3 look at the dynamics of land use and the impact of the use of woody forest products, especially charcoal, on the evolution of forests. The trends in land cover change in southwestern Angola in recent decades (1990-2019) were analysed, which may be related to the social and demographic dynamics in this region. The main land cover transitions occurred in the direction of forest (Miombo forest and Mopane forest) to savannah, from savannah to agriculture and bare soil, meaning deforestation and forest degradation. The reverse trend also occurred, especially during the civil war period (1990-2000). Very high annual deforestation rates were achieved, particularly in the last decade (2009-2019) in the municipality of Cacula. The cities grew exponentially, tripling the urban area, especially the city of Lubango, while the municipality of Cacula grew its agricultural area. Reforested areas, in addition to the rural exodus during the war period, may indicate greater government oversight and large estates, while severely deforested areas may be linked to an increase in communication routes, infrastructure and urban centres. Charcoal is one of the forest products most consumed by the urban population in the region, with each charcoal-producing rural family using between 17 and 26 hectares of forest each year. Other important results obtained were in relation to the evolution of the forests. The Mopane forest may take longer to regenerate compared to the Miombo forest, as it develops in areas with less favourable climates and soils. However, the selective felling of carbonisable species in the two formations does not significantly affect biodiversity, unlike agricultural activity, since part of the stem and root of the felled trees remains on the ground and all species regenerate by stumps.

Chapters 4 and 5 refer to more sustainable alternatives for utilising forest products, in particular through the valorisation of non-timber forest food products. Two types of products were studied, among the most commercialised throughout the year in south-west Angola, namely wild plant leaves, known as "*lombi*", and wild mushrooms, respectively. As a result, it was possible to morphologically characterise the species, the techniques used to harvest, store and sell the food products by the communities. It was also possible to identify important nutritional and bioactive properties, including molecular profiling in the case of the mushrooms, almost all of which were referred for the first time in Angola.

Studies on land cover changes and the effect of logging woody species on the structure and composition of forests can help in forest resource management measures. In addition, greater valorisation of non-timber forest resources by the people of Angola is an added value in mitigating the impacts of exploiting forest resources.

Keywords: Biomass, Deforestation, Food Security, Forest Degradation, Non-Timber Forest Products.

CAPÍTULO 1

Introdução geral

1. Florestas *vs* savanas em África

Por definição, a floresta é considerada como um terreno com mais de 0,5 hectares contendo árvores com uma altura superior a 5 metros e uma cobertura do dossel acima de 10%, ou árvores capazes de atingir estes limiares *in situ*, não incluindo, terrenos de área agrícolas ou urbano (FAO, 2004). Dentre muitas funções, as florestas, além de cobrir um terço da superfície terrestre, asseguram o sequestro do carbono, o ciclo da água e a manutenção dos solos, (FAO, 2010). Uma ampla gama de serviços de ecossistemas é fornecida pelas florestas, dependendo delas milhões de famílias no mundo para a sua sobrevivência (Campbell et al., 2007; Chidumayo & Gumbo, 2010). Na África austral, a floresta representa uma média de 32% da cobertura, dos 190 milhões de hectares de florestas existentes no mundo (De Cauwer et al., 2018), sendo mais de metade da sua superfície ocupada por florestas abertas e savanas arborizadas (Murphy & Lugo, 2008). As florestas de Miombo e de Mopane são as mais representativas (White, 1983; Timberlake, 2010).

O termo *woodland*, em geral traduzido para português como floresta aberta, é o mais utilizado para descrever as florestas abertas ou bosques que apresentam um dossel mais aberto, como exemplo as florestas de Miombo e de Mopane, quando comparadas com as florestas subtropicais densas (De Cauwer et al., 2018). O Miombo tem uma cobertura de cerca de 2,7 milhões km², abrangendo regiões de Angola, Malawi, Moçambique, República Democrática do Congo, República do Congo, Tanzania, Zambia e Zimbabwe, clima subtropical seco e húmido e precipitação anual acima dos 700 mm (Frost, 1996); enquanto o Mopane ocupa uma área menor, de cerca de 600.000 km² de cobertura, localizando-se em Angola, Botswana, Malawi, Moçambique, Namibia, Zimbabwe, Zambia e África do Sul, em clima subtropical semiárido, com elevação normalmente entre 300-900 m e precipitação anual entre 400 a 700 mm (Burgess et al., 2004, Timberlake, 2010). Nestas florestas são predominantes espécies semi-decíduas da família Fabaceae, nomeadamente dos géneros *Brachystegia*, *Julbernerdia* e *Isoberlinia*, no caso do Miombo, e *Cholophospermum mopane*, no caso do Mopane (Timberlake, 2010). A maioria dos residentes rurais dependem dessas florestas para sua subsistência, principalmente através da agricultura de sequeiro, pecuária e coleta de produtos florestais lenhosos nomeadamente madeira, carvão e lenha e não lenhosos como raízes, frutos, folhas, sementes, cascas, óleos, resinas, que também sustentam as indústrias locais (Chidumayo & Gumbo, 2010). Os principais factores socioeconómicos que promovem a sua rápida degradação e desflorestação estão associados a uma maior intensidade da produção agrícola, do uso dos produtos lenhosos (e. i., produção de carvão e extração de madeira), à conversão para pastagens e a um aumento das indústrias madeireiras (Bamalli et al., 2014).

2. Degradação florestal e desflorestação

Enquanto a degradação florestal representa a redução temporária ou permanente na densidade, bem como alterações na estrutura, composição de espécies ou produtividade da cobertura vegetal, a desflorestação caracteriza-se pela perda mais ou menos completa de cobertura florestal, ou seja, ocorre quando as florestas são convertidas para usos não florestais (Chidumayo & Gumbo 2013). A prática agrícola é uma das actividades humanas mais importante em todo mundo, principalmente quanto à segurança alimentar, porém, a sua expansão promove em grande medida a desflorestação e a perda da biodiversidade florestal. Ao remover a maioria da biomassa acima do solo, através da conversão da floresta para a agricultura, o sequestro do carbono nos ecossistemas é cada vez mais comprometido (Walker & Desanker, 2004). Entre 2000 e 2010, a agricultura comercial em grande escala (principalmente pecuária e cultivo de soja e dendêm) foi responsável por 40% da desflorestação na região tropical e a agricultura de subsistência local por 33% (FAO &UNEP, 2020). Em África a agricultura é maioritariamente familiar, pouco desenvolvida e itinerante (Egoh et al., 2012). Este tipo de agricultura para além de ser a chave para a segurança alimentar rural e urbana em muitas regiões de África promove o crescimento económico auxiliando na diminuição da pobreza (Kalinda et al., 2008). A maior preocupação incide na prática tradicional da agricultura de corte e queima (Syampungani et al., 2016; Tomo & Givá, 2014), pelo facto de proporcionar a abertura de novos campos agrícolas em pouco tempo como consequência da procura de mais terras agricultáveis, contribuindo para o aumento das mudanças climáticas (Tinker et al., 1996), uma vez que a produtividade dos solos é baixa (Brady, 1996; Kleinman et al., 1996).

Em África, cerca de 90% dos habitantes utilizam carvão e lenha como fonte de calor para cozinhar os alimentos e como renda familiar, tanto nas zonas rurais quanto nas urbanas (Adkins et al., 2012; Babulo et al., 2009; Sunderland & Ndoye, 2004; Zulu & Richardson, 2013). Geralmente as comunidades rurais utilizam a lenha para consumo próprio e produzem carvão para vender nas cidades, sendo que a demanda do carvão concorre grandemente para o aumento da degradação da flora em África (Chidumayo & Gumbo, 2013). A produção de carvão já foi responsável pela degradação de 29 hectares (25%) de mata fechada e 93 hectares (51%) de mata aberta na bacia hidrográfica a oeste e norte de Dar es Salaam, na Tanzania (Malimbwi & Zahabu, 2008). Segundo (Luoga et al., 2000, Malimbwi et al., 2010), a utilização sustentável do carvão passa por não exceder os valores de produtividade anual da floresta e melhorar os diversos tipos de fornos ao nível da sua eficiência, uma vez que a sua maioria são fornos tradicionais feitos de terra.

A exploração da madeira é outro produto com impactos socioeconómicos e ecológicos de grande importância em África. A exploração pode ser industrial e não industrial, sendo que a exploração não industrial tem menos impactos e é a mais praticada em toda a África sub Sahariana. A exploração da madeira é uma actividade antiga que tem gerado receitas no sector florestal em muitos países africanos e tem alimentado o mercado da matéria-prima em todo o mundo. O mercado global de madeira e produtos madeireiros está avaliado em mais de US$ 140 bilhões e espera-se que cresça continuamente, criando receitas e empregos (Sitoe et al., 2010). Cerca de 62 espécies lenhosas são consideradas com grande valor económico. A questão da sustentabilidade desses recursos é palco de muitas discussões; espécies lenhosas com grande valor económico como *Dalbergia melanoxylon, Pterocarpus* spp. e *Guibourtia* spp., têm sido exportadas para a Europa e Ásia há décadas, o que tem despertado preocupação devido à intensidade da sua exploração, uma vez que a taxa de regeneração é muito baixa (Sitoe, et al., 2010). Actualmente em muitos países, programas e medidas de gestão têm sido desenvolvidas para mitigar os efeitos da sobreexploração dessas espécies (Dumenu, 2019; Phiri et al., 2015; Stahle et al., 1999; Tosso et al., 2015). De referir o exemplo da Tanzania que em 2010 implementou várias medidas envolvendo as populações, para a conservação de áreas de pousios e pastagens com o objetivo de restaurar a vegetação (Marunda & Bouda, 2010). Outra mais-valia é o alargamento das reservas florestais, com efeitos positivos, para o continente africano (Shumba et al., 2010).

O crescimento populacional é um factor indirecto, porém fundamental, na desflorestação e degradação florestal no continente africano (Zulu & Richardson 2013, Word Bank Group 2016). África é o segundo continente mais populoso, com mais de mil milhões de habitantes, onde o crescimento populacional é cada vez maior, apresentando uma taxa de nascimento de 4,7 crianças por mulher (Pender 1998). O crescimento populacional exerce uma maior pressão sobre as florestas naturais devido à necessidade de produção de alimentos, criação de novos assentamentos urbanos, obtenção de espécies lenhosas de boa qualidade para fins de construção e para a produção de carvão levando à perda da biodiversidade e a desflorestação de grandes extensões de terra (Pender, 1998; Abbot & Homewood, 1999). É de notar que nesses países menos desenvolvidos, embora tenham maior cobertura e biodiversidade florestal em relação aos países desenvolvidos, as taxas de crescimento populacional e de pobreza são altas, o que favorece a utilização não sustentável dos recursos florestais (FAO & UNEP, 2020).

3. A deteção remota na quantificação e monitorização da floresta

Diversos estudos sobre os impactos das alterações no uso e coberto do solo têm sido levados a cabo com o objetivo de quantificar as emissões de gases com efeito de estufa, uma vez que a degradação florestal e a desflorestação respondem por 12% das emissões globais de GHG (*greenhouse gas emissions*) (Babulo et al., 2009; Van Der Werf et al., 2009). Iniciativas importantes têm sido desenvolvidas, como o projecto FCMC (Forest Carbon, Markets and Communities) cuja finalidade é a redução de emissões de GHG por desflorestação e degradação florestal nos países em desenvolvimento (REDD+) (United Nations, 2021). A FAO (Food and Agriculture Organization of the United Nations) e a FRA (Global Forest Resources Assessment) fornece informações essenciais para a compreensão da extensão dos recursos florestais, sua condição, gestão e usos (FAO, 2021) e têm sido uma mais valia no combate às emissões de gases com efeito de estufa. Esses programas são apoiados fundamentalmente pelas ferramentas de detecção remota. A detecção remota, permite avaliar a degradação florestal e a desflorestação em escala local, nacional ou global com confiança (FAO-FRA, 2000; DeFries et al., 2006; Hansen, 2013), através de informações multitemporais e a baixo custo, até em locais inacessíveis (Prins & Kikula, 1996; Yuan et al., 2005; Scheiter & Higgins, 2009; Yiran et al., 2012). Mesmo com algumas limitações, nomeadamente de acesso ao terreno (Calders et al., 2020; DeFries et al., 2007), a deteção remota é uma execelente ferramenta em programas de monitoramento da vegetação e conservação (Mayaux et al., 2003, 2008; Yuan et al., 2005; Pfeifer et al., 2012; Yiran et al., 2012; Pratihast et al., 2014; Law et al., 2018).

4. Produtos florestais não lenhosos e segurança alimentar

Os produtos florestais não lenhosos são de grande importância para as comunidades tanto rurais como urbanas em África. São usados na sua maioria como medicamentos e alimentos e surgem como alternativa na dieta, produção de bebidas, óleos essenciais, saúde e bem-estar das pessoas (FAO, 1995). Estudos que valorizam a utilização desses produtos são considerados de grande interesse mundial, uma vez que o impacto nos ecossistemas florestais é considerado baixo (Laverdière & Mateke, 2003, Louppe et. al., 2008a, 2008b). Em África, importantes estudos fitoquímicos sobre plantas alimentares e medicinais têm sido levados a cabo (e.g. Jayasekara et al., 2002; Addis et al., 2013; Catarino et al., 2016, 2021a; Bancessi et al., 2020). Cerca de 1.000 espécies são usadas como vegetais em toda a África continental, dos quais 80% são folhas silvestres, sendo o restante composto por frutos e sementes, raízes, tubérculos e caules (Maundu et al., 2009). Esses produtos também são fontes de rendimentos e têm aliviado a pobreza a muitas famílias rurais e urbanas, proporcionando excelentes oportunidades de negócio na indústria alimentar e farmacêutica (Shackleton & Shackleton, 2004; Vermaak et al., 2011; Bamalli et al., 2014; Molelekoa et al., 2018).

Actualmente, existe muita informação sobre usos e propriedades bioquímicas dos produtos florestais não lenhosos alimentares estando disponível online, inclusive podendo-se comprar esses produtos em muitas plataformas digitais (como Alibaba, 2021; Amazon, 2021; Ebay, 2021). Grande parte dos produtos são extraídos de espécies lenhosas, principalmente raízes, cascas, folhas, frutos e sementes (Uusiku et al., 2010; Catarino et al., 2019; Bancessi et al., 2020; Stadlmayr et al., 2020). Vários países e organizações regionais têm desenvolvido programas destinados a incentivar a utilização de produtos não lenhosos alimentares, avaliar, domesticar e disseminar determinadas espécies silvrestes com grande interesse comercial (FAO, 1995). Algumas foram consideradas como prioritárias para a domesticação, nomeadamente *Uapaca kirkiana, Parinari curatellifolia, Strychnos cocculoides, Sclerocarya birrea, Adansonia digitata*, etc., de modo a promover cada vez mais a segurança alimentar (Laverdière, 2010; Laverdière & Mateke, 2003; Shackleton, et al., 2010; Shackleton & Dumbo, 2010).

Os macrofungos (cogumelos) alimentares são um dos mais importantes produtos florestais não lenhosos, em todo o mundo. Os cogumelos comestíveis são muito comuns, encontrando-se à venda em mercados e restaurantes. Há pouca informação sobre a comestibilidade e taxonomia dos cogumelos em África. Porém, o interesse em estudar e disponibilizar tais informações é cada vez maior (e.g. Boa, 2002, 2004; Kumar et al., 2021; Degreef & De Kesel, 2022). No Miombo, grande parte dos cogumelos comestíveis são micorrízicos. Apesar do seu impacto socioeconómico e importância para a saúde humana, os serviços ecossistémicos prestados pelos cogumelos comestíveis estão comprometidos pela destruição sistemática e declínio das árvores hospedeiras mais utilizadas, particularmente na região do miombo a mais habitada, uma vez que o carvão e a lenha continuam a ser as fontes de energia de mais fácil acesso para as populações dentro e à volta das grandes cidades (Degreef et al., 2020).

5. Visão global sobre a diversidade da flora de Angola

Angola é um país que ocupa uma posição geograficamente privilegiada, situa-se na costa atlântica sul da África Ocidental e faz fronteira com a Namíbia a sul, com a República do Congo e a República Democrática do Congo a norte, e com a Zâmbia, a este, o que lhe confere uma rica diversidade fisiográfica, climática e biológica, considerada incomum. Embora apresente uma grande riqueza a nível de biomas e ecorregiões, as informações são ainda escassas e limitadas (Huntley, 2019). Mesmo assim, a informação disponível dá conta duma grande biodiversidade vegetal em Angola distinguida por mais de trinta tipos de vegetação, desde as florestas fechadas sempre verdes, florestas abertas de Miombo e savanas arborizadas às estepes e desde os mangais, às florestas ripícolas e ao deserto (Barbosa, 1970).

Tendo em vista a composição biológica, os factores edáficos, climáticos e fisionómicos são distinguidos em Angola seis biomas, nomeadamente: Guinéo-congolês, Zambezíaco, Mosaico de floresta Guinéo-Congolês-Zambezíaco, Afromontanhas, Karoo-Namibe, Planalto de Kalahari (White, 1983; Shumba et al., 2010). O bioma Zambezíaco ocupa uma vasta área do território nacional cobrindo mais de 80%, no qual fazem parte as florestas abertas e savanas arborizadas de *Brachystegia* e de *Colophospermum* do Miombo e o Mopane, respectivamente. O bioma Guinéo-Congolês compreende as florestas sempre verdes da região noroeste de Angola e recebe de 1.200 a 1.800 mm de chuva por ano. O bioma Afromontanhas são formações florestais representadas como manchas isoladas nas encostas protegidas das montanhas. Ocorrem nas províncias de Huambo, Benguela, Kwanza Sul e Huíla. O Karoo-Namibe é uma região de grande endemismo, o deserto do Namibe, clima árido com estações secas prolongadas, sendo que a espécie *Welwitschia mirabilis* é a mais comum das espécies subarbustivas. As zonas de transição compreendem o bioma do planalto do Kalahari e bioma de Savana Mosaico da Floresta Guineo-Congolesa. O planalto do Kalahari é uma zona de escarpa que abrange os arbustos e brenhas da cintura costeira da zona Karoo-Namibe e os bosques zambezíacos de *Brachystegia* do planalto interior, o bioma Savana Mosaico da Floresta Guineo-Congolesa é uma região vasta circundada por rios vales e florestas isoladas, onde predominam espécies de *Strichnos*, *Erythrina*, *Cussonia*, *Piliostigma* e *Combretum* e predominam herbáceas como a *Hiparrhenia*, *Andropogon*, *Trachypogon* e *Cordatia* (Ministério do Urbanismo e Ambiente, 2006).

Quanto às ecorregiões, em Angola podem ser distinguidas cinco, nomeadamente 1) Floresta Tropical de Baixa Altitude, situada no nordeste de Angola caracterizada por precipitação anual alta, alta evaporação e baixa fertilidade do solo; 2) Savana Húmida, ocupa cerca de 70% do território com precipitações que variam entre 500 a 1.400 mm/ano, grande variedade de tipos de solos geralmente pobres em nutrientes; 3) Savana Seca, ocorre no Sudeste de Angola com precipitação escassa e imprevisível que varia entre 500 e 250 mm/ano, solos geralmente férteis; 4) Nama-Karoo, ocorre no Sudoeste de Angola com precipitação em média de 100 a 400 mm/ano; e 5) Deserto, ocorre no Sudoeste de Angola ao longo de uma estreita faixa costeira, apresenta precipitação média muito baixa variando entre os 10 a 85 mm/ano (Ministério do Urbanismo e Ambiente, 2006).

Grande parte dos estudos sobre a flora de Angola foi feito na era colonial, mediante múltiplas expedições ultramarinas como descreveram Goyder e Gonçalves (2019). Baseando em estudos e colecções no período colonial, principalmente dos entudos de Gossweileri & Mendonça (1939), Barbosa (1970) e as colecões de *Conpectus florae angolense* e da *Flora Zambezíaca*, mais de 6500 especies nativas e quase 230 espécies não-nativas foram documentadas numa checklist publicada por Figueiredo & Smith (2008) que nove anos depois foi actualizada (Figueiredo & Smith, 2017).

Outros importantes estudos sobre levantamentos da vegetação florestal que têm sido desenvolvidos nas diferentes ecorregiões de Angola nas últimas décadas, baseando-se frequentemente num modelo-padrão proposto por Revermann et al. (2013b). Estudos dessa natureza têm contribuido no aumento da disponibilidade de dados ao nível nacional, regional e mundial (i. e. Revermann et al., 2016; Chissingui et al., 2018; Gonçalves et al., 2021; GBIF, 2021). Muitos desses dados resultam dos projectos regionais e transfronteiriços como, por exemplo, o TFO (“The Future of Okavango, 2010-2015”, 2015) e o SASSCAL (“Southern African Science Service Centre for Climate Change and Adaptive Land Management”, 2017). Estas pesquisas têm-nos brindado com o aumento de dados e actualização da informação sobre a biodiversidade e ecologia das espécies vegetais de Angola, com maior ênfase para a região centro e sul (Revermann et al., 2013b; Revermann & Finckh, 2013; De Cauwer et al., 2014, Revermann et al., 2017; Chisingui et al., 2018, Gomes et al., 2019; Goyder & Gonçalves, 2019; Goyder et al., 2018, Godlee et al., 2020; Finckh et al., 2021; Gomes et al., 2021), bem como a descoberta de novos taxas para Angola (Figueiredo et al., 2009; Hind & Goyder, 2014; Gonçalves & Goyder, 2016; Gonçalves et al., 2016; Lautenschläger et al., 2020). O livro de Huntley et al. (2019) resume os maiores eventos de pesquisas científicas que se fizeram em Angola. Portanto, o conhecimento das comunidades florísticas, a identificação das espécies-chave, bem como aquelas com maior valor económico em diversos locais em Angola, em particular as de produção de carvão, são contribuições importantes que permitem analisar, a *posteriori*, a evolução das florestas em resposta da perturbação.

6. Valorização e impactos dos produtos florestais de Angola

Em Angola, a cobertura florestal gira em torno de 69,3 milhões de hectares com grande potencial madeireiro (FAO, 2020). O Miombo e o Mopane ocupam cerca de 80% do território nacional, sendo o Miombo a maior ecorregião de Angola (Huntley & Matos, 1994). A maior informação sobre a importância das espécies em Angola, com grande utilidade e de interesse económico, data da época colonial (Huntley & Ferrand, 2019). Na década dos anos 60, o principal produto madeireiro explorado da maioria das províncias era a lenha (4.947.983 m³ de lenha, 520.114 m³ de madeira e 334.104 st de carvão por ano no comércio regional). A madeira touro chegou a ser exportada em média 40.219,67 ton/ano e a madeira serrada 7678.333 ton/ano. *Guibourtia coleosperma* “musivi”, *Pterocarpus angolensis* “mukula” e *Terminalia superba* “limba” e *Gossweilerodendron balsamiferum* “tola branca” foram as espécies mais exploradas provenientes principalmente de Cabinda e do Moxico (Baptista & De Cauwer, 2014).

Durante o período da guerra civil que decorreu entre 1975-2002, a maioria da população migrou para os centros urbanos por motivos de segurança e de procura de melhores condições de vida (Birkeland 2000, Robson & Roque 2001), o que fez diminuir a pressão sobre os recursos florestais. Atualmente, existe uma grande assimetria entre as classes sociais, onde apenas um pequeno grupo é privilegiado no mercado de trabalho qualificado. Angola e a Africa do Sul são os maiores produtores de petróleo da região da África Austral e representam 91% das emissões provenientes do sector energético desta região (USAID 2015). Exemplo, Angola em 2019 apresentou um PIB de mais de 3,000$ dólares per capita, que provinham de uma economia não diversificada e focada na exploração do petróleo. Apesar disso, a desiguladade social é muito acentuada (Da Rocha, 2015). As estimativas do Índice de Pobreza Multidimensional nacional estão acima dos 50% (INE, 2020) e a taxa de desemprego está acima dos 30% (INE 2019). Um dos recursos para a sobrevivência das pessoas que vivem nas zonas rurais e periurbanas é a venda de produtos florestais nos mercados informais e na beira das estradas, nomeadamente carvão, madeira para construção, cogumelos, raízes, cascas, frutos, flores, sementes, fibras, entre outros, para fins medicinais e alimentares. Os produtos florestais podem ser vendidos secos e frescos. Com excepção dos frutos e cogumelos frescos, a venda de produtos florestais é feita todo o ano e tem sido a alternativa de renda em muitas famílias pobres.

A exploração dos recursos florestais em Angola é regulamentada através da Lei de Bases das Florestas e Fauna Selvagem (República de Angola, 2017) e do regulamento florestal (República de Angola, 2018). O documento prevê o tamanho mínimo do diâmetro para o corte, a área e o tempo de exploração. Porém, a insuficiência de recursos humanos não tem ajudado a uma fiscalização eficaz, o que justifica uma taxa de desflorestação cada vez maior. No período 1990-2000, foi estimada uma taxa de desflorestação nacional de -0.20%, entre 2000-2010 foi de -0.74% e entre 2010-2020 foi de -0.80%, o que equivalente a mais de 500 mil hectares por ano (FAO 2020, 2021). Segundo USAID (2018), em Angola, o sector florestal e as alterações do uso do solo ocupam o segundo lugar nas emissões dos gases de efeito estufa com 37.4% das emissões, sendo o sector da energia o que mais emite, com 49,4% das emissões totais. Entretanto, a agricultura itinerante, a migração, a exploração da madeira, a produção do carvão e os fogos são apontadas como as principais causas da degradação florestal e da desflorestação no país (Schneibel et al. 2013 and 2016; Catarino et al., 2019).

Dos produtos lenhosos mais importantes em Angola, a lenha é o mais utilizado nas zonas rurais, enquanto o carvão aqui produzido é exportado para ser utilizado nas zonas urbanas. Dados do IDF (Instituto de Desenvolvimento Florestal de Angola) indicam que, dentre vários produtos florestais, a produção e consumo de carvão vegetal e lenha representa cerca de 60% do balanço energético nacional, resultante do crescimento da demanda nos centros urbanos e zonas periurbanas (Caetano, 2012). Um estudo realizado na província do Bié revelou que são consumidos 57,015,000 ton/ano de madeira, o que corresponde cerca de 27,000 hectares de floresta degradada anualmente, para produção do carvão (Chiteculo et al., 2018b). Um outro estudo estimou que a quantidade de biomassa total de árvores encontrada em pousio de carvão vegetal varia de 21,4 - 81,0 t/ha e no Miombo maduro varia de 89,0 - 197,4 t/ha (Gonçalves et al., 2019). Outros importantes estudos sobre o impacto da colheita das espécies na regeneração da vegetação florestal em Angola servem de referência por fornecer dados que permitam elaborar uma análise sobre a evolução da floresta após a perturbação, de que são exemplo os trabalhos realizados no Cusseque (Gonçalves et al., 2017b) e no Caiúndo (Wallenfang et al., 2015 e Golçalves et al., 2017a). As ferramentas de detecção remota têm sido utilizadas nas últimas décadas em estudos de impactos do uso da terra na vegetação. Dados significativos sobre as alterações do coberto e uso do solo foram obtidos e servem como referência na região norte (Temudo et al., 2019, 2020), centro e sul de Angola (Cabral et al., 2010; Schneibel et al., 2013, 2016, 2017a, 2017b; Chissingui, 2017; Chiteculo et al., 2018a).

Todavia, a utilização dos produtos florestais não lenhosos em Angola é cada vez maior, e além da utilização alimentar e medicinal, a produção de bebidas e forragem ganham destaque em muitas zonas do país (Baptista, 2013; Tchamba, 2019). Diversos estudos na era colonial têm sido referência na identificação e inventariação das espécies úteis para as comunidades locais (Ficalho, 1884; Gossweiler, 1953; Dos Santos, 1972). Após a era colonial, surgiram novos estudos focados no recenseamento das espécies de plantas e utilizações importantes para as comunidades em diversas localidades do país (i. e. Bossard, 1987; Dos Santos, 1982; Dos Santos, 1989; Van-Dúnem, 1983, 1993, 1994; Costa & Pedro, 2013, Piedade, 2013; Kissanga, 2008, 2016; Göhre et al., 2016; Urso et al., 2013, 2016; Heinze et ai. 2017 e 2019; Lautenschläger, et al., 2018; entre outros), inclusive na área da etnoveterinária (Bruschi, et al., 2017).

O conhecimento sistematizado e integrado sobre a biodiversidade de África ainda enfrenta muitos obstáculos, particularmente na região de Angola (Figueiredo & Smith, 2008; Droissart et al., 2018), e na área do mapeamento e da gestão do uso do solo. Em virtude da crescente pressão sobre os recursos naturais, estudos sistematizados sobre levantamentos da vegetação podem ser usados como estratégias para definir uma nova era em planeamento do uso e conservação do solo em Angola, como recomendam Revermann & Finckh (2018). Entretanto, estudos sobre a análise das alterações do coberto do solo, o efeito da exploração das espécies na estrutura e composição das comunidades vegetais, impactos ecológicos e socioecómicos que advém da produção do carvão, podem auxiliar nas medidas de gestão adequadas do uso dos recursos florestais lenhosos. Além disso, uma maior valorização dos recursos florestais não lenhosos nas populações de Angola, pode ser uma mais-valia na mitigação dos impactos que advém da exploração dos recursos florestais lenhosos, particularmente da produção do carvão.

7. Caracterização geral da área de estudo

O presente estudo foi desenvolvido no período de 2018 a 2019 em três municípios do sul de Angola, nomeadamente Lubango e Cacula da província da Huíla e Bibala da província do Namibe, numa área entre as coordenadas 14º00’ e 15º’21’ S, 12º33’ e 14º48’ E (Figura 1). O município do Lubango tem uma superfície de 3.140 km² e é constituído pelas comunas de Lubango (capital), Arimba, Hoque, Huila e Quilemba. O município de Cacula tem uma área de

3.445 km², é constituído pelas comunas, de Cacula (comuna sede), Chituto, Viti-Vivali e Chicuaqueia. O município da Humpata para além do Lubango, faz fronteira com o município da Chibia e é constituído pela comuna-sede, com o mesmo nome, Humpata, pelas comunas de Bata-Bata, Caholo, Neves e Palanca, apresenta uma área de cerca de 1261,25 km². Por último, o município da Bibala tem uma superfície de 7.612 km², e constituído pelas comunas de Bibala (comuna sede), Caitou, Capangombe e Lola.

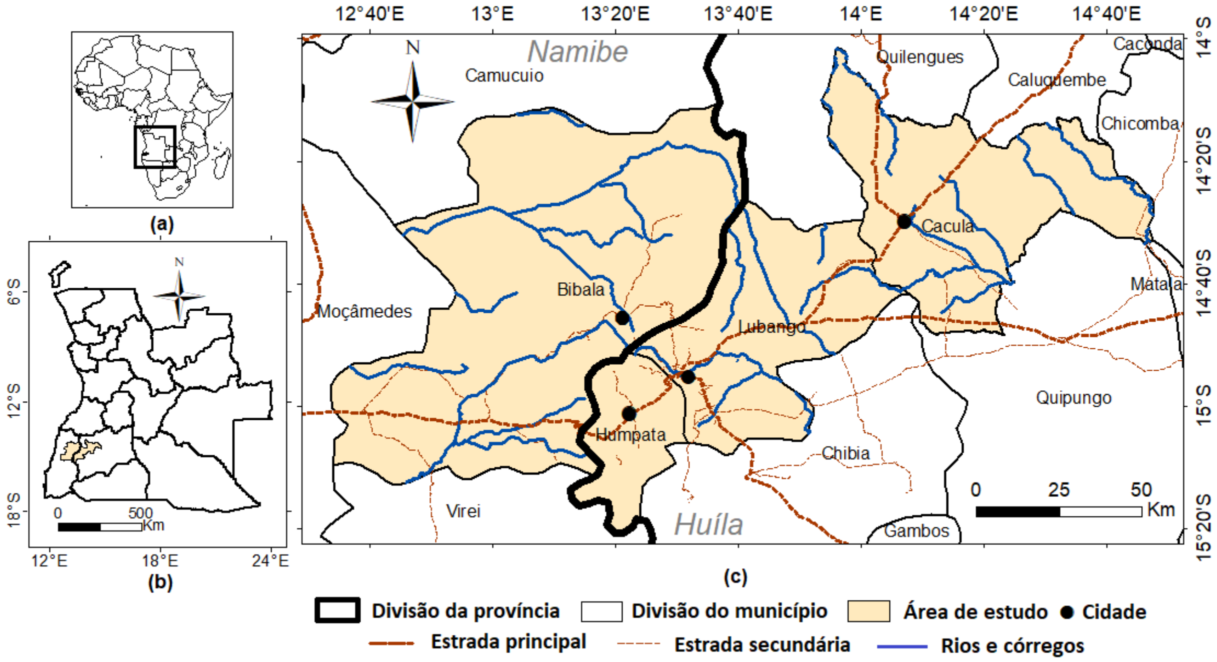

Figura 1. Localização da área de estudo em África (a), Localização da área de estudo em Angola (b), área de estudo (c).

De um modo geral a área de estudo faz fronteira com oito municípios, isto é, a norte pelos municípios de Quilengues e Camucuio, a leste pelos municípios de Caluquembe e Quipungo, a sul pelos municípios da Chibia, Humpata e Virei e a Oeste pelo município de Moçâmdes (Figura 1). Mais de um milhão de habitantes vivem nessa área; o município do Lubango é representado com mais de 70% dos residentes da região (INE 2016). A cidade de Lubango, além de Luanda e Huambo, é uma das que sofreram maior pressão demográfica, devido ao fluxo migratório durante a guerra civil. Nas zonas rurais desta região habitam tradicionalmente diversos grupos etnolinguísticos, dentre eles os Muila, Handas, Ovimbundos, Koissans e Mucubais. As suas principais atividades económicas são a agricultura e a pastorícia (Diniz, 1973; Redinha, 2009).

A área de estudo envolve o planalto central da Huila e a zona subplanáltica ou parte do litoral sul (Diniz, 1973), com altitudes compreendidas entre os 300 a 2200 metros (Figura 2). A geologia apresenta formações eruptivas antecâmbricas, granitos granodioritos e quartzodioritos, bem como sistema de congo ocidental e complexo de base (Diniz, 1973, Jones *et al.* 2012). Segundo a *Carta Fitogeográfica de Angola* de Barbosa (1970), a vegetação florestal é representada por dois tipos, nomeadamente as formações de Miombo e de Mopane.

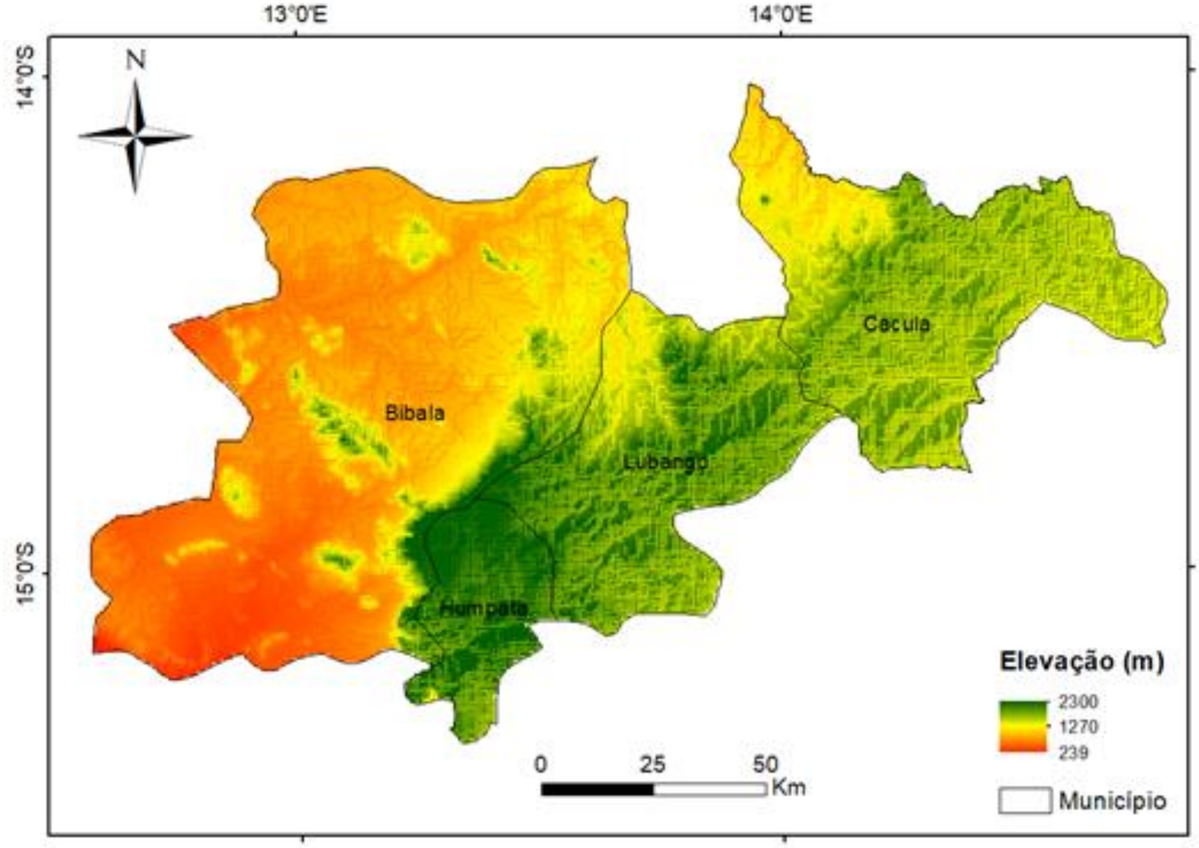

Figura 2. Área de estudo: Relevo (Fonte: Diva GIS, 2023).

Segundo a classificação de Koppen, apresenta um clima temperado com inverno seco no planalto central e semiárido na zona suplanáltica (Diniz, 1973, 1991; Le Houérou, 2009). Existem duas estações no ano, uma estação chuvosa (de meados de Agosto a meados de Maio e outra seca (de meados de Maio a meados de Agosto). As precipitações anuais no planalto central variam entre 750-1000 mm; a humidade relativa do ar oscila entre os 36-90% ao longo do ano e a temperatura média anual é de 18,5 °C.

Na zona subplanáltica apresenta um período de seca mais prologado, a temperatura média anual chega a 21,5 °C, atingem-se médias de pluviosidade na ordem dos 300-400 mm e humidade relativa é menor que nas restantes áreas de estudo (Diniz, 1991). A região é uma área onde dominam, principalmente, ferralsolos, leptosolos, cambissolos, calcisolos, luvisolos, afloramentos rochosos e areias (Figura 3).

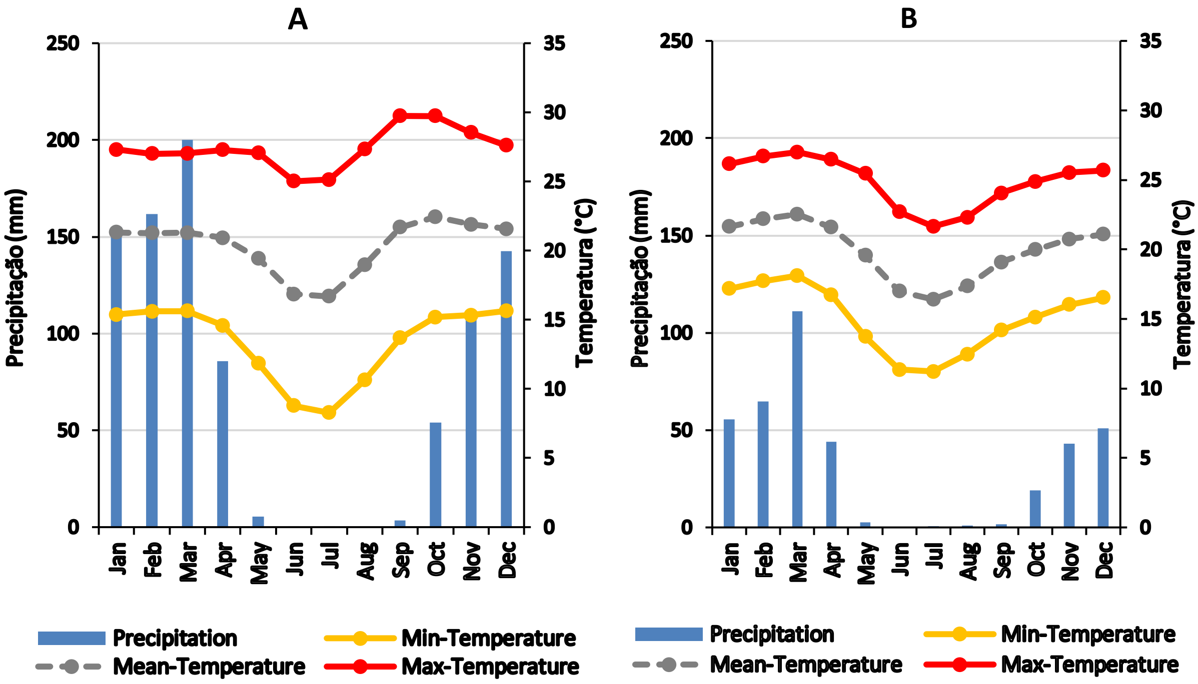

Figura 3. Temperaturas médias, minimas e máximas mensais e precipitação mensal da província da Huíla (A) e do Namibe (B), desde 1991-2020. Adaptado de: Word Bank Group (2021).

A vegetação de Miombo é caracterizada principalmente pela presença dos géneros *Brachystegia*, *Julbernardia*, *Isoberlinia* e *Combretum*, e a vegetação de Mopane pela dominância de *Cholophospermum mopane*, *Spirostachys africana*, bem como espécies do género *Combretum*, *Commiphora* e *Acacia* (Barbosa, 1970)

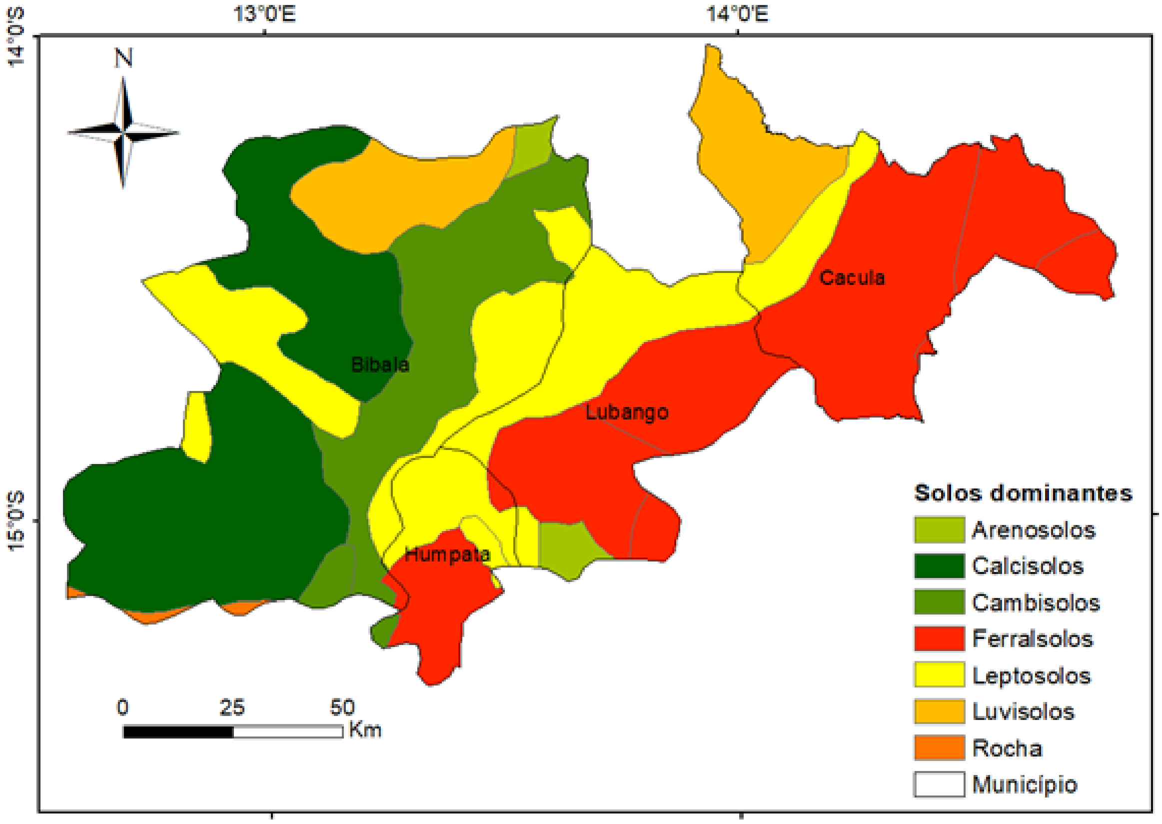

Figura 4. Área de estudo: Solos dominantes. Fonte: Dijkshoorn (2003).

8. Objectivos da tese

Com o aumento exponencial da população, as sociedades africanas estão cada vez mais dependentes dos recursos florestais o que faz com que as cidades sejam sorvedouros de recursos florestais. Este facto, promove a desflorestação e a degradação florestal associada às práticas tradicionais de utilização dos recursos naturais o que produz um impacte socioeconómico e ambiental severo. Nesse contexto, o presente estudo teve como objectivos gerais contribuir para a valorização de produtos florestais lenhosos e não lenhosos da região sudoeste de Angola, particularmente na província da Huíla, e avaliação do impacto socioeconómico e ambiental decorrente da utilização do carvão. Tendo em vista os objectivos, a tese está dividida em quatro capítulos descritos como manuscritos para publicação científica. Dentre os quais dois foram publicados, um submetido e o outro em preparação:

Capítulo. 2: *Dynamics of Land-cover Change and Characterization of Charcoal Production and Trade in Southwestern Angola* (artigo publicado em 2024 na revista *Remote Sensing Applications: Society and Environment*) Trata-se de um estudo sobre a dinâmica do coberto do solo na área de estudo, ao longo de três décadas (1990 a 2019) e da caracterização da produção de carvão e os seus impactos socioeconómicos e ambientais. Neste capítulo foi utilizada uma abordagem de deteção remota para identificar as mudanças espaço-temporais, combinada com levantamentos de campo para caracterizar as atividades relacionadas ao carvão vegetal nas florestas de miombo e mopane no sudoeste de Angola. Os objectivos principais foram: caracterizar o coberto do solo na área de estudo por meio da classificação supervisionada de imagens satélites Landsat para os anos 1990, 2000, 2009 e 2019, analisar as alterações do coberto do solo e das taxas de desflorestação, caracterizar a produção, transporte, venda do carvão produzido e vendido nos principais mercados da cidade do Lubango e avaliar o impacto socioeconómico e ambiental decorrente da produção.

Capítulo. 3: *Assessing the Impact of Charcoal Production on Southern Angolan Miombo and Mopane Woodlands* (artigo publicado em 2023 na revista *Forests*). Trata-se de um estudo de caso no sul de Angola sobre o impacto da produção de carvão vegetal nas comunidades florestais de Miombo e Mopane. Este capítulo teve como objectivos analisar o impacto da extração da madeira para a produção de carvão vegetal na estrutura e composição da vegetação no Miombo e no Mopane. Para tal, foram estudadas parcelas de vegetação em pousios de uso recente, intermediário e maduro e atraves de análises multivariadas como NMDS, correlações e de espécies indicadoras. Contudo, foi possível avaliar a dinâmica de recuperação das florestas de Miombo e Mopane após o uso seletivo de espécies arbóreas para produção de carvão.

Capítulo 4. *Nutritional and Functional Properties of Wild Leafy Vegetables for Improving Food Security in Southern Angola* (artigo publicado em 2021 na revista *Frontiers in Sustainable Food Systems*). Trata-se do estudo sobre as propriedades nutricionais e funcionais de folhas silvestres comestíveis denominadas tradicionalmente de "*lombi*" com vista em valorizar e melhorar a dieta alimentar e a segurança alimentar no Sul de Angola e não só. No presente capítulo, foram identificados três vegetais folhosos selvagens comestíveis de grande importância para as comunidades residentes na Huila, que são comercializados nos mercados do Lubango e consumidos ao longo do ano. Os principais objectivos foram: identificar as espécies de hortícolas folhosas silvestres comercializadas nos mercados do Lubango, os seus preços e a sua importância socioeconómica no sul de Angola, determinar as suas características bioecológicas e avaliar a composição nutricional e as propriedades funcionais das principais espécies e nas misturas vendidas.

Capítulo 5. *Biochemical and Molecular Profiling of Wild Edible Mushrooms from Huila, Angola* (artigo publicado em 2022 na revista *Foods*). Trata-se de estudo sobre o perfil bioquímico e molecular de cogumelos silvestres comestíveis na província da Huíla, em Angola. Neste capítulo, foram estudados cogumelos comestíveis selvagens colhidos pelas comunidades e comercializados ao longo do ano nos mercados do Lubango. Assim, os objectivos do capítulo foram: caracterizar a relevância socioeconómica do comércio e consumo de cogumelos comestíveis selvagens, identificar as espécies de cogumelos nas misturas secas vendidas no mercado da Humpata, com dados morfológicos e moleculares e documentar suas propriedades químicas, nutricionais e funcionais.

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CAPÍTULO 2

Dynamics of land-cover change and characterization of charcoal production and trade in southwestern Angola

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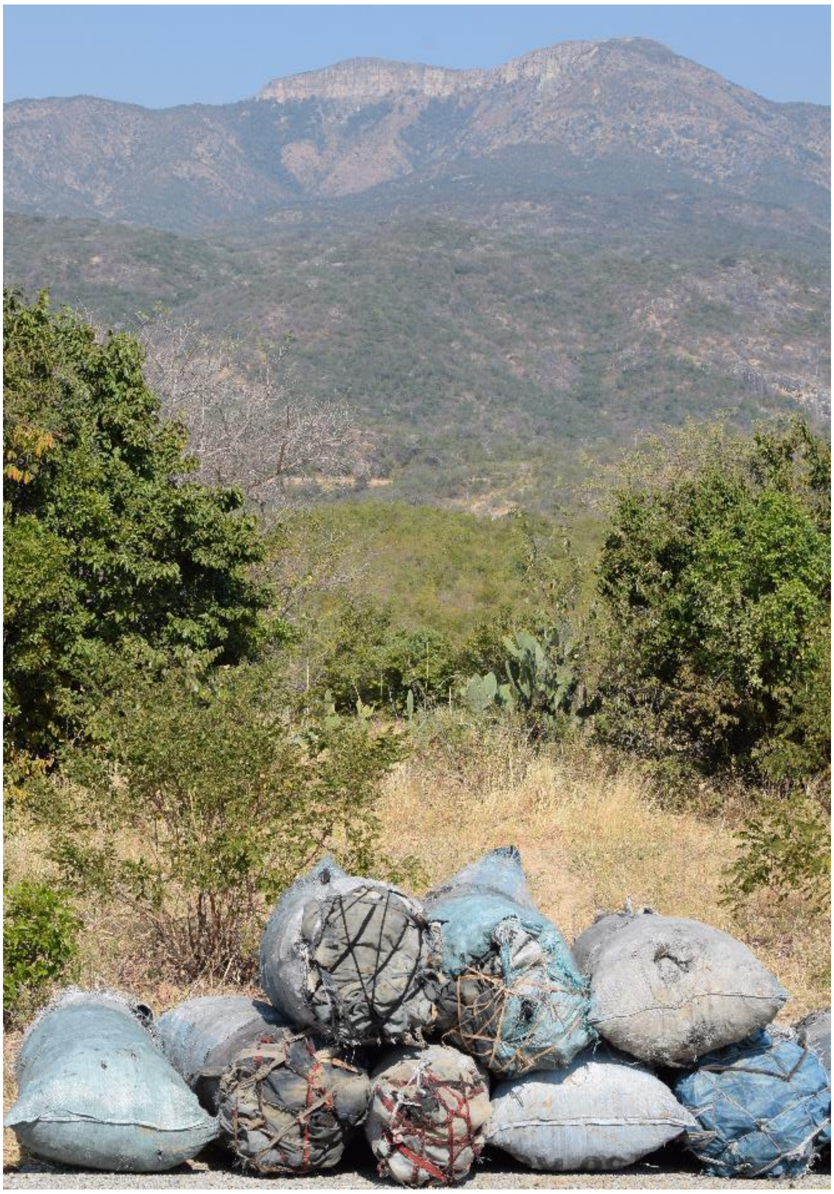

Abstract

Miombo and *mopane* woodlands of southwestern Angola have been overexploited for decades, leading to deforestation and forest degradation driven by social dynamics during and after the civil war (1975–2002), with different patterns of use of natural resources. Our objective was to study the changes in land-cover in three municipalities of southwestern Angola, and to characterize the charcoal production and trade on *miombo* and *mopane woodlands*, where that production was identified as one of the main causes of degradation. Land-cover dynamics between 1990 and 2019 was evaluated based on four land-cover maps, and the processes involved in deforestation and forest degradation were identified and discussed. Roadside charcoal sale locations, markets, the most exploited species, and the type, size, and efficiency of the kilns were assessed through field surveys. Between 1990 and 2019, the woodland area decreased and was converted to *savanna woodland* and agriculture, while the urban area continuously increased. Both *miombo* and *mopane woodlands* went through higher annual deforestation rates than those reported by FAO at the national level. The dynamics of land use were different between the war and post-war periods, respectively with the abandonment of agricultural land and migration of rural populations to the cities, and their return to the countryside and use of land and forest resources as primary subsistence activities. Agriculture and charcoal production were identified as the main income-generating activities, and the occupation of unused land by outsiders may have also contributed to intensify deforestation and forest degradation. To slow down the ongoing area loss of *miombo* and *mopane* woodlands, it seems crucial to implement conservation and restoration strategies promoting the sustainable use of the resources while ensuring the provision of essential goods to local populations and contributing to reduce poverty.

Keywords: Deforestation and forest degradation, Huíla, Miombo and Mopane woodlands, Remote sensing, Socioeconomic factors, rural migration

1. Introduction

Forest resources play an important role in the livelihoods of populations, providing several goods and services that contribute to improve and maintain human welfare. In Africa, forest resources are daily and directly used (Chidumayo and Gumbo, 2010; Mapaure and Ndeinoma, 2011; Carlson et al., 2022), so forest degradation is a critical issue for local people. In the last decades, forests and woodlands have been subject to different, and increasingly stronger human impacts such as agriculture, urbanization and population growth, wood extraction for fuelwood and charcoal production, and fires that cause deforestation and forest degradation, as well as depletion of soil and water resources (Walker and Desanker, 2004; Defries et al., 2010; Van Der Werf et al., 2010).

Until the late 19th century, deforestation and forest degradation prevailed in temperate zones of Europe and America, but today these processes are mainly concentrated in developing countries and particularly in tropical areas (FAO, 2016). Significant forest loss has been occurring in sub-Saharan Africa, mainly in East and Southern Africa, where about four million hectares were lost per year from 2010 to 2020 (FAO-UNEP, 2020; FAO, 2021). It should be noted that most vegetation, classified by FAO as tropical forest is commonly named “woodland” which is defined by De Cauwer et al. (2018) as vegetation characterized by trees or woody plants able to reach a minimum height of 5 m, crown cover between 10% and 60%, and an understory where grasses are present. Frequently, they are, also, named as open forests, but here the designation of “woodland” will be adopted. Located in sub-Saharan Africa, Miombo and Mopane woodlands are the most representative (White, 1983; Timberlake et al., 2010; Cauwer et al., 2018).

Moreover, at the local level, most African populations lack energy sources like electricity and gas for cooking or heating. When available, they are expensive and hardly accessible to those with low incomes (Diaz-Maurin et al., 2018). Most of the population uses wood-derived fuels, like charcoal and fuelwood, to meet daily needs; often, they are also traded to increase the household income in both rural and urban areas (Adkins et al., 2012). About 80% of the people in Angola use charcoal and firewood to satisfy their daily energy needs, thus contributing to the highest deforestation rate in sub-Saharan Africa (Chiteculo et al., 2018b). In 2010–2020, about 548 000 ha of forest were lost per year (FAO, 2020b). Moreover, charcoal is expected to remain the main source of energy in Africa in the near future and to increase until 2040 (Sedano et al., 2020).

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Southern Angola is characterized by two types of dry tropical woodlands – miombo, with Brachystegia spiciformis, Julbernardia paniculata, and Isoberlinea angolensis as dominant species, and mopane, dominated by Colophospermum mopane (White, 1983; Timberlake et al., 2010) – that provide important ecosystem services to the rural populations, including timber and non-timber products (Chidumayo and Marunda, 2010; Makhado et al., 2014), and contribution to water cycling regulation, reduction of soil erosion, and atmospheric CO_2 sequestration (Van Der Werf et al., 2009; Marunda and Bouda, 2010; Timberlake et al., 2010; Miapia et al., 2021). Agricultural expansion, fires, fuelwood extraction, charcoal production, and urban growth have been pressing these woodlands, enhancing deforestation and forest degradation and, in the long term, the loss of ecosystems and ecosystem services that could aggravate the effects of climate changes (Tinker et al., 1996; Bongers and Tennigkeit, 2010).

For several decades of the late 20th and early 21st centuries, Angola underwent significant political and military instability. During the most intense phases of civil war, and especially between 1992 and 2002, a large part of the population abandoned the rural areas and took refuge in the cities, resulting in the temporary abandonment of many agricultural fields and the recovery of forest vegetation (Birkeland, 2000; Robson and Roque, 2001). In 2002, when the warfare ended, the population went back to their homes and intensified the use of forest resources, with more aggressive land use practices. Forest areas around the cities also started to be used for agriculture, wood and firewood extraction, and to produce charcoal to be sold in the cities.

Several studies have analysed land-cover and land-use changes in Angola, some relating them with different types of household energy consumption. Cabral et al. (2010) quantified deforestation in the province of Huambo between 1990 and 2009. Others studied the agricultural expansion in southern Angola, the trade-offs between food production and timber extraction resulting from the conversion of *miombo* into agricultural land, and the spatio-temporal changes in *miombo* due to smallholder cultivation patterns (Schneibel et al., 2013, 2016, 2017a). Chiteculo et al. (2018a) assessed deforestation patterns in 2000–2017 in the Huambo province, based on the distribution of key *miombo* tree species. In the same region, Miapia et al. (2021) analysed the relationship between deforestation and biomass production in miombo woodlands, considering local and global needs. In the Zaire province (northern Angola), Temudo et al. (2019, 2020) studied urban expansion and energy consumption by local people in the city of Mbanza Kongo, as well as the relationship between deforestation patterns and urban area dynamics and household energy consumption in 1998–2016. Chiteculo et al. (2018b) studied the charcoal value chain in three municipalities of the Bié province to identify policies that contribute to reduce forest degradation. Chisingui (2017) analysed the landscape and land use changes from 1990 to 2010 in the *miombo* area of Lubango and surroundings, which covers part of our study area.

Understanding the dynamics of miombo and mopane woodlands over time and identifying their main drivers and impacts is extremely important because they play crucial roles at the social, economic, and environmental levels. This is relevant in rural areas of Angola where, to alleviate poverty and increase family income, activities such as agriculture, charcoal production, and logging have increased substantially in recent decades, with impacts on forests that might be irreversible. A historic understanding of the patterns and processes involved in deforestation and forest degradation is essential for stakeholders and governmental authorities to develop and implement measures that minimize impacts and foster more sustainable forest management practices (FAO, 2018). While existing studies have explored the land-cover dynamics and deforestation patterns in Angola, particularly in miombo and mopane woodlands, there remains a significant gap in understanding the long-term impact of charcoal production on these ecosystems in the post-civil war period. There is a lack of comprehensive research specifically focusing on the repercussions of charcoal production, a critical driver of forest degradation in the region. Additionally, the existing literature does not adequately address the historical context and the intricacies of the charcoal value chain, hindering the formulation of effective policies and sustainable forest management strategies.

In the present study, we analysed the land-cover dynamics and the impact of charcoal production in *miombo* and *mopane woodlands* of southwestern Angola, namely in two municipalities of the Huila province (Lubango and Cacula) and one municipality of the Namibe province (Bibala), all severely affected by the civil war that ended in 2002. A remote sensing approach to identify the spatio-temporal changes was used, combined with fieldwork surveys to characterize the charcoal-related activities.

2. Material and Methods

2.1. Study area

The study was conducted in an area of 15,060.92 km^2 in southwestern Angola (14° 32' – 15° 09' S, 12° 34' – 14° 47' E), including three municipalities: Lubango and Cacula (Huíla province), and Bibala (Namibe province) (Fig. 1). These municipalities were chosen because they are the main suppliers of forest products to the capital of Huíla, Lubango.

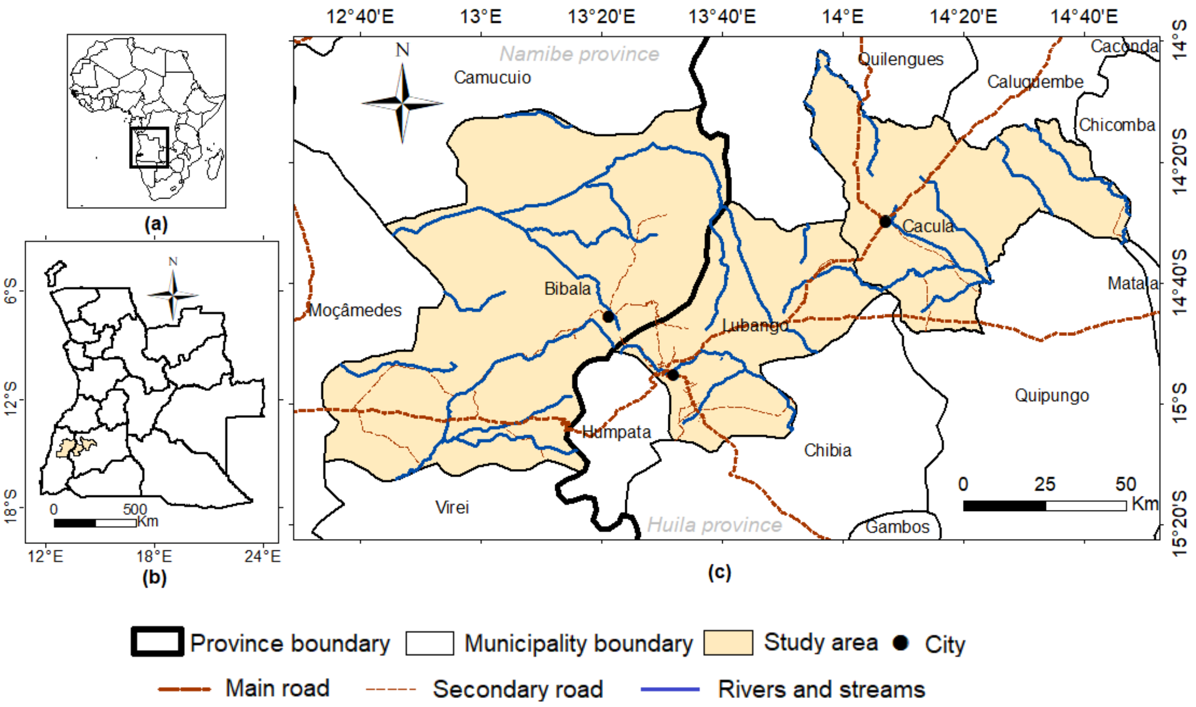


Fig. 1. Location of the study area in Africa (a) and in Angola(b); Study area (c).

The studied area is part of the central plateau of Angola and of the sub-plateau zone of the southern coast of the country (Diniz, 1973), with altitudes ranging from 300 to 2200 m. According to Koppen's classification, it has a temperate climate with dry winter in the central plateau, and a semi-arid climate in the sub-plateau (Diniz, 1973, 1991; Le Houérou, 2009), with a rainy season from mid-August to mid-May and a dry season during the rest of the year. The annual precipitation in the central plateau varies between 750 and 1200 mm, with the relative humidity ranging between 30 and 90% throughout the year, and an average annual temperature of 18.5 °C. The sub-plateau zone presents a more prolonged dry period, with an average annual temperature reaching 21.5 °C, a rainfall average of 300–400 mm, and relative humidity lower than in the rest of the study area (Diniz, 1991). Soils are mainly ferralsols, lithosols, and cambisols, with frequent rocky outcrops (Diniz, 1973).

The region is characterized by different types of land-cover. *Mopane woodland* and *miombo woodland* are dominated by deciduous and semi-deciduous woody species, essentially *Colophospermum mopane* and *Sprirostachys africana* (mopane), and *Brachystegia* spp. and *Julbernardia paniculata* (miombo), with discontinuous shrubby and herbaceous layers. *Savanna woodland* includes mixed and transitional vegetation comprising degraded forests and abandoned agricultural areas or fallows, with scattered trees and shrubs and a dominant herbaceous stratum in the wet season. *Agriculture/bare land* represents abundant herbaceous vegetation and/or bare soils, such as agricultural fields with or without vegetation during the year, recent fallows and rocky outcrops. *Urban* areas are artificialized, occupied by buildings and land surrounding them. *Water* corresponds to water bodies.

According to the 2014 Census, the study area has over one million inhabitants – 731 575 in Lubango, 128 411 in Cacula, and 471 613 in Bibala (INE, 2016). Of the three capital municipalities, Lubango city experienced the greatest demographic pressure due to the migratory flow during the civil war. The rural areas are inhabited by several ethnolinguistic groups, including the Muila, Handa, Ovimbundo, Koissan, and Mucubal, whose main economic activities are agriculture and pastoralism (Diniz, 1973; Redinha, 2009).

2.2.Landsat imagery

Three image dates of Landsat TM (1990, 2000, and 2009) and one of Landsat OLI (2019) were selected to cover the study area. For each year, four Landsat scenes were used, which were geometrically corrected to UTM (Universal Transverse Mercator), Zone 33 South, WGS84, with a spatial resolution of 30 m. Image selection followed the same criteria concerning cloud cover, quality, dry season (May to July), and proximity between the dates of the scenes of the same year, to minimize possible differences at the land-cover level. Data were downloaded from the United States Geological Survey EarthExplorer datacenter (United States Geological Survey, 2019). Four mosaics were composed to obtain a single image of the study area for each year, which was used to depict the land-cover classes.

2.3.Land-cover classification

To obtain the land-cover maps, a legend with five classes was defined according to the ancillary data: *woodland*, *savanna woodland*, *agriculture/bare soil*, *burnt*, and *water*. Then, a training dataset was built by collecting pixel samples, for each class, and visually interpretating various RGB band combinations of the Landsat satellite images, supported by points collected in the field and ancillary data: a phytogeographic map of Angola at a scale of 1:2500000 (Barbosa, 1970), detailed descriptions of vegetation (Diniz, 1973), Google Earth high-resolution imagery, and information made available by experts from LUBA herbarium (Herbarium of ISCED-Huíla, Lubango) and LISC herbarium (Herbarium of the University of Lisbon). To improve the land-cover pixel identification, high-resolution images from Google Earth were also used. The number of pixels per class included in the training dataset followed the criteria described by Lillesand et al. (2015), that is, it must be equal to n+1, where n is the number of spectral bands. To ensure that the collected samples were spectrally separable, they were subject to a spectral separability analysis based on the Jeffries-Matusita (J-M) distance (Richards, 2013).

As the study area is characterized by high altitudes, very steep slopes, and a large proportion of closed woodland, which generate high shading, a method proposed by Lillesand et al. (2015) was applied based on the ratio between the mid-infrared band (TM5 or OLI3) and the green band (TM2 or OLI7) of the visible region of the electromagnetic spectrum, to minimize the shadows and the topographic effects. This band ratio highlights the information in the most shaded areas – corresponding to vegetation, in this case –, due to its relatively high reflectance in the mid-infrared and lower reflectance in the green. The band ratio was calculated each year and included in the respective Landsat mosaic to improve the classification procedure. Finally, a maximum likelihood classifier was applied to obtain the land-cover maps.

Given that *agriculture/bare soil* and *urban* classes had similar spectral values, to correctly identify the urban area corresponding to Lubango city, this was digitized for each year using Landsat TM (7,4,3) and OLI (7,5,4) band combinations, converted to raster format and overlaid on the respective land-cover map. To separate *miombo* and *mopane* within the woodland class (also referred here as *woodland vegetation*, WV), first we used the phytogeographic map of Angola (Barbosa, 1970) to delineate each region. Then, the vector obtained for each type of woodland was overlaid on each land-cover map to separate the two vegetation types. Since fire occurrences were mainly detected in savanna areas, the burnt area was incorporated into that class. In addition, a water mask was applied to the final land-cover maps. Therefore, the final legend of the land cover maps was: *mopane woodland* (MO), *miombo woodland* (MI), *savanna woodland* (SW), *agriculture/bare soil* (AS), and *urban* (UR).

2.4.Accuracy assessment

To evaluate the accuracy of the land-cover maps, a dataset was created based on a systematic grid of points with a random origin and overlaid on high-resolution photographs, available on Google Earth, with dates between 2017 and 2019. The number of sample points used was 1000. Only points located within the study area were identified in terms of land-cover type (about 888 points). To minimize the errors associated with mislabelled points resulting from date differences, point labels were simultaneously checked in terms of spectral response observed in the Landsat images. Only the 2019 land-cover map was evaluated in terms of accuracy since there were no data for the other dates. This methodology was used in several previous studies (Cabral et al., 2010; Vasconcelos et al., 2015; Cabral and Costa, 2017; Temudo et al., 2020). When working with historical data series, the validation procedure (with a minimum of 80% accuracy) conducted for the most recent classification is considered valid for the earlier dates, if the same methodology is applied (Cabral et al., 2010; Vasconcelos et al., 2015; Cabral and Costa, 2017). Several accuracy measures were calculated: confusion matrix, kappa coefficient, and omissions and commission errors.

2.5.Land-cover transitions

Land-cover transitions between 1990 and 2019, and for each sub-period, were evaluated using a post-classification change detection technique performed with the Geographic Information System software ArcGIS 10.5.0.6491 (ESRI, 2016). Basically, it consisted of a cross-tabulation analysis of independently produced classifications for different dates, on a pixel-by-pixel basis, and it allowed quantifying the conversions from a particular land-cover to another and their corresponding areas in a specific period (Butt et al., 2015; Hassan et al., 2016; Negassa et al., 2020). The corresponding net change rates, which account for the expansion and reduction of the area of each land-cover class, were obtained using Puyravaud's (2003) formula. The net change rate of *woodland vegetation* was also evaluated by merging *miombo* and *mopane* into the same class. Finally, a map of change detection between 1990 and 2019 containing different combinations of “from-to” change classes was produced.

2.6.Charcoal production and selling

A fieldwork survey was done from June to September 2018, in the three municipalities, to characterize the production of charcoal and the associated commercial activity, and to understand how they might affect the *miombo* and *mopane woodlands*.

To characterize the production of charcoal, ten kilns were visited in the municipalities of Cacula and Bibala. In each case, the kiln type (earth mound kiln; rock mound kiln; earth pit kiln, see Fig. S1) and the vegetation used were recorded. Wood volume per kiln was measured and biomass per cubic metre was estimated for wood before production (by weighing a wood sample) and for charcoal after carbonisation (by counting the number of charcoal bags obtained).

Three main charcoal markets in Lubango municipality were identified (Mutundo, Hoque, and Rio Nangombe) where semi-structured interviews were done with charcoal sellers, complying with the code of ethics from the International Society of Ethnobiology (ISE, 2006), and methodologies referred in Alexiades and Sheldon (1996) and Albuquerque et al. (2014). The interviews were conducted after explaining the objectives of the work and obtaining informed consent. Prices were recorded in Angolan national currency (AKZ), and portable scales were used to weigh charcoal. To calculate monthly sales and profit figures at the markets, 25 days per month were considered, as each market closes one day per week. Thus, all retailers and wholesalers and/or suppliersin the markets were recorded, and the amount of charcoal bought and sold was estimated, as well as its price and economic importance for family income. With this information, it was possible to obtain an overview of how the charcoal chain was working in the three municipalities.

Additionally, the sale points along the roads linking Hoque to Cacula centre, and Rio Nangombe to Bibala centre, were identified (Fig. 2). These are points where rural communities sell wood-derived products such as charcoal and firewood. Sale points were selected to determine the selling price of charcoal at source and the quantity sold. Furthermore, as they are close to the production areas (i.e., near the kilns) and wood comes from the surrounding area, the main species used could be identified. To assess the environmental impact of this extraction of biomass from the woodlands, 5 km-buffer areas were defined around the main and secondary roads, and their patterns of land-cover dynamics and net change rates analysed in detail. The size of the buffer areas was defined considering the radius of action of firewood collection observed in the field.

3. Results

3.1.Land-cover analysis

The pairwise spectral separability analysis showed values higher than 1.5 (very high separability) for all class combinations. The accuracy of the 2019 land-cover map was evaluated by considering the woodlands as a single class (later separated into *miombo* and *mopane woodlands*), the *urban* area included in the *agriculture/bare soil* class, and the *water* class discarded.

The overall accuracy was above 90% and the Kappa coefficient was 0.84 for the 2019 land-cover map (Table S1), which indicates a high accuracy. Classes' accuracies were above 90%, except for the *agriculture/bare soil* and *urban* classes, which presented a higher omission error (19.34%) resulting from an incorrect assignment of the pixels to *savanna woodland*.

The land-cover maps for 1990, 2000, 2009, and 2019, and the corresponding land-cover evolution is displayed in Fig. 2, Fig. 3, respectively. The study area was dominated by *savanna woodland* and *agriculture/bare soil* in all the analysed years. Considering only the forest classes, *miombo woodland* had the largest area in all years except 2019, when the *mopane woodland* was larger.

Comparing the beginning and the end of the studied period (1990 and 2019), the *savanna woodland* increased by 22.15% (1418.82 km^2) and *agriculture/bare soil* by 4.49% (214.73 km^2), while *miombo woodland* decreased by 57.52% (1232.43 km^2) and *mopane woodland* by 33.51% (567.56 km^2). The *urban* area had an expansion of about 492.28% (166.44 km^2), occupying an area five-fold larger in 2019 than in 1990, though still representing only 1.33% of the total area (Fig. 3).

Between 1990 and 2000 (with ongoing civil war), forest cover increased by more than one-third (*miombo woodland* 32.91%, i.e., 705.04 km^2; *mopane woodland* increased about 34.80%, i.e., 589.39 km^2). The urban area increased by about 30.91% (10.45 km^2), whereas *agriculture/bare soil* and *savanna woodland* classes decreased by 24.21% (1157.64 km^2), and 2.30% (147.24 km^2), respectively (Fig. 3).

In this period (Table S2), most of the lost *savanna woodland* evolved into denser formations – about 18.09% (1159.32 km^2) to *miombo woodland* and 14.62% (936.75 km^2) to *mopane woodland*. A small part of *agriculture/bare soil* (about 2.32%, 111.09 km^2) became *miombo woodland* and 2.37% (113.69 km^2) became *mopane woodland*, while a large area (about 33.00%, 1578.25 km^2) was converted to *savanna woodland*.

In the last years of the civil war (2000–2009) and after its end (2009–2019), an inverse trend occurred: the area occupied by *agriculture/bare soil* and *savanna woodland* increased, and both *miombo* and *mopane woodlands* diminished. Between 2000 and 2009, about 35.47% (1819.58 km2) of *miombo woodland* and *mopane woodland* became *savanna woodland*, while in 2009–2019 the same occurred to 50.26% (1937.84 km2). Only a small proportion of non-savanna woodland (*miombo* and/or *mopane*) was converted to *agriculture/bare soil*: about 2.90% (148.95 km2) between 2000 and 2009, and 6.47% (249.84 km2) between 2009 and 2019. The expansion of *urban* areas continued throughout the studied period, although more profoundly in the last decade, at the expense of *agriculture/bare soil* and *savanna woodland* areas.

All municipalities presented the same trend for woodland classes: increased area in the first period, followed by a consistent decline. The opposite occurred in *agriculture/bare soil*, which decreased in the first period and increased subsequently. The *savanna woodland* exhibited a growing trend over the studied periods (except the first one) and was the most represented land use in the study area. However, in Lubango, the *agriculture/bare soil* class occupied the largest area. The urban area expanded in all periods, but with different intensities, and was only significant in Lubango. In the first period (1990–2000), the municipality of Cacula showed the highest increase in *miombo woodland* (with a gain of 36.02%, or 419.61 km2) and the more pronounced loss of *savanna woodland* (less 12.09%, or 250.92 km2). In that same period, Lubango had the smallest decrease in *agriculture/bare soil* (less 16.11%, or 269.35 km2) and the highest increase in *urban* area (more 36.68%, or 10.45 km2). In contrast, by end of the third decade (2009–2019) Cacula lost more than 65% of *miombo woodland* (762.55 km2) to *savanna woodland*, and about 16% (184.55 km2) to *agriculture/bare soil*; 25.24% (523.85 km2) of *savanna woodland* changed into *agriculture/bare soil* (Table S2).

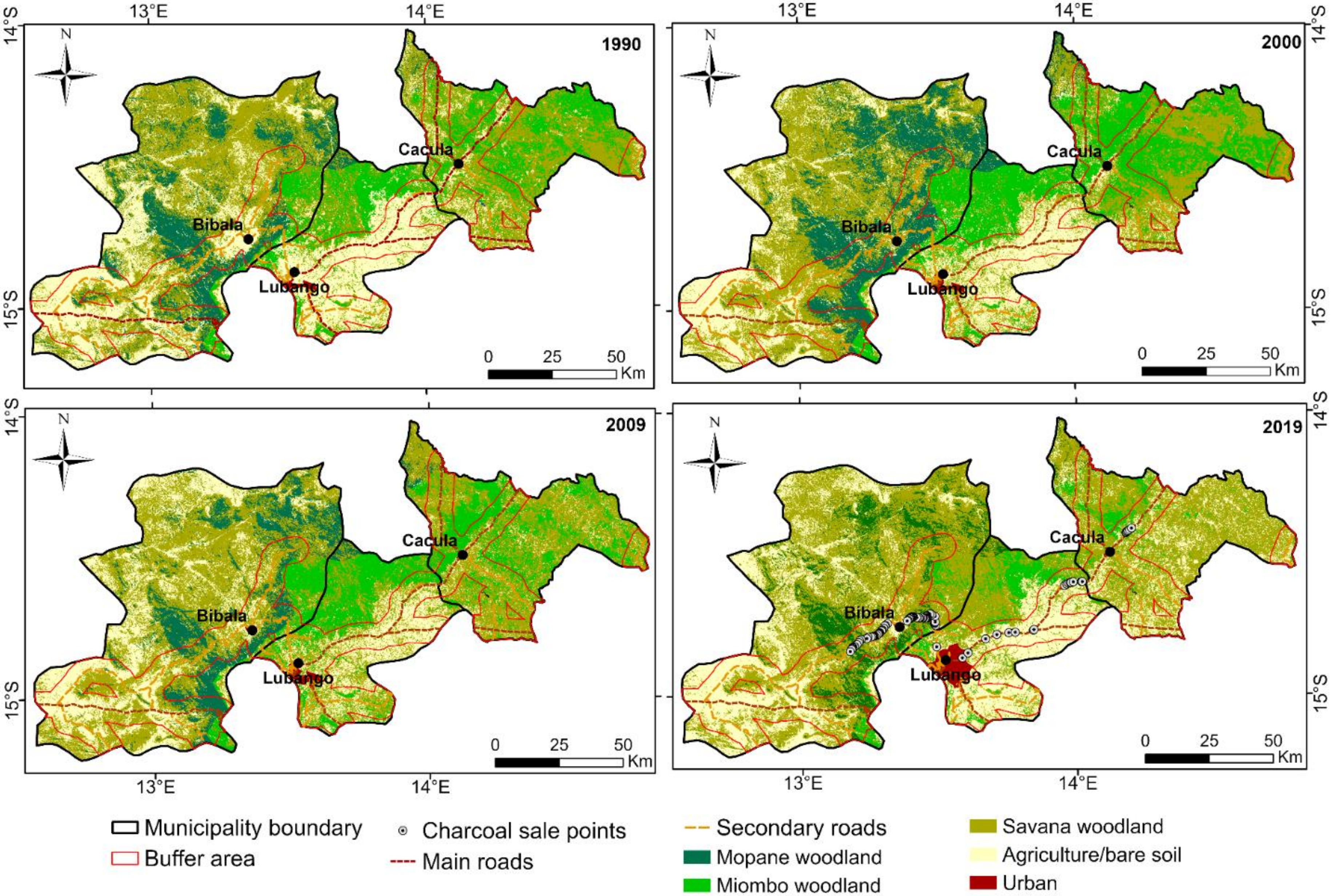
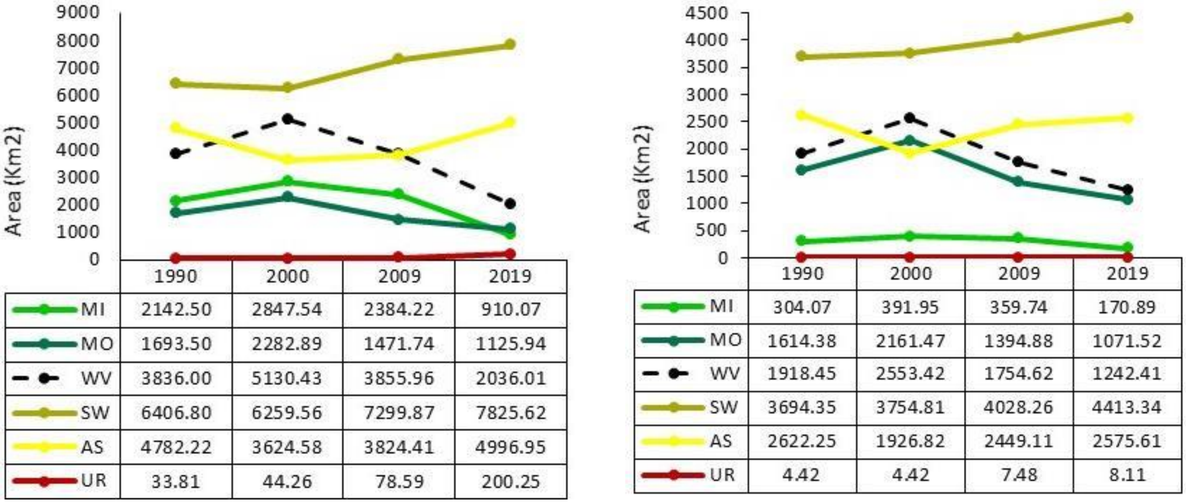


Fig. 1. Land-cover maps of the study area in 1990, 2000, 2009, and 2019. The white dots in the 2019 map represent the charcoal-selling places along the roads.

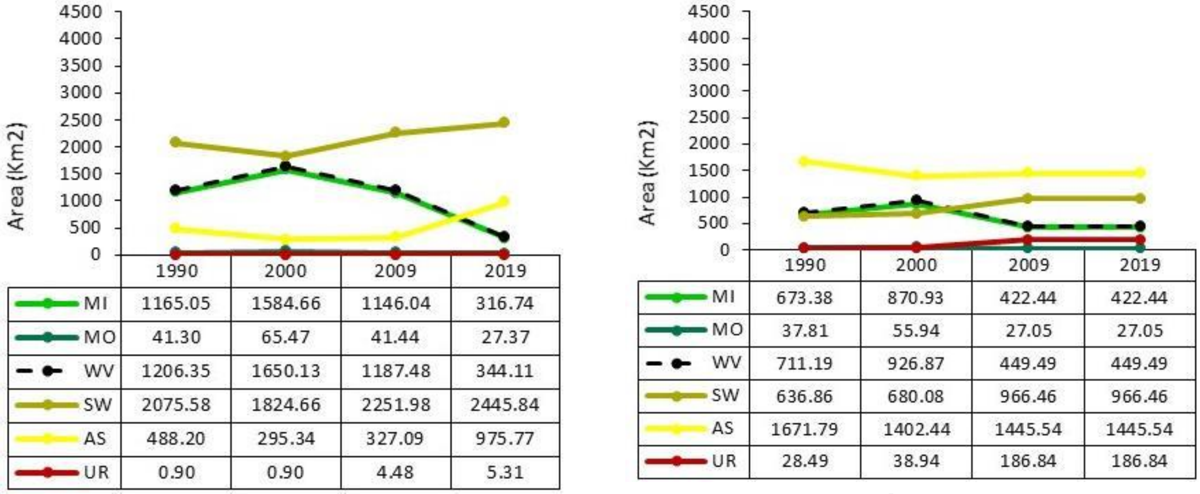


	1990	2000	2009	2019
MI	2142.50	2847.54	2384.22	910.07
MO	1693.50	2282.89	1471.74	1125.94
WV	3836.00	5130.43	3855.96	2036.01
SW	6406.80	6259.56	7299.87	7825.62
AS	4782.22	3624.58	3824.41	4996.95
UR	33.81	44.26	78.59	200.25

Study area

	1990	2000	2009	2019
MI	304.07	391.95	359.74	170.89
MO	1614.38	2161.47	1394.88	1071.52
WV	1918.45	2553.42	1754.62	1242.41
SW	3694.35	3754.81	4028.26	4413.34
AS	2622.25	1926.82	2449.11	2575.61
UR	4.42	4.42	7.48	8.11

Bibala



	1990	2000	2009	2019
MI	1165.05	1584.66	1146.04	316.74
MO	41.30	65.47	41.44	27.37
WV	1206.35	1650.13	1187.48	344.11
SW	2075.58	1824.66	2251.98	2445.84
AS	488.20	295.34	327.09	975.77
UR	0.90	0.90	4.48	5.31

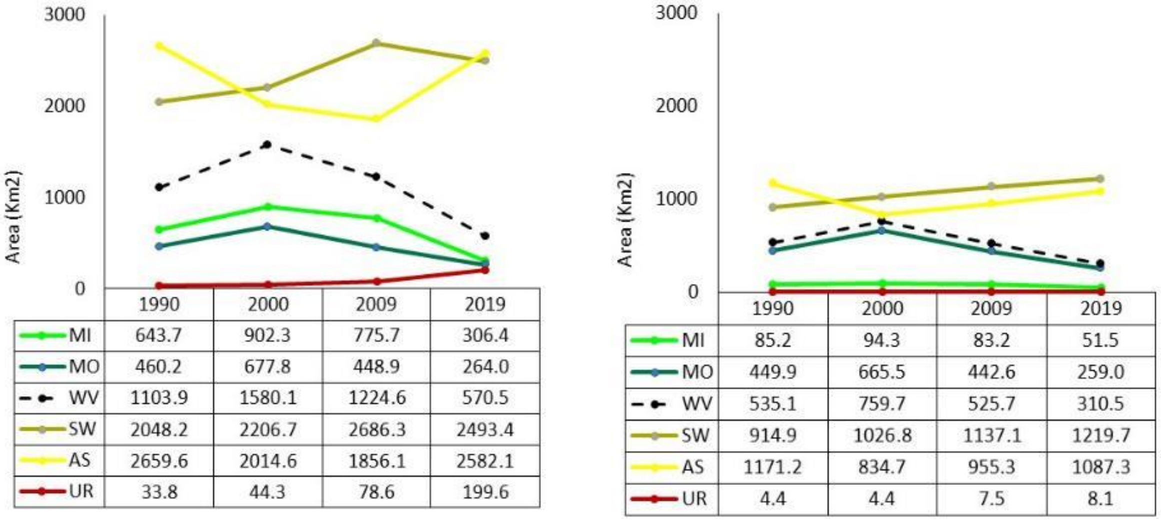
Cacula

	1990	2000	2009	2019
MI	673.38	870.93	422.44	422.44
MO	37.81	55.94	27.05	27.05
WV	711.19	926.87	449.49	449.49
SW	636.86	680.08	966.46	966.46
AS	1671.79	1402.44	1445.54	1445.54
UR	28.49	38.94	186.84	186.84

Lubango

Fig. 3. Representativeness of land-cover classes in the whole study area and in each of the three municipalities in the period 1990-2019. Land-cover classes: MI: *Miombo woodland*, MO: *Mopane woodland*; WV: *Woodland vegetation* (*miombo + mopane*); SW: *Savanna woodland*; AS: *Agriculture/bare soil*, UR: *Urban*.

The land-cover trend in the 5 km-buffer zones around the roads (Fig. 4) was similar: *savanna woodland* and *agriculture/bare soil* dominated in the three municipalities, and *woodland vegetation* decreased since 2000. *Savanna woodland* tended to increase and it was the most representative land-cover class except in Lubango municipality, where *agriculture/bare soil* dominated. Considering the whole period under analysis, the study area lost about 51.7% of the *woodlands* and Bibala was the municipality with the greatest loss (about 42.0%).

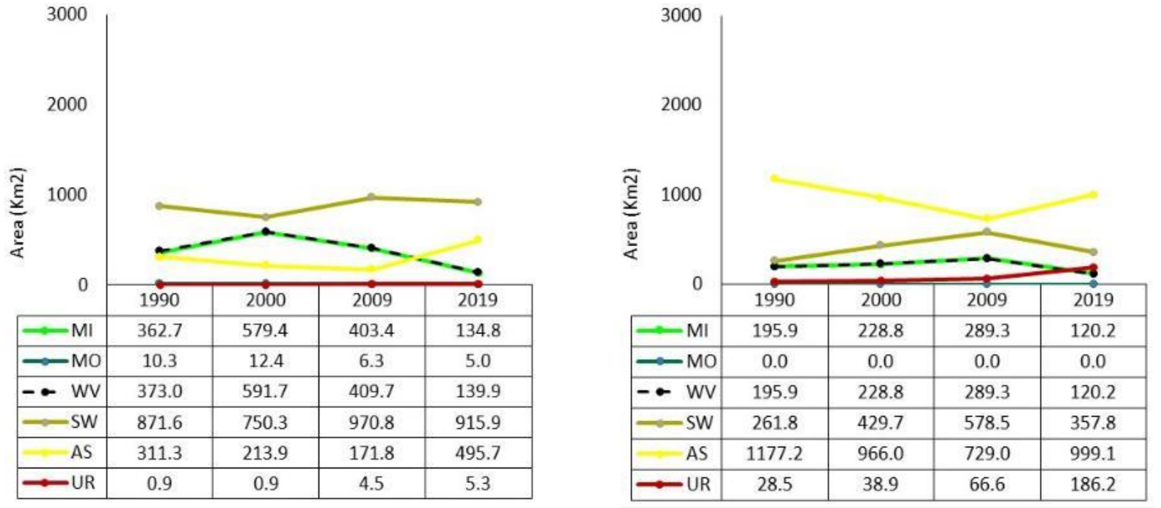


	1990	2000	2009	2019
MI	643.7	902.3	775.7	306.4
MO	460.2	677.8	448.9	264.0
WV	1103.9	1580.1	1224.6	570.5
SW	2048.2	2206.7	2686.3	2493.4
AS	2659.6	2014.6	1856.1	2582.1
UR	33.8	44.3	78.6	199.6

Study area

	1990	2000	2009	2019
MI	85.2	94.3	83.2	51.5
MO	449.9	665.5	442.6	259.0
WV	535.1	759.7	525.7	310.5
SW	914.9	1026.8	1137.1	1219.7
AS	1171.2	834.7	955.3	1087.3
UR	4.4	4.4	7.5	8.1

Bibala



	1990	2000	2009	2019
MI	362.7	579.4	403.4	134.8
MO	10.3	12.4	6.3	5.0
WV	373.0	591.7	409.7	139.9
SW	871.6	750.3	970.8	915.9
AS	311.3	213.9	171.8	495.7
UR	0.9	0.9	4.5	5.3

Cacula

	1990	2000	2009	2019
MI	195.9	228.8	289.3	120.2
MO	0.0	0.0	0.0	0.0
WV	195.9	228.8	289.3	120.2
SW	261.8	429.7	578.5	357.8
AS	1177.2	966.0	729.0	999.1
UR	28.5	38.9	66.6	186.2

Lubango

Fig. 4. Representativeness of land-cover classes in a 5 km-buffer area around the main and secondary roads in the period 1990-2019 for the whole study area, and for each of the three municipalities. Land-cover classes: MI: Miombo woodland, MO: Mopane woodland; WV: Woodland vegetation; SW: Savanna woodland; AS: Agriculture/bare soil, UR: Urban.

3.2.Net change rates

The change rates in the studied period are presented in Table 1, indicating the level of loss or gain for each land-cover class in a specific decade. From 1990 to 2019, *mopane woodland* and *miombo woodland* decreased, while *savanna woodland* and the non-forest classes (*agriculture/bare soil* and *urban*) increased, except in the buffer zone, where *agriculture/bare soil* showed a slight decrease. The greatest net loss of *miombo woodland* and *mopane woodland* occurred in the municipality of Cacula, associated with the largest net increase in *agriculture/bare soil* class (Table 1). The municipality with the highest net increase in urban area was Lubango, followed by Cacula. Between 1990 and 2000 the area of the forest classes considerably increased in all municipalities (Table 1). In the following periods, the rate became negative in those classes and positive in the non-forest cover classes, except for the buffer zone where *agriculture/bare soil* had negative increment in 2000–2009. The greatest forest loss occurred in the municipality of Cacula in 2009–2019, for *miombo woodland*.

Table 1. Net annual change rates of each land-cover class in the whole study area and in each of the three municipalities, considering whole areas and to 5 km-buffer areas around roads. Land-cover classes: MI: *Miombo woodland*; MO: *Mopane woodland*; WV: *woodland vegetation*; SW: *Savanna woodland*; AS: *Agriculture/bare soil*; UR: *Urban.*

		Net change rate (%/year)							
		1990-2000		**2000-2009**		**2009-2019**		**1990-2019**	
Area (km2)	Classes	Buffer	Whole	Buffer	Whole	Buffer	Whole	**Buffer**	**Whole**
Study area	MI	3.38	2.84	-1.68	-1.97	-9.29	-9.63	**-2.56**	**-2.95**
	MO	3.87	2.99	-4.58	-4.88	-5.31	-2.68	**-1.92**	**-1.41**
	WV	3.59	2.91	-2.83	-3.17	-7.64	-6.39	**-2.28**	**-2.18**
	SW	0.75	-0.23	2.19	1.71	-0.75	0.70	**0.68**	**0.69**
	AS	-2.78	-2.77	-0.91	0.60	3.30	2.67	**-0.10**	**0.15**
	UR	2.69	2.91	6.38	6.38	9.32	9.35	**6.12**	**6.13**
Bibala	MI	1.02	2.54	-1.39	-0.95	-4.80	-7.44	**-1.74**	**-1.99**
	MO	3.91	2.92	-4.53	-4.87	-5.36	-2.64	**-1.90**	**-1.41**
	WV	3.51	2.86	-4.09	-4.17	-5.27	-3.45	**-1.88**	**-1.50**
	SW	1.15	0.16	1.13	0.78	0.70	0.91	**0.99**	**0.61**
	AS	-3.39	-3.08	1.50	2.67	1.29	0.50	**-0.26**	**-0.06**
	UR	0.00	0.00	5.83	5.84	0.78	0.80	**2.08**	**2.09**
Cacula	MI	4.68	3.08	-4.02	-3.60	-10.96	-12.86	**-3.41**	**-4.49**
	MO	1.80	4.61	-7.48	-5.08	-2.29	-4.15	**-2.49**	**-1.42**
	WV	4.61	3.13	-4.08	-3.66	-10.75	-12.39	**-3.38**	**-4.33**
	SW	-1.50	-1.29	2.86	2.34	-0.58	0.83	**0.17**	**0.57**
	AS	-3.75	-5.03	-2.44	1.13	10.60	10.93	**1.60**	**2.39**
	UR	0.00	0.00	17.88	17.83	1.70	1.70	**6.14**	**6.12**
Lubango	MI	1.55	2.57	2.61	0.10	-8.78	-7.32	**-1.68**	**-1.61**
	MO	0.00	3.92	0.00	-5.08	0.00	-2.69	**0.00**	**-1.15**
	WV	1.55	2.65	2.61	-0.16	-8.78	-7.10	**-1.68**	**-1.58**
	SW	4.95	0.66	3.31	4.50	-4.80	-0.54	**1.08**	**1.44**
	AS	-1.98	-1.76	-3.13	-3.23	3.15	3.21	**-0.57**	**-0.50**
	UR	3.12	3.12	5.97	5.97	10.28	10.31	**6.47**	**6.49**

3.3.Land-cover transitions

The spatial transitions among land-cover classes between 1990 and 2019 are represented in a change detection map (Fig. 5A) and in a land transition matrix (Table 2). More than one-third of the study area (about 34.79%) changed from one class to another. About 23.17% (3489.91 km2) are associated with deforestation and forest degradation processes (from *miombo woodland* and *mopane woodland* to *savanna woodland* and *agriculture/bare soil*, and from *savanna woodland* to *agriculture/bare soil*), while 10.50% (1581.85 km2) represent *woodland* recovery (*agriculture/bare soil* to *savanna woodland*, *savanna woodland* to *miombo* and/or *mopane woodlands*, and *agriculture/bare soil* to *miombo* and/or *mopane woodlands*). The increase in *urban area* (1.1%, or 166.77 km2) mainly corresponds to the cities' surroundings that, in 1990, were mostly *agricultural/bare-soil* land and, to a lesser extent, *savanna woodland* and *miombo woodland*.

Table 2. Land transition matrix for land-cover classes in the study area between 1990 and 2019. Mopane and miombo woodlands are here included in the same class (Woodland vegetation). W: Woodland vegetation, SW: Savanna woodland; AS: Agriculture/bare soil and UR: Urban.

Study area (km^2)						
Year	**1990**					
2019	Class	W	SW	AS	UR	Total
	W	1546.06	428.50	61.45	0	2036.01
	SW	1969.80	4763.92	1091.90	0	7825.62
	AS	317.42	1202.69	3476.51	0.33	4996.95
	UR	2.72	11.69	152.36	33.48	200.25
	Total	3836	6406.8	4782.22	33.81	15058.80

Located to the north of Bibala (a municipality characterized by important charcoal production), Area 1 showed an increase in *woodland vegetation* (Fig. 5A), mainly associated with *mopane* recovery. Area 2 presented two trends, a conversion of *miombo woodland* into *savanna woodland* and some conversion of *agriculture/bare soil* into *savanna woodland* and *woodland vegetation*. Area 3, in the Cacula municipality, underwent a large expansion of *agriculture/bare soil* resulting from the loss of *woodland* and *savanna woodland* patches (Fig. 5B). In Lubango municipality, where the provincial capital is located, there was a large expansion of the *urban* area, mostly linked to the conversion of *agriculture/bare soil* and, to a lesser extent, of *savanna woodland*. In this municipality, there was also an increase of *savanna woodland*, resulting from the conversion of *agriculture/bare soil* and *woodland vegetation* areas.

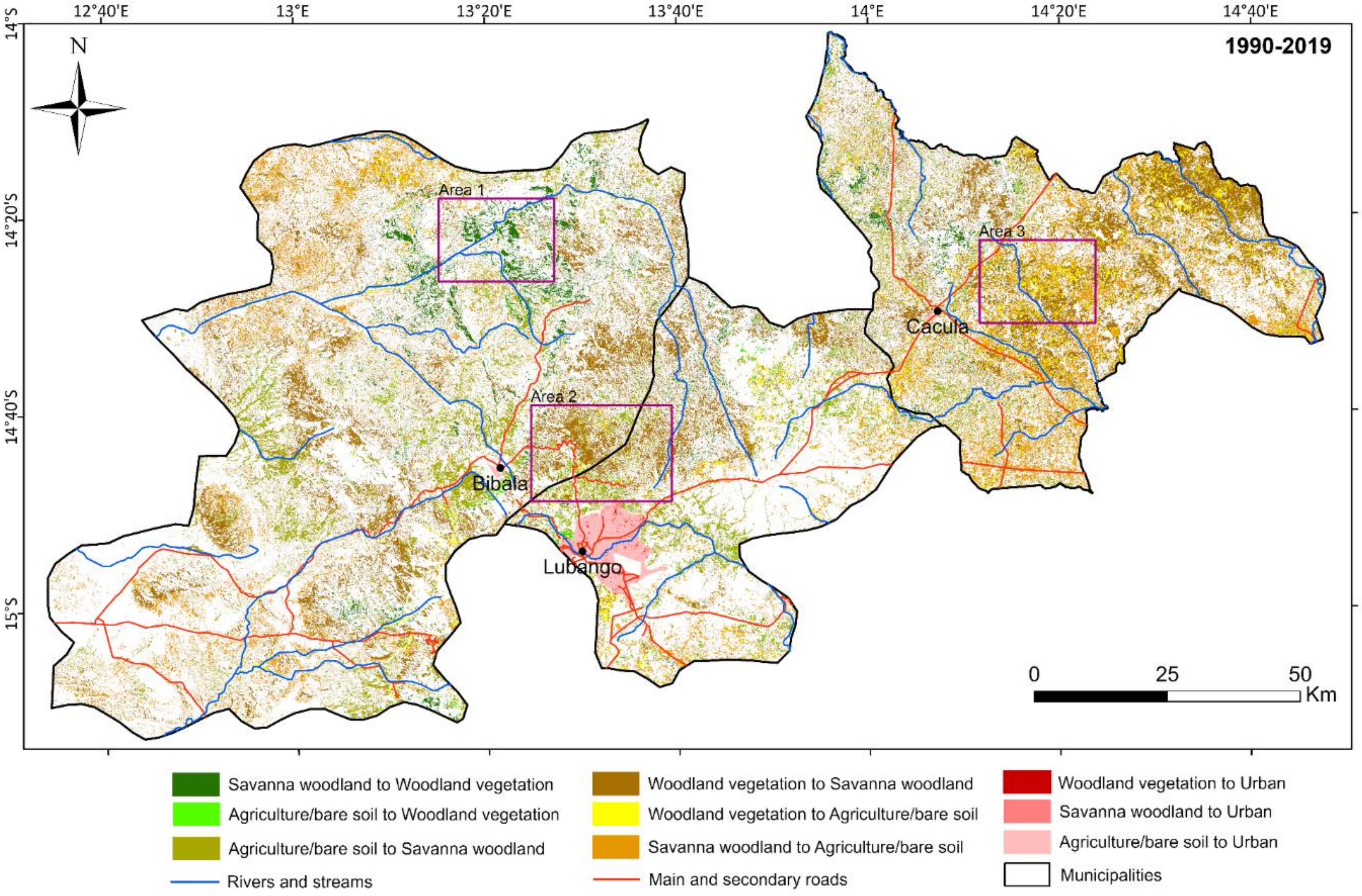
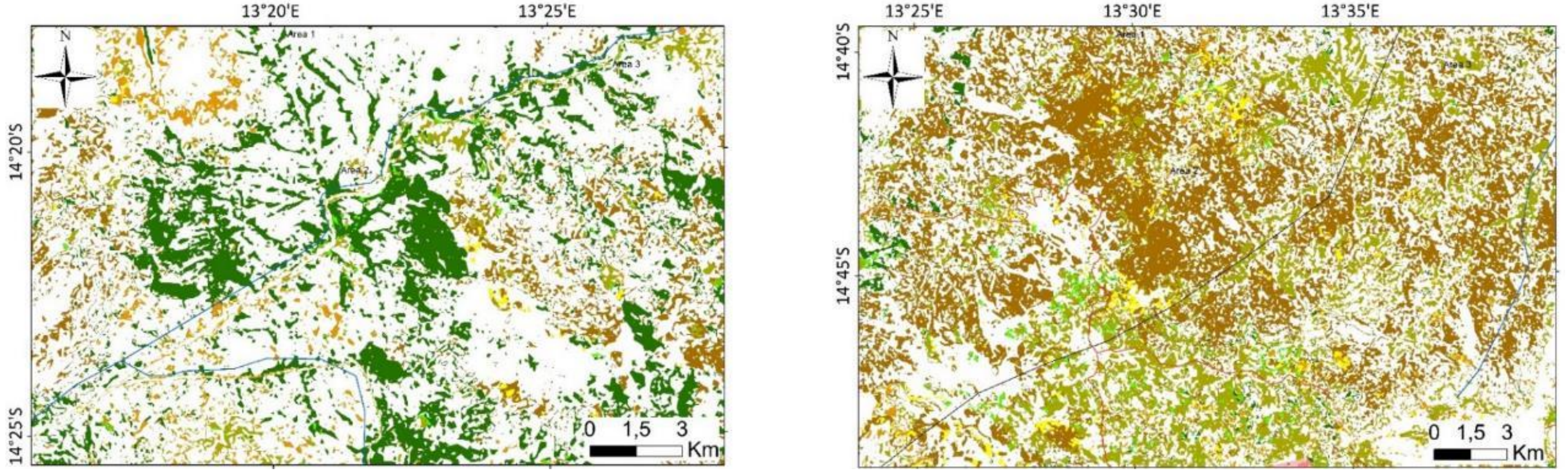
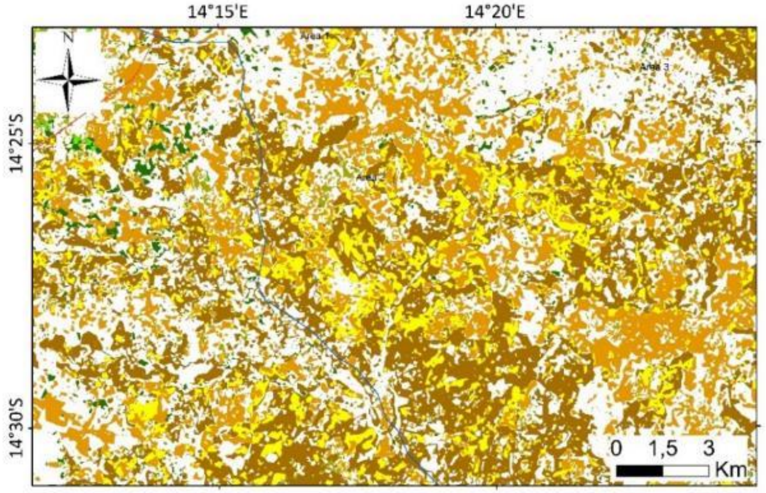


Fig. 5A. Change detection map for land-cover classes in the study area between 1990 and 2019. The purple rectangles represent areas detailed in Figure 5B. *Mopane* and *miombo* woodlands are here included in the same class (*Woodland vegetation).*



Area 1

Area 2



Area 3

Fig. 5B. Details of the change detection map, concerning the three areas marked with purple rectangles in Figure 5A, from the municipalities of Bibala (Area 1), Lubango and Bibala (Area 2) and Cacula (Area 3).

3.4.Dynamics of charcoal production and trade

3.4.1. The production of charcoal near Lubango

The charcoal traded in the markets of Lubango city chiefly originates from the municipalities of Cacula (miombo woodland) and Bibala (mopane woodland). Only small quantities of charcoal are produced in the Lubango municipality. Charcoal is primarily transported by motorcycles and trucks, but due to the high slopes in Bibala, train and donkey are frequently used. There are three types of traditional kilns: 1) earth pit kiln; 2) earth mound kiln, and 3) rock mound kiln.

Charcoal is named locally after the most common species of trees used in its manufacture. In *miombo*, *mupanda* charcoal is made from *Brachystegia spiciformis*, *mumwe* charcoal from *Julbernardia paniculata*, and *mupupu* charcoal from *Combretum collinum*. In *mopane* there is more variation: *mutiati* charcoal is made from *Colophospermum mopane*, *mupapa* charcoal from *Spirostachys africana*, *muviu* charcoal from *Pterocarpus* spp. and *mukondo* charcoal from *Acacia senegal*.

The charcoal is packed in several types of bags, namely: ordinary bags, with a capacity of about 50 L and 33.5–40 kg; big bags, of 60–65 kg; medium bags, of 20–25 kg; and small bags, of 10–12 kg. Most of the charcoal is sold in ordinary bags (Fig. S1).

Eight charcoal producers (called “carvoeiros”) were interviewed, five in Cacula and three in Bibala (Table 3A). Most of them (six) were men aged over 30 years, with primary level of schooling, and households of six members on average. Most respondents consider the sale of charcoal as their main source of income to pay for goods and services. Among these, the most frequently mentioned items were smartphones and motorcycles, as well as bicycles, radios, electric generators, and televisions.

Ten kilns of different types and sizes were visited and analysed, five of which were earth pit, two earth mound, and three rock mound kilns (Table 3B), with initial biomasses ranging from 10.6 to 109.4 tons of wood per kiln, and producing 1050 to 10 500 kg of charcoal (average 6709 kg). The average kiln efficiency was 13.83%, ranging from 6.91 to 26.06%. The rock mound kilns were more efficient than the other kiln types.

3.4.2. Charcoal trade and consumption

The fieldwork survey showed that charcoal is mainly traded in three markets of the Lubango municipality, and alongside the main roads linking this municipality with Cacula and Bibala (see Fig. 2). At those markets, 108 charcoal sellers were identified: 40 in Hoque, 45 in Mutundo and 23 in Rio Nangombe; 27 of them were wholesalers, and 81 retailers (Table 4A). Fifty-two interviews were carried out with sellers, among which 18 wholesalers and 34 retailers. The majority of charcoal sellers were young and middle-aged women with average households of 6 members.

Table 3
A Data on the production of charcoal in the villages of the Cacula and Bibala municipalities and profile of the interviewed producers.

Municipality	Cacula	Bibala
Type of vegetation source	Miombo	Mopane
Producers interviewed (M: male; F: female)	5 (5M)	3 (2F/1M)
Average household members	7	5
Average size of kilns (m^3)	87	35
Kilns made by family/month	2-3	2-3
Ordinary bags of charcoal by kiln	30-300	60-250
Approximate number of bags sold per day	7	6

Table 3
B Data on kilns visited during fieldwork: biomass before carbonification, final amount of charcoal, and kiln efficiency. The source vegetation type is also indicated.

Type of kiln	Vegetation type	Initial biomass (tons)	Charcoal produced (kg)	Kiln efficiency (%)
earth pit kiln	miombo	81.0	5600	6.91
earth mound kiln	miombo	10.6	1050	9.96
earth pit kiln	miombo	109.4	10500	9.60
earth pit kiln	miombo	77.5	7000	9.04
earth mound kiln	miombo	81.7	9450	11.56
rock mound kiln	mopane	15.2	2100	13.83
earth pit kiln	mopane	20.3	2280	11.26
earth pit kiln	mopane	57.5	8750	15.23
rock mound kiln	mopane	29.2	7600	26.06
rock mound kiln	mopane	26.0	6460	24.81

The contribution of charcoal trade to family income was considered important by all the interviewed sellers and always represented more than half of the total household income. Most of the charcoal sold in the markets originated in the *miombo woodland*, and the sellers bought it in the regions of Hoque (33 sellers) and Rio Nangombe (10 sellers), as well as Humbia (4), Cacula (3), and Kipamba (1).

Table 4B shows the results of the interviews at Lubango markets. The price (and obtained revenue) of charcoal varied between the three markets, and also depended on it being sold by retailers or wholesalers. The average selling price per kilogram reported by wholesalers ranged from about AKZ 37 to AKZ 60, while retailers indicated prices between AKZ 60 and AKZ 78. It should be noted that the wholesalers also sell to the public, but only in ordinary bags. Wholesalers sold between 135 and 350 kg of charcoal daily, while the figures for retailers ranged between 17 and 85 kg.

The estimated monthly profit from charcoal sale was much higher for wholesalers (between approximately AKZ 100000 and AKZ 130000) than for retailers (between AKZ 16000 and AKZ 47000). In either case, the lowest value was recorded in the Nangombe River market (Table 4B). It should be noted that this market, located in the outskirts, had only recently been established and had still a small number of sellers when the study was carried out.

Typically, wholesalers obtained charcoal from suppliers and/or producers at production sites and sold it to retailers and to the community. However, retailers could also source charcoal directly from producers, such as from the Nangombe River market. The charcoal sale points identified along the roads from Lubango to Cacula and Bibala can be seen in Fig. 2. As the distance increased from urban centres or suburban markets, there was an increase in the number of bags of charcoal for sale. The price is higher in the urban centres and in locations farther from the production areas.

Table 4
A Data on charcoal trade in Mutundo, Hoque and Rio Nangombe markets, in the municipality of Lubango, obtained from June to September of 2018: characterization of the sale and socio-economic profile of wholesalers and retailers.

	Type of seller	**Wholesalers**				**Retailers**				
	Market	Hoque	Mutundo	Rio Nangombe	Total	Hoque	Mutundo	Rio Nangombe	Total	**Grand Total**
Nr. Of Sellers	Total	5	15	7	27	35	30	16	81	**108**
	Interviewed	3	10	5	18	15	9	10	34	**52**
Gender	Female	1	10	5	16	15	9	10	34	**50**
	Male	2	-	-	2	-	-	-	-	**2**
Age	Young adult (<30 yrs)	-	6	-	6	8	4	3	15	**21**
	Adult (30-50 yrs)	2	4	5	11	4	4	3	11	**22**
	Senior (>50 yrs)	1	-	-	1	3	1	4	8	**9**
Household size	Average	9.7	5.7	5.8	6.4	6.1	7.4	5.8	6.3	**6.4**
	Min	9	4	4	4	3	5	2	2	**2**
	Max	10	7	8	10	13	14	9	14	**14**
Ethnic Group	Mwila	3	-	3	6	13	1	-	14	**20**
	Nyaneka	-	10	2	12	-	-	1	1	**13**
	Ovimbundo	-	-	-	-	2	8	9	19	**19**
Contribution to family Income	50-75%	3	10	2	15	15	9	10	34	**49**
	> 75%	-	-	3	3	-	-	-	-	**3**

Table 4
B Estimates of sales and profits obtained with the selling of charcoal by the interviewed wholesalers and retailers at the Lubango markets. Values without brackets are averages and values within brackets are the minimum and maximum for each parameter.

	Class of seller	**Wholesales**	**Retailers**
Hoque	Purchase price (AKZ/kg)	22.4 (14.9-26.9)	41.5 (37.3-44.8)
	Selling price (AKZ /kg)	37.3 (22.4-46.3)	60.9 (59.7-89.6)
	Daily sale (Kg)	357.3 (268.0-402.0)	57.0 (16.8-134.0)
	Daily profit (AKZ)	5 324.0 (2002.0-7 811.0)	1106.0 (376.0-6 003.0)
	Monthly profit (AKZ)	133 094.0 (50 049.0-195 272.0)	27 659.0 (9 408.0-150 080.0)
Mutundo	Purchase price (AKZ/kg)	29.9 (26.9-32.8)	40.1 (37.3-44.8)
	Selling price (AKZ /kg)	59.7 (44.8-74.6)	61.9 (59.7-89.6)
	Daily sale (Kg)	135.4 (100.5-167.5)	85.6 (33.5-268.0)
	Daily profit (AKZ)	4 035.0 (1 799.0-7 007.0)	1 866.0 (750.0-12 006.0)
	Monthly profit (AKZ)	123 158.0 (44 794.0-175 163.0)	46 652.0 (18 760.0-300 160.0)
Rio Nangombe	Purchase price (AKZ/kg)	29.9 (23.9-35.8)	41.7 (29.9-55.0)
	Selling price (AKZ/kg)	59.7 (53.7-62.7)	78.1 (61.5-90.0)
	Daily sale (Kg)	134.0 (134.0-134.0)	17.3 (5.0-50.3)
	Daily profit (AKZ)	3 993.0 (3 193.0-4 393.0)	630 (158.0-1760.0)
	Monthly profit (AKZ)	99 835.0 (79 835.0-109 835.0)	743 (3 950.0-44 012.0)

4. Discussion

Our study identified and quantified trends in land-cover change in southwestern Angola in recent decades, which can be related to social and demographic dynamics in this region. The main land-cover transitions in the study area occurred from forest vegetation (*miombo woodland* and *mopane woodland*) to *savanna woodland*, and from *savanna woodland* to *agriculture/bare soil*, which means deforestation and forest degradation; the inverse trend also occurred, upon forest vegetation recovery in certain areas and periods.

The multitemporal analysis showed an increase of the *miombo* and *mopane woodlands* in 1990–2000, and their decrease in the following two decades, which can be explained by the socioeconomic changes associated with the periods of civil war and post-civil war. The woodland regeneration observed in the first studied decade can be attributed to decreased agricultural activity due to the rural exodus prompted by the civil war (Birkeland, 2000; Robson and Roque, 2001). Then, forest vegetation expanded, in contrast with wild large mammals (Kibble, 2006), frequently hunted for human consumption during that period. Several authors report this tendency for different regions in central and southern Angola, namely Huambo (Cabral et al., 2010), Bié and Cuando Cubango (Schneibel et al., 2016, 2017b), Huíla (Chisingui, 2017), and Zaire (Temudo et al., 2020). A comparable trend of forest loss decrease during a war period was observed in other countries like Iran (Heidarlou et al., 2020). Also, FAOSTAT (2023) indicates a reduction of more than 65% of the land under permanent crops in Angola during war periods. Indeed, the civil war-driven rural migration occurred in almost all the Angolan territory, compromising people's food security due to the drop in food production (Hilhorst and Serrano, 2010). Deforestation targeting agricultural activities in the TFO (The Future Okavango) project area, in central and southern Angola, decreased by more than 70% per year (from 12 000 to 4000 ha) between 1994 and 1998, but increased to 12 000 ha per year after 2002 (Schneibel et al. (2017b).

Accordingly, our data showed that between 1990 and 2000 the cover of woodland classes in the study area was considerably extended, but decreased afterwards, while the non-forest classes increased. This phenomenon was observed when specifically analysing areas around the main and secondary roads, but also in all municipalities, meaning that human activities affect all the study area. Considering the whole studied period (1990–2019), deforestation rates in the study area, translate in “net annual change rates” (-2.18 % yr−1), and in each municipality (−1.50% yr−1 for Bibala, −4.33% yr−1 for Cacula, and −1.58% yr−1 for

Lubango) were higher than the figures published by FAO (2021): −0.20% yr−1 between 1990 and 2000, -0.74% yr−1 from 2000 to 2010, and -0.80% yr−1 from 2010 to 2020. These differences can be attributed to the fact that FAO calculates values at the country level while our values report to the regional level. Moreover, different data sources and methodologies were used, which might further explain the different estimates of deforestation rates, as mentioned by Ramankutty et al. (2007). For instance, McNicol et al. (2018) estimated an overall deforestation rate of −2.8% per year across southern Africa between 2007 and 2010, a value 7.8 and 9.4 times higher than those presented by FAO (2015) and Hansen et al. (2013), respectively. The systematization of forest inventories and the production of land-cover maps allow to obtain more accurate data at the local level (FAO-FRA, 2020a; FAO, 2021), as opposed to global data, which involve a high level of generalization (Fairhead and Leach, 1998).

Some social dynamic factors seem to have been of great importance in shaping land-cover in southwestern Angola in recent decades. In our study area, there is a clear sink effect of Lubango, Angola's second largest town, on the natural resources, and consequences on land-cover are reflected in the surrounding areas where goods are produced or harvested to supply the urban population. Overall a higher deforestation rate was detected along roads and around cities, where direct access to communication infrastructures facilitates the flow of agricultural and forest products (e.g., vegetables, fruits, charcoal, firewood, and mushrooms). Identical trends in other places of Angola have been reported (Schneibel et al., 2016, 2017a; Temudo et al., 2020). This can be explained by the return of many refugees to the rural areas and to traditional agricultural and extractive activities, after the end of the civil war in 2002. On the other hand, although areas close to roads are more easily accessible, the fact that deforestation is policed means that charcoal production moves to areas further away from roads, which may explain the lesser deforestation near roads in some places.

Another phenomenon in this period was the occupation of unused land by outsiders who sought to maximize yields within short periods, leading to intensified deforestation and forest degradation in some places. It is likely that this phenomenon also occurred in the study area over the last two decades. Furthermore, increased logging led to the overexploitation of valuable tree species, forcing the government to strengthen regulations and coercion measures against deforestation and forest degradation across the country. The *Lei de base da flora e fauna selvagem* (República de Angola, 2017), and the *Regulamento florestal* (República de Angola, 2018a) are intended to preserve wildlife and forest resources, and the

Executive Decree No. 278/18 (República de Angola, 2018b) aims to preserve the populations of important tree species such as *Guibourtia coleosperma* and *Swartzia fistuloides*. These actions are expected to slow down deforestation and forest degradation in the long term, particularly in areas close to populations and roads.

Considering the change map between 1990 and 2019, it can be stated that, despite the low population density in rural areas, there was human impact on the vegetation of the whole study area. Activities affecting natural vegetation include agriculture, cattle raising, charcoal and timber harvesting, and extraction of minerals for construction. The new *miombo* and *mopane woodland* areas are probably plots of forest that recovered in the first studied decade and have not been logged since. In areas far from the main settlements and roads, it is likely that some of the people who migrated to the cities did not return, as is the case of Area 1 in Fig. 5B, thus allowing the regeneration of woodlands. On the other hand, some areas closer to towns and roads underwent high levels of conversion from *woodlands* to *savanna woodland* associated with logging activities; these might be reduced or prevented through the monitoring of forest logging by the relevant authorities, namely the Forest Development Institute (Instituto de Desenvolvimento Florestal) (Area 2 in Fig. 5B). In fact, much of the forest-to-savanna conversion in the study area results from the selective felling of trees for timber, firewood, and charcoal production, as well as extraction of aggregates. These land patches are also often used for cattle grazing (Area 3 in Fig. 5B). Conversely, the transition from agricultural land and bare soil to *savanna woodland* can be explained by factors such as land abandonment by absentee owners and the delimitation of land to create state reserves under the land law (República de Angola, 2004; Foley, 2007; Unruh, 2012).

According to FAOSTAT (2023), the consumption of charcoal in Angola has continuously grown over the last decades (e.g., 1976: 82 129 tons; 1990: 130 139 tons; 2002: 220 768 tons; 2021: 417 563 tons). It seems clear that charcoal production contributes to deforestation and forest degradation. However, it can be difficult to separate charcoal production from the cutting of forest vegetation for fuelwood and agricultural activities, as they are often related (Chiteculo et al., 2018b). The International Energy Agency (2006) shows that an earth pit kiln measuring approximately 9 × 4 m can produce 1800–2000 kg of charcoal. The rate of forest degradation/destruction is related with the low efficiency of charcoal production since the firewood-to-charcoal conversion ratio accepted for Angola is 9.6 m3 of firewood to 1000 kg of charcoal, that is, 7 tons of wood to produce 1 ton of charcoal, with an efficiency of 14%. The efficiencies can vary depending on the tree species involved, the size and kiln type, as well as the experience of the producer. For example, the reported efficiency of traditional kilns is about 11–30% (Malimbwi et al., 2005; Chidumayo and Gumbo, 2010). According to these authors the most efficient kilns are from the larger and superficial type. Those values are comparable with those from our study: average efficiency of 13.83%, range 6.91–26.96%. Also, the rock mound kilns seem to be the most efficient ones.

The city of Lubango acts as a sink for the charcoal produced in the neighbouring municipalities. Our estimate of charcoal consumption in this city and of the wood biomass needed to make it indicates that in Lubango's three main markets about 9600 kg of charcoal are sold daily, i.e., 2879 tons per year. Considering the calculated carbonification efficiency, about 22 109 tons of wood per year are needed to produce that charcoal. Such rates of wood cutting for charcoal production in the woodlands of southwestern Angola are currently unsustainable, as reported by Miapia et al. (2021). Despite the small number of charcoal burners interviewed, we can estimate that by doing 2 or 3 kilns per month, each one uses between 1219.2 and 1828.8 tons of wood per year. Adopting the country's ground biomass density of 70 t/ha (Bouvet et al., 2018) for our study area, we can estimate that a charcoal-producing household can deforest between 17 and 26 ha per year, an average of c. 0,7 ha by kiln. However, given that not all tree species are used to make charcoal and not all individuals are of an appropriate size, the average area of forest used per kiln may be closer to 1 ha.

However, the data we collected have some limitations and only allow to make a rough estimate of the charcoal produced and consumed. Three markets were sampled in Lubango, but there are other markets that supply this city. On the other hand, most of the charcoal sold along the roads leading to the capital is bought by final consumers living either in the city of Lubango or in cities outside our study area (e.g., Namibe). Another uncertainty factor is that, as the production and sale of charcoal is monitored by local authorities, the values reported in the surveys may be lower than the real ones. Nevertheless, it can be stated that charcoal production is one of the activities that contributes most to deforestation and forest degradation in the outskirts of Lubango town. Other related factors are the clearing of forest vegetation for agriculture and livestock, as well as the extraction of firewood.

5. Conclusion

The miombo and mopane woodlands in the study area, in southwestern Angola, are affected by both deforestation for agricultural practices, and forest degradation from the extraction of woody forest products and charcoal production. Our research demonstrated that over the recent decades these woodlands underwent high rates of deforestation, which resulted in important land-cover changes, mainly for agricultural purposes after the end of the civil war. However, some patches of woodlands regenerated upon abandonment of agricultural areas and of decreased exploitation of savanna woodland. Agriculture and woody and non-woody forest products are vital for local livelihoods, preventing households from falling into poverty by providing alternative sources of income, food, medicine, and energy (Campbell et al., 2007; Chidumayo and Gumbo, 2010). Indirect factors such as population growth, proximity to roads and markets, soil and vegetation types, socio-cultural and ethnic factors such as the agricultural or pastoral traditions, and the ability to produce and trade charcoal, among others, modulate the supply and demand for forest products in rural and urban areas. Thus, it is essential to implement conservation measures that contribute to the maintenance of natural vegetation while providing access of local populations to essential goods, reducing poverty. One way is through community programs that offer payments to compensate for conservation activities. Also, increased valuation of non-timber forest products and agricultural products, increased promotion of the use of gas for cooking, sustainable charcoal production from forest plantations, and implementation of agroforestry systems can be good tools to halt the clearing of forests for agriculture, logging, and charcoal production.

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Ethical statement

The preparation of this manuscript needs no ethical consideration more than the necessary references.

CRediT authorship contribution statement

Raquel Kissanga: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Luís Catarino**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Cristina Máguas**: Conceptualization, Writing – review & editing. Ana **I.R. Cabral**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supporting Information

Table S1. Path/Row coordinates and dates of the Landsat images.

Path	Row	1st date	2nd date	3rd date	4th date
181	70	22/07/1990	01/07/2000	23/05/2009	06/07/2019
181	71	22/07/1990	01/07/2000	23/05/2009	06/07/2019
182	70	29/07/1990	22/06/2000	30/05/2009	11/06/2019
182	71	29/07/1990	22/06/2000	30/05/2009	27/06/2019

Fig. S1. A kiln dug into the ground before the carbonization process; B: the two main types of bags in which coal is usually packed and marketed: 1) ordinary bag; 2) large bag.

Table S2. Transition matrices of land cover classes (km^2) for the periods 1990-2000, 2000-2009, 2009-2019, and 1990-2019 to the study area and to each municipality. MO: Mopane woodland, MI: Miombo woodland, SW: Savanna woodland; AS: Agriculture/bare soil and UR: Urban.

	Study area								Bibala						
Year			1990					Year			1990				
	Class	MI	MO	SW	AS	UR	Total		Class	MI	MO	SW	AS	UR	Total
	MI	1577.10	0.00	1159.32	111.09	0.03	2847.54		MI	279.16	0.00	97.67	15.12	0.00	391.95
2000	MO	0.00	1232.45	936.75	113.69	0.00	2282.89	2000	MO	0.00	1170.16	882.84	108.47	0.00	2161.47
	SA	506.09	417.60	3757.33	1578.25	0.29	6259.56		SA	17.46	401.90	2416.30	919.15	0.00	3754.81
	AS	59.25	43.45	553.18	2968.48	0.22	3624.58		AS	7.45	42.32	297.54	1579.51	0.00	1926.82
	UR	0.06	0.00	0.22	10.71	33.27	44.26		UR	0.00	0.00	0.00	0.00	4.42	4.42
	Total	2142.50	1693.50	6406.80	4782.22	33.81	15058.83		Total	304.07	1614.38	3694.35	2622.25	4.42	8239.47
Year			2000					Year			2000				
	Class	MI	MO	SW	AS	UR	Total		Class	MI	MO	SW	AS	UR	Total
	MI	1861.77	0.00	437.30	85.07	0.08	2384.22		MI	330.88	0.00	18.80	10.06	0.00	359.74
2009	MO	0.00	1299.25	150.62	21.87	0.00	1471.74	2009	MO	0.00	1241.97	135.56	17.35	0.00	1394.88
	SA	884.75	934.83	4507.70	972.52	0.07	7299.87		SA	56.27	871.84	2764.23	335.92	0.00	4028.26
	AS	100.21	48.74	1152.99	2522.13	0.34	3824.41		AS	4.80	47.59	834.75	1561.94	0.03	2449.11
	UR	0.81	0.07	10.95	22.98	43.78	78.59		UR	0.00	0.07	1.47	1.55	4.39	7.48
	Total	2847.54	2282.89	6259.56	3624.57	44.27	15058.83		Total	391.95	2161.47	3754.81	1926.82	4.42	8239.47
Year			2009					Year			2009				
	Class	MI	MO	SW	AS	UR	Total		Class	MI	MO	SW	AS	UR	Total
	MI	777.13	0.00	124.67	8.25	0.02	910.07		MI	162.17	0.00	7.75	0.97	0.00	170.89
2019	MO	0.00	876.96	241.72	7.26	0.00	1125.94	2019	MO	0.00	839.96	224.42	7.14	0.00	1071.52
	SA	1388.10	549.74	5181.78	705.84	0.16	7825.62		SA	188.29	520.20	3228.81	476.04	0.00	4413.34
	AS	204.80	45.04	1699.87	3045.78	1.46	4996.95		AS	9.28	34.72	567.24	1963.64	0.73	2575.61
	UR	14.19	0.00	51.83	57.28	76.95	200.25		UR	0.00	0.00	0.04	1.32	6.75	8.11
	Total	2384.22	1471.74	7299.87	3824.41	78.59	15058.83		Total	359.74	1394.88	4028.26	2449.11	7.48	8239.47
Year			1990					Year			1990				
	Total	MI	MO	SW	AS	UR	Total		Class	MI	MO	SW	AS	AU	Total
	MI	715.37	0.00	157.90	36.80	0.00	910.07		MI	155.94	0.00	10.78	4.17	0.00	170.89
2019	MO	0.00	830.69	270.60	24.65	0.00	1125.94	2019	MO	0.00	792.47	256.14	22.91	0.00	1071.52
	SA	1175.17	794.63	4763.92	1091.90	0.00	7825.62		SA	138.42	758.51	2887.06	629.35	0.00	4413.34
	AS	249.24	68.18	1202.69	3476.51	0.33	4996.95		AS	9.71	63.40	540.33	1962.12	0.05	2575.61
	UR	2.72	0.00	11.69	152.36	33.48	200.25		UR	0.00	0.00	0.04	3.70	4.37	8.11
	Total	2142.50	1693.50	6406.80	4782.22	33.81	15058.83		Total	304.07	1614.38	3694.35	2622.25	4.42	8239.47

Table S2. (Conclusion)

Cacula

Year			**1900**				
	Class	MI	MO	SW	AS	UR	Total
2000	MI	741.23	0.00	791.60	51.83	0.00	1584.66
	MO	0.00	25.56	34.94	4.97	0.00	65.47
	SA	403.86	14.77	1119.22	286.81	0.00	1824.66
	AS	19.96	0.97	129.82	144.59	0.00	295.34
	UR	0.00	0.00	0.00	0.00	0.90	0.90
	Total	1165.05	41.30	2075.58	488.20	0.90	3771.03

Year			2000				
	Class	MI	MO	SW	AS	UR	Total
2009	MI	836.74	0.00	288.68	20.62	0.00	1146.04
	MO	0.00	22.82	14.28	4.34	0.00	41.44
	SA	667.35	41.60	1344.81	198.22	0.00	2251.98
	AS	80.54	1.05	176.02	69.48	0.00	327.09
	UR	0.03	0.00	0.87	2.68	0.90	4.48
	Total	1584.66	65.47	1824.66	295.34	0.90	3771.03

Year			200				
	Class	MI	MO	SW	AS	UR	Total
2019	MI	254.66	0.00	60.23	1.83	0.02	316.74
	MO	0.00	13.88	13.37	0.12	0.00	27.37
	SA	773.36	17.40	1519.62	135.32	0.14	2445.84
	AS	117.90	10.16	658.22	189.43	0.06	975.77
	UR	0.12	0.00	0.54	0.39	4.26	5.31
	Total	1146.04	41.44	2251.98	327.09	4.48	3771.03

Year			1990				
	Class	MI	MO	SW	AS	AU	Total
2019	MI	217.93	0.00	92.29	6.52	0.00	316.74
	MO	0.00	14.38	11.35	1.64	0.00	27.37
	SA	762.55	22.26	1447.69	213.34	0.00	2445.84
	AS	184.55	4.66	523.85	262.71	0.00	975.77
	UR	0.02	0.00	0.40	3.99	0.90	5.31
	Total	1165.05	41.30	2075.58	488.20	0.90	3771.03

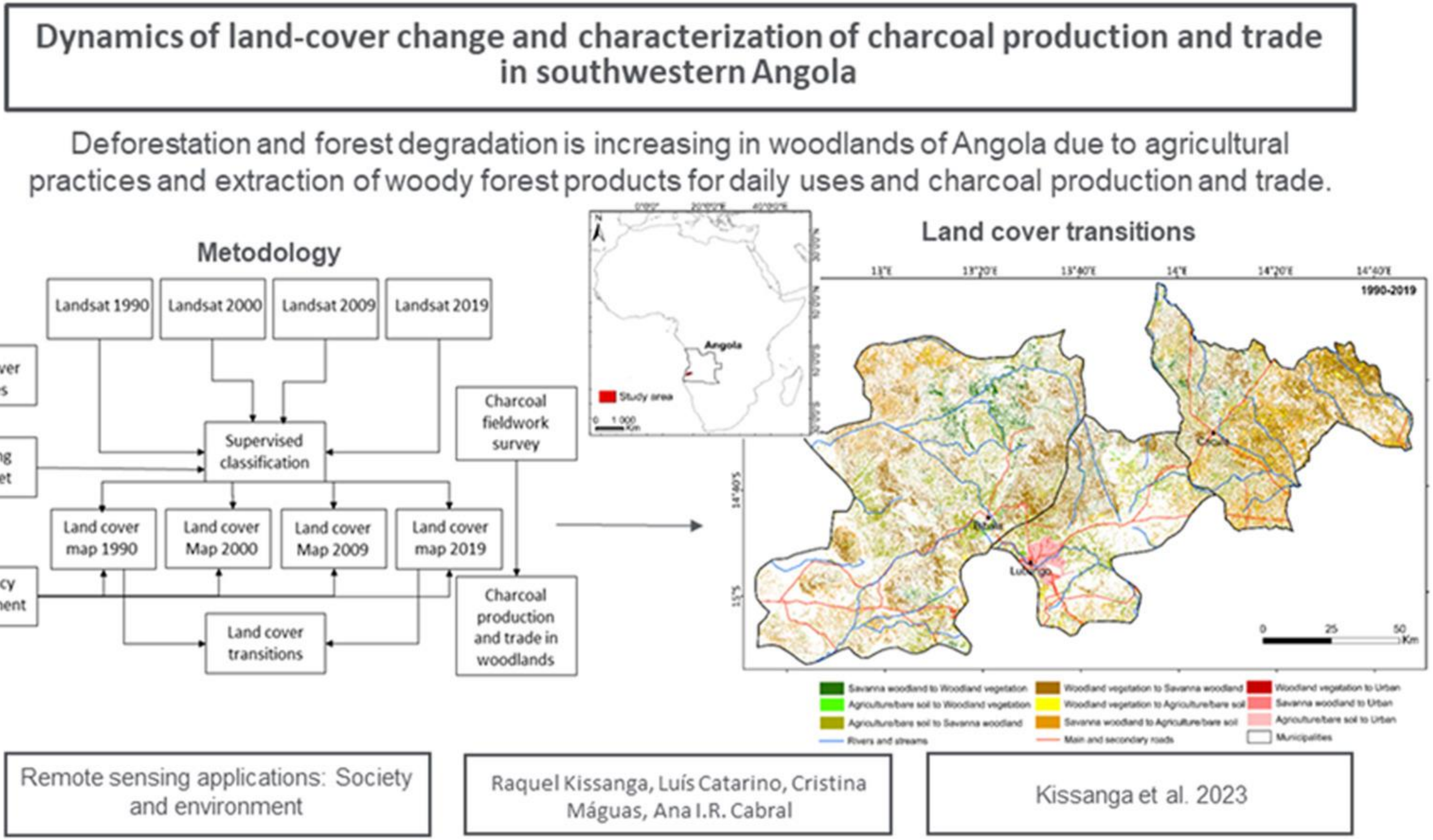
Lubango

Year			1990				
	Class	MI	MO	SW	AS	UR	Total
2000	MI	556.71	0.00	270.05	44.15	0.02	870.93
	MO	0.00	36.73	18.96	0.25	0.00	55.94
	SA	84.77	0.93	221.81	372.29	0.28	680.08
	AS	31.84	0.15	125.82	1244.39	0.24	1402.44
	UR	0.06	0.00	0.22	10.71	27.95	38.94
	Total	673.38	37.81	636.86	1671.79	28.49	3048.33

Year			2000				
	Class	MI	MO	SW	AS	UR	Total
2009	MI	694.17	0.00	129.82	54.39	0.08	878.46
	MO	0.00	34.45	0.77	0.19	0.00	35.41
	SA	161.13	21.38	398.66	438.37	0.07	1019.61
	AS	14.85	0.11	142.22	890.74	0.27	1048.19
	UR	0.78	0.00	8.61	18.75	38.52	66.66
	Total	870.93	55.94	680.08	1402.44	38.94	3048.33

Year			2009				
	Class	MI	MO	SW	AS	UR	Total
2019	MI	360.30	0.00	56.69	5.45	0.00	422.44
	MO	0.00	23.12	3.93	0.00	0.00	27.05
	SA	426.45	12.15	433.37	94.47	0.02	966.46
	AS	77.63	0.14	474.39	892.71	0.67	1445.54
	UR	14.08	0.00	51.23	55.56	65.97	186.84
	Total	878.46	35.41	1019.61	1048.19	66.66	3048.33

Year			1990				
	Class	MI	MO	SW	AS	AU	Total
2019	MI	341.51	0.00	54.82	26.11	0.00	422.44
	MO	0.00	23.84	3.11	0.10	0.00	27.05
	SA	274.21	13.86	429.17	249.22	0.00	966.46
	AS	54.96	0.11	138.49	1251.70	0.28	1445.54
	UR	2.70	0.00	11.27	144.66	28.21	186.84
	Total	673.38	37.81	636.86	1671.79	28.49	3048.33



Dynamics of land-cover change and characterization of charcoal production and trade in southwestern Angola

Deforestation and forest degradation is increasing in woodlands of Angola due to agricultural practices and extraction of woody forest products for daily uses and charcoal production and trade.

Remote sensing applications: Society and environment

Raquel Kissanga, Luís Catarino, Cristina Máguas, Ana I.R. Cabral

Kissanga et al. 2023

Fig S2. Graphical Abstract

CAPÍTULO 3

Assessing the Impact of Charcoal Production on Southern Angolan Miombo and Mopane Woodlands

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Abstract

About 80% of Angola’s forest surface is covered by Miombo and Mopane woodlands, which are explored for diverse activities such as fuelwood and food. This study aimed to assess the recovery dynamics of Miombo and Mopane woodlands after the selective cutting of tree species for charcoal production. For that, the structure and composition of plant communities in 37 plots, located in southwestern Angola, were characterized in fallows of different ages. Results showed that the diameter at breast height, basal area, biomass, and biovolume of trees all rose as the age of the fallow increased, and there were no significant differences in richness, diversity, or dominance of trees between adult–young classes or recent–older fallows. In Mopane, fallows took longer to regenerate, were more affected by environmental and anthropogenic factors, and also presented a higher species adaptation to disturbance. There were more sprouter and seeder trees in Miombo, and new kilns were more distant from roads and villages. Moreover, the selective removal of species deeply altered the community structure and dynamics, despite not directly affecting tree diversity. Thus, new management strategies are needed to ensure the survival of these woodlands such as expanding protected areas and increasing systematic research.

Keywords: *Brachystegia* spp.; *Colophospermum mopane*; Fallows; Forest degradation; Southern Africa

1. Introduction

More than half of southern Africa’s surface is covered with tropical dry forests and woodlands. The most representative forest vegetation types are the Miombo and Mopane woodlands [1,2]. Approximately 2.7 million km2 of Angola, Malawi, Mozambique, the Democratic Republic of the Congo, the Republic of the Congo, Tanzania, Zambia, and Zimbabwe are covered by the miombo [3]. Mopane occupies an area of about 600,000 km2 distributed by Angola, Botswana, Malawi, Mozambique, Namibia, Zimbabwe, Zambia, and South Africa [4].

Most of the tree species occurring in these woodlands are semi-deciduous nonnitrogen-fixing Caesalpinioideae legumes with broad leaves, which rely on the help of mycorrhizae as significant nutrient sources [3]. In Miombo woodland, species of *Brachystegia*, *Julbernerdia*, and *Isoberlinia* predominate, which are widely distributed on nutrient-poor soils in the Zambezian region of southern Africa with over 700 mm of annual rainfall and pronounced seasonality [5]. Mopane woodland is dominated by Cholophospermum mopane, which typically receives less than 700 mm of annual rainfall and is located on poor soils that are confined to lower-lying places [6].

Woody species in the Miombo and Mopane woodlands play an essential ecological role, but they additionally hold significant social and economic significance for the local population. For example, it is estimated that Miombo supports the livelihoods of more than 100 million people in both urban and rural areas [7]. Nonetheless, most African populations who depend on forest resources are impoverished [8]. Moreover, several human activities that improve family income and living conditions, including agricultural expansion, logging, burning, and charcoal and firewood consumption, impose significant pressure on land resources [9–12]. An important topic of debate today is how the needs of resident populations can be reconciled with the sustainability of forest resource use [13].

About 90% of urban people in Africa use charcoal, a forest product, primarily as a source of heat for cooking but, in many circumstances, as a source of family income [14,15]. Rural people typically produce charcoal to sell to consumers living in cities and, to a lesser extent, for their own consumption, which has helped to reduce poverty [16]. Charcoal production and trade in the Miombo region contribute between 60% and 80% of the household income of the families involved in both rural and urban areas [6,12]. Several studies demonstrate the benefits of this activity in diversifying the rural and domestic economies [12,17,18]. According to Mensah et al. [19], the Sub-Saharan Africa system accounts for an estimated 65% of global charcoal output with Nigeria, Ethiopia, Ghana, Tanzania, and Madagascar being among the top producers. Therefore, the production of charcoal and its impact on socio-economic, socio-ecological, and the environment have been important issues in various African countries [20–22]. The effects of charcoal production can never be overemphasized, behind the benefits, there have been also negative effects on the environment and human health [23]. A major concern is that this exploration could negatively impact forest regeneration once the annual rate of growth of these forests is low [24,25], as most of the trees in Miombo and Mopane woodlands are slow-growing. The net primary production in Miombo woodlands is estimated to be 900–1600 g m^{-2} yr^{-1} and the annual increment of the woody-plant biomass is no more than 3–4% in mature stands [3]. Some authors showed that it could take 19 to 55 years to recover the structure after logging [24–27]. Also, the exposure to wood smoke has been treated as a public health concern meanly the carbon monoxide and the mixture of solid and liquid particles suspended in the air for a long time [28–31].

Angola is a unique African country with great and diversified biomes and ecoregions, from tropical and subtropical moist forests to deserts and xeric shrublands and a strong endemism rate [32]. Like throughout the rest of sub-Saharan Africa, Angola is characterized by numerous intensively exploited forest resources, including wood (such as timber, firewood, and charcoal) and non-wood products (such as honey, fruits, leaves, roots, and mushrooms). However, the extraction of wood products has the largest impact on forest ecosystems [33,34]. Approximately 80% of Angolans depend on biomass for most of their energy needs, with Miombo contributing more than 75% of the charcoal produced, the largest source in Angolan territory [32,35]. Charcoal is valued in peri-urban and urban areas due to its greater purchasing power, ease of transport, and convenience of use, while firewood is more widely used in rural areas [35].

According to FAO [36], Angola is ranked fourth in the world for the largest forest area losses, with a forest loss of 500,000 ha per year and a net annual change of −0.8%. Moreover, the scarcity of energy options to replace biomass as an energy source is a cause for concern [37]. Therefore, the production of charcoal and its impact on forest ecosystems and the environment are important issues and integrated multidisciplinary studies are needed to mitigate the effects of the use of woody resources in ecosystems. However, few studies on forest degradation and deforestation caused by charcoal production have been conducted in Angola, and they have been focused in some areas of the country should be highlighted, namely in Kwanza Sul [38,39], Bengo [40], Bié [41,42], and Huambo [24,43,44]. Moreover, according to FAOSTAT [45], the consumption of charcoal has continuously grown over the last decades (e.g., 1976: 82,129 tons; 1990: 130,139 tons; 2002: 220,768 tons; 2021: 417,563 tons).

In summary, the plant communities of the Miombo and Mopane forests could be severely affected by wood extraction for charcoal production since this activity may compromise species regeneration and productivity. Thus, this study aims to analyze the changes in the composition and structure of woody plant communities located in fallows abandoned after cutting for charcoal production. This was carried out by assessing the recovery dynamics of Miombo and Mopane charcoal fallows with different ages: recent fallows (20 years) in southwestern Angola.

2. Material and methods

2.1. Study area

The study area was located in Huíla and Namibe provinces in southwestern Angola (13◦59′–15◦13′ S, 14◦47′–12◦27′ E), comprising 14,197 km2 (Figure 1). It presents elevations ranging from 300 to 2200 m of altitude, belonging to the central plateau of Angola (covering Lubango and Cacula municipalities in Huila) and the sub-plateau (covering Bibala municipality in Namibe). The climate is temperate in the central plateau, with dry winters, and semi-arid in the sub-plateau zone, with two seasons: the dry season (mid-May to mid-August) and the rainy season (mid-August to mid-May), but the sub-plateau region has a longer dry period. The central plateau area has mean annual temperatures of 18.5 ◦C and annual precipitation ranging from 750 to 1200 mm, whereas the sub-plateau region experiences mean annual temperatures of 21.5 ◦C and annual precipitation ranging from 300 to 400 mm [46,47].

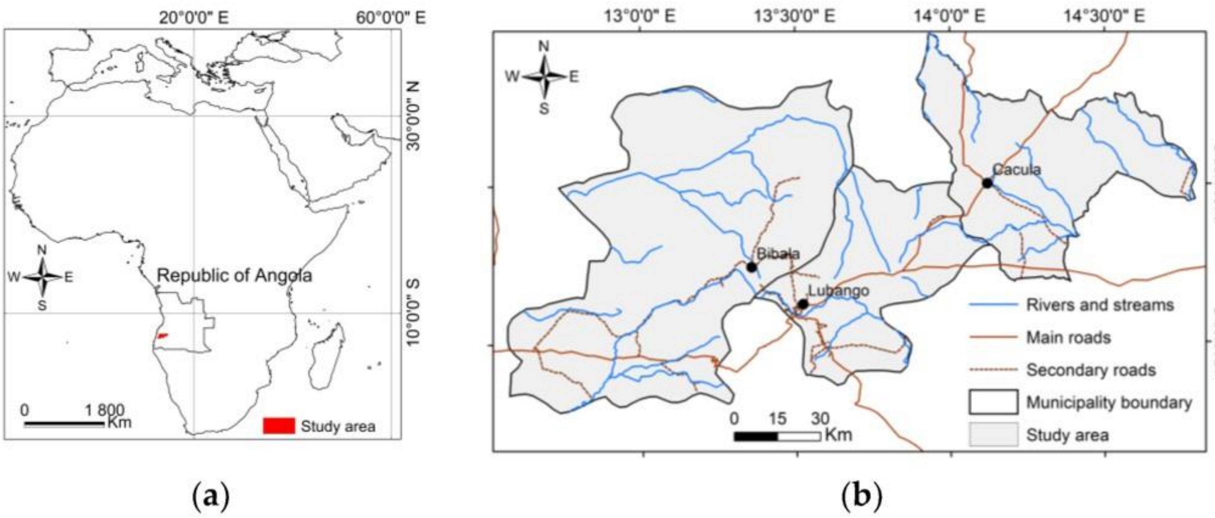

Figure 1. Location of the study area in Africa (a) and in Angola(b); Study area (c).

Miombo and Mopane woodlands are the dominant vegetation in the plateau and subplateau zones of the study area, respectively, and there are around one million people living here [48]. It is a multicultural land with several ethnolinguistic groups, such as the Ovimbundo, Muila, Handa, Koissan, and Mucubal peoples, who live in rural areas. Agriculture and pastoralism, as well as charcoal production, are the main economic activities of the population [49,50].

2.2. Vegetation Sampling and Explanatory Variables

Sampling of wood vegetation was performed in three areas: Humbia and Garganta in Bibala municipality, where Mopane woodland is dominant, and Mawengue in Cacula municipality, where Miombo predominates. Based on a model developed by Oldeland et al. [51] and applied by other researchers, including Gonçalves et al. [52], a total of 37 charcoal fallow sites, over a total area of about 3.7 ha, were sampled. Plots of 1000 m2 (20 × 50 m) with a central sub-plot of 100 m2 (10 × 10 m) were used. Regeneration plots were selected based on the information provided by local charcoal producers. According to the number of years since the last disturbance, three different classes were established: recent plots (20 years), with 20 made in Miombo woodlands (9 recent, 5 intermediate, and 6 mature) and 17 in Mopane (4 recent, 6 intermediate, and 7 mature). Plot geographical coordinates and their altitude, slope, and distance to the nearest road were recorded. For slope, three classes there were considered: flat: 10%. The distance to the road was measured using the QGIS 2.18.16 software [53].

DBH and height were measured in each plot for individuals with DBH ≥ 5 cm, and they were categorized as seeders (seed-growing) or sprouters (stump-growing). All seeders and sprouters with DBH ≥ 5 cm were classified, size classes, as adults (adult class), while those with DBH 5 cm were classified as young (young class). Adult seeders and adult sprouters were separated from the adult class.

Individuals from the young class were only sampled in the 100 m2 sub-plot, and results were extrapolated to the 1000 m2 plots. They were classified into three groups: (1) young from seed regeneration with a height greater than 1.30 m (young seeders), (2) young from seed regeneration with a height less than 1.30 m (seedlings), and (3) young from stump regeneration (young spouters).

To estimate the aboveground biomass (AGB) and above-ground biovolume in charcoal fallows and mature woodlands, two allometric equations developed in the miombo woodlands of Tanzania and Malawi were calculated [54,55].

1) Biomass equation [54]: $\text{Biomass}=0.1027 \times \text{DBH}^{2.4798}$

2) Biovolume equation [55]: $\text{Biovolume}=0.0213+0.000011\text{DBH}^{3}$

The results were transformed into hectares. Values for the charcoal-bearing species were also calculated. Plant nomenclature followed the African Plants Database [56], and the field guide developed by Van Wyk and Van Wyk [57]. Species identification was performed in situ, except for those that were unknown, for which herbarium vouchers were collected. The local names of trees were obtained in Umbundu and Lunyaneka from local field guides. The vouchers were identified with the support of experts from the University of Lisbon herbarium (LISC), and by comparison with other specimens, and deposited in the ISCED-Huíla Herbarium, at Lubango (LUBA).

2.3. Comparative analyses

First, plant richness and diversity indices were calculated, namely Shannon and Dominance (D = Simpson index), using the vegan package in R [58,59] in both communities. The numbers of seeder and sprouter species were also calculated. Gradients in plant composition through time for each vegetation type were described using Non-metric Multidimensional Scaling ordinations (NMDS) [60] based on tree species density [61], using the “metaMDS” function of the R package vegan v2.5-7 [62]. All the analyses were performed separately for adult and young trees in both Miombo and Mopane woodlands (see Supporting information, Tables S1A–D and S3A, B). Then, the relationships between a set of broad exploratory variables and the dynamics of vegetation regeneration were explored by correlating these variables with the NMDS ordination using the “envfit” function of vegan [63,64]. These variables included the number of individuals per plot by size class (adult and young) and regeneration type (seeders and sprouters); allometric variables such as DBH, basal area, the total and charcoal-bearing biomass, the biovolume, tree height; species richness (for all species and only for species bearing charcoal), the Shannon and Dominance indices; lastly, altitude, slope, and distance to roads (Tables 1 and 2). The strength of those relationships was evaluated through the squared correlation coefficient (r2). Multicollinearity among potential explanatory variables was handled by dropping collinear covariates [65,66] when correlated at |Spearman r| > 0.8 [67] Pairwise comparisons were then performed to assess differences in all exploratory variables among recent, intermediate, and mature plots throughout Wilcoxon tests using the Bonferroni correction for p value adjustment (Table S1).

Finally, the indicator value for each species (IndVal) was calculated aiming to identify the indicator species in Miombo and Mopane woodlands [68]. Indicator species are used as ecological indicators of communities and ultimately represent the qualitative characteristics of the ecosystem [69]. This index measures each species’ specialization and faithfulness to a certain kind of community. IndVal was calculated using the R package labdsv (v2.0-1) [70].

3. Results

3.1. Diversity and abundance of wood species

A total of 55 species of trees were identified, with 32 found in Miombo woodlands, 19 adults and 30 young, and 31 in Mopane woodlands, with 21 adults and 29 young (Table 1). Nine species were found in both woodlands. In Mopane, a total of 5804 individuals were measured or counted: 3960 young and 1844 adults; in Miombo, 11,998 individuals were measured or counted: 10,350 young and 1648 adults (see Supporting Information, Table S1A–D).

Concerning charcoal-bearing species, 18 species were recorded in Miombo and nine in Mopane. All the charcoal-bearing species are present in young classes, but only 11 were found as adults in Miombo and seven in Mopane (Table 1). At the vegetation structure level, in both woodland types, the density of both adult and young trees increases from recent to intermediate fallows and decreases from intermediate to mature. The average height of adult trees increases steadily from recent to mature fallows but is remarkably higher in Miombo than in Mopane (13.30 and 8.12 m, respectively). A similar pattern is also verified in the mature fallows for biovolume, total biomass, and charcoal-bearing biomass (Table 1).

From the total of 23 plant families identified, the most representative was Fabaceae with 17 species, followed by Combretaceae with seven, Rubiaceae (five species), Euphorbiaceae (three species), Annonaceae, Apocynaceae, Burseraceae, and Ebenaceae with two species each; the remaining 15 families have a single representative species (Table 2). At Miombo, of the total 32 species, 18 are charcoal-bearing species, 11 are found in the adult class, and 18 are in the young class. At Mopane, of the total of 31 species, nine were charcoal-bearing species, seven were adults and nine young (Table 1). The average values of the Shannon and Dominance indices were low for both formations, except for the Shannon indices for some young fallows. The values for recent, intermediate, and mature fallows of the young class ranged, respectively from H’ = 1.58 to 2.39, H’ = 2.14 to 2.68, and H’ = 0.7 to 0.24 for Miombo and H’ = 0.44 to 1.52, H’ = 1.09 to 2.92, and H’ = 0 to 2.03 for Mopane (see Supporting Information, Table S2A–D).

In both the young and adult classes, *Brachystegia spiciformis* and *Julbernardia paniculata* are the Miombo species with the greatest number of individuals (Table S1).

Baphia massaiensis subsp. *obovata, Diplorhynchus condylocarpon*, *Hexalobus monopetalus, Parinari curatelifolia, Pericopsis angolensis, Ptaeroxylon obliquum, Strychnos cocculoides,* and *Xylopia odoratissima* were found only in the recent fallows, and except for *X. odoratissima* and *P. curatilifolia* that were seedlings, all the species were young sprouters. *Brachystegia floribunda* was recorded only in intermediate fallow in young sprouters' class. Some species were found in different age and regeneration stages, such as *Faurea rochetiana* and *Erythrina baumii* found in recent and intermediate fallows, whereas others occur in intermediate and mature fallows, namely *Pterocarpus lucens* subsp. *antunesii* and *Vangueriopsis lanciflora* (found only as young sprouters).

In Mopane, *Colophospermum mopane*, *Spirostachys africana*, *Acacia senegal*, and *Terminalia prunioides* are the species with the largest number of individuals (Table 1) and were found in all age stages and regeneration types and counted in all the fallows. Two species, *Peltophorum africanum* and *Ximenia americana* var. *microphylla*, were only found in recent fallows as young and adult sprouters, respectively. A larger number of species were found in intermediate fallows, and there was a great variation in regeneration type and age. For example, *Croton mubango* and *Euclea divinorum* were found as seeders and sprouters, young and adult trees; *Terminalia sericea* tree was found only as a sprouter, *Pterocarpus lucens* subsp. *antunesii*, *Pterocarpus rotundifolius*, *Diospyros mespiliformis,* and *Xylopia odoratissima*, were only found as seeders. Also, several species were found at the same time in recent and intermediate fallows such as *Combretum collinum,* which was found in all fallow ages and regeneration stages, and others occur in both intermediate and mature fallows such as *Adansonia digitata,* only as seeder, *Chaetachme aristata* and *Combretum imberbe,* both in all forms and regeneration stages, *Ptaeroxylon obliquum* and *Strychnos cocculoides*, both in the young class (see Supporting Information, Table S1A–D). The most common species were *Brachystegia floribunda*, *Combretum collinum*, *Ptaeroxylon obliquum*, *Pteleopsis anisoptera*, *Pterocarpus lucens* subsp. *antunesii*, *Pterocarpus rotundifolius*, *Strychnos cocculoides*, *Terminalia sericea*, and *Xylopia odoratissima*.

Table 1. Tree species richness and structural variables for the Recent, Intermediate and Mature fallows of Miombo and Mopane woodlands. (Ind.: individuals; avg: average; SD: standard deviation.

	Maturity	**Nº Tree Species**	**Nº Adult Tree Species**	**Nº Young Tree Species**	**Charcoal-Bearing Species**	**Adult Charcoal-Bearing Species**	**Young Charcoal-Bearing Species**	**Density of Adults (Ind ha^{-1} ; avg ± SD)**	**Density of Young (Ind. ha^{-1}; avg ± SD)**	**DBH of Adults (cm; avg ± SD)**	**Height of Adults (m; avg ± SD)**	**Basal Area (m^2 ha^{-1} avg ± SD)**	**Biovolume (m^3 ha^{-1} avg ± SD)**	**Biomass (ton ha^{-1} avg ± SD)**	**Biomass Charcoal Bearing (ton ha^{-1} avg ± SD)**
Miombo	**Recent**	26	11	22	14	7	13	830 ± 229	5022 ± 2683	9.1 ± 2.8	5.0 ± 1.4	4.8 ± 1.0	29.6 ± 7.0	19.2 ± 5.8	18.8 ± 5.2
	Intermediate	18	8	17	11	4	11	1170 ± 882	6360 ± 2466	4.2 ± 7.0	7.9 ± 3.3	9.2 ± 4.4	82.7 ± 29.1	57.9 ± 19.8	55.0 ± 22.9
	Mature	21	13	17	14	9	12	525 ± 193	4417 ± 950	24.4 ± 5.3	13.3 ± 1.8	17.5 ± 7.0	232.0 ± 260.0	130.0 ± 95.3	107.0 ± 40.4
	Total	32	19	30	18	11	18	824 ± 506	5175 ± 2260	14.9± 8.1	8.2 ± 4.1	9.7 ± 7.0	103.7 ± 160.9	62.1 ± 69.4	54.2 ± 44.9
Mopane	**Recent**	12	10	10	5	5	5	1098 ± 275	3325 ± 1626	8.0 ± 3.0	6.2 ± 1.25	5.3 ± 3.3	36.7 ± 20.6	21.2 ± 17.3	19.5 ± 16.9
	Intermediate	32	17	24	9	6	9	1205 ± 205	2817 ± 1485	10.5 ± 3.8	6.3 ± 1.4	9.8 ± 2.9	67.2 ± 43.7	38.4 ± 15.9	31.8 ± 10.6
	Mature	14	11	10	6	5	5	974 ± 107	1343 ± 932	18.4 ± 3.1	8.1 ± 1.4	18.8 ± 6.6	174.0 ± 96.3	108.0 ± 48.8	68.6 ± 25.2
	Total	31	21	29	9	7	9	1085 ± 206	2329 ± 1508	13.2 ± 5.6	7.0 ± 1.6	12.4 ± 7.4	104.0 ± 89.1	63.0 ± 50.7	44.1 ± 28.2

Table 2. Tree species richness and structural variables for the Recent, Intermediate and Mature fallows of Miombo and Mopane woodlands. (Ind.: individuals; avg: average; SD: standard deviation.

Family / Species	**Acronym**	**Forest type (Mi/Mo)**	**Average Dens. Adults (stem/ha)**	**Average Dens. Young (stem/ha)**	**Basal area (m2/ha)**	**Biomass (ton/ha)**	**Volume (m3/ha)**	**Max Average heigth (m)**	**Average adult DBH ≥ 5cm**	**Sprout observation**	**Charcoal-bearing species**	**Others uses**	**Local names**
Anacardiaceae													
Sclerocarya birrea (A. Rich.) Hochst.	Sbir	Mo	4,0	6,0	3,3	26,6	43,7	24,0	45,5	No	No	Food, alcoholic beverage (fruits), oil (seeds), Shadow tree	Omungongo (Nya)
Annonaceae													
Hexalobus cf. *monopetalus* (A. Rich.) Engl. & Diels	Hmon	Mi	-	50,0	-	-	-	-	-	Yes	No	…	Omutundu (Nya, Umb)
Xylopia odoratissima Welw. ex Oliv.	Xodo	Mi/Mo	-	5/12	-	-	-	-	-	No	No	Medicine (roots)	Mumbungululu (Nya, Umb)
Apocynaceae													
Carissa spinarum L.	Cspi	Mo	-	11,8	-	-	-	-	-	No	No	Food, juice, alcoholic beverage (fruits)	Oiangola (Nya), Mirangolo (Umb)
Diplorhynchus condylocarpon Müll. Arg.	Dcon	Mi	-	10,0	-	-	-	-	-	Yes	No	Medicinal (roots)	Muli (Umb)
Burseraceae													
Commiphora angolensis Engl.	Cang	Mo	6,5	23,5	0,6	2,4	4,0	6,0	10,0	Yes	No	Medicinal (bark)	Omulema-wowo (Nya)
Commiphora mollis (Oliv.) Engl.	Comol	Mo	27,1	41,2	3,2	19,9	29,2	16,0	55,1	Yes	No	Medicinal (bark)	Mulenda (Nya)
Chrysobalanaceae													
Parinari curatellifolia Planch. ex Benth.	Pcur	Mi	-	5,0	-	-	-	-	-	No	No	Food, juice, alcoholic beverage (fruits)	Oloncha (Umb)
Combretaceae													
Combretum molle R. Br. ex G. Don	Cmol	Mi/Mo	1/0	5/47	0,3	2,0	2,3	11,0	22,5	Yes	Yes	Medicinal (bark)	Mupupu (Umb)
Combretum collinum Fresen.	Ccol	Mi/Mo	17/18	785/18	0.57/ 0.61	2.02/ 1.94	3.73/ 4.49	5.2/6.0	9.71/6.25	Yes	Yes	Medicinal (bark)	Mupupu (Umb)
Combretum imberbe Wawra	Cimb	Mo	23,5	11,8	0,6	2,4	3,4	6,0	9,0	Yes	Yes	Medicinal (bark)	Mukuku (Nya)
Combretum zeyheri Sond.	Czey	Mi	-	100,0	-	-	-	-	-	Yes	Yes	Medicinal (bark)	Mumbumbungi (Umb), Mupupu (Nya)

Table 2. *Cont.*

Family / Species	**Acronym**	**Forest type (Mi/Mo)**	**Average Dens. Adults (stem/ha)**	**Average Dens. Young (stem/ha)**	**Basal area (m2/ha)**	**Biomass (ton/ha)**	**Volume (m3/ha)**	**Max Average heigth (m)**	**Average adult DBH ≥ 5cm**	**Sprout observation**	**Charcoal-bearing species**	**Others uses**	**Local names**
Pteleopsis anisoptera (Welw. ex M.A. Lawson) Engl. & Diels	Pani	Mi/Mo	11/1	150/0	12.1/ 0.05	143.18/0.06	377.4/0.41	7.0/ 5.5	30/3.5	yes	No	charcoal sak cover	Omuhihi (Nya, Umb)
Terminalia prunioides M.A. Lawson	Tpru	Mo	141,8	441,2	7,1	38,2	104,4	15,0	28,5	yes	yes	Medicinal (bark)	Omuhaina (Nya)
Terminalia sericea Burch. ex DC.	Tser	Mi/Mo	-	20/6	-	-	-	-	-	yes	yes	Medicinal (leaves, roots)	Mungolo (Nya, Umb)
Ebenaceae													
Diospyros mespiliformis Hochst. ex A. DC.	Dmes	Mo	-	18,0	-	-	-	-	-	No	No	Food (fruits)	Munhangue (Nya)
Euclea divinorum Hiern	Ediv	Mo	6,0	12,0	0,6	2,1	3,1	6,0	10,0	Yes	No	Food (fruits)	Munhime (Nya)
Euphorbiaceae													
Bridelia cathartica G. Bertol.	Bcat	Mi	-	30,0	0,1	0,4	0,5	5,0	11,0	Yes	No	Food (fruits)	Olohuliungo (Umb)
Croton mubango Müll. Arg.	Cmub	Mo	2,0	47,0	0,7	0,2	0,6	5,0	5,5	Yes	No	Medicinal (roots)	Mumbango (Nya)
Spirostachys africana Sond.	Safr	Mo	248,2	358,8	4,4	24,8	102,5	13,0	21,2	yes	yes	Medicinal (bark)	Omupapa (Nya)
Fabaceae													
Acacia ataxacantha (DC.) Kyal. & Boatwr.	Aata	Mo	0,6	11,8	0,0	0,1	0,2	3,5	5,0	yes	No	Strings (bark)	Mukete (Nya)
Acacia senegal (L.) Willd.	Asen	Mo	73,5	129,4	2,3	11,6	13,0	16,0	26,1	Yes	Yes	Medicinal (roots)	Mukondo (Nya)
Albizia adianthifolia (Schumach.) W. Wight	Aadi	Mi	16,0	140,0	2,1	8,3	11,9	8,2	11,3	Yes	Yes	Medicinal (roots)	Homem amargo (Port)
Baphia massaiensis subsp. *obovata* (Schinz) Brummitt	Bmas	Mi	-	5,0	-	-	-	-	-	Yes	Yes	Strings (bark)	Pau-ferro (Port)
Brachystegia boehmii Taub.	Bboe	Mi	-	135,0	-	-	-	-	-	Yes	Yes	Strings (bark)	Munsamba (Umb)
Brachystegia floribunda Benth.	Bflor	Mi	-	5,0	-	-	-	-	-	Yes	Yes	Strings (bark)	Mutundu (Nya)
Brachystegia longifolia Benth.	Blon	Mi	8,5	80,0	1,7	9,8	13,7	12,0	21,7	Yes	Yes	Strings (bark)	Mungolo (Umb)
Brachystegia spiciformis Benth.	Bspi	Mi	328,5	745,0	17,9	173,8	377,9	17,3	34,6	Yes	Yes	Medicinal, string (bark)	Mupanda (Um)

Table 2. *Cont.*

Family / Species	**Acronym**	**Forest type (Mi/Mo)**	**Average Dens. Adults (stem/ha)**	**Average Dens. Young (stem/ha)**	**Basal area (m2/ha)**	**Biomass (ton/ha)**	**Volume (m3/ha)**	**Max Average heigth (m)**	**Average adult DBH ≥ 5cm**	**Sprout observation**	**Charcoal-bearing species**	**Others uses**	**Local names**
Brachystegia tamarindoides Welw. ex Benth.	Btam	Mi	0,5	5,0	0,0	0,1	0,2	4,5	6,0	Yes	Yes	Strings (bark)	Mungai (Umb)
Burkea africana Hook.	Bafr	Mi	70,0	6,0	0,3	1,1	2,3	9,5	11,5	Yes	No	Construction (stem)	Osese (Umb)
Colophospermum mopane (J. Kirk ex Benth.) J. Kirk ex J. Léonard	Cmop	Mo	514,7	958,8	13,1	66,6	86,3	11,1	28,4	Yes	Yes	Medicinal (leaves, roots)	Mutiati (Nya)
Erythrina baumii Harms	Ebau	Mi	5,0	345,0	0,2	0,8	1,6	4,0	7,8	Yes	Yes	…	Pau-ferro (Port)
Julbernardia paniculata (Benth.) Troupin	Jpan	Mi	390,0	1520	14,0	80,1	110,7	12,5	31,5	Yes	Yes	Medicinal (roots), string (bark)	Omumwe (Umb)
Peltophorum africanum Sond.	Pafr	Mo	-	12,0	-	-	-	-	-	No	No	Medicinal (roots)	Mupala (Nya)
Pericopsis cf. *angolensis* (Baker) Meeuwen	Pang	Mi	-	10,0	-	-	-	-	-	Yes	Yes	Medicinal (bark, leaves, roots)	Pau-ferro maco (Umb)
Pterocarpus lucens subsp. *antunesii* (Taub.) Rojo	Pluc	Mi/Mo	1/1	15/18	0.03/ 0.02	0.11/ 0.07	0.23/ 0.21	3/5.5	6.5/6	yes	No	artisanal (stem)	Muviu (Nya), Muvibu (Umb)
Pterocarpus rotundifolius (Sond.) Druce	Prot	Mi/Mo	-	15/12	-	-	-	-	-	No	yes	artisanal (stem)	Muviu (Nya), Ulumba (Umb)
Hernandiaceae													
Gyrocarpus americanus Jacq.	Game	Mo	-	6,0	-	-	-	-	-	No	No	Medicinal (bark, leaves)	Omuxilia (Nya)
Kirkiaceae													
Kirkia acuminata Oliv.	Kacu	Mo	24,0	12,0	5,7	38,8	53,5	12,3	35,0	Yes	No	Medicinal (stem, latex)	Mumbowo (Nya)
Loganiaceae													
Strychnos cocculoides Baker	Scoc	Mi/Mo	1/0	0/12	0,5	2,7	3,3	15,0	24,0	No	No	Food, alcoholic beverage (fruits)	Omwi (Umb), Maboka (Nya)
Malvaceae													
Adansonia digitata L.	Adig	Mo	1,8	11,8	6,0	53,3	115,9	7,5	42,9	No	No	Food, oil, medicinal (fruits, seeds), shadow tree, string (bark)	Omukwa (Nya)
Ochnaceae													
Ochna cf. *pulchra* Hook.	Opul	Mi	25,5	480,0	2,8	14,2	17,3	8,0	12,0	Yes	Yes	….	Omia (Umb)

Table 2. *Cont.*

Family / Species	**Acronym**	**Forest type (Mi/Mo)**	**Average Dens. Adults (stem/ha)**	**Average Dens. Young (stem/ha)**	**Basal area (m2/ha)**	**Biomass (ton/ha)**	**Volume (m3/ha)**	**Max Average heigth (m)**	**Average adult DBH ≥ 5cm**	**Sprout observation**	**Charcoal-bearing species**	**Others uses**	**Local names**
Olacaceae													
Ximenia americana L.	Xame	Mo	1,0	-	0,1	2,4	3,4	5,5	9,0	yes	No	Edible fruit tree, medicine and cosmetic (fruits)	Omingua, Omumpeke (Nya)
Schrebera alata (Hochst.) Welw.	Sala	Mo	-	18,0	-	-	-	-	-	yes	No	…	Omulica Nya)
Phyllanthaceae													
Uapaca nitida Müll. Arg.	Unit	Mi	1	45,0	0,3	2,0	2,3	7,0	21,0	yes	yes	Food, juice, alcoholic beverage (fruits)	Lombula (Umb)
Proteaceae													
Faurea rochetiana (A. Rich.) Chiov. ex Pic. Serm.	Froc	Mi	6,0	15,0	0,4	5,4	6,2	6,5	16,0	Yes	No	Construction (stem)	Ondjunge (Umb)
Rubiaceae													
Afrocanthium lactescens (Hiern) Lantz	Alac	Mo	-	5,9	-	-	-	-	-	No	No	Construction (stem), food (fruits)	Muholiholi (Nya)
Gardenia ternifolia subsp. *jovis-tonantis* (Welw.) Verdc.	Gter	Mi	6,0	100,0	0,4	2,3	2,8	11,0	22,5	Yes	No	Food (fruits)	Otchilavi (Umb)
Gardenia volkensii subsp. *spatulifolia* (Stapf & Hutch.) Verdc.	Gvol	Mo	1,0	6,0	0,0	1,0	0,2	6,0	5,0	Yes	No	…	Muvali (Nya)
Rothmannia engleriana var. *terniflora* (Ficalho & Hiern) Somers	Reng	Mi	1,0	270,0	0,3	2,0	2,3	10,0	21,0	yes	No	Food (fruits)	Upu (Umb)
Vangueriopsis lanciflora (Hiern) Robyns	Vlan	Mi	-	-	-	-	-	-	-	yes	No	Food (fruits)	Mandjunju (Nya)
Ptaeroxylon obliquum (Thunb.) Radlk.	Pobl	Mi/Mo	-	5/18	-	-	-	-	-	yes	No	Medicine (bark, leaves, roots)	Omumbungululu (Nya, Umb)
Sapotaceae													
Englerophytum magalismontanum (Sond.) T.D. Penn.	Emag	Mi	1,0	-	0,0	0,1	0,2	3,0	5,0	No	No	Food (fruits)	Omutomboti (Umb)
Tiliaceae													
Grewia flavescens Juss.	Gfla	Mo	1,0	-	0,2	0,1	1,1	3,3	16,0	No	No	Food, juice, alcoholic beverage (fruits)	Munamba (Nya)
Ulmaceae													
Chaetachme aristata Planch.	Cari	Mo	0,6	35,3	0,0	0,1	0,2	3,5	6,0	Yes	No	Medicinal (roots)	Munguedja (Nya)

3.2. Effect of Charcoal Production on Diversity, Structure, and Regeneration of Miombo and Mopane Woodlands

The main gradients in vegetation composition were described by the two-dimensional ordination of the plots based on the species density data, with final stresses of 15.64% and 17.01% in Miombo and 17.44% and 15.79% in Mopane for adult and young individuals, respectively (Figure 2). In Miombo woodlands, the ordination separated young (recent fallows) from older communities (intermediate and mature fallows) for both adults (Figure 2a) and young trees (Figure 2b). Whereas for Mopane woodlands, there was a distinction between recent, intermediate, and mature fallows in the adult class (Figure 2c), but no distinction in the young class (Figure 2d).

At Miombo, the first axis accounts for most variance for adult trees (40.18% of 41.43%), whereas the second axis is for young trees (33.96% of 57.41%). Both axes described a gradient between the oldest fallows (both intermediate and mature) and recent ones in both age classes (Figure 2a, b). According to the correlation analyses (Table 3), oldest fallows are richer in the total number of tree species (r2 = 0.84 ***), in charcoal-bearing species (r 2 = 0.72 ***), seed regeneration individuals (r2 = 0.63 ***), and stump regeneration individuals (r2 = 0.35 *). These fallows also presented a higher diversity (Shannon-H' index, r2 = 0.54 **) and larger trees (DBH average, r2 = 0.40 **). While recent fallows are located further away from roads (r2 = 0.35 *) and had a lower level of diversity (Dominance index, r 2 = 0.31 *). In the young class, recent fallows were also further away from roads (r 2 = 0.52 **) and higher in altitude (r2 = 0.40 **) and had a higher number of sprouter individuals (r2 = 0.40 **), whereas older fallows were more diverse (Shannon-H index, r 2 = 0.34 *) and presented a higher number of seeder individuals (r2 = 0.46 **).

At Mopane vegetation, the first axis explained most of the variance in both cases: 33.31% of 49.22% for adult trees and 35.09% of 55.25% for young trees. Concerning adults, all fallow classes were distinct (Figure 2c), with a clear separation of the mature fallows. Regarding young trees, only mature fallows were distinctly separated (Figure 2d).

According to correlation analyses, adult trees in the oldest fallows were larger (average DBH and Height of trees, $r^2 = 0.39$ * and $r^2 = 0.37$ *, respectively), both mature and intermediate fallows were richer in a total number of species ($r^2 = 0.84$ ***), number of seeders, and charcoal-bearing individuals ($r^2 = 0.61$ and $r^2 = 0.52$, respectively), and more diverse

(Shannon-H' index and Dominance, $r^2 = 0.65$ *** and $r^2 = 0.60$ ***, respectively). In the young class, mature fallows had lower levels of diversity (Dominance $r^2 = 0.36$ *) while both recent and intermediate fallows were richer in charcoal-bearing individuals ($r^2 = 0.36$*).

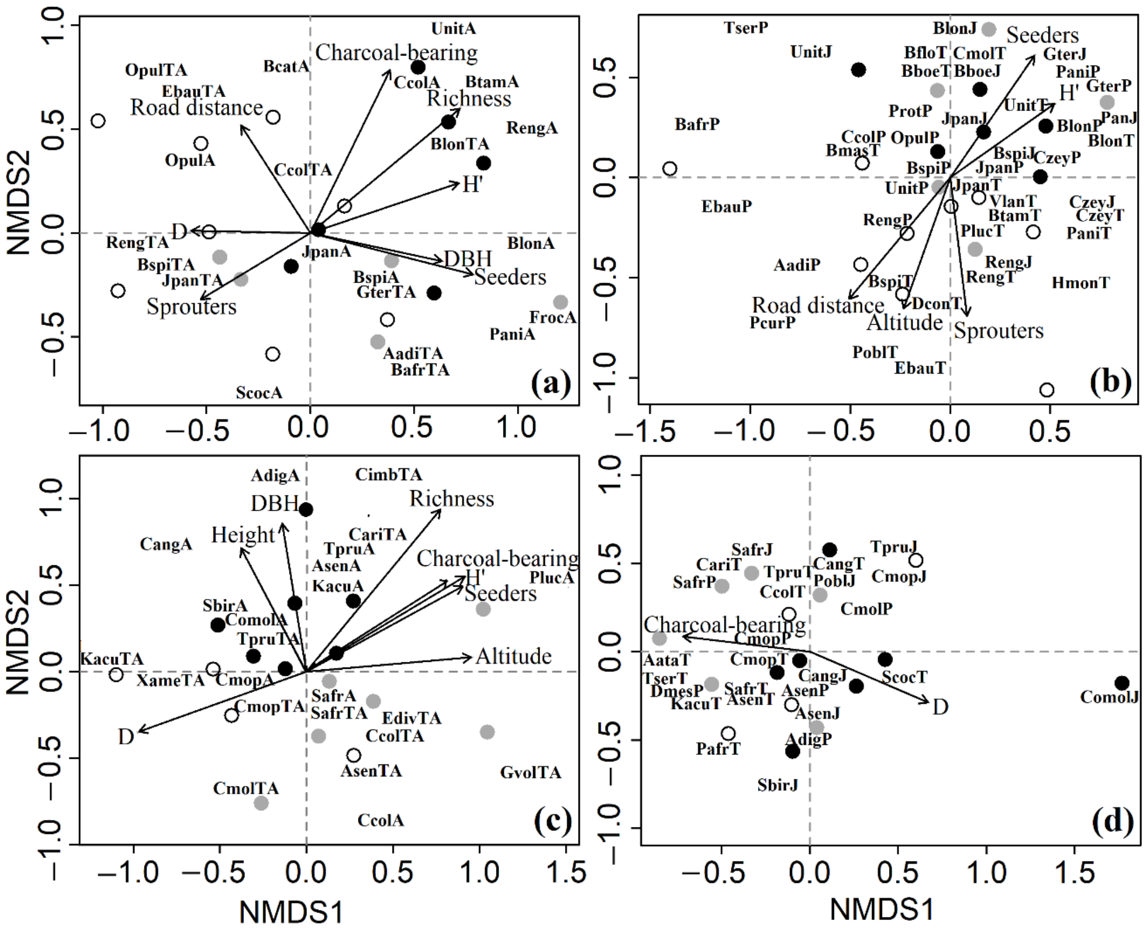

Figure 2. Axes 1 and 2 of the 3-dimensional non-metric multidimensional scaling ordinations of study sites based on the individual's number of trees species. (NMS1 and NMS2). Adult class (left) and young class (right), trees of Miombo (a, b) and Mopane (c, d). Recent fallow (white circles), intermediate allow (grey circles), and old growth/mature fallow (black circles.). Vectors represent significant correlations between species composition and the environmental variables, DBH and diversity indices. D (Dominance index); H' (Shannon index). Species codes according to Table 1, when added A (means adult seeders), TA (means adult sprouters), J (means young seeders), T (means young sprouters,) and P (means seedling).

Overall, these data showed a trend for an increase in tree size (DBH, tree height, biovolume, and biomass) and richness as the age of the fallow increases, both in Miombo and Mopane woodlands. Also, there was an increasing trend for seed regeneration individuals and a reduction in the number of stump regeneration individuals as the age of the fallows increased (see Supporting Information, Tables S3 and S4A–D).

Table 3. Significant squared correlation coefficient (r^2) of environmental factors and functional groups onto the NMS ordination.

Miombo woodland	**r2**	**Mopane woodland**	**r2**
Adult trees		**Adult trees**	
Altitude	ns	Altitude	0.52**
Road distance	0.35*	Road distance	ns
Slope	ns	Slope	ns
Average DBH	0.40**	Average DBH	0.43*
Basal area	ns	Basal area	38*
Richness	0.84***	Richness	0.84***
Richness charcoal-bearing	0.72***	Richness charcoal-bearing	0.57**
Seeders	0.63***	Seeders	0.61**
Sprouters	0.35*	Sprouters	ns
Diversity indices		***Diversity indices***	
Dominance index	0.83***	Dominance index	0.60***
Shannon index	0.54**	Shannon index	0.65***
Young trees		**Young trees**	
Altitude	0.40**	Altitude	ns
Road distance	0.52**	Road distance	ns
Slope	ns	Slope	n
Richness	ns	Richness	ns
Richness charcoal-bearing	ns	Richness charcoal-bearing	0.36*
Seeders	0.46**	Seeders	ns
Sprouters	0.40*	Sprouters	ns
Diversity indexes		***Diversity indexes***	
Shannon index	0.34*	Shannon index	ns
Dominance index	ns	Dominance index	0.36*

Significance level *$p<0.05$, **$p<0.01$ and ***$p<0.001$.

Pairwise Wilcoxon tests confirmed that Miombo recent fallows had considerably lower values of average height, DBH, and basal area than mature fallows (p = 0.001, 0.0012, and 0.001, respectively). Biovolume, total, and charcoal-bearing biomass also presented higher values in intermediate at mature fallows than in recent fallows (p = 0.003 and 0.001, respectively). The differences in average tree height among Mopane fallows were not statistically significant, although it was important in Non-metric Multidimensional Scaling ordinations (NMDS) analysis. Other variables, including mean DBH (p = 0.012 and 0.012), basal area (p = 0.009 and 0.007), biovolume (p = 0.018 and 0.021), total biomass (p = 0.009 and 0.004), and charcoal-bearing biomass (p = 0.018 and 0.014), had considerably greater values in mature and intermediate fallows compared to recent fallows, in Mopane fallows (see Supporting Information, Table S3).

Still, according to the Pairwise Wilcoxon test, there were no significative differences in the richness, Shannon, and Dominance indices among recent, intermediate, and mature fallow, for adult and young tree classes. Other non-significant differences found were the number of individuals of sprouters and seeders at Mopane, including the average height of trees. At Miombo, the value of young and adult tree sprouters was significantly higher in recent fallow than in mature fallow (p = 0.04 and p = 0.008, respectively), whereas the value of adult seeders occurs opposite, i.e., the number of individuals that grew by seed was significantly higher in intermediate and mature fallows than in recent ones (Figure 3, Table S3).

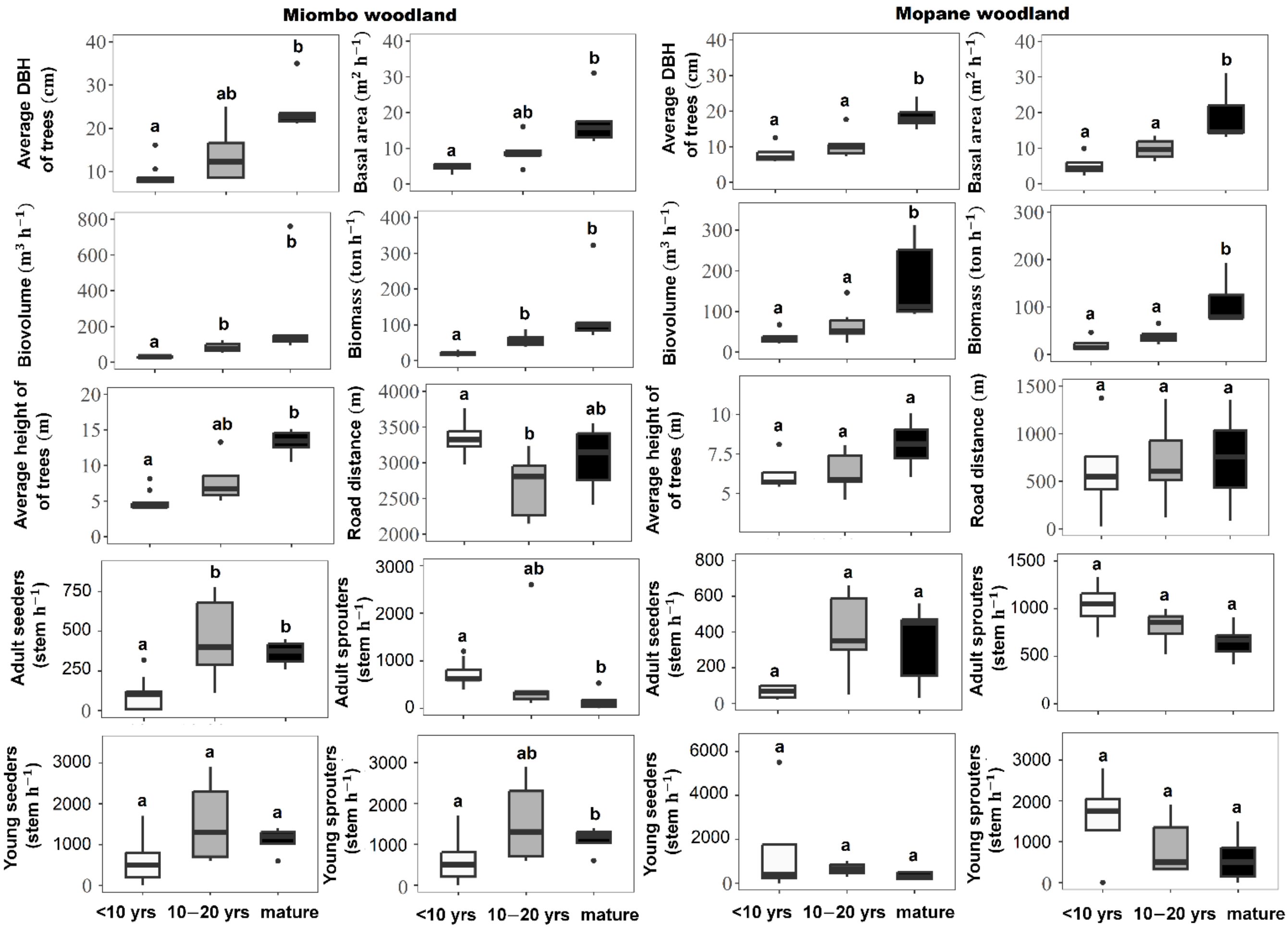

Figure 3. Boxplots resulting from the Pairwise Wilcoxon test using the Bonferroni correction for p-value adjustment, recording the principal differences between recent (<10 yrs), intermediate (10–20 yrs), and mature plots, using important variables namely, average DBH of trees, basal area, average height of trees, Biomass, Biovolume, Distance of the plot to road (Road distance), and density of seeders and sprouters, into Miombo and Mopane woodlands. Different letters indicate statistically significant differences.

Except for the road distance in Miombo, environmental variables showed no significantly different values between fallows. The recent fallows are significantly farther from the roads if compared to mature fallows (p = 0.021) (Figure 3, Table S3).

The IndVal analyses identified two species, *Julbernadia paniculata* and *Brachystegia spiciformis*, as indicators in Miombo and three species, *Colophospermum mopane*, *Spirostachys africana*, and *Combretum molle,* as indicators in Mopane (Table 4).

The Miombo species with the highest IndVal values were both from seed regeneration individuals: *J. paniculata* (0.62) for intermediate fallow and *Brachystegia spiciformis* (0.54) for mature fallow. *Julbernadia paniculata* and *B. spiciformis* are common in all plots but predominate in intermediate and mature fallows, respectively. No indicator species were found in the recent fallows of Miombo for the adult class and for all fallows for the young class.

The Mopane species with the highest IndVal values were essentially for adult class and stump regeneration and for *Colophospermum mopane* (0.50) in recent fallow. No indicator species were found in the mature fallow, and these values may indicate easy regeneration in open areas. However, the species with the greatest IndVal for the young class were the seedlings of *Combretum molle* (0.57) in mature fallows and both the seedling and young seeders of *Spirostachys africana* (with values of 0.58 and 0.50, respectively) in intermediate fallows.

Table 4. Indicator species and probabilities, regeneration type, combined groups of fallows stages as observed in the Miombo and Mopane area. 1 (recent fallow), 2 (intermediate fallow), and 3 (mature fallow).

Veget. type	**Tree age**	**Specie**	**Acron.**	**Regen. type**	**Denomin.**	**Fallow age**	**Ind. value**	**Prob. (p<0.05)**
Mopane	Young	*Spirostachys africana*	PafrT	Stump	Young sprouter	1	0.50	0.043
		Spirostachys africana	SafrJ	seed	Young seeders	2	0.58	0.033
		Spirostachys africana	SafrP	seed	Seedling	2	0.50	0.04
		Combretum cf. *molle*	CmolP	seed	Seedling	3	0.57	0.041
	Adult	*Colophospermum mopane*	CmopTA	Stump	Adult sprouters	1	0.50	0.03
		Acacia senegal	AsenTA	Stump	Adult sprouters	2	0.72	0.004
Miombo	Young	*Brachystegia spiciformis*	BspiT	Stump	Young sprouters	1	0.55	0.045
	Adult	*Julbernardia paniculata*	JpanA	Seed	Adult seeders	2	0.6193	0.022
		Brachystegia spiciformis	BspiA	seed	Adult seeders	3	0.5387	0.042

4. Discussion

Overall, findings suggest that selective removal of woody species as a result of selective cutting for charcoal production has a significant impact on the structure and dynamics of Mopane and Miombo tree communities, despite having no direct effect on their diversity. As expected, size-related variables such as the diameter at breast height (DBH), basal area, biomass, and biovolume of trees increased as the age of the fallow increased. Nevertheless, there were no significant differences in the richness, diversity, or dominance of trees between the adult and young classes or between recent and older fallow lands. The height of trees in Mopane was more variable in all fallows than in Miombo, probably because it contained fewer charcoal-bearing species. Regardless of the impact on the tree communities, the selective logging of species for charcoal production is very important for rural communities, as many species in addition to charcoal, provide medicinal, food, pasture, and shade uses. Most of Angola's forest resources arise from the dry tropical forests and woodlands, known as Mopane and Miombo, which constitute more than half of the country's total forest area [71]. The extensive use and exploitation of wood forest resources involves environmental, social, and economic impacts [35,41]. In this context, considering the results obtained, essential considerations were presented that can contribute to explaining how charcoal production can affect the structure and composition of these woodlands. It was found that most species regenerate from stumps after cutting, as demonstrated by Chidumayo [72]. Immediately after felling, the capacity of regeneration of individuals by stumps increased. Moreover, as soon as the canopy opens and the precipitation increases, the specific competition between individuals regenerated by seeds and by stumps increases. Both vegetation types, Miombo and Mopane, had more multi-stemmed trees in recent and intermediate fallows (Table S1), corroborating the results obtained in Bicuar National Park by Godlee et al. [73] In the plots, it was found a significant difference between the number of sprouter and seeder trees in Miombo, but not in Mopane (Table S3). It was also found that Mopane fallows seem to take longer to regenerate than Miombo, probably because Mopane vegetation is more affected by environmental and anthropogenic factors. For instance, the climate in the Mopane region, with its high temperatures and low rainfall, may not facilitate vegetation recovery after cutting. Moreover, soil poverty, low water storage capacity, and poor infiltration in Mopane are important characteristics to consider [2]. Populations have a great scarcity of resources, which causes a greater trend towards charcoal production to generate family income and to do dry farming just for household consumption. Moreover, the rise in cattle breeding and hunting practices has resulted in an increase in the practice of fire for hunting and creating new pastures, as recorded in Zigelski et al. (2019) [74]. However, in both regions, there is a wealth of nontimber forest resources, particularly fruits and seeds, roots, leaves, and mushrooms [75–78]. However, the residents in the Mopane zone seem to invest scarcely in selling these products to replace their source of income, especially during the most difficult periods. Therefore, the fear is that with this intensity, Mopane’s fallow land will probably not reach the mature stage. Additionally, the new Miombo kilns are increasingly distant from villages and roads. As rural families are poor, charcoal production is the basis of family subsistence for almost all of them, and they are, therefore, exempt from taxes. On the other hand, the sale of charcoal by the producing families is controlled by the authorities. If they sell large quantities, they must pay taxes just as they are levied on companies [79,80]. Probably this is the reason why most families, particularly in the Miombo region, try to produce charcoal away from the eyes of the inspectorate, as there is a shortage of means and human resources to control such acts. Therefore, it makes sense for the new fallows to be far from the road and closer to the mature forest. It is evident that to produce large quantities of charcoal for profit, it is necessary to find areas with more biomass to burn while allowing those areas adjacent to roadways and under the supervision of inspectors to regenerate freely. Moreover, the conversion of woody biomass is affected by a number of factors, including the type of kiln, the experience of the charcoal producer, and the quality of the wood. Chiteculo et al. (2018) [42] refer to a conversion factor of 0.19 for biomass and Miapia et al. (2021) [24] indicate a conversion factor of 0.23 for volume; however, in a recently submitted work [81], we estimated an efficiency of only 0.14 comparable to the value referred to in [35], implying an even higher environmental risk of this practice.

In addition to socio-economic and edaphoclimatic reasons, data confirmed that the indicator species in Mopane are those considered sun-tolerant and drought-tolerant, namely *Colophospermum mopane*, *Spirostachys africana*, and *Acacia senegal*. While in Miombo, the indicator species are those considered shade semi-tolerant or shade-tolerant and are also considered as no fire-tolerant at a young age, namely *Brachystegia spiciformis* and *Julbernadia paniculata*. However, other species such as *Burkea africana*, *Diplorhynchus condylocarpon, Pericopsis angolensis, Combretum* spp., and *Strychnos* spp. are described by many authors as species growing in disturbed areas and being fire-resistant [27,82–86].

Gonçalves et al. (2017) [87] showed similar results confirming that *J. paniculata* is an indicator species of medium and old fallow lands in Miombo. Furthermore, they observed that *B. spiciformis* was quite frequent even though it was not selected as an indicator species. Furthermore, the study area overlaps with the region previously investigated by Chisingui et al. (2018) [88]. These authors defined a set of characteristic plant communities, with Miombo and Mopane woodlands corresponding to the *Brachystegia spiciformis-Julbernardia paniculata* and *Colophospermum mopane-Spirostachys africana*, respectively.

Regarding the different impacts that agriculture and charcoal production have on the recovery of forests in Africa, the selective removal of tree species for the production of charcoal permits a comparatively quick regeneration by sprouting [25], with the unfortunate exception of the detrimental effect that kiln construction has on soil biodiversity [89]. In contrast, agriculture results in the removal of almost all trees. In Zambia, it was observed that stem densities were significantly higher in charcoal than in agriculture fallows, despite that the difference decreased with fallow age [27]. However, cultural production practices and poor post-harvest management of charcoal, including kiln efficiency and the short production cycle, increase the negative environmental impacts of charcoal production [90,91]. Also, in Zambia, the Miombo production rate is approximately 2.49 tons per hectare per year [92–94], meaning that it could take six to 29 years to reach maturity. As a result, the current level of Miombo exploration could be excessive, compromising the future of this woodland. Still, the production and consumption of forest products in many African countries, which are generally rudimentary, could be more efficient [95]. Strategies that contribute to the sustainability of charcoal production should be developed and implemented. Replacing charcoal with other sources of energy, particularly for cooking in cities, should be promoted to reduce the appetite of the rural community that uses charcoal as its main source of income [22,27,91]. The reuse of the gases resulting from charcoal production, or the use of a low-cost retort kiln or eco-charcoal are already additional proposals [96,97]. More protective measures are also important. For example, *B. spiciformis* is an abundant species in Angola, but a recent study reported that about 47% of its distribution includes areas with “High” and “Very High” threat levels, and only 4.2% are in protected areas [98], reinforcing the concern of Shumba et al. (2010) [99] and Romeiras et al. (2014) [100], about the importance of increasing conservation areas for the most vulnerable forest species. The production rates of Miombo wood in regrowth require long cutting cycles for maturation, which conditions the sustainable production of charcoal [26].

However, a greater diversification of rural populations' sources of income, particularly through the valorization of non-timber forest products such as mushrooms, edible wild fruits and leaves, beekeeping, etc. could be an alternative for the sustainable management of forest resources.

5. Conclusion

Ecosystem services obtained from Miombo and Mopane woodlands are important to the livelihoods of millions of people in Central and Southern Africa. In southern Angola, many species of trees are used as firewood and to make charcoal, with a growing trend in recent decades. If this trend continues, the use of Miombo and Mopane resources may become unsustainable. This study demonstrated that the two types of woods have distinct recovery tendencies following their felling for charcoal production and that the tree community structure takes a lot longer to regenerate. It is also shown that the species assemblage seems to change only slightly after the cutting of charcoal-bearing species. This could be possible since species that are used to make charcoal sprout instead of dying after being cut, allowing the species composition to basically remain unchanged. Moreover, many of the tree species here reported are key species with significant socioeconomic significance in Angola and the way these resources are managed is an important concern. Overexploitation can affect not only the composition and structure of the vegetation but also the way of life for those living in rural areas. Finally, in the present study, first-hand data was obtained, particularly in southern Angola, regarding the impact of charcoal exploitation in Miombo and Mopane woodlands. Hopefully, this methodology might be replicated in other regions of Angola, allowing for improved forest monitoring and management strategies.

Supplementary Materials: The following supporting information can be downloaded at: https: //www.mdpi.com/article/10.3390/f15010078/s1. Kissanga_et_al_Row_data.xls (contains the Supplementary Tables: S1, S2, S3, and S4: Species names and acronyms of the surveyed trees; Table S1A Adult individuals in Miombo woodland plots; Table S1B Young individuals in Miombo woodland plots; Table S1C Adult individuals in Mopane woodland plots; Table S1D Young individuals in Mopane woodland plots; Table S2A Environmental and response variables in Miombo woodland; Table S2B Environmental and response variables in Mopane woodland; Table S2C Diversity variables in Miombo woodlands; Table S2D Diversity variables in Mopane woodlands; Table S3 Statistics and pair-wise Wilcoxon test summaries; Table S4 Spearman correlation coefficients between environmental and functional variables).

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Supporting Information

Table S1A. Matrix of the adult individuals number counted from Miombo woodland plots. A (seeders adult), TA (sprouters adult). Simbol sample: C (Plots of Miombo), R (recent plot), I (Intermediate plot), M (mature plot). Acronimo of species (view Table 1).

Sample	BcatA	BlonA	BspiA	BtamA	CcolA	CmolA	EmagA	FrocA	GterA	JpanA	OpulA	PaniA	PlucA	RengA	ScocA	UnitA	AadiTA	BafrTA	BcatTA	BlonTA	BspiTA	CcolTA	EbauTA	FrocTA	GterTA	JpanTA	OpulTA	PaniTA	RengTA	NMDS1	NMDS2
CR1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	29	13	7	0	0	7	0	0	0	-0.545	0.4161
CR10	0	0	10	0	0	0	0	0	0	10	0	1	0	0	0	0	32	0	0	0	0	0	0	0	0	30	0	0	0	0.3618	-0.419
CR11	0	1	20	0	1	0	0	0	0	10	0	0	0	0	0	0	0	0	0	1	40	0	0	0	0	20	0	0	0	0.1627	0.1308
CR12	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	50	0	0	1	-0.489	-0.046
CR13	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	20	0	0	-1.021	0.5536
CR14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	70	0	0	0	-0.943	-0.244
CR16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0	0	0	0	40	0	0	0	-0.943	-0.244
CR22	0	0	11	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	10	0	0	0	0	30	0	0	0	-0.185	-0.581
CR4	1	0	0	0	3	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	13	0	2	0	0	46	0	0	0	-0.177	0.5617
CI14_1	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	25	0	0	0	-0.434	-0.247
CI15	0	0	1	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	230	0	0	0	-0.341	-0.168
CI17	0	0	8	0	0	0	0	0	0	21	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	10	0	0	0	0.342	-0.532
CI7	0	0	33	0	0	0	0	1	0	34	0	0	0	0	0	0	0	0	1	0	20	0	0	1	1	10	0	0	0	0.4064	-0.107
CI8	0	12	33	0	0	0	0	10	10	3	0	10	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	10	0	1.2142	-0.318
CM9	0	0	26	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	52	0	0	0	0	1	0	0	0	-0.09	-0.124
CM18	0	0	22	0	0	0	0	0	0	20	0	1	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0.5902	-0.322
CM19	0	1	22	1	2	0	0	0	0	10	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	10	0	0	0.6722	0.5279
CM2	0	0	17	0	2	0	1	0	0	3	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0.5269	0.8141
CM20	0	0	24	0	0	0	0	0	0	11	10	0	0	0	0	0	0	0	0	0	10	0	0	0	0	10	0	0	0	0.0499	0.0247
CM3	0	0	26	0	3	1	0	0	1	8	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8417	0.3238

Table S1B. Matrix of the young individuals number counted from Miombo woodland plots. J (seeders young), T (sprouters young), p (seedling). Simbol sample: C (Plots of Miomboe), R (recent plot), I (Intermediate plot), M (mature plot). Acronimo of species (view Table 1).

Sample	AadiJ	BafrJ	BboeJ	BlonJ	BspiJ	CcolJ	CzeyJ	EbauJ	GterJ	JpanJ	OpulJ	PaniJ	RengJ	UnitJ	AadiP	BafrP	BboeP	BcatP	BlonP	BspiP	CcolP	CzeyP	EbauP	FrocP	GterP	JpanP	OpulP	PaniP	PcurP	ProtP	RengP
CR1	0	0	0	0	40	10	0	0	0	0	0	0	0	0	0	10	0	0	0	80	20	0	0	0	0	10	20	0	0	10	20
CR10	0	0	0	0	0	0	0	10	0	10	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
CR11	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	10	40	0	50	0	0	0	0	0	0	0	0
CR12	10	0	0	0	0	0	0	0	0	0	10	0	0	0	200	0	0	0	0	50	10	0	50	0	0	180	30	0	10	0	20
CR13	0	0	0	0	10	10	0	0	0	10	50	0	0	0	0	0	0	0	0	20	0	0	0	0	0	60	10	0	0	0	0
CR14	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	30	10	0	10	0	0	30	0	0	0	0	0
CR16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	10	0	0	20	10	0	0	0	30
CR22	0	0	0	0	20	0	10	0	0	60	0	10	0	0	0	0	0	0	0	80	0	30	0	0	0	90	10	0	0	0	0
CR4	0	0	0	0	20	50	0	0	0	70	0	0	30	0	0	0	0	0	0	50	70	0	0	0	0	140	0	0	0	0	40
CI14_1	20	0	0	0	10	0	0	0	0	80	20	0	0	0	0	0	0	0	0	30	40	0	0	0	0	140	50	0	0	0	0
CI15	0	0	0	0	20	0	0	0	0	0	40	0	0	0	0	0	0	0	0	20	10	0	0	0	0	40	10	0	0	0	70
CI17	0	10	20	0	10	60	0	0	0	130	50	0	0	10	0	30	0	0	0	60	70	20	0	0	0	180	30	20	0	0	0
CI7	0	0	10	10	0	10	0	0	10	30	0	0	0	0	0	0	20	0	0	20	0	0	0	0	0	70	0	0	0	0	0
CI8	0	0	0	10	30	0	0	0	20	110	0	60	0	0	0	0	0	0	20	30	0	0	0	20	90	280	0	30	0	0	0
CM9	0	0	0	0	20	20	0	0	20	20	10	10	0	0	0	0	0	0	0	20	0	0	0	0	20	40	0	30	0	0	0
CM18	0	0	30	0	0	40	0	0	10	40	20	0	0	0	0	0	40	0	0	30	80	0	0	0	0	30	20	10	0	20	0
CM19	0	0	0	0	0	20	10	0	0	60	40	0	0	0	0	0	0	0	40	0	100	30	0	0	0	30	10	0	0	0	0
CM2	0	0	0	0	20	10	0	0	0	10	20	0	0	0	0	0	0	0	0	110	10	0	0	0	0	140	40	0	0	0	0
CM20	0	0	60	0	10	0	0	0	0	20	20	0	0	0	0	0	0	0	40	10	40	10	0	0	10	130	20	0	0	0	10
CM3	0	0	0	20	0	30	0	0	0	60	0	0	10	10	10	10	0	40	0	20	100	0	0	0	0	50	100	0	0	0	90

Table S1B. Conclusion

Sample	TserP	UnitP	XodoP	AadiT	BafrT	BboeT	BcatT	BflorT	BlonT	BmasT	BspiT	BtamT	CcolT	CmolT	CzeyT	DconT	EbauT	FrocT	GterT	HmonT	JpanT	OpulT	PangT	PaniT	PlucT	PoblT	RengT	UnitT	VlanT	NMDS1	NMDS2
CR1	0	0	10	0	0	20	0	0	0	10	40	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.44055	0.073522
CR10	0	0	0	20	0	0	0	0	0	0	10	0	20	0	20	0	130	10	0	0	10	0	20	10	0	0	10	0	0	0.481571	-1.06075
CR11	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.40175	0.046238
CR12	0	0	0	0	0	0	0	0	0	0	20	0	10	0	0	10	390	0	0	0	20	0	0	0	0	0	10	0	0	-0.44714	-0.43294
CR13	0	0	0	0	0	0	0	0	0	0	60	10	90	0	0	0	20	0	0	0	50	60	0	0	0	0	0	10	0	0.142846	-0.09913
CR14	0	0	0	0	0	0	0	0	0	0	130	0	60	0	0	0	0	0	0	0	150	50	0	0	0	0	0	0	0	-0.21641	-0.27754
CR16	0	0	0	0	0	0	0	0	0	0	50	0	40	0	0	0	20	0	0	0	30	0	0	0	0	10	30	0	0	-0.2395	-0.58236
CR22	0	0	0	0	0	0	0	0	0	0	80	0	150	0	10	10	0	0	0	100	0	0	0	40	0	0	0	0	0	0.41417	-0.27085
CR4	0	0	0	0	0	0	0	0	0	0	30	0	60	0	0	0	0	0	0	0	70	0	0	0	0	0	60	0	0	0.003589	-0.1431
CI14_1	0	20	0	10	0	0	0	0	0	0	60	0	90	0	0	0	0	0	0	0	120	60	0	0	0	0	0	10	0	-0.05649	-0.04701
CI15	0	0	0	0	0	0	0	0	0	0	70	0	40	0	0	0	0	0	0	0	0	70	0	30	20	0	50	0	10	0.123476	-0.35822
CI17	0	0	0	0	30	30	0	10	0	0	0	0	10	0	0	0	0	0	0	0	50	20	0	0	10	0	0	10	0	-0.06349	0.434906
CI7	0	0	0	0	0	10	20	0	0	0	0	0	10	0	0	0	0	0	20	0	30	0	0	0	0	0	0	0	0	0.192946	0.740783
CI8	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	30	0	0	40	0	0	0	0	0	0.784581	0.375578
CM9	0	0	0	0	0	0	0	0	0	0	10	0	30	0	40	0	0	0	0	0	10	0	0	0	0	0	0	10	0	0.47762	0.257407
CM18	0	0	0	0	0	20	0	0	0	0	10	0	20	10	10	0	0	0	0	0	10	10	0	10	0	0	0	10	0	0.148785	0.44048
CM19	0	0	0	0	0	0	0	0	10	0	0	0	20	0	10	0	0	0	0	0	30	40	0	0	0	0	10	0	0	0.450296	0.004964
CM2	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	-0.0621	0.130068
CM20	0	0	0	0	0	10	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	10	0	0	0	0	10	0	10	0.166125	0.228708
CM3	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.45858	0.539244

Table S1C. Matrix of the adult individuals number counted from Mopane woodland plots. A (seeders adult), TA (sprouters adult). Simbol sample: B (Plots of Mopane), R (recent plot), I (Intermediate plot), M (mature plot). Acronimo of species (view Table 1).

Sample	AataA	AdigA	AsenA	AsenTA	CangA	CarisTA	CcolA	CcolTA	CimbTA	CmopA	CmopTA	CmubA	CmubTA	ComolA	ComolTA	EdivA	EdivTA	GflaA	GvolA	GvolTA	KacuA	KacuTA	PaniA	PaniTA	PlucA	SafrA	SafrTA	SbirA	TpruA	TpruTA	XameTA	NMDS1	NMDS2
BR1	0	0	0	0	1	0	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	1	0	0	0	-1.1001	-0.0158
BR14	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	10	0	-0.4316	-0.2537
BR14_1	0	0	0	10	0	0	10	10	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	20	0	0.27329	-0.4847
BR8	0	0	0	0	0	0	0	0	0	3	100	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	20	0	1	10	1	-0.5388	0.01362
BIp6	0	0	20	10	0	0	0	0	0	0	0	3	1	0	0	0	0	1	1	1	1	0	0	0	0	40	40	0	0	0	0	1.04517	-0.3482
BI12	0	0	0	10	0	0	0	0	0	30	60	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2619	-0.76
BI13	0	0	0	10	0	0	0	0	0	0	70	0	0	10	0	0	0	0	0	0	0	0	0	0	0	20	20	0	0	0	0	0.07016	-0.3729
BI3	0	0	0	10	0	0	0	0	0	0	21	0	0	0	0	0	10	0	0	0	10	0	0	0	0	30	20	0	0	11	0	0.387	-0.1708
BI6	0	0	0	10	0	0	0	0	0	0	40	0	0	1	1	0	0	0	0	0	2	0	0	0	0	1	10	0	1	31	0	0.13256	-0.0557
BIp5	1	0	0	10	0	0	0	10	10	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	40	60	1	20	0	0	1.02262	0.36139
BM10	0	1	10	0	10	0	0	0	10	11	38	0	0	3	0	0	0	0	0	0	8	0	0	0	0	0	0	1	12	1	0	-0.0334	0.80333
BM15	0	0	1	0	0	0	0	0	0	10	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	11	2	0	10	0	-0.1221	0.01714
BM2	0	0	0	0	0	0	0	0	0	1	70	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	20	0	-0.5125	0.26835
BM4	0	0	2	10	0	0	0	0	0	0	50	0	0	1	0	0	0	0	0	0	5	0	0	0	0	11	0	1	2	10	0	0.17336	0.10553
BM5	0	0	2	0	0	0	0	0	0	1	50	0	0	6	0	0	0	0	0	0	0	1	0	0	0	0	3	0	0	20	0	-0.3063	0.08904
BM7	0	0	10	0	0	1	0	0	0	0	20	0	0	6	0	0	0	0	0	0	0	0	0	0	0	10	10	0	20	30	0	0.27029	0.40752
BM9	0	2	0	0	0	0	0	0	0	23	31	0	0	7	0	0	0	0	0	0	1	0	0	0	0	14	0	0	1	10	0	-0.0678	0.39593

Table S1D. Matrix of the young individuals number counted from Mopane woodland plots. J (seeders young), T (sprouters young), p (seedling). Simbol sample: B (Plots of Mopane), R (recent plot), I (Intermediate plot), M (mature plot). Acronimo of species (view Table 1).

Sample	PoblJ	AsenJ	CmopJ	CangJ	SafrJ	TpruJ	AlacJ	GvolJ	CimbJ	EdivJ	SbirJ	ComolJ	CspiJ	PlucP	ProtP	ScocP	XodoP	AsenP	CmopP	TpruP	CspiP	CimbP	DmesP	KacuP	AdigP	AataP	CariP	GameP
BR1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BR14	0	10	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	20	0	0	0	0	0	0	0	0	0
BR14_1	0	0	0	10	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0
BR8	0	0	380	0	0	170	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BIp6	0	10	30	0	10	0	10	10	0	0	0	0	0	0	0	0	0	0	0	0	10	10	10	10	0	0	0	0
BI12	20	0	50	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	10	220	0	0	0	0	0	0	0	0
BI13	0	20	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	10	0	0	0	0	0	20	0	0	0
BI3	0	0	0	0	60	0	0	0	0	0	0	0	0	0	0	0	0	0	130	0	0	0	0	0	0	0	0	0
BI6	0	0	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0
BIp5	0	10	10	0	50	0	0	0	10	10	0	0	10	30	20	10	20	0	0	0	0	20	20	0	0	10	40	10
BM10	0	20	0	10	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BM15	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	10	0	0	0	0	0	0	0	0
BM2	0	10	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BM4	0	10	10	0	0	10	0	0	0	0	0	20	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
BM5	0	0	0	0	10	20	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0
BM7	0	0	10	0	0	10	0	0	0	0	0	0	0	0	0	0	0	30	40	20	0	0	0	0	0	0	0	0
BM9	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table S1D. Conclusion.

Sample	SalaP	CmolP	SafrP	CcolT	PoblT	ScocT	TserT	CmopT	SafrT	AsenT	ComolT	TpruT	CmubT	KacuT	AataT	EdivT	SalaT	CangT	PafrT	CariT	NMDS1	NMDS2
BR1	0	0	0	0	0	0	0	150	10	0	0	0	0	0	0	0	0	0	10	0	-0.4599	-0.4659
BR14	0	0	0	0	0	0	0	140	0	20	10	0	0	0	0	0	0	0	10	0	-0.101	-0.2998
BR14_1	0	0	0	30	0	0	0	210	10	0	0	30	0	0	0	0	0	0	0	0	-0.1199	0.21261
BR8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.59569	0.52312
BIp6	0	0	30	0	0	0	0	10	80	10	0	0	80	10	0	0	0	0	0	0	-0.5543	-0.1876
BI12	0	0	0	0	0	0	0	0	10	0	0	50	0	0	0	0	0	0	0	0	0.05515	0.32165
BI13	0	0	0	0	0	0	0	30	0	10	0	0	0	0	0	0	0	0	0	0	0.04206	-0.4282
BI3	0	0	80	0	0	0	0	0	10	0	0	10	0	0	0	0	0	0	0	10	-0.5007	0.369
BI6	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	-0.3326	0.44341
BIp5	20	0	10	0	0	0	10	0	80	30	0	0	0	0	10	10	10	0	0	10	-0.8529	0.07145
BM10	0	10	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0.26411	-0.1907
BM15	0	0	0	0	0	0	0	110	20	10	10	0	0	0	0	0	0	0	0	0	-0.184	-0.1179
BM2	0	0	0	0	0	0	0	10	60	0	0	0	0	0	0	0	0	0	0	0	-0.0933	-0.5622
BM4	0	40	0	0	0	10	0	10	0	0	0	30	0	0	0	0	0	0	0	0	0.4256	-0.0403
BM5	0	20	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	10	0	0	0.1071	0.57866
BM7	0	10	0	0	10	0	0	50	20	0	10	0	0	0	0	0	0	10	0	0	-0.0586	-0.0502
BM9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.76743	-0.177

Table S2A. Environment variables of Miombo woodland. Slope class: 1) plan; 2) light; 3) slope.

Sample	Age fallow	Slope class	Altititude (m)	Road distance (m)	Average Height (m)	Average DBH (cm)	Basal area (m2/ha)	Biovolume (m3/ha)	Total biomass (ton/ha)	Charcoal-bearing biomass species (ton/ha)
CR1	<10yrs	2	1612	3760	3.96	7.39	2.68	16.64	9.94	9.94
CR10	<10yrs	1	1628	3325	6.55	10.59	5.78	32.68	23.69	22.84
CR11	<10yrs	2	1623	3487	4.74	7.46	4.08	26	14.86	14.86
CR12	<10yrs	1	1623	3443	4.07	7.88	4.41	23.54	14.31	13.96
CR13	<10yrs	3	1632	3357	4.64	8.64	5.15	31.83	22.81	22.81
CR14	<10yrs	1	1629	3224	4.19	7.67	5.23	30.89	18.6	18.6
CR16	<10yrs	2	1632	3299	4.25	7.75	5.61	33.76	20.12	20.12
CR22	<10yrs	2	1634	2974	8.14	16.14	5.67	41.49	29.45	26.73
CR4	<10yrs	1	1637	3086	4.21	8.05	4.38	29.9	19.26	19.19
CI14_1	10-20yrs	1	1633	2954	5.81	8.56	4	124.19	87.71	87.71
CI15	10-20yrs	3	1628	3232	5.02	8.21	16.09	99.67	66.01	66.01
CI17	10-20yrs	2	1628	2808	13.27	25.06	9.23	73.58	54.19	53.12
CI7	10-20yrs	2	1593	2145	6.73	12.28	8.19	51.13	37.54	30.71
CI8	10-20yrs	2	1599	2262	8.56	16.64	8.25	65.15	44.15	37.39
CM9	Mature	2	1609	2413	12.5	23.76	17.93	148.81	106.63	106.63
CM18	Mature	1	1617	2635	14.74	34.99	31.09	760.5	322.5	184.38
CM19	Mature	3	1618	3551	14.17	22.83	14.96	131.29	96.01	96.01
CM2	Mature	2	1636	3109	10.46	21.26	12.11	111.17	80.71	80.65
CM20	Mature	3	1598	3486	15.13	22.42	12.44	92.79	70.72	70.72
CM3	Mature	3	1618	3187	12.68	21.04	16.69	148.98	103.43	101.12

Table S2B. Environment variables of Mopane woodland. Slope class: 1) plan; 2) light; 3) slope.

Sample	Age fallow	Slope class	Altititude (m)	Road distance (m)	Average Height (m)	Average DBH (cm)	Basal area (m2/ha)	Biovolume (m3/ha)	Total biomass (ton/ha)	Charcoal-bearing biomass species (ton/ha)
BR1	<10yrs	2	653	555	8.1	5.94	2.29	21.76	8.21	4.27
BR14	<10yrs	2	668	541	5.42	6.52	4.16	28.73	13.81	13.81
BR14_1	<10yrs	1	747	27	5.68	7.17	4.66	29.2	16.3	16.3
BR8	<10yrs	3	730	1373	5.75	12.49	9.94	67.29	46.68	43.54
BIp6	10-20yrs	3	1097	119	4.6	7.3	6.37	22.23	20.7	15.06
BI12	10-20yrs	2	691	1006	5.82	9.49	8.7	48.17	36.59	35.31
BI13	10-20yrs	2	668	512	8.04	10.69	12.45	55.77	45.29	40.42
BI3	10-20yrs	1	656	685	5.9	10.5	10.53	145.99	35.39	32.44
BI6	10-20yrs	2	656	521	7.9	17.68	13.47	86.03	65.91	43.5
BIp5	10-20yrs	1	1095	1362	5.74	7.6	7.16	45.1	26.49	24.25
BM10	Mature	3	738	1267	10.08	20.14	23.88	312.04	163.81	67.81
BM15	Mature	3	723	154	9.68	17.63	14.28	111.88	78.59	52.03
BM2	Mature	2	643	757	7.38	14.94	19.98	102.74	87.19	84.95
BM4	Mature	2	650	801	8.4	19.02	14.61	208.11	78.72	39.48
BM5	Mature	2	661	712	7.1	17.8	13.17	94.24	77.69	60.85
BM7	Mature	2	666	82	6.04	15.42	14.63	96.48	76.42	58.9
BM9	Mature	3	766	1358	8.13	24.14	30.99	292.88	192.39	116.26

Table S2C. Variables adult and young species of Miombo woodland. Dom (Dominance index); Shann (Shannon index)

	Adult class							Young class							
Fallow	Richness	Charcoal-bearing species	Total individuals	Seeders	Sprouters	Dom.	Shann	Richness	Charcoal-bearing species	Total individuals	Seeders	Sprouters	Seedling	Dom	Shann
CR1	4	4	57	1	56	0.34	1.27	14	10	340	50	110	180	0.12	2.39
CR10	4	3	83	21	62	0.31	1.3	14	9	320	30	260	30	0.2	2.15
CR11	4	4	93	32	61	0.29	1.41	6	4	160	10	40	110	0.23	1.58
CR12	3	2	91	10	81	0.42	0.99	16	12	1030	20	460	550	0.22	1.93
CR13	2	2	70	10	60	0.43	0.96	14	14	470	80	300	90	0.11	2.34
CR14	2	2	110	0	110	0.54	0.66	9	9	520	50	390	80	0.18	1.89
CR16	2	2	120	0	120	0.56	0.64	11	8	290	0	180	110	0.11	2.27
CR22	3	2	52	12	40	0.41	1.04	14	10	700	100	390	210	0.12	2.28
CR4	5	3	71	9	62	0.46	1.1	12	9	690	170	220	300	0.11	2.37
CI14_1	2	2	75	40	35	0.41	0.97	15	15	760	130	350	280	0.11	2.41
CI15	2	2	271	11	260	0.73	0.53	14	10	500	60	290	150	0.1	2.45
CI17	3	2	49	29	20	0.29	1.31	22	18	870	290	170	410	0.1	2.68
CI7	5	2	101	68	33	0.27	1.46	13	10	270	70	90	110	0.12	2.34
CI8	7	3	90	78	12	0.2	1.81	14	8	780	230	80	470	0.18	2.14
CM9	2	2	82	29	53	0.5	0.83	15	11	310	100	100	110	0.08	2.6
CM18	4	3	53	43	10	0.35	1.12	21	17	480	140	110	230	0.07	2.83
CM19	6	6	48	36	12	0.3	1.44	15	14	460	130	120	210	0.11	2.46
CM2	7	6	27	26	1	0.42	1.34	10	10	380	60	20	300	0.24	1.75
CM20	3	3	65	45	20	0.24	1.53	17	13	430	110	50	270	0.14	2.38
CM3	6	4	40	40	0	0.47	1.07	14	10	590	130	0	460	0.11	2.35

Table S2D. Variables adult and young species of Mopane woodland

	Adul class							Young class							
Fallow	Richness	Charcoal-bearing species	Total individuals	Seeders	Sprouters	Dom.	Shann	Richness	Charcoal-bearing species	Total individuals	Seeders	Sprouters	Seedling	Dom	Shann
BR1	4	1	2	70	72	0.71	0.54	3	2	170	0	170	0	0.79	0.44
BR14	3	3	10	110	120	0.71	0.57	8	6	260	50	180	30	0.33	1.52
BR14_1	5	5	10	100	110	0.22	1.64	8	7	350	30	280	40	0.39	1.38
BR8	5	3	4	133	137	0.56	0.92	2	2	550	550	0	0	0.57	0.62
BIp6	6	3	66	52	118	0.27	1.54	15	8	330	70	190	70	0.14	2.29
BI12	3	2	30	80	110	0.39	1.12	7	6	380	90	60	230	0.38	1.35
BI13	4	3	30	100	130	0.35	1.3	7	6	110	30	40	40	0.17	1.85
BI3	6	3	40	72	112	0.17	1.85	6	5	300	60	30	210	0.3	1.38
BI6	6	4	5	92	97	0.29	1.47	3	3	100	40	30	30	0.34	1.09
BIp5	10	6	65	91	156	0.24	1.7	24	10	470	100	160	210	0.07	2.92
BM10	9	4	56	49	105	0.19	1.96	5	4	70	50	10	10	0.22	1.55
BM15	5	4	45	67	112	0.28	1.5	7	6	290	50	150	90	0.26	1.56
BM2	5	2	3	91	94	0.6	0.74	4	3	90	20	70	0	0.48	1
BM4	7	4	22	70	92	0.34	1.49	9	7	150	50	50	50	0.16	2.03
BM5	6	4	9	74	83	0.43	1.15	6	5	100	30	20	50	0.2	1.7
BM7	6	4	46	61	107	0.18	1.85	11	8	220	20	100	100	0.13	2.2
BM9	6	3	48	41	89	0.23	1.64	1	0	20	20	0	0	1	0

Table S3. Statistic descriptive and pair-wise Wilcoxon test summary between plots age into Miombo and Mopane forests for all variables. Bolt number P-value significant (<0.05).

					Pairwise Wilcoxon test					
Miombo	Fallows age	Recent Fallow (N=9)	Intermediate Fallow (N=5)	Mature fallow (N=6)	R-I (N=14)		R-M (N=15)		I-M (N=11)	
	Variable/indice	Mean (SD)	Mean (SD)	Mean (SD)	Statistic	*p.*	Statistic	*p.*	Statistics	*p.*
	Altitude (m)	1628(7,55)	1616(18,7)	1616(12,5)	31	ns	43	ns	16	ns
	Slope (1-plan; 2-light; -slope)	1.67(0.7)	2(0.7)	2.33(0.82)	16.5	ns	14.5	ns	11	ns
	Road distance (m)	3328(7.55)	2680(18.7)	3064(12.5)	42	ns	35	ns	8	ns
Young tree	Sprouters (Stem/plot)	261(139)	196(120)	66,7(50,5)	30	ns	48.5	**0.04**	24	ns
	Seeders (Stem/plot)	56,7(53,4)	156(101)	112(29,3)	7	ns	8.5	ns	17.5	ns
	Seedling (Stem/plot)	184(159)	284(157)	263(116)	13	ns	14	ns	16.5	ns
	Dominance_index(D)	0,16(0,05)	0,12(0,03)	0,13(0,06)	34	ns	37	ns	16	ns
	Shannon_index(H)	2,13(0,28)	2,4(0,10)	2,4(0,36)	8.5	ns	11	ns	13	ns
Adult tree	Average Height (m)	4.97(1,42)	7,88(3.29)	13,3(1,75)	5	ns	0	**0.001**	3	ns
	Average DBH (cm)	9.06(2,83)	14.2(6.99)	24.4(5.29)	7	ns	0	**0.0012**	5	ns
	Basal area (m2/ha)	4.78(1)	9.15(4.37)	17.54(7.02)	8	ns	0	**0.001**	3	ns
	Total biomass (ton/ha)	19.2(5.79)	57.9(19.8)	130(95.3)	0	**0.003**	0	**0.001**	2	ns
	Charcoal-bearing biomass species (ton/ha)	18.8(5.18)	55(22.9)	107(40.4)	0	**0.003**	0	**0.001**	2	ns
	Biovolume (m3/ha)	29.6(7)	82.7(29.1)	232(260)	0	**0.003**	0	**0.001**	3	ns
	Sprouters (Stem/plot)	72.4(26.4)	72(106)	16(19,6)	36	ns	53	**0.008**	24	ns
	Seeders (Stem/plot)	10.6(10.5)	45.2(27.6)	36.5(7.66)	4	**0.049**	2	**0.011**	17	ns
	Dominance_index(D)	0,42(0,10)	0,34(0,11)	0,38(0,10)	34	ns	32.5	ns	10	ns
	Shannon_index(H)	1.04(0.28)	1.26(0.33)	1.23(0.26)	14	ns	14	ns	16	ns

Table S3. Conclusion.

					Pairwise Wilcoxon test					
Mopane	Fallows age	Recent Fallow (N=4)	Intermediate Fallow (N=6)	Mature fallow (N=7)	R-I (N=10)		R-M (N=11)		I-M (N=13)	
	Variable/indice	Mean (SD)	Mean (SD)	Mean (SD)	Statistic	*p.*	Stat.	*p.*	Stat.	*p.*
	Altitude (m)	700(46)	810(222)	692(48,9)	10.5	ns	17	ns	26	ns
	Slope (1-plan; 2-light; -slope)	2(0.82)	1.83(0.75)	2.43(0.54)	13.5	ns	9.5	ns	11.5	ns
	Road distance	624,00(556,50)	700,83(432,91)	733,00(489,98)	12	ns	11	ns	9	ns
Young tree	Sprouters (Stem/plot)	158(116)	85(71,2)	57,1(54,1)	16	ns	21.5	ns	27	ns
	Seeders (Stem/plot)	158(262)	65(27,4)	34,3(15,1)	8.5	ns	16	ns	35.5	ns
	Seedling (Stem/plot)	17,5(20,6)	132(94,3)	42,9(41,5)	2	ns	8	ns	32	ns
	Dominance_index(D)	0,52(0,21)	0,23(0,12)	0,35(0,31)	22	ns	22	ns	18	ns
	Shannon_index(H)	0,99(0,54)	1,81(0,69)	1,43(0,74)	5.5	ns	6	ns	25	ns
Adult tree	Average Height (m)	6.24(1.25)	6.33(1.35)	8.12(1,43)	10	ns	3	ns	6	ns
	Average DBH (cm)	8.03(3.02)	10.5(3.77)	18.4(3.11)	5	ns	0	**0.018**	3	**0.024**
	Basal area (m2/ha)	5.26(3.28)	9.78(2.86)	18.8(6.62)	3	ns	0	**0.018**	1	**0.007**
	Total biomass (ton/ha)	21.2(17.3)	38.4(15.9)	108(48.8)	5	ns	0	**0.018**	0	**0.004**
	Charcoal-bearing biomass species (ton/ha)	19.5(16.9)	31.8(10.6)	68.6(25.2)	7	ns	1	**0.036**	2	**0.014**
	Biovolume (m3/ha)	36.7(20.6)	67.2(43.7)	174(96.3)	6	**0.003**	0	**0.018**	4	**0.042**
	Sprouters (Stem/plot)	103(26,1)	81,2(17,3)	64,7(16,5)	18.5	ns	25.5	ns	33.5	ns
	Seeders (Stem/plot)	6,5(4,12)	39,3(23,3)	32,7(21,1)	2	ns	5	ns	24	ns
	Dominance_index(D)	0,55(0,23)	0,29(0,08)	0,32(0,15)	19	ns	22	20		ns
	Shannon_index(H)	0,92(0,51)	1,5(0,27)	1,48(0,42)	4	ns	5.5	ns	19.5	ns

Table S4A. Spearman correlation between the ambiental and functional variables of the Miombo woodland plots, for Adult class. Altit (altitude), Decli (slope), Droad (distance from the plots to the road), Hmed (average tree height), DBH (average diameter at breast height), Barea (basal area), Biovol (biovolume), Biomas (biomass), BiomasC (biomass charcoal bearing), bolt number (correltion excluded)

Variable	Altit	Decli	Droad	Hmed	DBH	Barea	Biovol	Biomas	BiomasC	Richness	Richness Charcoal-bearing Richness	Total individuals	Seeders	Sprouters	D
Altit	1														
Decli	-0.27869	1													
Droad	0.047494	0.279971	1												
Hmed	-0.37392	0.368722	-0.33383	1											
DBH	-0.29325	0.251732	-0.46466	**0.935338**	1										
Barea	-0.3905	0.401802	-0.34135	**0.807519**	**0.813534**	1									
Biovol	-0.21033	0.295301	-0.44812	**0.825564**	**0.803008**	**0.821053**	1								
Biomas	-0.22691	0.283198	-0.45113	**0.852632**	**0.843609**	**0.815038**	**0.990977**	1							
BiomasC	-0.22691	0.283198	-0.45113	**0.852632**	**0.843609**	**0.815038**	**0.990977**	1	1						
Richness	-0.24051	0.063527	-0.07842	0.316758	0.266015	0.181444	0.1184	0.136852	0.136852	1					
Charcoal-bearing Richness	-0.16855	0.195647	0.376013	0.274498	0.131564	0.130752	0.121818	0.139685	0.139685	0.781436	1				
Total individuals	-0.07991	-0.23963	-0.01053	-0.5609	-0.6	-0.29023	-0.41504	-0.45414	-0.45414	-0.45822	-0.52626	1			
Seeders	-0.59343	0.212113	-0.41792	0.756778	0.635543	0.478916	0.615965	0.647591	0.647591	0.449674	0.257424	-0.24849	1		
Sprouters	0.332453	-0.26656	0.334964	-0.78585	-0.75348	-0.50282	-0.65789	-0.68122	-0.68122	-0.62577	-0.50571	0.767784	-0.74746	1	
D	0.513208	-0.04685	0.030862	-0.40572	-0.29582	0.03312	0.029356	-0.02635	-0.02635	-0.50184	-0.33863	0.225819	-0.66528	0.492464	1
H’	-0.47644	0.140389	-0.01504	0.473684	0.356391	0.109774	0.052632	0.103759	0.103759	0.765755	0.602595	-0.35489	0.661145	-0.61649	-0.9093

Table S4B. Correlation of the Spearman between the ambiental and functional variables of the Miombo woodland plots, for young class. Altit (altitude), Decli (slope), Droad (distance from the plots to the road), bolt number (correltion excluded).

Variable	**Altit**	**Decli**	**Droad**	**Richness**	**Richness Charcoal-bearing Richness**	**Total individuals**	**Seeders**	**Sprouters**	**Seedling**	**D**
Altit	1									
Decli	-0.27869	1								
Droad	0.047494	0.279971	1							
Richness	-0.36028	0.059448	-0.10157	1						
Richness Charcoal-bearing Richness	-0.10874	0.129491	-0.09318	**0.825345**	1					
Total individuals	0.266115	-0.2122	-0.25263	0.42319	0.329174	1				
Sprouters	0.51226	-0.4126	0.093303	0.113192	0.152864	0.448458	1			
Seeders	-0.11338	0.096671	-0.53374	0.515341	0.472475	0.539768	-0.18446	1		
Seedling	-0.02764	-0.01824	-0.21601	0.402697	0.268908	0.688074	-0.19917	0.554715	1	
D	0.046711	-0.18645	0.336811	-0.47442	-0.5159	-0.12678	-0.09592	-0.5054	0.004987	1
H’	-0.25377	0.19452	-0.2076	0.708147	0.699853	0.130876	-0.00677	0.592762	0.119759	-0.87596

Table S4C. Correlation of the Spearman between the ambiental and functional variables of the Mopane plots, for Adult class. Altit (altitude), Decli (slope), Droad (distance from the plots to the road), Hmed (average tree height), DBH (average diameter at breast height), Barea (basal area), Biovol (biovolume), Biomas (biomass), BiomasC (biomass charcoal bearing), bolt number (correltion excluded)

Variable	Altit	Declia	Droad	Hmed	DBH	Barea	Biovol	Biomas	BiomasC	Richness	Richness Charcoal-bearing Richness	Seeders	Sprouters	Total individuals	D
Altit	1														
Decli	0.313683	1													
Droad	0.077301	0.167453	1												
Hmed	-0.2815	0.290876	0.141191	1											
DBH	-0.20872	0.440508	0.413243	0.774571	1										
Barea	-0.06258	0.491554	0.227941	0.73665	0.787247	1									
Biovol	-0.0908	0.424033	0.257353	0.715778	**0.855917**	**0.894608**	1								
Biomas	-0.16442	0.426734	0.276961	0.747699	**0.889025**	**0.892157**	**0.958333**	1							
BiomasC	-0.04417	0.41323	0.240196	0.600369	0.676885	**0.867647**	**0.821078**	**0.872549**	1						
Richness	0.34902	0.211135	0.217561	0.112696	0.389005	0.343647	0.458608	0.423996	0.186657	1					
Charcoal-bearing Richness	0.229853	-0.12265	0.020238	0.266743	0.372728	0.314949	0.419932	0.389575	0.199847	0.727233	1				
Seeders	0.669533	0.197404	-0.00736	-0.11309	-0.0178	0.215951	0.320246	0.246626	0.231902	0.602739	0.376756	1			
Sprouters	-0.14567	-0.43564	0.003683	-0.26691	-0.42015	-0.42235	-0.56722	-0.58809	-0.3585	-0.48051	-0.15206	-0.5839	1		
Total individuals	0.510442	-0.07436	-0.03067	-0.48371	-0.55433	-0.29202	-0.36196	-0.42086	-0.12515	0.022278	0.086116	0.348894	0.462815	1	
D	-0.39472	0.1081	0.175353	-0.086	-0.17423	-0.21827	-0.32005	-0.3458	-0.28817	-0.60051	-0.64737	-0.71885	0.487101	-0.1105	1
H’	0.433047	-0.06355	-0.07975	0.109404	0.213014	0.267485	0.395092	0.391411	0.305522	0.696801	0.707922	0.779484	-0.5169	0.130221	-0.97851

Table S4D. Correlation of the Spearman between the ambiental and functional variables of the Mopane plots, for young class. Altit (altitude), Decli (slope), Droad (distance from the plots to the road), bolt number (correltion excluded).

	Altit	Decli	Droad	Richness	Richness Charcoal-bearing Richness	Total individuals	Sprouters	Seeders	Seedling	D
Altit	1									
Decli	0.313683	1								
Droad	0.077301	0.167453	1							
Richness	0.254468	-0.35263	-0.39262	1						
Charcoal-bearing Richness	0.287316	-0.3612	-0.41313	**0.988832**	1					
Total individuals	0.376305	-0.26214	-0.04414	0.4569	0.478978	1				
Sprouters	0.117936	-0.34613	-0.60491	0.662973	0.621073	0.429098	1			
Seeders	0.423718	0.060085	0.363096	0.301812	0.313321	0.684477	-0.05087	1		
Seedling	0.143568	-0.39503	-0.2188	0.7064	0.746101	0.505891	0.273522	0.455001	1	
D	-0.13865	0.15935	0.227941	-0.79385	-0.80152	-0.13611	-0.20859	-0.28626	-0.65639	1
H’	0.226519	-0.15675	-0.28939	0.869464	0.872558	0.21227	0.337017	0.288919	0.650609	-0.97854

Table S5. Geographic coordinates of the plots.

ID	Latitude	Longitude	Age	Vilage	Municipality
CR1	-14.3143	14.24462	Recent	Mauwengue	Cacula
CM2	-14.319	14.25241	Mature	Mauwengue	Cacula
CM3	-14.3205	14.25132	Mature	Mauwengue	Cacula
CR4	-14.3171	14.25048	Recent	Mauwengue	Cacula
BIp5	-14.714	13.43224	Intermediate	Humbia	Bibala
BRp6	-14.7293	13.42329	Intermediate	Humbia	Bibala
CI7	-14.3215	14.25814	Intermediate	Mauwengue	Cacula
CI8	-14.3202	14.25792	Intermediate	Mauwengue	Cacula
CI9	-14.3202	14.25598	Intermediate	Mauwengue	Cacula
CR10	-14.3147	14.24692	Recent	Mauwengue	Cacula
CR11	-14.3141	14.24689	Recent	Mauwengue	Cacula
CI12	-14.314	14.24753	Intermediate	Mauwengue	Cacula
CR13	-14.315	14.24905	Recent	Mauwengue	Cacula
CR14	-14.315	14.24905	Recent	Mauwengue	Cacula
CI14_1	-14.3184	14.25092	Intermediate	Mauwengue	Cacula
CI15	-14.3171	14.24861	Intermediate	Mauwengue	Cacula
CR16	-14.3166	14.24824	Recent	Mauwengue	Cacula
CI17	-14.3188	14.25234	Intermediate	Mauwengue	Cacula
CM18	-14.3186	14.25375	Mature	Mauwengue	Cacula
CM19	-14.3197	14.25391	Mature	Mauwengue	Cacula
CM20	-14.3214	14.25672	Matur	Mauwengue	Cacula
CR22	-14.3175	14.25149	Recent	Mauwengue	Cacula
BR1	-14.8481	13.17979	Recent	Garganta	Bibala
BM2	-14.8502	13.17933	Mature	Garganta	Bibala
BI3	-14.8428	13.16863	Intermediate	Garganta	Bibala
BM4	-14.8412	13.1688	Mature	Garganta	Bibala
BM5	-14.8417	13.16946	Mature	Garganta	Bibala
BI6	-14.8433	13.17031	Intermediate	Garganta	Bibala
BM7	-14.8382	13.18009	Mature	Garganta	Bibala
BR8	-14.8428	13.19238	Intermediate	Garganta	Bibala
BM9	-14.8423	13.19244	Mature	Garganta	Bibala
BM10	-14.8423	13.19152	Mature	Garganta	Bibala
BI12	-14.8415	13.1892	Intermediate	Garganta	Bibala
BI13	-14.8393	13.18532	Intermediate	Garganta	Bibala
BR14	-14.8393	13.18532	Recent	Garganta	Bibala
BR14_1	-14.8012	13.21722	Recent	Garganta	Bibala
BM15	-14.8162	13.20281	Mature	Garganta	Bibala

CAPÍTULO 4

Nutritional and Functional Properties of Wild Leafy Vegetables for Improving Food Security in Southern Angola

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Abstract

In Southern Angola, numerous non-woody forest products are sold at local markets, namely in Lubango (Huíla Province). Such is the case of herbaceous wild plants, locally known as *lombi,* that are sold fresh throughout the year and cooked as a vegetable. Although these wild leafy vegetables are commercialized and widely used in local food, there is still a lack of scientific knowledge about their properties. Thus, this study aimed to identify and characterize the species sold, and to determine their nutritional and functional properties. Our results revealed that three species – *Amaranthus hybridus*, *Bidens pilosa*, and *Galinsoga parviflora* – are usually sold at Lubango markets and consumed by local populations. These are annual exotic plants, native to Southern America, and usually occur spontaneously in croplands or disturbed areas, but can also be cultivated, particularly *A. hybridus*. Physico-chemical analyses of *lombi* species and mixtures sold at the markets included measurements of moisture, protein, lipid, and mineral content, as well as total phenolic content, antioxidant activity, and levels of heavy metal contaminants. The results revealed that *lombi* contain a significant amount of protein (20–28 g/100 g, dry basis), high values of macronutrients and micronutrients, as well as of phenolic compounds (10–40 mg GAE/g) and a good antioxidant capacity. Given the availability of *lombi* throughout the year, our study demonstrated the importance of wild edible plants in Angola, both as a valuable natural resource and as a complementary food source, as well as additional sources of income for many families.

Keywords: bioactive properties, ethnobotany, nutritional composition, Southern Africa, traditional leafy vegetables, wild edible plants

1. Introduction

Wild Edible Plants (WEP) and mushrooms are important resources commonly used by rural communities around the world, and often traded in urban markets, particularity in Africa (Ambrose-Oji, 2009; Uusiku et al., 2010; Cernansky, 2015). With generally affordable prices and good acceptance by consumers, they allow a diversification of food sources, contribute to food security of the populations, and help to fight poverty (Weinberger and Pichop, 2009; Yang and Keding, 2009).

WEP are important in rural communities as they are cheap and easy to obtain by families, allowing a more diversified diet and representing a source of sufficient macro- and micronutrients, thus reducing vulnerability to diseases (Shackleton and Shackleton, 2004; Shackleton et al., 2007, Garekae and Shackleton, 2020). Also, these plants can be very resistant to environmental changes and are an alternative for local communities during droughts or food shortages (Ohiokpehai, 2003). According to FAO (2017), indigenous food systems have characteristics that make them particularly attractive, including the use of both cultivated crops and gathered WEP, synergies with the natural environment and biodiversity, close adaptation to local conditions, a high level of diversification, a light carbon footprint, fewer negative externalities and reduced use of external inputs.

African ecosystems support a rich plant biodiversity (White, 1983), among which many naturalized species (Maundu et al., 2009). The terms African Indigenous Vegetables or Traditional African Vegetables refer those vegetables originating from the African continent and those with a long history of cultivation and domestication adapted to African conditions, due to their frequent and traditional use (Maundu et al., 2009).

About 1000 species are used as vegetables across the African continent, of which 80 per cent are Wild Leafy Vegetables (WLV) or African Leafy Vegetables, the rest consisting of fruits, seeds, roots and tubers, stems, and flowers (Maundu et al., 2009). Leafy vegetables are dominated by plant families such as the Amaranthaceae, Asteraceae, Brassicaceae, Cucurbitaceae, Fabaceae, Solanaceae, and Tiliaceae (e.g., Njume et al., 2014). Most of these belong to herbaceous genera (e.g., *Amaranthus, Bidens, Solanum, Brassica, Phaseolus,* and *Vigna*), but there are also leafy vegetables from tree genera such as *Adansonia, Bombax, Ficus, Sterculia* and *Moringa* (Maundu et al., 1999; Catarino et al., 2019a; Bancessi et al., 2020; Fernandes et al., 2021).

An interesting group of plants that stands out and has been very useful for indigenous communities are ruderal species, that thrive in environments strongly disturbed by human actions. They are able to disseminate rapidly in natural environments and gardens, and grow either on productive soils such as cropland or on poor soils such as fallows (e.g., Damalas, 2008). This capacity helped people to increasingly know them, and the easy access and low cost promoted a greater use of this resource over time (Ambrose-Oji 2009). Due to the cultural diversity, the communities adopted different ways of use, domestication, storage, and culinary preparation of wild edible plants (Oluoch et al., 2009; Yang and Keding, 2009).

Over the last decades, a large amount of work was done on the importance of nutritional and medicinal uses of African plants (Addis et al., 2013; Catarino et al., 2016; 2021a). These plants already contribute to food security of local populations, are often harvested and traded in town markets, and some are also used in traditional medicine (Shackleton et al., 2007; Shackleton et al., 2009; Cernansky, 2015; Charrua et al., 2021).

With globalization, important socio-economic changes took place in Africa, influencing people’s dietary habits in both rural and urban areas. Today, most people prefer introduced crop plants to traditional foods, including plant foods whose consumption is widely regarded as a primitive culture manifesting poor lifestyles (Uusiku et al., 2010). As in other African countries, the Angolan population concentrated in urban centers after the civil war (1975-2002) and grew exponentially (Raleigh and Hegre, 2009). The social asymmetries are visible; low income and increased unemployment in a population living in a state of war until recently has contributed to it (Da Rocha, 2015). This population growth and increasing urbanization in Angola led to an increase in the consumption of woody and non-woody natural resources in the areas surrounding the cities (Romeiras et al., 2014).

In Angola, a large number of plant species is traditionally used by rural communities for food, medicinal purposes (Catarino et al., 2019b), or both, as reported by Urso et al. (2016) and Kissanga (2016) for southern Angola, and Heinze et al. (2017) for northern Angola. Many forest products are also sold in markets and on roadsides, representing a source of income for the families that harvest and sell them (Heinze et al., 2019). However, the available information about them is scarce and a lot more research is needed to inventory and evaluate the nutritional properties and socio-economic potential of wild edible plants and mushrooms across the country.

In the markets of Lubango, capital of Huíla Province, in southern Angola, a large number of non-wood forest products are sold, both from this municipality and from the surrounding ones. Among those marketed products, three major types can be considered: i) wild fruits, sold throughout the year according to their ripening seasons; ii) fresh leafy vegetables, sold throughout the year and cooked as pot herbs, known locally as *lombi*, and iii) mushrooms, sold fresh at the time of ripening of the fruiting bodies, and dried throughout the year.

This study focused on the *lombi*, edible leaves and young shoots of plant species that grow spontaneously in fallows, abandoned land and home gardens, some of them also cultivated. Several cultivated species of *lombi* that are locally grown are cabbage, spinach, common beans, pumpkin, amaranth, and *Hibiscus* spp.; these *lombi* are usually cooked alone.

The spontaneous species of *lombi* are included among the WLV, which are often characterized as weeds for agriculture but, being edible, abundant, and easy to obtain, are an important resource that must be known and valued. Also, these traditional leafy vegetables are commonly used in the gastronomy of central and southern Angola and can contribute to the food security for both rural and urban communities. Wild *lombi* are usually consumed as a component of traditional meals, as side dishes for "*pirão*" (corn paste), or “*funje*” (cassava paste), accompanying a meat or fish preparation.

The main objective of this work was to identify the species of wild leafy vegetables sold at Lubango markets, their prices and their socio-economic importance in southern Angola, as well as to determine their bio-ecological characteristics and to evaluate the nutritional composition and functional properties of the main species and the mixtures sold.

2. Material and Methods

Study site and field data collection

The socio-economic part of the study took place from June to November 2018, involving the municipalities of Lubango and Humpata, from Huíla Province (Figure 1). The wild leafy vegetables on sale in the markets of Mutundo, Rio Nangombe, and Hoque (Lubango municipality), and Humpata (Humpata municipality) were initially prospected, followed by semi-structured interviews with vendors about the prices, origin, and characteristics of the *lombi* sold. The interviews were preceded by explanation of the study objectives and by informed consent from the respondents.

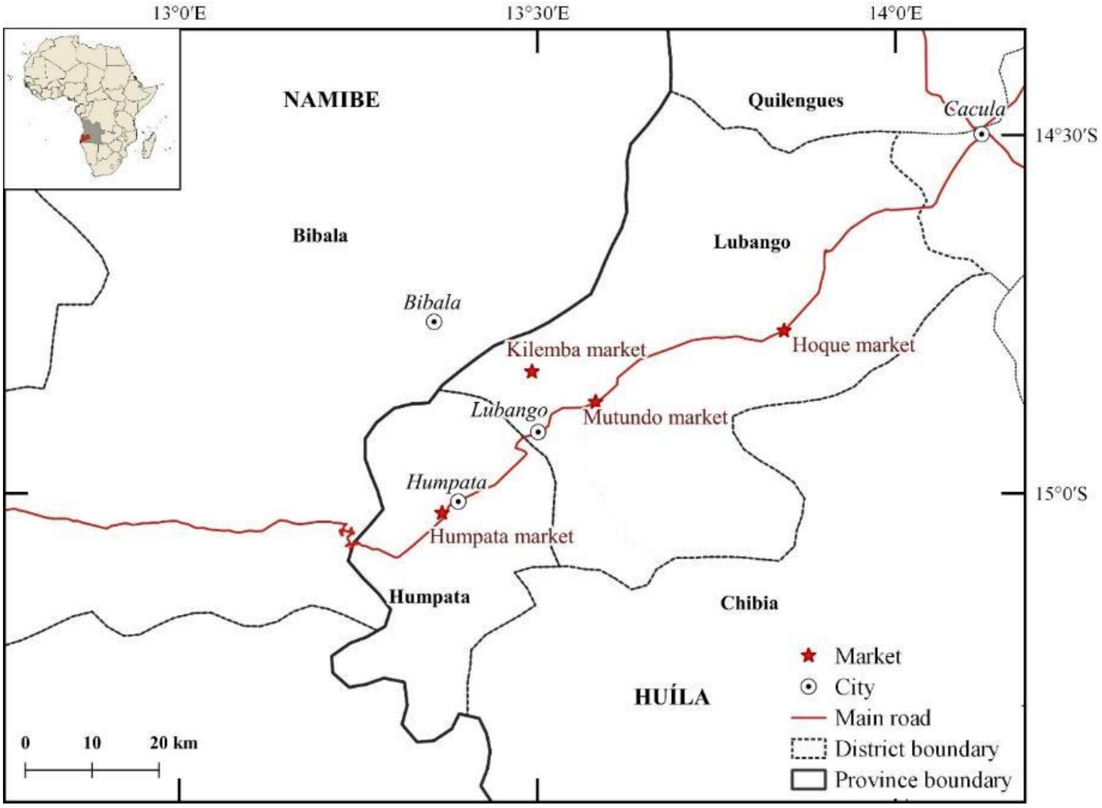

Figure 1 Study site, at Huíla Province, Southern Angola.

The *lombi* samples for analysis were obtained in early October 2019, at Mutundo market, the one with higher availability of *lombi* year-round. Samples of the piles of wild leafy vegetables for sale were acquired and weighed on site with a portable scale, and the morphospecies they comprised were identified (Figure 2a). The samples were separated according to morphospecies, the proportion of each one in the mixtures sold was quantified, and then dried (species' samples). Herbarium vouchers of the morphospecies were made for later identification. By the end of October, samples of the mixture were acquired from a different seller at the same market (mixture sample) and dried.

The morphospecies vouchers were identified at the LISC herbarium of the University of Lisbon by comparison with specimens already identified and using the available bibliography, namely Figueiredo and Smith (2008) as well as the African Plant Database site http://africanplantdatabase.ch). The herbarium vouchers are deposited at LISC and LUBA herbaria.

After identifying the species of *lombi*, a literature search was conducted to document their origin and distribution, bio-ecological characteristics and food and phytochemical properties. The websites JSTOR Global Plants (https://plants.jstor.org/), Pl@ntUse (https://uses.plantnet-project.org/en/) and Useful Tropical Plants (http://tropical.theferns.info/) were initially searched, and then a targeted literature search on the identified species was conducted.

Sample preparation

At the LUBA herbarium facilities, the samples of the three morphospecies (*Amaranthus hybridus* L., *Bidens pilosa* L., and *Galinsoga parviflora* Cav) as well fresh samples of the mixture sold at the markets were weighed fresh, subsequently dried at 45 ºC for 72 hours in a household electrical food dehydrator (SilverCrest SDA 350 A1, Hoyer Handel GmbH, Hamburg, Germany) and re-weighed after drying. Then, the samples were packed in paper bags and transported to the ISA (School of Agriculture, University of Lisbon) laboratory in Lisbon, where the physico-chemical analyses were performed.

Physico-chemical Characterization of *lombi*

The *lombi* were characterized for: moisture, protein, lipids, minerals, total phenolic content and antioxidant activity (DPPH, FRAP and ABTS), as well as metallic contaminants. Physico-chemical determinations were conducted in triplicate.

Moisture, protein and lipid contents

The moisture content was determined by drying the samples at 105 ^{0}C until constant weight (Bi et. al., 2018). Protein analysis was performed by the Kjeldhal method (Jimoh et al., 2018); the total nitrogen content was multiplied by 6.38 to determine total (crude, total N 6.38) protein, expressed in g/100 g of dry weight. Protein determination was performed in triplicate. The total lipid content was determined by the Soxhlet method. Extraction was done with hexane for about 90 min.

Mineral content

The mineral content was evaluated by inductively coupled plasma spectrometry (ICP) (iCAP Spectrometer equipped with ASX-520 AutoSampler (Thermo Scientific, Waltham, MA, USA)). Samples (0.25 g) were digested in aqua regia (9 mL of HCl and 3 mL of HNO_3). Digestion took place in several stages: 1) 30 min / 40 °C, 2) 30 min / 80 °C and 3) 90 min / 105 °C in a SCP Science equipment (DigiPREP MS, Baie d'Urfe, QC, Canada). After cooling, 50 mL of distilled water was added and waited to decant. The cleared supernatant was used in inductively coupled plasma to determine macronutrients (potassium, calcium, magnesium, phosphorus, and sulphur); micronutrients (sodium, iron, copper, zinc, manganese, and boron) and contaminants (lead, chromium, nickel, and cadmium).

Total phenolic content (TPC)

The total phenolic content (TPC) of the samples was determined according Heredia and Cisneros-Zevallos (2009), and Swain and Hillis (1959). Extract aliquots (150 µL) were diluted with 2400 µL nanopure water, mixed with 150 µL Folin-Ciocalteu reagent (Panreac AppliChem, Germany) (0.25 $mol.L^{-1}$). The reaction was interrupted by adding 300 µL sodium carbonate (1 $mol.L^{-1}$) and the mixture was incubated (2 h) in darkness. The samples were read at 725 nm in spectrophotometer (UNICAM UV/Vis Spectrometer). The total phenolic content was determined by a standard curve of equivalent of gallic acid (GAE) and expressed as mg $GAE.g^{-1}$ dry weight. Each extract was analysed in triplicate and the average was used for each condition.

Antioxidant activity (DPPH, FRAP and ABTS)

The antioxidant capacity by DPPH (2,2-diphenyl-1-picrylhydrazyl) method was applied following the procedure of Brand-Williams et al. (1995). The DPPH solution was prepared with DPPH reagent (Sigma–Aldrich, Germany) diluted in methanol until reaching 1.1 units of absorbance at 515 nm. The supernatant (100 µL) was added with a DPPH solution (3.9 mL). The reaction occurred for 40 min. The samples were read at 515 nm, using a spectrophotometer (Agilent Technologies, Cary 100 UV/Vis, Santa Clara, USA).

The FRAP (Ferric Reducing Antioxidant Power) test was performed according to Benzie and Strain (1996). The reaction initiated by mixing the FRAP solution (2.7 mL), 270 µL nanopure water with the extract samples (90 µL), and afterwards warmed in a water bath at 37 °C for 30 min. The coloured product (ferrous tripyridyltriazine complex) was read at 595 nm.

Antioxidant activity was measured using the ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)) method as described by Re et al. (1999) and Rufino et al. (2007). The reaction was performed by mixing 2970 µL ABTS solution (Sigma-Aldrich, Germany) with sample aliquots (30 µL) during 6 min, and the absorbance was read at 734 nm. The antioxidant activity (DPPH, FRAP and ABTS) was determined using Trolox (Acrós Organics, Belgium), and the results were expressed by Trolox Equivalent Antioxidant Capacity [TEAC (µmol Trolox.g^{-1} dry matter)]. For each antioxidant determination method (DPPH, FRAP and ABTS), each extract was analysed in triplicate and the average was used for each condition.

Statistical Analysis

Significant differences were determined by one-way analysis of variance (ANOVA) followed by Tukey’s test. Statistically significant differences ($p < 0.05$) between samples were defined using Tukey’s honestly significant difference test. Statistical analyses were carried out using the data analysis software system STATISTICA TM version 8.0 (StatSoft Inc., Tulsa, OK, USA, 2007).

3. Results

The trade and use of WLV’s at Huila

In the present study, the communes (sub-municipality administrative rank) of Hoque, Quilemba, Cacula and Humpata were found to be the main suppliers of WLV’s to Lubango’s markets (Figure 1). WLV is sold in the markets exclusively by women, who also sell other fresh food products. A total of 22 sellers were interviewed, 6 at Mutundo market, 10 at Hoque market, and 3 at Quilemba and Humpata markets. From the interviewed sellers, 12 were young adults under 30 years-old, eight were adults between 30 and 50 years-old, and the remaining were two seniors over 50 years-old.

During the dialogue with the vendors, we learned that the *lombi*, traditionally, are herbaceous plants that have always been highly appreciated by the majority of the rural population at the peripheral area of the city of Lubango and that, currently, there is a greater demand from customers in the city center.

The *lombi* are sold in piles of about 1 kg (see Figure 2a), at a price of 50 Angolan Kwanzas (AKZ) each (c. 0.10 USD), but the quantities sold per day per seller are difficult to know because most of them also sell other agricultural products. The found *lombi* species grow spontaneously, and are harvested by the peasants from several types of environments, both in rural and peri-urban areas, such as home gardens, fallows and in croplands, where they grow as adventive species.

As the *lombi* are sold year-round and each species has a different phenology, namely concerning the harvest period, the proportion of each species in the mixture can vary largely along the year, and even from seller to seller. Also, since *lombi* are typically collected from fallows, home gardens and disturbed places, their species composition can vary from one place to another.

The proportion of each species in the mixtures sold showed some variability, probably related with the availability and growth cycle of each of the species composing it. In the five samples analysed, *Bidens pilosa* was the most abundant species, corresponding to about 60% of the fresh weight, followed by *Galinsoga parviflora* with 30% and *Amaranthus hybridus* with 10%. (Table 1).

Table 1. Weights in grams, percentage of each species by pile (n=5), and moisture content by species.

	Average	StDev	min-max	Moisture content
Pile weight (g)	**999.6**	65.0	887-1090	
Amaranthus hybridus (%)	**10.2**	2.1	6.0-11.9	81.2
Bidens pilosa (%)	**59.6**	16.1	40.0-75.0	86.5
Galinsoga parviflora (%)	**30.1**	17.6	13.9-54.0	88.1

It is also possible that there are residual amounts of some other species that are also used as *lombi*, such as *Amaranthus spinosus*, *A. caudatus*, *A. viridis*, *Chenopodium quinoa*, *Cleome ginandra* and *Portulaca oleracea.* All species showed high moisture content, which ranged from 81 to 88 percent of fresh weight (Table 1). Similar values were found by Catarino et al. (2019a) for WLV in Guinea-Bissau.

Figure 2. Species of traditional leafy vegetables sold at Lubango markets. (a) Mixture in piles, at the market; (b) *Amaranthus hybridus*; (c) *Bidens pilosa* and (d), *Galinsoga parviflora*. Photos by Ruth Francisco (a) and F. Lages (b–d).

The WEP are eaten in Huila as pot vegetables or side-dishes, and included in several recipes. After washing, the mixture of leafy vegetables is usually cooked for 15 to 20 minutes, depending on the cook. Some people remove the water from the first boil, claiming that this reduces the initial bitter taste. A paste is then prepared by sautéing onions, garlic, and tomatoes in vegetable oil, which is mixed with the cooked vegetables.

During fieldwork, it was verified that a pile of fresh *lombi* is usually used to prepare a family meal for four adult people, which represents about 250 g of fresh matter per person and meal. Using a water content of c. 86% as a reference, this individual dose corresponds to a dry matter of 35 g per person per meal, which can be considered the average edible portion.

Characterization of the identified species of WEP

In terms of distribution and ecology, the three WLV species are exotic, annual plants of South American origin, and occur spontaneously in cultivated fields, house gardens, recent fallows and other disturbed places. They can also be cultivated for consumption, namely *A. hybridus*.

***Amaranthus hybridus* L.,** Amaranthaceae (R Kissanga 619, LISC, LUBA; Figure 2b)

Local names: jimboa, mboa; olombwa. English name: amaranth.

An annual, erect, branched herb that can reach 50-200 cm in height. It can be grown for its leaves and seeds. Originally from tropical America, it is now naturalized in all tropical regions and in Europe. In Southern Angola it is a ruderal species, growing in cultivated fields, fallow land, roadsides and other disturbed places, and often cultivated.

The leaves and young branches are eaten fresh or cooked, as an accompaniment to various dishes and can also be used in stews and soups. The seeds, *in natura* or cooked, are eaten as a cereal. *A. hybridus* is also used for various medicinal and phytochemicals purposes. It is frequently cultivated and can be consumed by livestock (Burkill 1985). It is a high-productivity species with a C4 photosynthetic mechanism that can produce 30-60 tons of biomass annually and is widely cultivated in other southern African countries (Van Wyk and Gericke, 2017). According to several authors, the seeds and leaves of various *Amaranthus* species are quite rich in nutrients, with high protein content and good amounts of other nutrients, including mineral salts, and can be considered a high-quality food (Van Wyk and Gericke, 2017; Fern, 2021).

***Bidens pilosa* L.,** Asteraceae (R Kissanga 620, LISC, LUBA; Figure 2c)

Local names: jisongo-jia-ngoma, olokoso, osungua. English name: black jack.

An erect annual herb, branched, fast growing, that can reach a height of 60-80 cm. It is a heliophilous plant that grows easily in various climates and soil types and is considered a weed in crop fields. It is usually obtained from spontaneous growth but can be cultivated for its leaves and young branches, which can be repeatedly cut. Native to South and Central America, this species has now a cosmopolitan distribution. In Angola it is a ruderal plant, growing in cultivated fields, fallow land and disturbed places, including in urban environments.

The leaves and young branches are eaten after cooking and are often used in sauces and as a side dish. They can also be dehydrated, ground and preserved for later use. *B. pilosa* is an aromatic plant, rich in secondary metabolites, also used for medicinal purposes in many regions of Africa, as well as Asia and tropical America. Roots, leaves and seeds are reported to possess antibacterial, antidysenteric, anti-inflammatory, antimicrobial, antimalarial, diuretic, hepato-protective and hypotensive activities (Burkill, 1986; Mvere, 2004; Van Wyk and Gericke, 2017). However, the roots, leaves and flowers are considered phototoxic and harmful to the skin (Fern, 2021).

***Galinsoga parvifolia* Cav.,** Asteraceae (R Kissanga 624, LISC, LUBA; Figure 2d)

Local names: felisberto, lume, okalume, otulume. English name: gallant soldier.

Annual, erect herb with a branched stem that can reach a height of 40-80 cm. It can be cultivated for food (leaves and seeds). Native to Central America, this species is now naturalized in all tropical regions and in Europe. It is a ruderal plant, growing in cultivated fields, fallow land, disturbed places, and home gardens.

The leaves and young branches are cooked as a vegetable and eaten as an accompaniment to traditional dishes. The dehydrated leaves are sometimes used as a condiment in some dishes (Schippers, 2004). *G. parviflora* is also used in traditional medicine for skin inflammations and wounds, as well as for fodder and in veterinary medicine (Burkill, 1985). An analysis of the composition per 100 g of fresh mass showed a water content of almost 90% and moderate contents of protein, carbohydrates and minerals (Wehmeyer and Rose, 1983).

Physico-chemical Characterization of *lombi*

Protein content

The protein content of the three analysed WEP is presented in Figure 3. The samples had a protein content higher than 20%, between around 21% for *A. hybridus* and 28% for the mixture, which is considered high for vegetable products. Among the individual species' samples, *B. pilosa* showed the highest protein content (around 25%). These values are quite high, and the slightly higher values obtained for the mixture can be attributed to compositional differences related with the date of acquisition of samples, and probably also because they were from different sellers. On the other hand, the values obtained in this study for protein content were higher than those reported by Chatepa and Masamba (2020) for a similar set of species, and by Akubugwo et al. (2007) for *A. hybridus*.

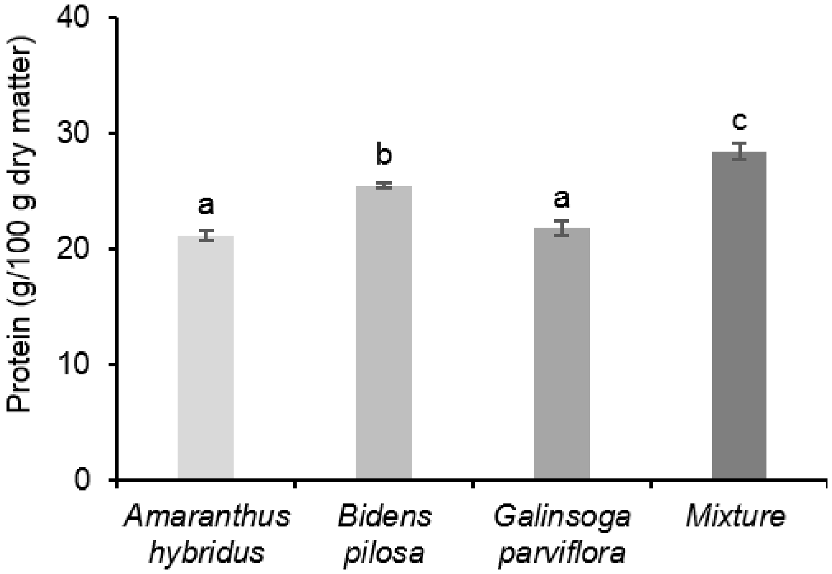

Figure 3. Protein contents of *lombi*. Bars represent means ± standard deviations (n = 9). Different letters indicate significant differences between samples.

Lipid content

The lipid content of each of the three species can be considered low (Figure 4), ranging from about 1.3 g/100 g of dry matter in *A. hybridus* and *B. pilosa* to c. 1.6 g/100 g in *G. parvifolia*.

These values are moderate if compared with other African leafy vegetables (e.g., Catarino et al. 2019a). The slightly higher values obtained for the mixture can be attributed to compositional differences between the samples used for separated species analysis.

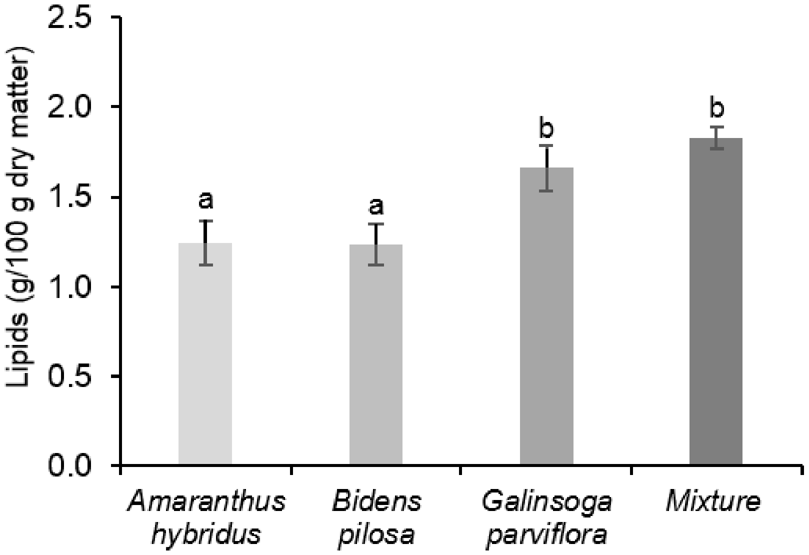

Figure 4. Lipid contents of *lombi*. Error bars represent ± standard deviation (n = 9). Different letters indicate significant differences between samples.

Mineral content

The macro and micronutrient contents of the three analysed species is presented in Tables 2 and 3, respectively.

Concerning the macronutrients, among the individual samples, *A. hybridus* showed a significantly higher amount of potassium (44551 ± 4082 mg.kg^{-1}), calcium (19498 ± 158 mg.kg^{-1}) and magnesium (6964 ± 13 mg.kg^{-1}), while *B. pilosa* stands out for its significantly higher content of phosphorous (5262 ± 42 mg.kg^{-1}). Regarding micronutrients, the individual samples of *A. hybridus* showed the highest amount of sodium (494.8 ± 38.9 mg.kg^{-1}) and zinc (37.3 ± 0.6 mg.kg^{-1}), *G. parviflora* had the highest contents of iron (466.7 ± 19.6 mg.kg^{-1}) and copper (10.9 ± 0.2 mg.kg^{-1}), and *B. pilosa* presented the highest values for manganese (50.6 ± 0.5 mg.kg^{-1}) and boron (25.7 ± 0.3 mg.kg^{-1}). The mineral content values of the mixture were not always within the range determined for individual species: calcium (12481 ± 234 mg.kg^{-1}), sulphur (3070 ± 54 mg.kg^{-1}), iron (291.5 ± 7.9 mg.kg^{-1}), copper (12.9 ± 0.4 mg.kg^{-1}) and manganese (28.8 ± 0.4 mg.kg^{-1}). This might be due to the variability of the amount of each species in *lombi* mixtures, to different vegetative stages of the plants and the location of harvest. Still, the values for the mixture were in the same order of magnitude of those reported for individual species.

Table 2. Macronutrients' contents of *lombi* (mg.kg^{-1} dry matter). Mean values ± standard deviations (n = 9). Different letters in a column indicate significant differences between samples.

Products/Species	K	Ca	Mg	P	S
Amaranthus hybridus	44551±4082^{a}	19498±158^{a}	6964 ± 13^{a}	3553 ± 25^{a}	2775 ± 2^{a}
Bidens pilosa	28750± 444^{b}	9832± 194^{b}	3251 ± 84^{b}	5262 ± 42^{b}	2438 ± 15^{b}
Galinsoga parviflora	30534± 331^{b}	16059 ± 89^{bc}	4091 ± 38^{cd}	3792 ± 34^{a}	2888 ± 20^{a}
Mixture	28743± 307^{a}	12481 ± 234^{bc}	5961 ± 57^{cd}	3921 ± 55^{a}	3070 ± 54^{a}

Table 3. Micronutrients' contents of *lombi* (mg/kg dry matter). Mean values ± standard deviations (n = 9). Different letters in a column indicate significant differences between samples.

Sample	Na	Fe	Cu	Zn	Mn	B
Amaranthus hybridus	494.8 ± 38.9^{a}	460.0 ± 8.4^{a}	6.0 ± 0.1^{a}	37.3 ± 0.6^{a}	49.8 ± 0.5^{a}	18.2 ± 0.8^{a}
Bidens pilosa	274.1 ± 1.6^{b}	329.8 ± 7.9^{b}	9.5 ± 0.1^{b}	44.0 ± 0.2^{b}	50.6 ± 0.5^{a}	25.7 ± 0.3^{b}
Galinsoga parviflora	440.6 ± 28.4^{a}	466.7 ± 19.6^{a}	10.9 ± 0.2^{b}	33.1 ± 0.2^{c}	33.8 ± 0.7^{b}	16.5 ± 0.2^{a}
Mixture	367.5 ± 27.7^{c}	291.5 ± 7.9^{c}	12.9 ± 0.4^{c}	43.6 ± 0.5^{b}	28.8 ± 0.4^{c}	18.1 ± 0.1^{a}

Total phenolic content (TPC) and antioxidant activity (DPPH, FRAP and ABTS)

The results for total phenolic content are presented in Figure 5. *B. pilosa* presented a TPC around two times and four times higher than that of *G. parviflora* and *A. hybridus*, respectively. The mixture presented a TPC value around 20 mg EGA/dry matter, to which the major contribution is probably from *B. pilosa*.

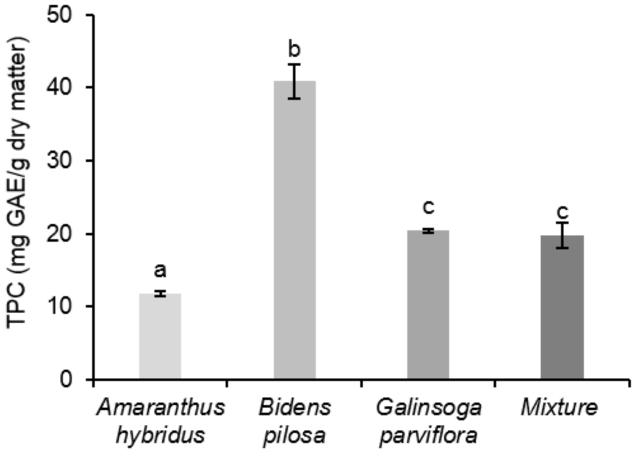

Figure 5. Total phenolic contents (TPC) of *lombi*. Error bars represent ± standard deviation (n = 9). Different letters indicate significant differences between samples.

The antioxidant activity values quantified *in vitro* by three different methods and expressed as TEAC (Trolox Equivalent Antioxidant Capacity) are presented in Figure 6.

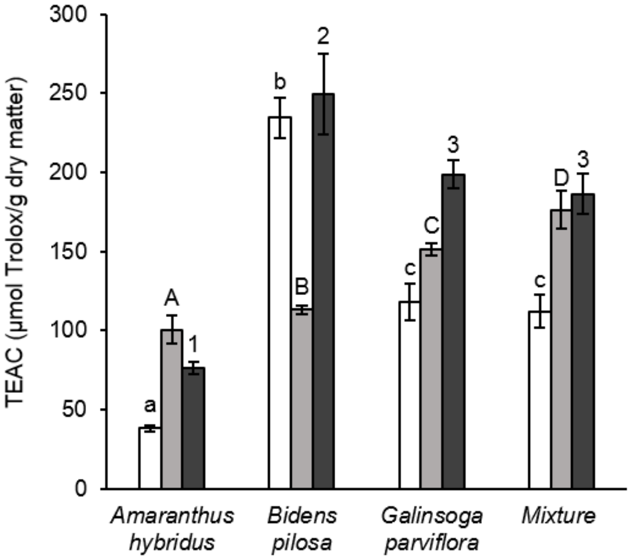

Figure 6. Antioxidant activity in *lombi* by different methods: DPPH (□), ABTS (▨) and FRAP(■). The results are expressed by µmol Trolox Equivalent Antioxidant Capacity (TEAC). Error bars represent ± standard deviation (n = 9). Statistically significant differences between samples are indicated for DPPH (lowercase letters), ABTS (capital letters) and FRAP (ordinal number).

TEAC results indicate that all the analysed species present a good antioxidant capacity. When applying the DPPH and FRAP methods, the antioxidant activity follows the same trend as TPC. It is significantly higher for *B. pilosa* than in the other species and in the mixture. These results are attributed to the bioactivity generally observed for phenolic compounds in terms of antioxidant activity (Stagos, 2020). However, the same correlation between TEAC and TPC values is not perceived when the ABTS method is used. This might be related to the complexity of the chemical composition of plant extracts, which also include compounds with different reactivities to *in vitro* methods.

Metallic contaminants

The levels of lead, chromium, nickel, and cadmium in the samples of the three species and the mixture are shown in Table 4, as well as the maximum limits according to EU Commission and Nagajyoti et al. (2010). The indicated limit values for Pb and Cd are presented on a fresh matter basis.

The Pb contents of the analysed samples (0.52-0.69 mg/kg dry matter) are apparently out of range, but when expressed on a fresh matter basis (0.07-0.08 mg/kg fresh matter) they are below the maximum limits.

Table 4. Metallic contaminants' contents of *lombi* (mg/kg dry matter).

Products/Species	Pb	Cr	Ni	Cd
Amaranthus hybridus	0.69 ± 0.05^a	2.28 ± 0.05^a	0.58 ± 0.06^a	0.09 ± 0.01^a
Bidens pilosa	0.52 ± 0.02^b	1.31 ± 0.04^b	0.37 ± 0.07^b	0.09 ± 0.01^a
Galinsoga parviflora	0.68 ± 0.01^a	2.25 ± 0.07^a	0.57 ± 0.11^a	0.16 ± 0.01^b
Mixture	0.44 ± 0.03^b	1.57 ± 0.03^b	0.58 ± 0.07^a	0.11 ± 0.01^a
Maximum limits	0.30 mg kg^{-1} fresh matter (a)	0.2-1.0 mg kg^{-1} dry matter (b)	1.0 mg kg^{-1} dry matter (b)	0.20 mg kg^{-1} fresh matter (c)

Mean values ± standard deviations (n = 9). Different letters in a column indicate significant differences between samples. **(a)** Commission Regulation (EU) 1005/2015 (2015); **(b)** Nagajyoti et al. (2010); **(c)** Commission Regulation (EU) 488/2014 (2014).

The values obtained for Cr (1.31-2.28 mg/kg dry matter) are clearly beyond the limits and can be concern. The cause of such high values of Cr is not evident, and it could not be ascertained whether it is predominantly hexavalent or trivalent chromium. Still, these plants tend to grow in disturbed places, with a high potential to present a non-negligible degree of soil contamination with domestic and industrial residues (e.g., batteries and metallic packages).

4. Discussion

Socioeconomic analysis

Available year-round and easy to obtain in home gardens and to buy at low price in the markets, *lombi* and other WLVs are very convenient food products. The wild food plants, in particular the three species of herbaceous plants analysed in this study, can contribute to the food and nutritional security of populations and be additional sources of income for families. Thus, the characterization of their composition and functional characteristics, as well as of their bioecology, is important for the knowledge and appreciation of these traditional food products.

Also, it is important to investigate the antinutritional and toxicological properties of the wild edible plants (Brilhante et al., 2021). Despite their use as ingredients in food, their toxicity for humans and animals is still inadequately and insufficiently studied (Damalas, 2008; Frida et al., 2008; Bartolome et al., 2013), and soil contamination with heavy metals can be a cause of concern (Atayese et al., 2008; Chia et al., 2019. Amadi et al., 2020).

Climate changes and difficulties in agricultural production contribute to change families' diets, reducing their quality and diversity due to income reductions and high food prices, promoting an increase in the consumption of imported processed products (FAO et al., 2018). The consumption of WLVs varies and usually decreases with urbanization in many sub-Saharan African populations (Uusiku et al. 2010). Also, changes in diet and environmental factors, particularly among urban dwellers, have caused a significant increase in lifestyle diseases (Walker et al., 2002).

Angola has a high floristic diversity and endemism, resulting from a great diversity of ecogeographical regions, and the effective in situ and ex situ conservation of Angolan wild food plants is both a national and a global priority (Catarino et al., 2021b). Nevertheless, information about wild leafy vegetables is still very scarce, namely about their diversity, distribution and conservation, as well as about their consumption and methods of preparation, as revealed in our study.

Little is known about the actual quantities of traditional dishes and WEP consumption, but it seems that many families, particularly from urban and peri-urban areas, resort to the traditional diet at least twice a week, on weekends (Yang and Keding, 2009). In Angola, the *lombi* are mainly used as side-dishes to accompany traditional dishes made of cassava and maize and fish or meat. Although our study provides more information about WEP, the availability, prices, and consumption per person should be important to address in further studies, as well as the contribution of *lombi* to the food security of local communities.

In a comparative study of 10 countries in sub-Saharan Africa, Ruel et al. (2005) demonstrated that the vegetable consumption per capita may range from 19.6 to 88.3 kg/person/year, and that the price ranges from 0.13 to 0.57 USD/kg in those countries. In the present study, WLVs were sold at 50 AKZ/kg, which corresponds to c. 0.10 USD (average exchange rate for 2019: 1USD=500AKZ, National Bank of Angola) and ranks them among the cheapest vegetables in sub-Saharan Africa.

Physico-chemical Analyses

Protein and lipids

The protein contents found in this work is higher than those reported by Chatepa et al. (2020) for the same species in Malawi (around 18, 19 and 16% for *Amaranthus* spp., *B. pilosa* and *G. parviflora*, respectively). As in the present study, the species with the highest protein content is *B. pilosa*. However, other studies report much higher values for *B. pilosa* (from 20% up to 42%), as well as for *G. parviflora* (36%) (Uusiku et al., 2010). This difference may be due to differences in the agro-climatic conditions between these studies. In addition, when compared with other African leafy plants, the species of *lombi* show an intermediate protein content. A lower protein content is reported for *Adansonia digitata* (10.1%), *Bombax costatum* (10.8%), *Sesamum radiatum* (13.3%) and *Hibiscus sabdaria* (13.7%) in Guinea-Bissau (Catarino et al., 2019a), whereas higher protein content values are presented for *Portulaca oleracea* (43%), *Vigna unguiculata* (36%) and *Senna occidentalis* (30%) (Uusiku et al., 2010). Protein contents from 11.3% (*Vernonia amygdalina*) to 30.6% (*Telfairia occidentalis*) were found in vegetable leaves from markets in Southern Nigeria (Dan et al., 2013), and from 13.2% (*Sonchus asper*) to 26.4% (*Chenopodium album*) when studying wild leafy vegetables in South Africa (Afolayan and Jimoh, 2009).

Lipid contents measured in this study ranged from 1.3% in A. *hybridus* and *B. pilosa* to c. 1.65% for *G. parvifolia*. For the same species in Malawi, Chatepa et al. (2020) reported much higher values (13.1%, 9.0% and 9.0%, respectively). The values were also lower than those of wild leafy vegetables in South Africa (*Chenopodium album*, *Sonchus asper*, *Solanum nigrum* and *Urtica urens*) which present values ranging from 4.2% to 8.5% (Afolayan and Jimoh, 2009).

Macro- and micronutrients

Dietary minerals play an important role in human health, such as in the control of blood pressure (sodium/potassium ratio), growth and maintenance of bones, teeth, and muscles (calcium and phosphorous) and control of anaemia (iron). Indigenous leafy vegetables have been reported to be valuable sources of macro and micronutrients (Uusiku et al., 2010; Njume et al., 2014), and this is in agreement with the results of the present study. Dietary minerals contents depend substantially, not only on the type of plant, but also on the location and moment of harvest. To understand the dietary impact of the consumption of the wild plants targeted in the present study, the percentages of Daily Recommended Doses (DRDs) (NHI, 2021) for some elements provided by *lombi* were estimated. A daily intake of 35 g of dry matter per person provides about 90% of the recommended daily dose, so it can be regarded as an excellent source of iron. In addition, 55% and 45% of DRDs of Mg and Ca are also expected, though a lower intake was estimated for Zn and P (15% and 20% of DRDs, respectively). The results indicate that *lombi* have a high potential to substantially contribute for enriching the mineral diet of local consumers.

Metallic contaminants

Of the metallic contaminants analysed (Pb, Cr, Ni and Cd), the one raising major concerns is Cr, as all *lombi* species present contents above the limit referred by Nagajyoti et al. (2010). Chromium oxidation states range from –2 to +6, with +3 and +6 being the most often studied in relation to human health (EFSA, 2014). The high energy needed to oxidise Cr (III) to Cr (VI) results in the fact that oxidation does not occur in biological systems. Some authors refer a positive role of Cr (III) in human physiology (e.g. Mandiwana et al., 2011). However, according to EFSA, the mechanisms for these roles and the essential function of Cr (III) in metabolism have not been substantiated and there is no evidence of beneficial effects associated with chromium intake in healthy individuals (EFSA, 2014). In terms of chromium intake, the EFSA Panel on Contaminants in the Food Chain (CONTAM Panel) derived a tolerable intake of 300 μg Cr (III)/kg body weight per day from the lowest

No Observed Adverse Effect Level (NOAEL) identified in a chronic oral toxicity study in rats (EFSA, 2014).

However, Cr (VI) is toxic and carcinogenic to humans (Ebdon et al., 2001). Data presented in the current work refers to total Cr, like in most literature. Still, speciation studies have been carried out in the determination of Cr (VI) in plants, showing that the amount of Cr (VI) was only 8% and 6% of total Cr for plants from Russia and South Africa, the latter harvested from soil with chromatite (Panichev et al., 2005).

Taking into account the Cr toxic threshold of 0.2 mg person-1 day-1 considered by Marini et al. (2021), and the consumption levels observed, the risk of toxic or negative health effects by consuming *lombi* seems to be negligible. Also, the practice of discarding the boiling water during initial stages of cooking can help to reduce the ingestion of this contaminant. The same happens for Cd considering the provisional tolerable intake of 2.5 µg person-1 week-1 (EFSA, 2011), for Pb considering the benchmark dose level of 1.5 µg person-1 day-1 (EFSA, 2012), and for Ni, taking into account the tolerable intake of 13 µg person-1 day-1 (EFSA, 2020). For negative health effects to happen, an amount much higher than 30 kg of fresh plants should be ingested per day, considering a body weight of 60 kg.

TPC and antioxidant activity

The *lombi* species present an important content of phenolic compounds, *B. pilosa* showing the highest value (around 41 mg GAE/g dry matter), followed by *G. parviflora* and the mixture (around 20 mg GAE/g dry matter) and *A. hybridus* with around 12 mg GAE/g dry matter. These values are within the range presented by Catarino et al. (2019a) for several leafy vegetables from West Africa (from 13.1 mg GAE/g dry matter for *Hibiscus sabdariffa* to 40.3 mg GAE/g dry matter for *Sesamum radiatum*). Regarding the antioxidant activity, the *lombi* species used in the present study showed DPPH values from 32.3 to 234.6 µmol Trolox/g dry matter, lower than the values referred for leafy vegetables from West Africa, from 111.5 to 681.9 µmol Trolox/g dry matter (Catarino et al., 2019a). Anyway, the TPC and the antioxidant capacity values measured by DPPH, FRAP and ABTS methods are an important indication of the potential health benefits that may arise from the regular consumption of *lombi*.

Comparative Phytochemical analyses

As demonstrated above, *B. pilosa* is the predominant component of the *lombi* mixtures sold at Lubango markets. This species attracted the attention of many leading researchers for its potential nutraceutical use in both functional and medicinal foods. Chiang et al. (2004) demonstrated that, adding to antioxidant properties, the extract of *B. pilosa* exhibited significant inhibitory effect on NO production (an inflammatory mediator) in macrophages. An essential oil extracted from *B. pilosa* var. *radiata* proved to have antibacterial and antifungal activities (Deba et al., 2008). A study reported the effect of *B. pilosa* leaf extract in uterine muscle in labor (Frida et al., 2008). Polyenes, flavonoids, phenylpropanoids, fatty acids, and phenolics are the main bioactive compounds of *B. pilosa* and they have been reported effective to treat different diseases – e.g. tumors, inflammation/immune modulation, diabetes viruses, gastrointestinal diseases, hypertension, cardiovascular diseases (Bartolome et al., 2013). Some harmful effects of this species have also been reported, such as phototoxicity and a possible carcinogenic effect of leaf consumption (e.g., Mvere, 2004). However, these effects were not mentioned in more recent studies (e.g., Xuan and Khanh, 2016, Kuo et al., 2020). An interesting finding about the phytochemical properties of the three analyzed species of *lombi* is that the most abundant species in the mixtures sold (*B. pilosa*) is the one with the highest contents of protein, P, Cu, B and total phenolics. In addition, *B. pilosa* also presented a significantly lower concentration of some of the metallic contaminants (Pb and Cr).

5. Conclusion

The wild leafy vegetables are important food resources for both rural and urban populations in many parts of the world. In southern Angola they are called *lombi* and are important components of peoples' diet, being collected and traded in the local markets, and thus contributing to the income of many families.

Our study demonstrated the socio-economic importance of Amaranthus hybridus, Bidens pilosa, and Galinsoga parviflora, which are abundant and grow spontaneously in southern Angola. As stated above, these species are sold in local markets, and the species composition of the mixtures depends on the local availability and abundance along the year.

Although, they are good alternative sources of nutrients for both rural and urban populations, namely of protein, iron, magnesium or calcium, the contents of some heavy metals, particularly chromium, can be a matter of concern and deserves further analyses. Thus, more field surveys are needed in various areas of Angola, namely to identify the plants and their proportions used in the mixtures traded in the local markets, as well as to carry out more chemical analyses (e.g., functional, nutritional, and antinutritional properties) of individual species and mixtures, currently consumed in Angola.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation

Authors' contributions

RK Methodology, Fieldwork, Writing - Original Draft Writing - review & editing; JS Methodology, Laboratory analyses; MM Methodology, Resources, Supervision, Writing - review & editing; VA Methodology, Laboratory analyses, Writing - Original Draft, Writing - review & editing; HM Methodology, Fieldwork; MMR Resources, Supervision, Writing - Original Draft, Writing - review & editing; FL Conceptualization, Resources, Writing - review & editing; LC Conceptualization, Methodology, Resources, Supervision, Writing - Original Draft, Writing - review & editing; All authors contributed to the drafts and gave final approval for publication.

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Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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CAPÍTULO 5

Biochemical and Molecular Profiling of Wild Edible Mushrooms from Huíla, Angola

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Abstract

The harvesting, processing, and sale of wild edible mushrooms (WEM) is a relevant economic activity in Angola and a good example of the use of non-wood forest products for food. Although there is deep traditional knowledge about the general properties of WEMs, a huge gap remains in detailed scientific knowledge. Thus, this study aimed to investigate the socio-economic importance of the species sold at local markets in Huila, Angola, from their molecular identification to the assessment of their nutritional, chemical, and bioactive profiles. From the eight WEM morphotypes studied, five were identified based on phenotypical and molecular approaches (four *Russula* spp., and *Amanita loosei*). The studied mushrooms proved to be a rich source of carbohydrates, proteins, and ashes, also presenting low amounts of fat. Chemical analyses further revealed mannitol as the main free sugar in all samples, and organic acids, namely, oxalic, quinic, malic, citric, and fumaric acids in low amounts. Additionally, the _-tocopherol isoform and monounsaturated fatty acids were predominant. Regarding phenolic acids, protocatechuic, p-hydroxybenzoic, p-coumaric, and cinnamic acids were detected in all mushroom hydroethanolic extracts, being responsible for their antioxidant, antibacterial, and antifungal activities. Our investigation contributes to the identification and knowledge of WEMs as important complementary food sources in Angola, some of which were reported for the first time, promoting their utilization as a basis of nutritional and functional ingredients, as being able to be part of a balanced diet and to be used in new bio-based formulations.

Keywords: fungi; wild ediblemushrooms; nutritional value; chemical composition; molecular identification

1. Introduction

For centuries, wild edible mushrooms (WEMs) have been collected from forests, or later cultivated and consumed, due to their nutritional value, medicinal utility, and unique flavour [1]. In recent decades, worldwide research on the use of WEMs has gained ground as their consumption and commercialization in local businesses proved to be important for the rural subsistence of developing countries [2–4]. However, some cultures avoid their consumption due to religious beliefs, fear of poisoning, and the fact that habitats where wild mushrooms grow may contain decomposing matter [5].

Fresh and preserved mushrooms are consumed in many countries as a delicacy, particularly for their unique aroma, flavour, and texture [2]. Worldwide, WEMs are known to be a healthy source of food with valuable nutritional qualities, such as their richness in carbohydrates, proteins, fibers, vitamins (B and C complexes) and minerals, and the presence of unsaturated fatty acids, mainly linoleic acid, and low-fat totals, which makes them an excellent food product to be included in low-calor diets [6,7]. The proteins that are commonly part of mushrooms hold all the essential amino acids for human nutrition, being mainly rich in lysine and leucine, normally absent from cereal-based foods [8,9], present in an easily digested form [8–10]. In addition, mushrooms are seen as functional foods and/or bases of nutraceuticals, given the presence of physiologically and biologically active substances such as phenolic acids [11], largely responsible for their strong antibacterial and antifungal activities, often with superior antimicrobial responses to frequently used drugs [12,13]. Knowledge about the uses and properties of WEMs has generally been passed from one generation to another by word of mouth and without written documentation. Although ethnomycological knowledge among African communities has been addressed in several published works [14–16], which document a wide range of traditional uses of WEMs for food and medicinal purposes, this subject remains largely unstudied. In many Tropical African countries, WEMs are an important food source, being largely consumed fresh in the periods of fruiting bodies development or dried along the year. Several works have been published on the chemical composition and nutritional value of WEMs in African countries demonstrating its valuable nutritional, medicinal, functional, and nutraceutical properties [17–21]. Thus, the deepening of knowledge about the taxonomy, ecology, traditional uses, food, and functional properties of WEMs contributes to the food security of rural communities and a way to promote the sustainable use of natural resources [3].

Correctly identifying mushrooms is challenging [22] as no single tool can allow unambiguous species identification in most cases [23]. In recent decades, mycologists have classified mushroom species based on morphology, niche types, growth behavior, interaction with the host, and ecological factors, which, in many cases, are insufficient for accurate identification [24]. An integrative taxonomical approach seems to be the best practice for species identification, aiming at evaluating diagnostic characters, either phenotypic, molecular, or both, also combining genealogy (phylogeny), phenotype (including autecology), and reproductive biology data (when feasible). In the last decade, molecular biology techniques have been increasingly used to identify unknown samples and cryptic species based on current classification. Although there is currently no single tool for identifying fungi, DNA barcoding has succeeded in identifying between and within several fungi genera [22]. The ITS region is the most widely analyzed for fungal species identification, namely macro-fungi, remaining the first diagnosis at the genus level [23]. However, when this ribosomal RNA region is coupled with other marker genes, multi-locus fungal identification is achieved with an enhancement of identification resolution. Several gene makers have been analyzed in molecular studies of *Russula*, with multiple genes being identified as good intra- and inter-specific markers. Secondary DNA barcodes, such as RPB1, RPB2, and LSU, are being increasingly implemented for taxonomic groups where ITS does not provide sufficient distinctiveness [23].

In Central and Southern Africa, the collection of WEMs for consumption is an important activity that contributes both to the food security of local populations and to the livelihoods of many families [24–27]. Edible mushrooms are exploited for food and trade by local populations also in the miombo area [28,29], but very little information is available for Angola. For instance, in “The Edible Fungi of Tropical Africa” annotated database [27], only 24 harvests are registered for Angola, in the provinces of Kwanza Sul and Benguela, belonging to 11 species: *Cantharellus congolensis* Beeli [30], *C. defibulatus* (Heinem.) Eyssart and Buyck, *C. densifolius* Heinem., *C. ruber* Heinem., *C. splendens* Buyck [31], C. sublaevis Buyck and Eyssart., *Gyrodon miretipes* Heinem. and Rammeloo, *Mackintoshia persica* Pacioni and C. Sharp [32], *Russula congoana* Pat., [32], *R. flavobrunnea* Buyck [33], and *R. phaeocephala* Buyck [33]. Many species of non-timber forest products (NTFP) and their derivatives are currently used in this country [34–38], with many WEMs being collected and sold at roadsides, local markets, and city markets, including in the capital, Luanda. However, despite its large socio-economic importance, there is very little information on the fungi species occurring or being used in Angola [27,39,40], nor about the identification and properties of WEMs collected and traded. In the province of Huila, southwest Angola, rural communities collect a wide variety of mushrooms, both for self-consumption and for informal sales, particularly in Lubango, the capital of the province, and neighboring municipalities. In the city markets, dried mushrooms are sold throughout the year, whereas fresh mushrooms are sold only at harvest time.

Thus, the main objectives of this study were: (i) to characterize the socio-economic relevance of the mushroom trade and consumption in Huíla (Angola); (ii) to identify the mushroom species in the dried mixtures sold in the Humpata market, Huila, based in morphological and molecular data; and (iii) to document their chemical, nutritional and functional properties.

2. Materials and Methods

2.1. Markets and Mushroom Material

The field prospection took place between June and October 2018 at the markets of Lubango and surrounding municipalities: Mutundo, Humpata, Hoque, and Rio Nangombe (Figure 1). The selling prices of the dried mushroom mixtures were documented, and 5 replicates of each selling unit were weighed. In addition, sales prices and weights of fresh mushrooms were recorded at each market at the beginning of the day. Samples of the dried mushroom mixtures were purchased from the Humpata municipal market, the only place where sufficiently intact samples could be acquired for the accurate separation of morphotypes. With the cooperation of selected sellers, the mushroom morphotypes present in the samples were identified, separated, and numbered, and their common names were recorded in the two main local languages used in Huila, Umbundu, and Nyaneka. Information regarding harvest sites, the ecology of the species, mushroom picking and drying processes was also documented through visits to the collecting sites.

2.2. Morphological Characterization

Mushroom samples were stored in dry conditions, and macromorphological features and field characters were recorded at the collecting location. According to these features, eight different morphotypes were separated and numbered from M1 to M8. As measurements on fresh material were not taken in the field, cap and stipe dimensions were taken on the dried specimens for comparison. Micromorphological characters were observed from small tissue pieces of lamellae of the dried material mounted in a mixture of 5% KOH and 1% Congo red with the help of a compound microscope (Olympus BX50). Staining of basidiospores was performed by chemical reaction with Melzer's reagent. The following macro- and micromorphological parameters were recorded: Cap: color, surface aspect, and diameter in cm; Stipe: color, diameter and length in cm; Spores: shape, surface morphology, and dimensions in _m; Basidia: dimensions in _m. Available bibliography on mushrooms in southern and tropical Africa as well as websites with relevant information on the mushroom species that occur in the region were used to obtain information on the African mushrooms, particularly on edible species [25–29].

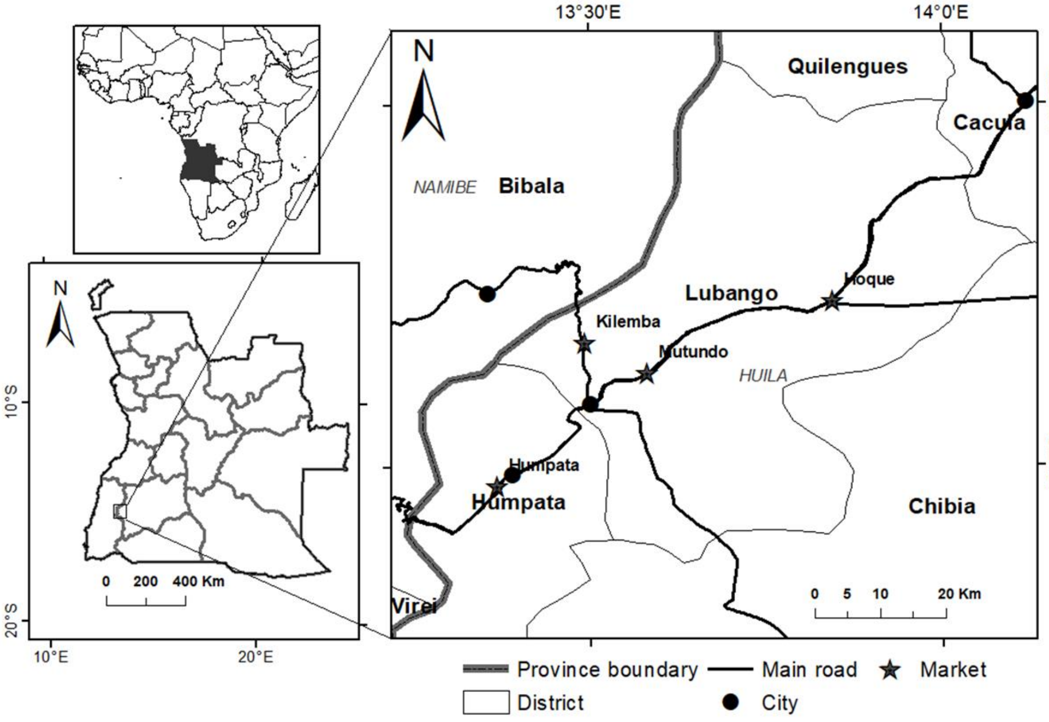

Figure 1. Location of the study site in Angola.

2.3. Molecular Analysis

2.3.1. DNA Extraction, Amplification, and Sequencing Individual specimens of samples M1 to M8 were ground into power with liquid nitrogen and stored at -80 °C until further analysis. Total genomic DNA was extracted with the commercial kit DNeasy plant mini kit (Qiagen, Germany) according to the manufacturer's instructions. DNA concentration and purity were measured at 260/280 nm and 260/230 nm in a Multiskan SkyHigh Microplate Spectrophotometer (Thermofisher scientific, Waltham, MA, USA). Amplification of DNA was performed in a MyCycler Thermal Cycler (Bio-rad, Hercules, CA, USA), in a polymerase chain reaction (PCR) mixture containing 2 µL genomic DNA (10 ng/µL), 4 µL of 5 x GoTaq G2 Flexi buffer (Promega, Madison, WI, USA), 0.5 µL of dNTP (Fermentas, Waltham, MA, USA) (0.2 mM), 2 µL of MgCl2 (1.5 mM) (Promega, Madison, WI, USA), 1 µL of each primer (1 mM) (Stabvida, Caparica, Portugal), 0.2 µL of GoTaq G2 Flexi DNA (5 U/µL) (Promega, Madison, WI, USA), and sterile ultrapure water. Three nuclear markers were amplified as described: (1) the internal transcribed spacer region of ribosomal DNA (ITS), comprising the ITS1 and ITS2 spacer regions and the ribosomal gene 5.8 S, using primers ITS1 and ITS4 [41]; (2) a part of the ribosomal large subunit 28 S region (LSU), using primers LR0R and LR5 [42]; (3) the region between the conserved domains 6 and 7 of the second largest subunit of the RNA polymerase II (rpb2), using primers bRPB2-6F and bRPB2–7.1R [43]. PCR products were visualized by electrophoresis in 1,2% agarose gel in an omniDOC Gel (Cleaver scientific, Rugby, UK). PCR products were purified with SureClean (Bioline, Alvinston, ON, Canada) according to the manufacturer's instructions and sequenced by Stabvida (Caparica, Portugal). Sequences were edited with DNASTAR lasergene version 11.1.0.54 (Madison, WI, USA) and deposited in GenBank (accession numbers in Table S1).

2.3.2. Phylogenetic Analyses

Generated sequences from all samples (M1-M8) were queried against nucleotide sequences available in the NCBI database, using BLASTn 2.10.0+ [44], directly on the NCBI webpage (https://blast.ncbi.nlm.nih.gov (accessed on 11 July 2022)). Those with the most significant hits, as well as species representative sequences from previous phylogenetic works and from type-specimens, whenever available, were retrieved from GenBank (78, 92, and 91 sequences of ITS, LSU, and rpb2, respectively) and included in the phylogenetic analyses. A total of 99 individuals (five specimens of *Amanita* spp and 94 specimens of

Russula spp) were analyzed. Reference publications and accession numbers for the sequences employed are provided in the Supplementary Table S1.

Sequences for each DNA region were aligned with MAFFT version 7.453 [45] and then examined manually using the AliView version 1.25 [46]. The alignment matrices were converted to the appropriate format and concatenated using the TriFusion V0.4.12 software (https://github.com/OdiogoSilva/TriFusion (accessed on 24 May 2022)). Phylogenetic relationships using Maximum Likelihood (ML) and the Bayesian inference (BI) methods were inferred using a concatenated alignment matrix (ITS, LSU, and rpb2). For ML analysis, RAxML version 8.2.12 [47] was used with unlinked partitions corresponding to each DNA region and the GTRCAT nucleotide substitution model. Branch support was estimated by performing 1000 bootstrap replicates. The BI analyses were conducted in Mr-Bayes version 3.2.6 [48] and two runs were performed applying the Monte Carlo Markov Chain (MCMC) method iterated for 4,000,000 generations, with a sampling frequency of 4000 generations. A 50% majority rule consensus tree was obtained after discarding the first 25% of trees. TRACER version 1.7.1 [49] was used to verify the files and ensure that the chains had reached convergence. A GTR + GAMMA model of sequence evolution was applied to each DNA partition, as estimated by the software jModelTest2 [50] using the corrected Akaike Information Criterion (AICc) [51].

2.4. Extract Preparation

The samples of ground powdered mushrooms (2 g) were twice stirred with ethanol: water (80:20 v/v; 30 mL) at 25 _C and 150 rpm for 1 h, with subsequent filtration through Whatman paper no. 4. The two combined fractions were then evaporated using a rotary evaporator (Büchi R-210; Flawil, Switzerland) at 40 _C under reduced pressure, to evaporate the ethanolic portion of the extract. The obtained aqueous extracts were finally frozen at 4 ºC and freeze-dried for further analysis [52].

2.5. Chemical Characterization

2.5.1. Nutritional and Energetic Value

The nutritional composition of the mushroom samples was performed using AOAC procedures [53], relating to its configuration in proteins, fat, carbohydrates, and ashes. Crude protein content (N x 4.38) was estimated using the macro-Kjeldahl method; the crude fat quantity was determined by extracting a known weight of sample with petroleum ether using a Soxhlet apparatus; the ash content was determined by incineration at 550 ± 15 ºC. The total carbohydrate quantity (g per 100 g of dried weight (dw)) was calculated by difference and total energy given to the next equation: Energy (kcal/100 g dw) = 4 x (g protein + g carbohydrates) + 9 x (g fat).

2.5.2. Hydrophilic Compounds

Free individual sugars were measured by high-performance liquid chromatography coupled to a refraction index detector (HPLC-RI, Knauer, Smartline system 1000; Berlin, Germany), as previously described by Spréa et al. [54]. Briefly, dried sample powder (1 g) was spiked with melezitose as internal standard (IS, 5 mg/mL), and was extracted with 40 mL of 80% aqueous ethanol at 80 ºC for 30 min. The resulting suspension was centrifuged at 30 x g for 10 min. The supernatant was concentrated at 60 ºC under reduced pressure and defatted three times with 10 mL ethyl ether, successively. After concentration at 40 ºC, the solid residues were dissolved in water to a final volume of 5 mL and filtered through 0.2 μm nylon filters from Whatman. Identification was achieved by comparing the relative retention times of sample peaks with standards under the same chromatographic conditions, and the obtained data were analyzed using Clarity 2.4 Software (DataApex, Podohradska, Czech Republic). The internal standard (IS, raffinose) method was used, and the quantification was based on the RI signal response of each standard. The results were expressed in g per 100 g of dw.

Organic acids were assessed using a Shimadzu 20 A Series UFLC (Shimadzu Corporation, Kyoto, Japan), as previously described [55]. Samples (~2 g) were extracted by stirring with 25 mL metaphosphoric acid (25 ºC at 30 x g) for 45 min and subsequently filtered through Whatman No. 4 paper. Before analysis, the sample was filtered through 0.2 μm nylon filters. The detection was performed using a diode array detector (DAD), at 215 nm as preferred wavelengths. The organic acids found were quantified using calibration curves obtained for each commercial compound. The results were expressed in g per 100 g of dw.

2.5.3. Lipophilic Compounds

The tocopherol content was evaluated as previously described [54]. BHT solution in hexane (10 mg/mL; 100 μL) and internal standard (IS) solution in hexane (tocol; 50 μg/mL; 400 μL) were added to the sample prior to the extraction procedure. The samples (~500 mg) were homogenized with methanol (4 mL) by vortex mixing (1 min). Subsequently, hexane (4 mL) was added and again vortex mixed for 1 min. After that, saturated NaCl aqueous solution (2 mL) was added, the mixture was homogenized (1 min), centrifuged (5 min, 4000 x g) and the clear upper layer was carefully transferred to a vial. The sample was re-extracted twice with hexane. The combined extracts were taken to dryness under a nitrogen stream, redissolved in 2 mL n-hexane, dehydrated with anhydrous sodium sulfate, filtered through 0.2 μm nylon filters from Whatman, transferred into a dark injection vial and analysed using an HPLC system (Knauer, Smartline system 1000; Berlin, Germany) coupled with a fluorescence detector (FP-2020; Jasco, Oklahoma City, OK, USA). Individual compounds were identified by comparison with authentic standards under the same chromatographic conditions. By using the internal standard method (IS), the quantification was based on the fluorescence signal response, and the tocopherol content was expressed in μg per 100 g of dw.

Fatty acid methyl esters (FAME) were investigated after trans-esterification of the lipid fraction attained through Soxhlet extraction as previously described [54]. Fatty acids were methylated with 5 mL methanol–sulfuric acid–toluene 2:1:1 (v/v/v), during at least 12 h in a bath at 50 ºC and 30 x g; then 3 mL deionized water was added to obtain phase separation; the FAME were recovered with 3 mL diethyl ether by shakingin a vortex, and the upper phase was passed through a micro-column of anhydrous sodium sulfate in order to eliminate the water; the sample was recovered in a vial with Teflon, and before injection the sample was filtered with a 0.2 μm nylon filter from Whatman. The analysis was performed by gas–liquid chromatography with flame ionization detection, using a YOUNG IN Chromass 6500 GC System instrument equipped with a split/splitless injector, a flame ionization detector (FID) and a Zebron-Fame column. The identification and quantification of fatty acids were achieved by comparing the relative retention times of FAME peaks from samples with standards (standard mixture 47885-U, Sigma, St. Louis, MO, USA) and results were recorded and processed using the Software Clarity DataApex 4.0 Software (Prague, Czech Republic) and expressed in relative percentage of each fatty acid. 2.6. Determination of Phenolic Acids and Related Compounds, and Bioactive Properties 2.6.1. Phenolic Acids and Related Compounds Phenolic acids and related compounds were analyzed with UFLC equipment coupled to a diode array detector (DAD) [56], after dissolving the hydroethanolic extracts in 20% aqueous methanol, at a known concentration. The phenolic acids and related compounds were quantified by comparison of the area of their peaks recorded at 280 nm, with calibration curves obtained from commercial standards. The results were expressed in μg per g of extracts.

2.6.2. Antioxidant Activity

The antioxidant activity was evaluated by a cell-based procedure, namely, through the inhibition of the production of thiobarbituric acid reactive substances (TBARS). For this assay, the lyophilized hydroethanolic extracts were dissolved in water and subjected to dilutions from 5 to 0.625 mg/mL. Lipid peroxidation inhibition in porcine (Sus scrofa) brain homogenates was estimated by the diminution in TBARS; the color strength of malondialdehyde–thiobarbituric acid (MDA–TBA) was measured by its absorbance at 532 nm; the inhibition ratio (%) was calculated using the following formula: [(A - B)/A] x 100%, where A and B were the absorbances of the control and the sample solutions, respectively [57]. The results were expressed in EC50 values (mg/mL, sample concentration providing 50% of antioxidant activity). Trolox was used as a positive control.

2.6.3. Antimicrobial Activity

The extracts were redissolved in 5% dimethyl sulfoxide (DMSO) to a concentration of 10 mg/mL and further diluted. The microdilution method [58] was performed to assess the antimicrobial activity against the Gram-negative bacteria *Escherichia coli* (ATCC 25922), *Salmonella typhimurium* (ATCC 13311) and *Enterobacter cloacae* (ATCC 35030), and Grampositive bacteria: *Staphylococcus aureus* (ATCC 11632), *Bacillus cereus* (clinical isolate), *Listeria monocytogenes* (NCTC 7973). For antifungal assays, six micromycetes were used: *Aspergillus fumigatus* (human isolate), *Aspergillus niger* (ATCC 6275), Aspergillus versicolor (ATCC11730), *Penicillium funiculosum* (ATCC 36839), *Trichoderma viride* (IAM 5061) and *Penicillium verrucosum* var. *cyclopium* (food isolate).

The minimum extract concentrations that completely inhibited bacterial growth (MICs) were determined by a colorimetric microbial viability assay, and minimum bactericidal concentration (MBC) and minimum fungicidal concentration (MFC) were also calculated. Streptomycin, ampicillin, ketoconazole, and bifonazole (Sigma-Aldrich, St. Louis, MO, USA) were used as positive controls, and 5% DMSO was used as a negative control.

2.7. Data Analysis

Eight mushroom samples were analyzed for all the experiments, and the antioxidant assays were carried out in triplicate. The results are expressed as mean values ± standard deviation (SD). The differences between samples were analyzed using one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference post hoc test with $\alpha = 0.05$, coupled with Welch's t-test. This analysis was carried out using the SPSS v. 22.0 program.

A Principal Component Analysis (PCA) was performed to evaluate if chemical and functional characteristics could separate the samples analyzed. As they were measured in different units, PCA was applied to standardized variables (centered by the mean and scaled by the variance). The analysis was performed in R version 3.6.3 (R Core Team, 2017) using the "prcomp" function from the "stats" package, and figures were produced using the package "ggplot2" version 3.2.1 [59].

3. Results and Discussion

3.1. Prices, Quantities Sold, and Socio-Economic Importance

The harvesting, processing, and sale of WEMs is an important economic activity in Huíla, and the consumption of edible mushrooms is a good example of the use of nonwood forest products in human nutrition. During prospection, 35 mushroom vendors were found in the four markets visited: 15 at Mutundo market, 10 at Humpata, 6 at Hoque, and four at Rio Nangombe. In total, 21 vendors were interviewed: 10 at Mutundo market, 5 at Humpata, and 3 at Hoque and Rio Nangombe markets each. The selling units and prices for dried mushrooms do not vary much among vendors, who tend to sell the products in the same containers or arrange them in similarly shaped piles. Vendors adopt a characteristic medium-sized dish that may contain 65–120 g of dried mushrooms, with an average of ~90 g. Additionally, the prices practiced are uniform in each market. In all markets, the price per unit is AKZ 100, except in the Hoque market, where the unit was sold at AKZ 150 (0.20 and 0.30 USD/kg, respectively, considering the official exchange rate of the Bank of Angola, at the date of the fieldwork, USD 1 = AKZ 500). As for fresh mushrooms, they are sold in bowls or large plates, and prices vary among markets and also throughout the day in the same market. As they are perishable products, it is common for vendors who still have fresh mushrooms in the evening to reduce the price to sell them all. The prices recorded in the morning varied between AKZ 100 and 500 for quantities between 200 and 1500 g. When converted to price per kilogram, the dried mushrooms were sold between AKZ 1322 and 1741 (2.64 and 3.48 USD/kg, respectively) and the fresh mushrooms between AKZ 250 and 333 (0.50 and 0.67 USD/kg, respectively). The recorded selling prices for dried WEMs make them an affordable food source that can contribute to food security in both rural and urban communities, as well as a source of income for households. In the Huila markets, the prices of dried mushrooms seem to have little variation along the year and among markets. Conversely, he prices of fresh mushrooms may vary during the day because they cannot be stored until the next day, and presumably also throughout the year, as the abundance of mushrooms varies and is related to the climatic conditions, namely, the occurrence of rains.

Regarding the quantity of mushrooms sold daily per seller, there is great variability but, with the information that was possible to obtain, each vendor may sell about 900 g of dried mushrooms per day. Knowing that the dried mushrooms are sold throughout the year and considering the 35 vendors that resulted from the census, we can consider that in the four markets will be sold about 31.5 kg of dried mushrooms per day, which corresponds to 11.3 tons per year. Each vendor interviewed can earn at least AKZ 900 daily (c. USD 1.8) from the sale of mushrooms and thus contribute to the family income of around AKZ 21,600 per month (USD~43.2), considering 24 days of sales per month. On the other hand, it is not possible, with the data obtained, to make an accounting regarding fresh mushrooms. These are sold according to the maturation of the fruiting bodies, which depends on the occurrence of rainfall. Additionally, the sale of fresh mushrooms is largely carried out along the roads by informal vendors, often children, and prices vary greatly both throughout the year and during the day.

The mushrooms sampled in the present study are mycorrhizal and abundant in the Miombo forests in the central highlands of Huila, in association with key tree species, particularly *Julbernardia*, *Brachystegia* and *Uapaca*, occurring alone or in groups. They can be found both on litter-covered soils from the shadiest sites under the tree canopy, as well as in more open sites with rocky soil and herbaceous or shrubby strata on sloping terrain. Although spore germination occurs in the rainy season, the production of fruiting bodies is highly dependent on the intensity and frequency of rainfall throughout the year.

Eight morphotypes of mushrooms were recognized in the mixtures sold at the Humpata market and separated and numbered as M1 to M8. Through the visit to the harvesting sites, it was observed that the WEMs are harvested in forest vegetation of Miombo and Mopane, as well as fallow land and forest areas cleared for cultivation, with soil being the predominantly substrate. The mushrooms, usually of a mixture of species, are air-dried until they are brittle, the moisture reduced (Figure 2), and then packaged and stored.

The mushroom species identified correspond to the ones present in the mixtures sold at the Humpata market at the time of acquisition. Several other species are sold both fresh and dried in the city markets and along roadsides. In fact, during the fieldwork, it was possible to observe several other species of mushrooms that are harvested and sold fresh, namely, of the genera *Amannita*, *Cantharellus*, *Lactarius* and *Termitomyces*. However, according to information obtained from local informants, such species are not suitable for drying and long-term preservation, probably because they have high moisture contents and degrade before drying.

Despite the socio-economic importance and scientific interest, the knowledge about the diversity and properties of macrofungi in Angola is very incipient, with only 24 occurrences of edible mushrooms recorded, belonging to 11 species of four genera [27]. None of them coincides with the species identified in this work, although the genus *Russula* is well represented in both cases. Additionally, no accessions from Angola were found in DNA sequence databases, and no publications are available on the subject. The information available for neighboring countries to Angola, where many dozens of edible WEM species are known [25–27], allows us to infer that there is a great diversity of edible fungi in Angola too, but it is still almost totally unknown. In fact, it is very frequent to find a great variety of fresh and dried mushrooms for sale all over Angola, both in the markets and at the roadside.

3.2. Morphological Characterization and Molecular Identification of Sampled WEM

With the purpose of identifying the collected mushroom morphotypes up to the species level and improving the knowledge on these local food resources, a comprehensive morphological and molecular characterization was performed. Table 1 summarizes the set of observations made on the mushroom samples, supplemented with data from the vernacular names and ecological data obtained during the fieldwork campaign, and the molecular characterization performed in this study. By combining field information and the observations made at the laboratory on the dry material, samples M1 to M7 were recognized as belonging to the Russulaceae family and *Russula* genus. The presence of ring and volva revealed sample M8 to be an Amanitaceae. The genus *Russula* is easily morphologically distinguished from other common mushrooms by several recognizable features, such as free white gills, absence of partial veil or volva tissue on the stipe, and brittle fleshy basidiocarp due to the presence of spherocytes. However, given its high species diversity, *Russula* has been one of the most difficult genera for fungal systematics and taxonomy. The macromorphological features such as cap color can be highly variable within a species, and there are relatively few features to distinguish many closely related species within the genus. Much of the morphotypes found in the samples analyzed belong to the genus *Russula*, one of the most speciose genera in Africa, with about 200 species being identified in this continent, most of them edible, and with no reported serious toxicological problems [27]. Another important factor for the abundance of *Russula* in the dried mushroom mixtures sold may be the good drying and preservation capacity of the species in this genus.

DNA barcoding is a powerful tool for accurate identification at the species level, usually disentangling closely related and cryptic species that could not be distinguished by morphological characters. In this process, the selection of appropriate DNA barcodes is vital to assure resolution of species recognition, and even then, some fungi taxonomic groups can be quite challenging, as is the case of the *Russula* genus.

Figure 2. Mushrooms picking in a Miombo woodland area (**top**) and mixtures of fresh edible mushrooms, and mushrooms at different stages of drying (**bottom**). Photos by Herose Mendes.

In our study, we apply a sequencing multi-locus strategy based on the ITS region (ITS1-5.8S ribosomal RNA gene-ITS2), 28S large subunit ribosomal RNA gene (LSU), and RNA polymerase II second largest subunit (rbp2) gene to analyze our samples. Fragments ranging from 137–702 bp, 464–947 bp, and 691–805 were obtained for the ITS LSU and rbp2, respectively. Homology of identity was first investigated by querying our sequences against sequences available in the NCBI nucleotide database. Samples M1 to M7 had the most significant hits with sequences characterized as *Russula* (% of identity > 90%), but no species designation could be undoubtedly assigned. In contrast, a hit of 100% similarity was obtained for M8 sample sequences identified as belonging to the species *Amanita loosei* (synonym *A. zambiana*), in accordance with the morphological data. Having this into account, a phylogenetic analysis was performed using a large set of *Russula* and *Amanita* species sequences (Table S1; Figure 3).

Table 1. Characterization of the eight morphotypes found in the dried mushrooms sample from Humpata market, Angola (Note: cap and stipe dimensions were taken on dried specimens).

Samples	**Species**	**Common Name**	**Ecology/Morphology**
M1	*Russula aff. cellulata* Buyck	Ombando (Umbundu)	Occurs in closed to open Miombo woodland, under the tree canopy, sometimes in moss-covered soil, mainly from March to May. Cap: brown cream or light brown, often cracked, 5–10 cm Ø. Stipe: whitish, 4–5 × 1.5–2.5 cm. Spores: hyaline, with small warts, very occasionally connected by fine lines, subglobolose 6.5–8 µm. Basidia: 50 × 10 µm.
M2	*Russula* sp1 [*R.* gr. *rosea* Pers. (=*R. lepida* Fr.)]	Opembe (Nyaneka); Membe, Umputu (Umbundu)	Occurs in closed to open Miombo woodland, under the tree canopy, often near the base of the tree trunks, mainly in March to May. Cap: vinaceous or blood-red, 3.5–7.5 cm Ø. Stipe: white with red or rosaceous flush, 3–5 × 1.8–2 cm. Spores: with warts, some connected by fine lines, broadly ellipsoid, 10 × 9 µm. Basidia: 45–50 × 10 µm.
M3	*Russula* sp2 (subgenus Heterophyllidia, section Heterophyllae, subsection Cyanoxanthinae)	Chelene preto [black chelene] (Umbundu/Nyaneka)	Occurs in closed to open Miombo woodland, under the tree canopy, mainly in March to May. Cap: dark purple with greenish tones, mucilaginous, 3–5 cm Ø. Stipe: whitish, 3.5–4 × 2 cm. Spores: with warts, ellipsoid 7 × 5.5 µm. Basidia: 9 × 5 µm.
M4	*Russula* sp3. (*R.* aff *madagassensis* R. Heim)	Chelene amarelo [yellow chelene] (Umbundu/Nyaneka)	Occurs in open Miombo woodland and open rocky areas on sloping terrains, mainly in March to May. Cap: brownish yellow, mucilaginous, 5–6 cm Ø. Stipe**:** 3.5–4 × 1.5–2 cm. Spores: with warts, ellipsoid, 7–8 × 5 µm. Basidia: 55 × 10 µm.
M5	*Russula* sp3. (*R.* aff *madagassensis* R. Heim)	Chelene amarelo [yellow chelene] (Umbundu/Nyaneka)	Occurs in open Miombo woodland and open rocky areas on sloping terrains, mainly in March to May. Cap: brownish yellow, viscid, 5–6 cm Ø. Stipe**:** 3.5–4 × 1.5–2 cm. Spores: sub-spherical, with small warts interconnected by narrow veins giving a reticulated aspect, 7–7.5 µm. Basidia: 50–55.5 × 12 µm.
M6	*Russula* sp3. (*R.* aff *madagassensis* R. Heim)	Chelene vermelho [red chelene] (Umbundu/Nyaneka)	Occurs in open Miombo woodland, under the tree canopy, mainly in March to May. Cap: reddish or pink 5–6 cm Ø. Stipe: 3.5–4 × 1.5–2 cm. Spores: ornamented with small warts interconnected by narrow veins giving a reticulated aspect, spherical, 8–9 µm. Basidia: 50 × 10 µm.
M7	*Russula* sp3. (*R.* aff *madagassensis* R. Heim)	Chelene vermelho [red chelene] (Umbundu/Nyaneka)	Occurs in open Miombo woodland, under the tree canopy, mainly in March to May. Cap: reddish or light pink, 5–6 cm Ø; Stipe: 3.5–4 × 1.5–2 cm. Spores: ornamented with small warts interconnected by narrow veins giving a reticulated aspect, spherical, 8–9 µm. Basidia: 50 × 10–12.5 µm.
M8	*Amanita loosei* Beeli (=*A. zambiana*)	Ndenda (Umbundu); Ondenda (Nyaneka)	Occurs in closed to open Miombo woodland, under the tree canopy, often in rocky soil, mainly in December to May. Cap: brownish at the centre becoming paler towards the margin, 10–25 cm Ø, (can reach 30–40 cm in fresh). Stipe: white, 5–10 × 2–3 cm. Ring and volva: present. Spores: hyaline, smooth, spherical a sub-spherical, 12 µm. Basidia: 50 × 10 µm

Maximum likelihood and Bayesian Inference analyses from the concatenated dataset showed the existence of two major phylogenetic lineages that correspond to *Amanita* and *Russula* genera, as expected, placing M8 sample within *Amanita* species group (BS: 93 and

BI:1.0) and the remaining samples (M1 to M7) within *Russula* clade (BS:100 and BI:1.0). Seven *Russula* subgenera as recognized by Buick et al. and Vera et al. [60,61] (*Russula*; *Malodora; Brevipes; Compactae; Glutinosae; Heterophyllidia* and *Ingratula*) were identified in our phylogeny. In this framework, M1 clustered within the subgenus Malodora (BS:99 and BI:1.0), showing a close relationship with *Russula cellulata* (BS:100 and BI:1.0). Given its phylogenetic placement, it is quite probable that sample M1 belongs to *R. cellulata*, which is an edible species common in central and southern Africa. M2 is in a basal position of a well-supported group (BS:100 and BI:1.0) that cluster *R. rosea* (synonym *R. lepida*) and *R. flavisiccans*, within subgenus *Russula*. However, despite the affinity to the *R. rosea*/*R. flavisiccans* group, no confident assignment can be made to a particular species. Similarly, M3 seems to be a basal lineage of a group identified as the subsection Cyanoxanthinae, section Heterophyllae of subgenus Heterophyllidia (BS:100 and BI:1.0) [62], but at this point, our data does not provide further specific resolution. The closest phylogenetic relationship of M3 is found with *R. cyanoxantha*, *R. variata*, *R. langei,* and *R. lakhanpalii,* species that are not reported for Africa. Subsection Cyanoxanthinae encompasses varied species characteristics and great similarities to *R. cyanoxantha*, as reported in a study for Central Africa [63] in which three new species similar to *R. cyanoxantha* were identified, namely *R. flavobrunnea*, *R. pseudopurpure*, and *R. striatoviridi,* being the first one recorded to Angola in miombo too. The remaining samples M4-M7 make up a well-supported, single, and differentiated sub-group (BS:100 and BI:1.0) within the subgenus Heterophyllidia. This result suggests that all these samples belong to the same species, although they exhibit morphological differences in the color of the hat (from yellow to red) and foot, in the size of the cystidia and basidia, as well as in the ornamentation of the spores. Although they cannot be assigned to any species with sequence resources publicly available, samples M4–M7 are closely related to *R. madagassensis,* common in Madagascar but not reported for the African continent. Considering the phylogeny, the possibility that these samples may belong to a species not yet described cannot be ruled out.

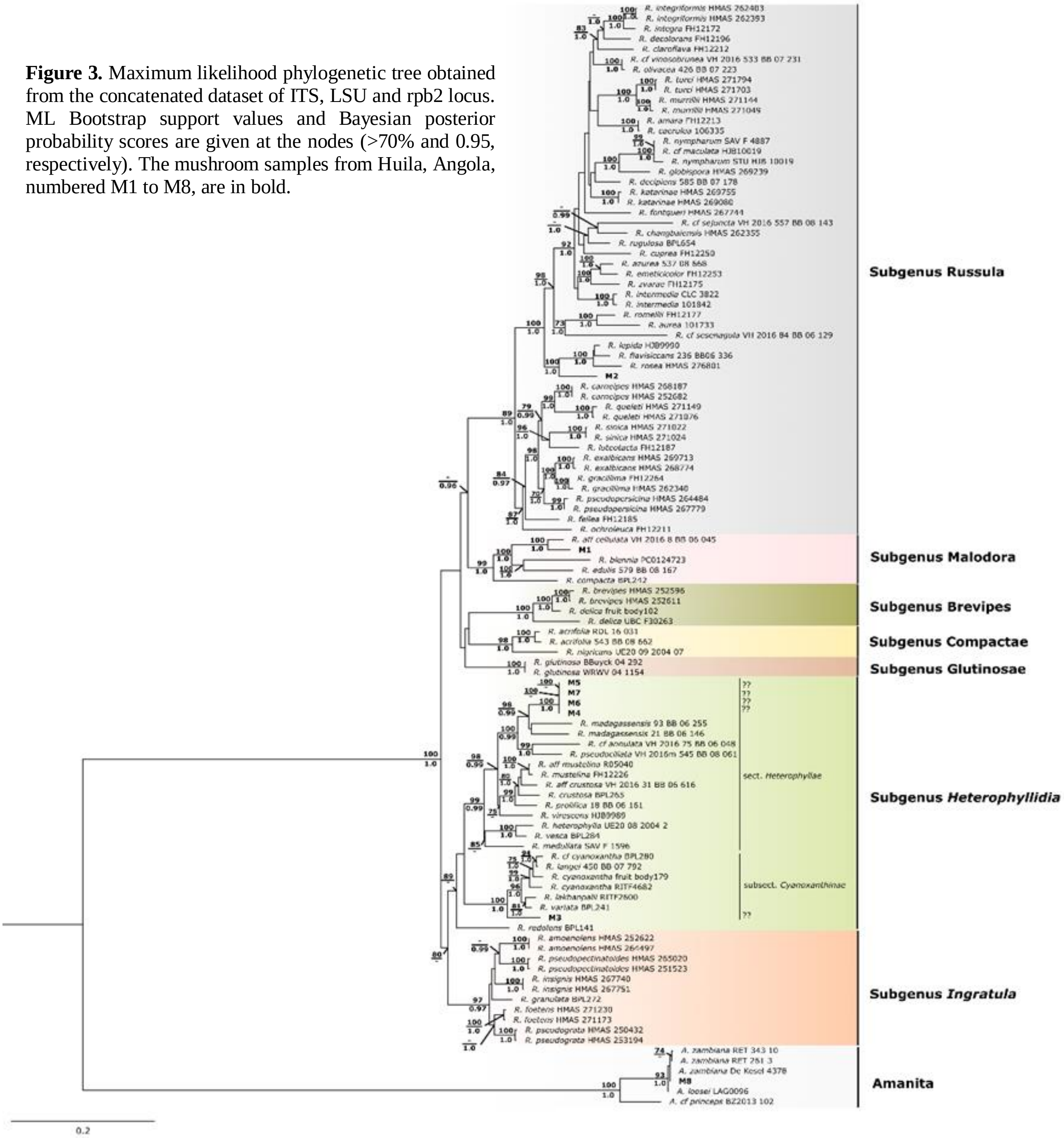

Figure 3. Maximum likelihood phylogenetic tree obtained from the concatenated dataset of ITS, LSU and rpb2 locus. ML Bootstrap support values and Bayesian posterior probability scores are given at the nodes (>70% and 0.95, respectively). The mushroom samples from Huila, Angola, numbered M1 to M8, are in bold.

The limitations of distinguishing individual *Russula* species found in our work are not surprising as is well known that the genus *Russula* is one of the most highly diverse among Agaricomycetes, comprising over 780 species, and hard to resolve [23]. The high intra-specific variability and extensive phenotypic plasticity, as well as inaccurate descriptions in the literature and limited availability of DNA sequences in global databases, has long caused large difficulties in species resolution and taxonomic confusion [60,23]. As such, an increasing number of emerging species has arisen in recent years mainly based on molecular data, for which the combination of ITS-rpb2 has recently been suggested as the best target DNA barcode for *Russula* [23]. Our work using the barcode markers ITS, LSU, and rpb2 combined with morphological observations, despite limitations, allowed us to identify five different mushroom species in the dry samples of eight morphotypes from Humpata market (Huíla, Angola) (Table 1): *A. loosei*, *Russula* aff. *cellulata*, *Russula* sp1 (*R*. group *rosea*), *Russula* sp2 (subgenus Heterophyllidia, section Heterophyllae, subsection Cyanoxanthinae), and *Russula* sp3. (*R*. aff. *madagassensis*).

3.3. Chemical Characterization of Mushroom Species

The results accomplished for the nutritional composition and energetic value of the studied mushroom samples from Huila, Angola, are presented in Table 2. In all of the analyzes, carbohydrates were the most abundant macromolecule, followed by proteins, ashes, and fat. Among them, M1 (*Russula* aff. *cellulata*) and M2 (*Russula* sp1) presents the highest amount of carbohydrates (77.1 and 76.1 g/100 g dw, respectively), followed by M6, M4, M5 and M7 (*Russula* sp3), which present values ranging from 63.8 to 68.1 g/100 g dw, and finally M8 (*A. loosei*), which display the lowest value (61.7 g/100 g dw). As for proteins, similar amounts were observed between the studied mushrooms, varying from 14.1 to 16.2 g/100 g dw, except for M7, which presents the higher content (18.1 g/100 g dw), and M2 (12.64 g/100 g dw) the smallest. Additionally, very interesting amounts of ashes are detected in the analyzed samples, with values ranging from 6.85 to 16.19 g/100 g dw, suggestive of good micronutrient concentrations, which are involved in several mechanisms in the human organism. When compared to the above-mentioned constituents, the studied species are much less abundant in fat which, together with the high protein and carbohydrate contents, make them suitable for low-calorie diets. Although allegedly, samples M4 to M7 belong to the same species, they present significant differences in all parameters analyzed, which may possibly be related to the collection date of the mushrooms and their stage of development [64]. In a recent investigation, Kostić et al. [65] studied the nutritional composition of three *Russula* species from Serbia, among them *Russula rosea*, which molecular analysis showed affinity with our M2 sample. Overall, their results are partially consonant with ours, presenting similar amounts of carbohydrates (82.031 g/100 g dw) and proteins (12.21 g/100 g dw). However, the authors also detected much lower contents of ashes (4.9 g/100 g dw) and fat (0.84) when compared to our M2 sample, which may be due to the fact that these samples have different origins (Angola and Serbia), being therefore subject not only to different edaphoclimatic factors but also to different storage and processing techniques. About the other mushroom species under investigation and their possible affinities, to our best knowledge, this is the first study regarding their nutritional characterization.

The occurrence of free sugars was also analyzed in the mushrooms under investigation, and the results are described in Table 2. Mannitol and trehalose were the only two sugars identified in all samples, with mannitol presenting the highest concentration (4.88 to 20.48 g/100 g dw). Fructose was also detected in quite low amounts in M4 to M8 samples, ranging from 0.05 g/100 g dw found in *A. loosei* to 0.10–0.28 in *Russula* sp3. Through this analysis, it was possible to verify quite different values of the identified sugars, not only between species but within each species, which may be related, firstly, to genetic differences between species and, lastly, to possible different stages of development of the mushrooms as well as different processing/storage approaches [64]. The free sugar profile of *R. rosea* was also studied by Kostić et al. (2020) [65] whose results showed considerable discrepancies with our study since these authors only detected the presence of mannitol in this species and in amounts much higher (25.8 g/100 g dw) than those detected in the present study (16.49 g/100 g dw).

Regarding organic acids (Table 2), in all analyzed samples oxalic, quinic malic, citric, and fumaric acids were detected, with M6 (*Russula* sp3) presenting the highest content in total organic acids (11.80 g/100 g dw). As for samples M1, M2, M3, M6, M7 and M8, quinic acid is the main compounds (5.33, 5.65, 5.01, 4.72, 4.57 and 1.66 g/100 g dw, respectively). Regarding the total organic acids, *A. loosei* presents the lowest concentration among the analyzed mushrooms (3.86 g/100 g dw). Ribeiro et al. [64] studied the organic acids profile of *R. cyanoxantha*, which presents similarities with our M3 sample (*Russula* sp2). These authors were able to identify oxalic, citric, malic, quinic, and fumaric acids in this species, with malic and quinic acids presenting the highest concentration and oxalic the minor one, which was also observed in our study. In contrast, Kostić et al. (2020) [65] observed in *R. rosea* only the presence of oxalic and malic acids, and trace amounts of fumaric acid, which differs greatly from the present study, since quinic and citric acids were also identified, of which the first was present in greater amounts in this species. Given their ability to perform antioxidant activity, organic acids may play a protective role against a wide variety of diseases. Oxalic acid, for example, has proven to be able to perform antibacterial activity against a wide spectrum of microorganisms, whereas fumaric acid has been shown to have anti-inflammatory as well as antimicrobial properties, among others [66,67].

Lipophilic compounds, namely tocopherols and fatty acids were also examined in the studied mushroom samples (Table 2). It was possible to identify the presence of only α- and β-tocopherol isoforms, with the last being only identified in *Russula* sp1 in significant amounts (45.9 µg/100 g dw). Additionally, the α-tocopherol isoform was not detected in M4, M5, and M7 samples, although present in interesting amounts in the other analyzed samples, reaching its higher concentration in *A. loosei* (50.4 µg/100 g dw). Tocopherols were also able to perform antioxidant activity through the production of new free radicals and neutralization of existing ones. These compounds may consequently reduce the risk of degenerative diseases associated with oxidative stress [68,69].

The fatty acid assessment (Table 2) revealed oleic acid (C18:1n9c) as the main fatty acid present in all the analyzed samples, with values ranging from 42.81 to 55.80%, followed by palmitic acid (C16:0; 12.1 to 30.46%), and linoleic acid (C18:2n9c; 1.87 to 26.85%). Stearic acid (C18:0), in turn, was the one present in lower quantities. Comparing the studied mushrooms, *A. loosei* presents the highest content in oleic acid (55.80 ± 0.01%), *Russula* sp3 (M3) in palmitic acid (30.46%), and *Russula* sp1 (M2) in linoleic acid (26.85%). As about the percentage analysis of the saturated (SFA), monounsaturated (MUFA), and polyunsaturated (PUFA) fatty acids, the latter is present in smaller amounts in all samples under investigation, presenting its lowest value in M3 and M6 samples (2.2 and 11.5%, respectively), followed by SFAs, whose highest amount are present in the M3 sample (47.3%), and finally MUFA, the most prevalent class in overall samples (43.7 to 56.4%). The above-mentioned fatty acids were also detected by Kostić et al. (2020) [65] in *R. rosea* although, except for palmitic acid, in quite different amounts. Despite that, in this study, oleic acid was also the prevalent compound in *R. rosea*, as well as in our study, followed by linoleic acid. To the best of our knowledge, there are no available reports on the fatty acid profile of the other species in the study.

Table 2. Nutritional, hydrophilic, and lipophilic compounds of the studied mushrooms’ samples from Huila, Angola (mean ± SD, *n* = 3).
nd—not detected, tr—traces; different letters in the same line show significant difference between means according to Tukey’s HSD test ($p < 0.05$); C16:0—palmitic acid; C18:0—stearic acid;

	M1 (*Russula* aff. *cellulata*)	**M2 (*Russula* sp1)**	**M3 (*Russula* sp2)**	**M4 (*Russula* sp3)**	**M5 (*Russula* sp3)**	**M6 (*Russula* sp3)**	**M7 (*Russula* sp3)**	**M8 *(Amanita loosei)***
Nutritional value (g/100 g dw)								
Fat	1.99 ± 0.05 ^{h}	2.17 ± 0.06 ^{g}	5.24 ± 0.02 ^{b}	2.43 ± 0.02 ^{f}	3.70 ± 0.06 ^{c}	3.16 ± 0.01 ^{e}	3.51 ± 0.09 ^{d}	8.20 ± 0.01 ^{a}
Proteins	14.1 ± 0.5 ^{d}	12.6 ± 0.4 ^{e}	14.1 ± 0.1 ^{d}	15.8 ± 0.1 ^{bc}	16.2 ± 0.1 ^{ab}	15.4 ± 0.1 ^{c}	18.1 ± 0.3 ^{a}	15.2 ± 0.2 ^{c}
Ash	6.85 ± 0.03 ^{f}	9.20 ± 0.01 ^{e}	15.87 ± 0.01 ^{a}	14.47 ± 0.03 ^{b}	14.05 ± 0.01 ^{c}	13.39 ± 0.04 ^{d}	16.19 ± 0.04 ^{a}	14.92 ± 0.06 ^{b}
Carbohydrates	77.1 ± 0.4 ^{a}	76.1 ± 0.4 ^{b}	64.82 ± 0.05 ^{f}	67.3 ± 0.1 ^{d}	66.0 ± 0.1 ^{e}	68.1 ± 0.1 ^{c}	63.8 ± 1.4 ^{f}	61.7 ± 0.1 ^{g}
Energy value (kcal/100 g dw)	382.6 ± 0.3 ^{a}	374.1 ± 0.2 ^{b}	362.7 ± 0.1 ^{c}	354.3 ± 0.2 ^{d}	362.3 ± 0.2 ^{c}	362.2 ± 0.1 ^{c}	352.8 ± 0.4 ^{d}	381.4 ± 0.2 ^{a}
Hydrophilic compounds (free sugars and organic acids, g/100 g dw)								
Frutose	nd	nd	Nd	0.16 ± 0.03 ^{c}	0.10 ± 0.01 ^{d}	0.23 ± 0.01 ^{b}	0.28 ± 0.04 ^{a}	0.05 ± 0.01 ^{e}
Mannitol	20.48 ± 0.04 ^{a}	16.49 ± 0.07 ^{b}	12.45 ± 0.03 ^{f}	13.67 ± 0.03 ^{d}	14.29 ± 0.01 ^{c}	13.01 ± 0.04 ^{e}	6.71 ± 0.02 ^{g}	4.88 ± 0.07 ^{h}
Trehalose	0.77 ± 0.03 ^{g}	0.83 ± 0.01 ^{e}	1.28 ± 0.04 ^{c}	1.38 ± 0.02 ^{b}	0.71 ± 0.05 ^{h}	1.08 ± 0.08 ^{d}	0.77 ± 0.07 ^{f}	6.50 ± 0.08 ^{a}
Total sugars	21.25 ± 0.06 ^{a}	17.32 ± 0.07 ^{b}	13.74 ± 0.01 ^{f}	15.21 ± 0.02 ^{c}	15.09 ± 0.06 ^{d}	14.32 ± 0.04 ^{e}	7.76 ± 0.09 ^{h}	11.43 ± 0.01 ^{g}
Oxalic	0.022 ± 0.001 ^{e}	0.029 ± 0.002 ^{e}	0.105 ± 0.001 ^{c}	0.115 ± 0.003 ^{c}	0.106 ± 0.001 ^{c}	0.49 ± 0.02 ^{a}	0.150 ± 0.003 ^{b}	0.057 ± 0.001 ^{d}
Quinic	5.33 ± 0.05 ^{b}	5.65 ± 0.06 ^{a}	5.01 ± 0.01 ^{c}	2.59 ± 0.01 ^{f}	2.48 ± 0.01 ^{g}	4.72 ± 0.01 ^{d}	4.57 ± 0.01 ^{e}	1.66 ± 0.01 ^{h}
Malic	2.39 ± 0.05 ^{f}	1.64 ± 0.01 ^{g}	3.99 ± 0.01 ^{d}	4.09 ± 0.03 ^{c}	3.48 ± 0.01 ^{e}	4.55 ± 0.01 ^{a}	4.39 ± 0.02 ^{b}	1.42 ± 0.01 ^{h}
Citric	0.85 ± 0.01 ^{f}	0.84 ± 0.01 ^{f}	1.22 ± 0.01 ^{e}	1.71 ± 0.01 ^{c}	1.56 ± 0.01 ^{d}	2.04 ± 0.01 ^{b}	2.60 ± 0.06 ^{a}	0.718 ± 0.007 ^{g}
Fumaric	tr	tr	Tr	tr	tr	tr	tr	tr
Total organic acids	8.59 ± 0.01 ^{d}	8.16 ± 0.05 ^{f}	10.34 ± 0.01 ^{c}	8.51 ± 0.02 ^{e}	7.63 ± 0.01 ^{g}	11.80 ± 0.01 ^{a}	11.71 ± 0.08 ^{b}	3.86 ± 0.01 ^{h}
Lipophilic compounds (fatty acids, % and tocopherol, µg/100 g dw)								
C16:0	19.81 ± 0.03 ^{d}	12.1 ± 0.1 ^{e}	30.46 ± 0.02 ^{a}	23.2 ± 0.3 ^{c}	20.03 ± 0.04 ^{d}	24.5 ± 0.1 ^{b}	19.95 ± 0.06 ^{d}	19.5 ± 0.1 ^{d}
C18:0	5.03 ± 0.04 ^{g}	9.4 ± 0.1 ^{b}	11.9 ± 0.1 ^{a}	6.68 ± 0.09 ^{d}	5.93 ± 0.01 ^{e}	7.78 ± 0.1 ^{c}	6.56 ± 0.01 ^{d}	5.15 ± 0.05 ^{f}
C18:1n9c	50.8 ± 0.1 ^{c}	48.55 ± 0.05 ^{d}	46.67 ± 0.08 ^{e}	42.810.5 ^{f}	48.9 ± 0.5 ^{d}	53.3 ± 0.01 ^{b}	50.3 ± 0.3 ^{c}	55.80 ± 0.01 ^{a}
C18:2n6c	17.4 ± 0.1 ^{e}	26.85 ± 0.07 ^{a}	1.87 ± 0.01 ^{h}	19.04 ± 0.09 ^{c}	20.7 ± 0.1 ^{b}	8.6 ± 0.1 ^{g}	18.7 ± 0.1 ^{c,d}	15.7 ± 0.2 ^{f}
SFA (%)	26.4 ± 0.1 ^{f}	22.2 ± 0.1 ^{g}	47.3 ± 0.1 ^{a}	35.0 ± 0.5 ^{b}	27.4 ± 0.7 ^{e}	34.5 ± 0.1 ^{c}	28.3 ± 0.1 ^{d}	26.22 ± 0.1 ^{f}
MUFA (%)	51.8 ± 0.1 ^{c}	49.1 ± 0.1 ^{g}	50.6 ± 0.1 ^{e}	43.7 ± 0.6 ^{h}	49.7 ± 0.5 ^{f}	54.0 ± 0.1 ^{b}	51.0 ± 0.3 ^{d}	56.4 ± 0.1 ^{a}
PUFA (%)	21.8 ± 0.1 ^{c}	28.7 ± 0.2 ^{a}	2.2 ± 0.1 ^{h}	21.3 ± 0.1 ^{d}	22.9 ± 0.1 ^{b}	11.5 ± 0.1 ^{g}	20.7 ± 0.2 ^{e}	17.4 ± 0.1 ^{f}
α-Tocopherol	36.9 ± 0.7 ^{b}	22.8 ± 0.8 ^{d}	23.1 ± 0.1 ^{c}	nd	nd	21.8 ± 0.8 ^{e}	nd	50.4 ± 0.8 ^{a}
β-Tocopherol	nd	45.9 ± 0.4	Nd	nd	nd	nd	nd	nd
Total tocopherols	36.9 ± 0.7 ^{c}	68.7 ± 1.3 ^{a}	23.1 ± 0.1 ^{d}	-	-	21.8 ± 0.8 ^{e}	-	50.4 ± 0.8 ^{b}

C18:1n9—oleic acid; C18:2n6—linoleic acid; SFA—Saturated fatty acids; MUFA—Monounsaturated fatty acids; PUFA—Polyunsaturated fatty acids.

3.4. Determination of Phenolic Acids and Related Compounds, and Bioactive Properties

3.4.1. Phenolic Acids and Related Compounds

The phenolic acids and related compounds assessment were performed in the hydroethanolic extracts of the mushrooms under investigation, with the attained results being presented in Table 3. In all experiments, protocatechuic, *p*-hydroxybenzoic, and *p*-coumaric acids, and a related compound, cinnamic acid, were identified. Overall, *p*-hydroxybenzoic acid was the main phenolic acid in all studied mushrooms, reaching its higher amount in *A. loosei* (320.1 µg/g extract) and *Russula* sp3, which samples present values ranging from 139.4 to 286.7 µg/g extract. Protocatechuic acid, in turn, presents its higher value in M2 sample (120 µg/g extract), and *p*-coumaric acid in the M8 sample (48.2 µg/g extract). As for cinnamic acid, its concentration is quite diverse between samples, with the minimum values being identified in M5 sample (3.43 µg/g extract), and the maximum in M7 (79 µg/g extract). In general, *Amanita loosei* presents the highest concentration (400.3) in phenolic acids (without cinnamic acid), followed by similar amounts in *Russula* sp3, namely in samples M4 and M5. The smallest concentration was, in turn, found in *Russula* sp2 (41 µg/g extract). Ribeiro et al. [70] in a study with entire mushrooms of *R. cyanoxantha*, were able to identify vestigial amounts of *p*-hydroxybenzoic acid, whereas in another study [64] this compound was not present in the same species, which may be due to the collection date and/or the development stages of the mushrooms. Additionally, Kostić et al. [65], when evaluating the phenolic profile o *R. rosea* methanolic and ethanolic extracts, were only capable to detect cinnamic acid (20 and 89 µg/g extract, respectively), which are present in lower amounts in our present study (16.5 µg/g extract). Moreover, in the present study, the above-mentioned compounds were all present in this species. Published data had shown that some bioactive properties performed by different mushroom species are related to their constitution in phenolic acids, namely anti-inflammatory activity by the expression of inflammatory markers, including the production of nitric oxide (NO), IL-6, and IL-1β [71].

3.4.2. Antioxidant Activity

In the present investigation, the antioxidant capacity of the hydroethanolic extracts of mushroom samples was evaluated through lipid peroxidation inhibition, and the results for the thiobarbituric acid reactive substances (TBARS) assay are presented in Table 3. From the attained results, it was possible to observe that the highest lipid peroxidation was performed by M2, M7, and M4 samples (EC_{50} = 1.07, 1.08, and 1.15 mg/mL, respectively), whereas *Russula* sp2 demonstrated the lowest antioxidant capacity (EC_{50} = 2.47 mg/mL). Very few reports on the antioxidant capacity of the studied mushroom species are available in the literature. However, some of them describe a moderate capacity to perform this bioactivity by some of the species under investigation [50,64,72], which may be related to their content in organic acids, tocopherols, phenolic acids, and others, whose presence is associated with good antioxidant assets.

3.4.3. Antimicrobial Activity

Ethanolic extracts of the mushroom samples under investigation presented antimicrobial activity against all tested strains at different degrees (Table 4). The minimum inhibitory concentration (MIC) values range between 0.5 and 4 mg/mL, whereas the minimum bactericidal concentration (MBC) was between 1 and 8 mg/mL. The most sensitive strains analysed were *E. coli* (MICs = 0.5 with all extracts), and *B. cereus* (MICs 0.5–2 mg/mL), whereas the most resilient was *S. aureus* (MICs 1–4 mg/mL). None of the extracts investigated revealed greater antibacterial activity than the commercial antibiotics used as a positive control, namely streptomycin and ampicillin. The antibacterial potential of *R. rosea* ethanolic and methanolic extracts were also studied by Kostić et al. (2017) [52], whose results also demonstrated considerable growth inhibition of the analyzed strains., with the best MIC values being accomplished by the methanolic extract against *M. luteus* and by the ethanolic one against *S. dysgalactiae* (MIC = 0.20 mg/mL, both).

Table 3. Antioxidant activity, phenolic acids, and related compounds of the studied mushroom hydroethanolic extracts (mean ± SD, *n* = 3).

Morphotypes/Species	**M1 (*Russula* aff. *cellulata*)**	**M2 (*Russula* sp1)**	**M3 (*Russula* sp2)**	**M4 (*Russula* sp3)**	**M5 (*Russula* sp3)**	**M6 (*Russula* sp3)**	**M7 (*Russula* sp3)**	**M8 *(Amanita loosei)***
Antioxidant activity (EC$_{50}$ mg/mL)								
TBARS	2.09 ± 0.05 ^{c}	1.07 ± 0.08 ^{e}	2.47 ± 0.04 ^{a}	1.15 ± 0.03 ^{d}	2.25 ± 0.06 ^{b}	2.52 ± 0.05 ^{a}	1.08 ± 0.09 ^{e}	2.25 ± 0.08 ^{b}
Phenolic acids and related compounds (µg/g of extract)								
Protocatechuic acid	9.1 ± 0.5 ^{g}	120 ± 1 ^{a}	2.89 ± 0.01 ^{h}	56.7 ± 0.6 ^{b}	46.3 ± 0.3 ^{c}	33.5 ± 0.4 ^{d}	19.8 ± 0.4 ^{f}	31.9 ± 0.6 ^{e}
p-Hydroxybenzoic acid	93.3 ± 0.6 ^{f}	28.0 ± 0.4 ^{h}	31.8 ± 0.9 ^{g}	274.0 ± 0.1 ^{c}	286.7 ± 0.2 ^{b}	145.2 ± 0.5 ^{d}	139.4 ± 0.9 ^{e}	320.1 ± 0.4 ^{a}
p-Coumaric acid	21.4 ± 0.3 ^{f}	15 ± 1 ^{g}	6.7 ± 0.2 ^{h}	43.6 ± 0.4 ^{c}	45.1 ± 0.5 ^{b}	39.4 ± 0.6 ^{d}	29.3 ± 0.6 ^{e}	48.2 ± 0.5 ^{a}
Total	123.8 ± 0.5 ^{g}	163.3 ± 0.8 ^{f}	41 ± 1 ^{h}	374 ± 1 ^{c}	378.1 ± 0.9 ^{b}	218.1 ± 0.1 ^{d}	188 ± 1 ^{e}	400.3 ± 0.6 ^{a}
Cinnamic acid	55.0 ± 0.7 ^{b}	16.5 ± 0.3 ^{c}	6.37 ± 0.07 ^{d}	6.2 ± 0.1 ^{d}	3.43 ± 0.01 ^{e}	3.8 ± 0.7 ^{e}	79 ± 3 ^{a}	16.3 ± 0.9 ^{c}

EC$_{50}$: extract concentration corresponding to a 50% of antioxidant activity. Trolox EC$_{50}$ values: 23 µg/mL (TBARS inhibition) and 19.6 µg/mL; Different letters in the same line show significant difference between means according to Tukey's HSD test ($p < 0.05$).

Table 4. Antibacterial activity of the studied mushroom hydroethanolic extracts (mg/mL).

		***Staphylococcus aureus* (ATCC 11632)**	***Bacillus cereus* (clinical isolate)**	***Listeria monocytogenes* (NCTC 7973)**	***Escherichia coli* (ATCC 25922*)***	***Salmonella typhimurium* (ATCC 13311)**	***Enterobacter cloacae* (ATCC 35030)**
M1 (*Russula* aff. *cellulata*)	MIC	2	1	2	0.5	1	2
	MBC	4	2	4	1	2	4
M2 (*Russula* sp1)	MIC	1	1	2	0.5	1	1
	MBC	2	2	4	1	2	2
M3 (*Russula* sp2	MIC	2	1	2	0.5	1	1
	MBC	4	2	4	1	2	2
M4 (*Russula* sp3)	MIC	1	0.5	1	0.5	1	2
	MBC	2	1	2	1	2	4
M5 (*Russula* sp3)	MIC	4	1	2	0.5	1	2
	MBC	8	2	4	1	2	4
M6 (*Russula* sp3)	MIC	1	0.5	2	0.5	2	2
	MBC	2	1	4	1	4	4
M7 (*Russula* sp3)	MIC	4	1	1	0.5	1	2
	MBC	8	2	2	1	2	4
M8 (*Amanita loosei*)	MIC	1	1	2	0.5	1	2
	MBC	2	2	4	1	2	4
Streptomycin	MIC	0.10	0.04	0.20	0.20	0.20	0.25
	MBC	0.20	0.10	0.30	0.30	0.30	0.50
Ampicilin	MIC	0.25	0.25	0.40	0.40	0.25	0.75
	MBC	0.40	0.45	0.50	0.50	0.50	1.20

MIC—minimal inhibitory concentration; MBC—minimal bactericidal concentration.

The antifungal activity of the tested mushroom's hydroethanolic extracts resulted in MIC and MFC (minimum fungicidal concentration) values slightly above those of positive controls, ketoconazole, and bifonazole (Table 5). Despite that, all extracts showed good antifungal capacity, mainly against T. viride (MICs 0.5 mg/mL), and to a lesser extent against *Penicillium verrucosum* var. *cyclopium* (MICs 1–4 mg/mL). To the best of our knowledge, this is the first report on the antifungal activity of the species under investigation.

Table 5. Antifungal activity of studied mushrooms hydroethanolic extracts (mg/mL).

		***Aspergillus fumigatus* (Human Isolate)**	***Aspergillus niger* (ATCC 6275)**	***Aspergillus versicolor* (ATCC11730)**	***Penicillium funiculosum* (ATCC 36839)**	***Trichoderma viride* (IAM 5061)**	***Penicillium verrucosum var. cyclopium* (Food Isolate)**
M1 (*Russula* aff. *cellulata*)	MIC	1	1	1	2	0.5	4
	MFC	2	2	2	4	1	8
M2 (*Russula* sp1)	MIC	0.5	1	1	1	0.5	1
	MFC	1	2	2	2	1	2
M3 (*Russula* sp2	MIC	0.5	1	1	0.5	0.5	1
	MFC	1	2	2	1	1	2
M4 (*Russula* sp3)	MIC	0.5	2	1	0.5	0.5	1
	MFC	1	4	2	1	1	2
M5 (*Russula* sp3)	MIC	0.5	1	1	0.5	0.5	1
	MFC	1	2	2	1	1	2
M6 (*Russula* sp3)	MIC	0.5	1	1	1	0.5	4
	MFC	1	2	2	2	1	8
M7 (*Russula* sp3)	MIC	0.5	1	1	0.5	0.5	1
	MFC	1	2	2	1	1	2
M8 (*Amanita loosei*)	MIC	1	1	1	1	0.5	1
	MFC	2	2	2	2	1	2
Ketoconazole	MIC	0.25	0.20	0.20	0.20	2.50	0.20
	MFC	0.50	0.50	0.50	0.50	3.50	0.30
Bifonazole	MIC	0.15	0.15	0.10	0.20	0.20	0.10
	MFC	0.20	0.20	0.20	0.25	0.25	0.20

MIC—minimal inhibitory concentration; MFBC—minimal fungicidal concentration.

3.5. Multivariate Analysis of Chemical and Functional Characteristics of Samples

Projecting the chemical and functional variables analyzed in a PCA revealed a close correspondence between the chemical and functional properties of the samples, distinguishing completely the eight morphotypes. Interestingly, the cluster organization obtained corresponded directly with the five taxa identified by morphological and molecular characterization. Additionally, considering the common names registered in Huila, a good correspondence between the local names, the taxonomic entities, and their chemical and functional properties can be noted (Figure S1).

There is important traditional knowledge about the identification of WEMs as well as their properties. Regarding local common names, it is interesting to note that the names given to the morphotypes have a good correspondence with nutritional characteristics, as is the case of *chelenes* (yellow, black, and red) that in the multivariate analysis were grouped together (Figure S1). This wealth of traditional knowledge about natural resources, which is learned and transmitted orally, may be eroding and must be preserved and documented.

4. Conclusions

Despite the great socio-economic importance and the potential to contribute to food security for both rural and urban populations, very little information is available so far on the edible mushroom species in Angola and their food and functional properties. However, although many African mushroom species are edible and have good nutritional properties, there is also a traditional belief that eating wild mushrooms can be dangerous and even deadly. Therefore, the correct identification of mushroom species and the research about their properties are important for the sustainable and safe use of this renewable natural resource. The present study represents the first assessment of wild edible mushrooms consumed and sold in local markets in Angola, providing a comprehensive profiling at the morphological, molecular, chemical, nutritional, and bioactive levels. Although species identification proves to be very difficult, our results brought useful insights that can assist future studies aiming to improve the mushroom taxonomic classification.

For the majority of the analyzed mushroom species, nutritional, chemical, antioxidant, and antimicrobial activities are reported for the first time, indicating that these are valuable sources of nutrients and bioactive compounds, with good in vitro performances. Given its rich composition in a wide range of compounds of interest, and the scarcity of studies focusing on these species, investigations must go further to explore them as nutraceuticals and in the development of new value-added food products. Additionally, the bioactive properties displayed by mushrooms must be fully understood and explored in the future, both through in vitro and in vivo studies.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: List of specimens and respective accession numbers for the DNA sequences used in this study [23, 73–78]. Figure S1: Principal Component

Analysis (PCA) plot obtained with the nutritional and functional chemistry variables from Tables 2–5. Samples are marked with different symbols according to phylogenetic groups (Figure 3), and the local common names are included.

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Data Availability Statement: The data used in the preparation of the article are presented in the published version and Supplementary Table S1. The DNA sequences are deposited in GenBank (accession numbers in Table S1).

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Supporting Information

Table S1. List of specimens and respective accession numbers for the DNA sequences used in this study.

Species	Voucher/isolate ID	Origin	ITS	LSU28S	rpb2	Reference
AMANITACEAE						
Amanita cf. princeps	BZ2013 102	Thailand	MF461588	--	MF440408	[73]
Amanita loosii	LAG0096	--	MW829789	MK908831	--	Direct Submission NCBI
Amanita zambiana	RET 343-10	Zambia	--	KF877312	KF877097	[74]
Amanita zambiana	RET 261-3	Burundi	--	KF877311	KF877096	[74]
Amanita zambiana	De Kesel 4378	Togo	--	KF877309	KF877095	[74]
Amanita loosei	M8	Angola	OP082440	OP082425	OP099864	This study
RUSSULA						
Russula acrifolia	RDL 16-031	Italy (Tuscany)	MW172313	MW182474	MW306679	[75]
Russula acrifolia	543/BB 08.662	--	--	KU237535	KU237821	Direct Submission NCBI
Russula aff. *cellulata*	VH 2016/8/BB 06.045	--	--	KU237454	KU237740	Direct Submission NCBI
Russula aff. *crustosa*	VH 2016/31/BB 06.616	--	--	KU237461	KU237747	Direct Submission NCBI
Russula aff. *mustelina*	r-05040	USA (California)	JF834362	JF834509	JF834459	Direct Submission NCBI
Russula amoenolens	HMAS 264497	China	KX441078	KX441325	KX442066	Direct Submission NCBI
Russula amoenolens	HMAS 252622	China	KX441035	KX441282	KX442023	Direct Submission NCBI
Russula amara	FH-12-213	--	KT933998	KT933859	KT933930	[76]
Russula aurea	101733	Estonia	--	KX812878	KX813659	Direct Submission NCBI
Russula azurea	537/08.668	--	JN944002	JN940591	--	Direct Submission NCBI
Russula blennia	PC0124723	--	MH545687	KU237556=NG_064398	KU237842	Direct Submission NCBI
Russula brevipes	HMAS 252596	China	KX441030	KX441277	KX442018	Direct Submission NCBI
Russula brevipes	HMAS 252611	China	KX441033	KX441280	KX442021	Direct Submission NCBI
Russula carneipes	HMAS 252682	China	KX441039	KX441286	KX442027	Direct Submission NCBI
Russula carneipes	HMAS 268187	China	KX441116	KX441363	KX442104	Direct Submission NCBI
Russula changbaiensis	HMAS 262355	China	KX441057	KX441304	KX442045	Direct Submission NCBI
Russula caerulea	106335	--	--	KX812895	KX813676	Direct Submission NCBI
Russula cf. *annulata*	VH 2016/75/BB 06.048	--	--	KU237470	KU237756	Direct Submission NCBI
Russula cf. *cyanoxantha*	BPL280	USA (Tennessee)	KT933976	KT933837	--	[76]
Russula cf. *sesenagula*	VH 2016/84/BB 06.129	--	--	KU237473	KU237759	Direct Submission NCBI
Russula cf. *vinosobrunea*	VH 2016/533/BB 07.231	--	--	KU237525	KU237811	Direct Submission NCBI
Russula claroflava	FH-12-212	Germany	KT933997	KT933858	KT933929	[76]
Russula compacta	BPL242	--	KT933960	KT933819	KT933890	[76]
Russula crustosa	BPL265	--	KT933966	KT933826	KT933898	[76]
Russula cuprea	FH12250	--	KT934010	KT933871	KT933942	[76]
Russula cyanoxantha	RITF4682	China	MW646981	MW646993	--	[77]
Russula cyanoxantha	fruit body179	China	MN704834	MN710574	--	Direct Submission NCBI
Russula decipiens	585/BB 07.178	--	--	KU237569	KU237855	Direct Submission NCBI
Russula decolorans	FH12196	--	KT933992	KT933853	KT933924	[76]

Russula delica	fruit body102	--	MN704836	MN710576	--	Direct Submission NCBI
Russula delica	UBC:F30263	--	KX812842	KX812864	--	Direct Submission NCBI
Russula edulis	strain 579/BB 08.167	--	--	KU237564	KU237850	Direct Submission NCBI
Russula emeticicolor	FH12253	--	KT934011	KT933872	KT933943	[76]
Russula exalbicans	HMAS 268774	China (Sichuan)	MG493205	MG493219	MG495110	[23]
Russula exalbicans	HMAS 269713	China (Sichuan)	KX441161	KX441408	KX442149	Direct Submission NCBI
Russula flavisiccans	strain 236/BB 06.336	--	--	KU237485	KU237771	Direct Submission NCBI
Russula fellea	FH12-185	Germany	KT933989	KT933850	KT933921	[76]
Russula foetens	HMAS 271173	China	KX441223	KX441470	KX442211	Direct Submission NCBI
Russula foetens	HMAS 271230	China	KX441229	KX441476	KX442217	Direct Submission NCBI
Russula fontqueri	HMAS 267744	China	KX441096	KX441343	KX442084	Direct Submission NCBI
Russula glutinosa	WRWV 04-1154	USA (west Virginia)	MN315540	MN315511	MN326798	[78]
Russula glutinosa	B.Buyck 04-292	USA (North Carolina)	MN315543	MN315512	MN326795	[78]
Russula granulata	BPL272	USA (Tennessee)	KT933971	KT933832	KT933903	[76]
Russula globispora	HMAS 269239	China	KX441136	KX441383	KX442124	Direct Submission NCBI
Russula gracillima	FH12-264	Germany	KR364094	KR364226	KR364342	[76]
Russula gracillima	HMAS 262340	China	MG493206	MG493221	MG495112	[23]
Russula heterophylla	UE20.08.2004-2	Sweden	DQ422006	--	DQ421951	Direct Submission NCBI
Russula intermedia	CLC 3822	USA (Alaska)	MT583250	--	MT500711	Direct Submission NCBI
Russula intermedia	101842	Estonia	--	KX812888	KX813669	Direct Submission NCBI
Russula insignis	HMAS 267740	China	KX441094	KX441341	KX442082	Direct Submission NCBI
Russula insignis	HMAS 267751	China	KX441099	KX441346	KX442087	Direct Submission NCBI
Russula integra	FH12172	Germany	KT933984	KT933845	KT933916	[76]
Russula integriformis	HMAS 262393	China	KX441065	KX441312	KX442053	Direct Submission NCBI
Russula integriformis	HMAS 262403	China	KX441066	KX441313	KX442054	Direct Submission NCBI
Russula katarinae	HMAS 269080	China	KX441133	KX441380	KX442121	Direct Submission NCBI
Russula katarinae	HMAS 269755	China	KX441163	KX441410	KX442151	Direct Submission NCBI
Russula langei	450/BB 07.792	--	--	KU237510	KU237796	Direct Submission NCBI
Russula lepida	HJB9990	--	DQ422013	--	DQ421954	Direct Submission NCBI
Russula luteotacta	FH12187	--	KT933991	KT933852	KT933923	[76]
Russula maculata	HJB10019	Belgium	DQ422015	--	DQ421956	Direct Submission NCBI
Russula madagassensis	strain 21/BB 06.146	--	--	KU237456	KU237742	Direct Submission NCBI
Russula madagassensis	strain 93/BB 06.255	--	--	KU237475	KU237761	Direct Submission NCBI
Russula medullata	SAV F-1596	Slovakia	MT738281	MT738257	--	Direct Submission NCBI
Russula mustelina	FH12226	--	KT934005	KT933866	KT933937	[76]
Russula murrillii	HMAS 271049	China	KX441191	KX441438	KX442179	Direct Submission NCBI
Russula murrillii	HMAS 271144	China	KX441213	KX441460	KX442201	Direct Submission NCBI
Russula nigricans	UPS UE20.09.2004–07	--	DQ422010	DQ422010	DQ421952	Direct Submission NCBI
Russula nympharum	STU (HJB 10019)	--	--	MG944282	MG944258	Direct Submission NCBI
Russula nympharum	SAV F-4887	--	MG948640	--	MG944260	Direct Submission NCBI

Russula olivacea	426/BB 07.223	--	--	KU237492	KU237778	Direct Submission NCBI
Russula ochroleuca	FH12-211	--	KT933996	KT933857	KT933928	[76]
Russula prolifica	18/BB 06.161	--	--	KU237455	KU237741	Direct Submission NCBI
Russula pseudociliata	VH 2016m/545/BB08.061	--	MH545688	KU237537	KU237823	Direct Submission NCBI
Russula pseudograta	HMAS 250432	China	KX441012	KX441259	KX442000	Direct Submission NCBI
Russula pseudograta	HMAS 253194	China	KX441049	KX441296	KX442037	Direct Submission NCBI
Russula pseudopectinatoides	HMAS 251523	China	KX441016	KX441263	KX442004	Direct Submission NCBI
Russula pseudopectinatoides	HMAS 265020	China	KX441089	KX441336	KX442077	Direct Submission NCBI
Russula pseudopersicina	HMAS 264484	China	KX441077	KX441324	KX442065	Direct Submission NCBI
Russula pseudopersicina	HMAS 267779	China	KX441105	KX441352	KX442093	Direct Submission NCBI
Russula queleti	HMAS 271076	China	MG493211	MG493226	MG495117	[23]
Russula queleti	HMAS 271149	China	KX441215	KX441462	KX442203	Direct Submission NCBI
Russula redolens	BPL141	--	KT933950	KT933808	KT933879	[76]
Russula romellii	FH12177	--	KT933987	KT933848	KT933919	[76]
Russula rugulosa	BPL654	--	KY509494	--	KY701373	[76]
Russula rosea	HMAS 276801	China	LT602969	LT602946	KX442557	Direct Submission NCBI
Russula sinica	HMAS 271022	China	KX441186	KX441433	KX442174	Direct Submission NCBI
Russula sinica	HMAS 271024	--	KX441187	KX441434	KX442175	Direct Submission NCBI
Russula cf. *sejuncta*	VH 2016/557/BB 08.143	--	--	KU237547	KU237833	Direct Submission NCBI
Russula turci	HMAS 271703	China	KX441237	KX441484	KX442225	Direct Submission NCBI
Russula turci	HMAS 271794	China	KX441246	KX441493	KX442234	Direct Submission NCBI
Russula variata	BPL241	--	KT933959	KT933818	KT933889	[76]
Russula vesca	BPL284	--	KT933978	KT933839	KT933910	[76]
Russula virescens	HJB9989	Belgium	DQ422014	--	DQ421955	Direct Submission NCBI
Russula zvarae	FH12-175	Germany	KT933986	KT933847	KT933918	[76]
Russula aff. *cellulata*	M1	Angola	OP082434	OP082418	OP099858	This study
Russula sp. 1	M2	Angola	--	OP082419	OP099859	This study
Russula sp. 2	M3	Angola	OP082435	OP082420	OP099860	This study
Russula sp. 3	M4	Angola	OP082436	OP082421	--	This study
Russula sp. 3	M5	Angola	OP082437	OP082422	OP099861	This study
Russula sp. 3	M6	Angola	OP082438	OP082423	OP099862	This study
Russula sp. 3	M7	Angola	OP082439	OP082424	OP099863	This study

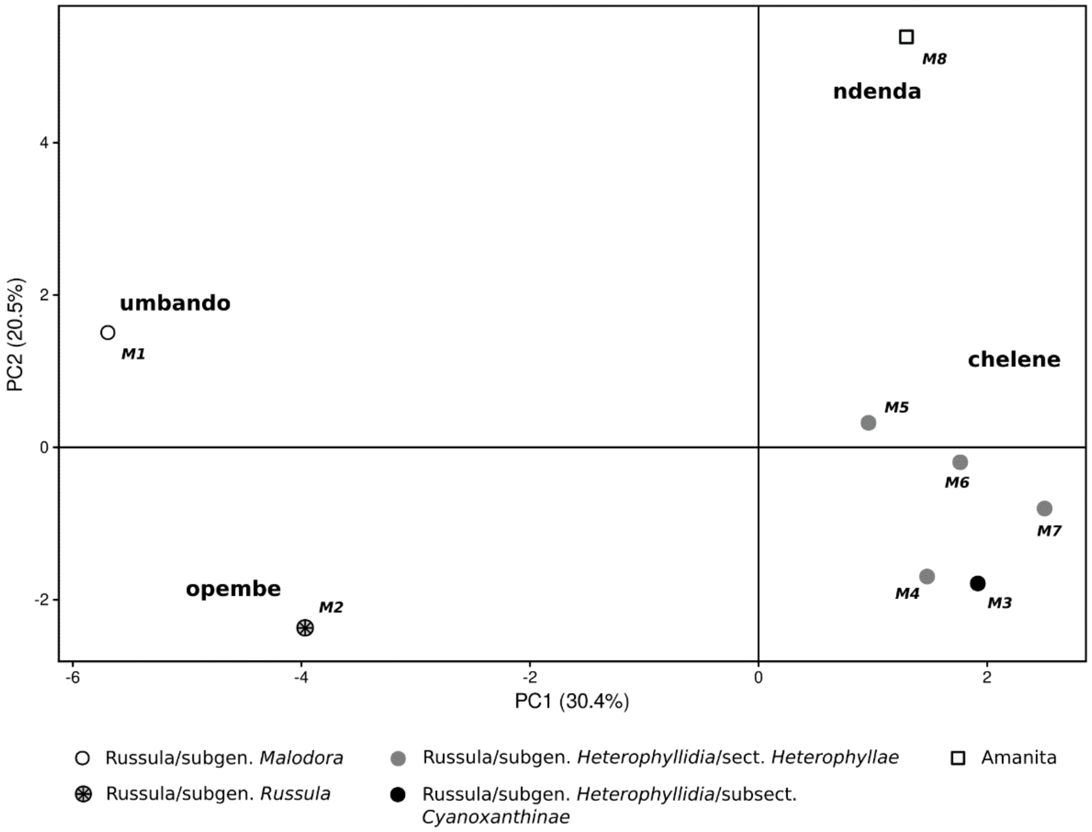

Figure S1. Principal Component Analysis (PCA) plot obtained with the nutritional and functional chemistry variables from Tables 3 to 5. Samples are marked with different symbols according to phylogenetic groups (Figure 3), and the local common names are included.

CAPÍTULO 6

Discussão Geral

1. Alterações do Uso do Solo na Região Sudoeste de Angola

Miombo e Mopane são formações florestais que ocupam grande parte da região zambezíaca de Angola, sobretudo onde predominam as areias de Kalahari. O Miombo e o Mopane proporcionam às populações rurais importantes bens e serviços dos ecossistemas, nomeadamente a utlilização para agricultura, madeira, carvão e lenha, produtos medicinais e alimentares que em parte são transacionados para os centros urbanos do país. O Miombo e Mopane, referidos no presente estudo cobrem uma área 15,060.92 km^2 do sudoeste de Angola, entre 300 e 2200 metros de altitude. Trata-se de uma zona de intensa actividade humana onde vivem mais de um milhão de habitantes de vários grupos etnolinguísticos, nomeadamente Umbundo, Lunyaneca-umbi, Mucubal, Koisan, que utilizam os recursos florestais para satisfação de grande parte das suas necessidades básicas.

Os mapas temáticos produzidos, a partir da classificação das imagens de satélite Landsat durante o período de 1990 a 2019, demostraram que ocorreu reflorestação no sentido agricultura-savana-floresta durante a guerra civil, entre os anos 1990 e 2000 e, no sentido inverso, ocorreu desflorestação entre os anos 2000 e 2019, tanto na área total de estudo como ao redor das estradas (Capítulo 2; Figura 2-4; Tabela 1). A área urbana cresceu cinco vezes mais em 2019 do que em 1990 (Capítulo 2; Tabela S2). Diversos autores apresentaram resultados similares noutras regiões de Angola (Cabral et al., 2010; Schneibel et al., 2016, Schneibel et al., 2017; Chisingui, 2017; Temudo et al., 2020). Assim, Lubango foi o município que mais cresceu em termos populacinais e em que diminuiu a área agrícola. Cacula foi o município que obteve maior taxa de desflorestação, perdendo mais área de floresta para savana e de savana para agricultura. O município da Bibala foi o que perdeu mais floresta junto às estradas, tendo assim uma taxa desflorestação maior nestas zonas. Os factores socioecómicos que provavelmente mais influenciaram na desflorestação e degradação florestal foram, nomeadamente, o êxodo rural, a expansão urbana, a expansão agrícola, assim como o aumento da exploração de madeira e da produção do carvão vegetal.

Na verdade, grande parte da conversão de floresta em savana na área de estudo resulta do abate selectivo de árvores para produção de madeira, lenha e carvão, bem como da extracção de inertes e utilização para pastagem de gado (Capítulo 2; Área 3 na Figura 5B). Os mapas temáticos também demostraram que há uma maior desflorestação ao redor das estradas e das cidades (Capítulo 2; Figura 5A), o que era espectável, uma vez que se trata de uma zona de maior acesso às infraestruturas de comunicação que facilitam o fluxo de produtos agrícolas e florestais. Isto também pode ser explicado pelo regresso de muitos refugiados às zonas rurais e às actividades agrícolas e extractivas tradicionais, em combinação com os novos programas de desenvolvimento do governo local, após o fim da guerra civil em 2002.

As novas áreas florestais e de savanas provavelmente seriam parcelas de floresta que recuperaram na primeira década estudada e que não foram mais exploradas desde então. Além disso, como a actividade de exploração florestal é fiscalizada e monitorada pelas entidades competentes, existe o deslocamento da exploração dos produtos florestais, sobretudo da produção de carvão vegetal para áreas mais distantes das estradas, o que explica a menor desflorestação perto das estradas em alguns lugares. Outro motivo é a delimitação de terras para criação de reservas estatais ou latifúndios ao abrigo da lei de terras (República de Angola, 2004; Foley, 2007; Unruh, 2012), uma vez que houve o abandono de terras pelo proprietário. Medidas de conservação e utilização sustentável dos recursos florestais devem ser implementadas, nomeadamente programas comunitários que oferecem pagamentos para compensar as actividades de conservação, o aumento da promoção do uso de gás para cozinhar, a produção sustentável de carvão vegetal a partir de plantações florestais, bem como o aumento da valorização dos produtos florestais não-madeireiros.

Considerando todo o período estudado (1990-2019), as taxas de desflorestação na área de estudo (2,18% ano^{-1}) e em cada município (1,50% ano^{-1} para Bibala, 4,33% ano^{-1} para Cacula, e 1,58% ano^{-1} para Lubango) foram discrepantes dos valores publicados pela FAO (2021) para Angola (0.58% entre 1990-2020). Estas diferenças podem ser atribuídas ao facto de a FAO calcular os valores ao nível nacional, enquanto os nossos valores reportam-se ao nível regional. McNicol et al. (2018) também obteve uma taxa anual de desflorestação de -2,8% para a África Austral entre 2007 e 2010, valor 7,8 a 9,4 vezes superior aos resultados apresentados pela FAO (2015), 0.2% entre 1990-2015 para Angola e Hansen et al. (2013), 0.4% entre 2000-2005 para a África. Entretanto, segundo Ramankutty et al. (2007), diferentes fontes de dados e metodologias podem também contribuir para as diferenças nas estimativas.

2. Impactos da Produção de Carvão na Região Sudoeste de Angola

A exploração do carvão é uma prática comum em Angola, sobretudo na região zambezíaca. Na época colonial já havia uma produção de carvão significativa. Por exemplo, nas províncias da Huíla e do Cunene, o carvão chegou a representar 63% em 1964 e 86% em 1965 da madeira explorada de Angola (Baptista & De Cauwer, 2014). A produção continua a aumentar e, segundo a FAOSTAT (2023), o consumo de carvão tem crescido significativamente nas últimas décadas. Os dados publicados apontam para um aumento de cinco vezes entre 1976 e 2021 (82,129 para 417,563 toneladas, respectivamente).

Actualmente o Lubango é a cidade da região sudoeste que consome a maioria do carvão produzida nos municípios vizinhos. O carvão recebe o nome correspondente ao nome local da espécie. O carvão mais vendido na zona de Miombo é o da espécie *Brachystegia spiciformis* “carvão mupanda” e de *Julbernardia paniculata* “carvão mumwe”, enquanto no Mopane o carvão mais comum é de *Colophospermum mopane* “carvão mutiati” e o de *Spirostachys africana* “carvão mupapa”.

Muitas famílias rurais e urbanas vêem a produção e venda de carvão como uma fonte de renda para suprir as necessidades básicas e diminuir a pobreza. O carvão é produzido nas zonas rurais e vendido nos centros urbanos e vias de acesso, transportado por camiões, carros ligeiros, triciclos, burros e comboio. Bibala e Cacula são os municípios que mais abasteceram os mercados do município do Lubango. O carvão produzido no município da Bibala, para além de abastecer a cidade do Lubango, abastece também a cidade capital do Namibe, Moçâmedes. Mais de 9.6 tons são vendidos diariamente e cerca de 2879 tons são vendidas anualmente, nos mercados informais do Lubango, nomeadamente no mercado do Mutundo, Hoque e Rio Nangombe.

Vários tipos de fornos tradicionais de carbonificação são usados no sudoeste de Angola, porém, os fornos de terra escavados e superficiais são os mais comuns. Os fornos superficiais são os que apresentam maior eficiência. Tendo em conta a eficiência dos fornos e a estimativa da quantidade de carvão consumida no Lubango, cerca de 22,109 tons de madeira são convertidos em carvão anualmente. Uma família produtora de carvão pode derrubar entre 17 a 26 hectares de floresta por ano, sendo que um forno pode implicar o derrube de 1 ha. No entanto, existem algumas limitações nos resultados, o que pode levar a valores subestimados, nomeadamente: i) não foram visitados dois mercados no Lubango; ii) existem muitos pontos de venda na beira das estradas sem controlo; iii) o tempo de pousio é em geral relativamente curto, resultando na utilização de espécies de menor qualidade para carbonização e, iv) a produção de carvão é uma actividade monitorada pelas autoridades locais, daí grandes quantidades a serem vendidas clandestinamente.

Além do impacto socioeconómico no seio das famílias mais carenciadas, a produção de carvão no sodoente de Angola, tem impactos na estrutura e composição da vegetação de Miombo e de Mopane a curto, médio e ao longo prazo. Uma vez que a intensidade desta actividade pode comprometer a regeneração e produtividade das espécies, avaliar a dinâmica de recuperação das florestas após o uso selectivo de espécies arbóreas em intervalos de 10 anos, permitiu compreender a capacidade de resiliência das espécies florestais face à perturbação.

Durante o levantamento de campo das espécies nos pousios, um total de 55 especies foram identificadas, 32 no Miombo (19 árvores adultas e 30 árvores jovens) e 31 no Mopane (19 árvores adultas e 29 árvores jovens). Nove espécies foram encontradas nos dois tipos de vegetação. A família mais representativa foi Fabaceae com 17 espécies, seguindo a Combretaceae com 7 espécies, Rubiaceae com 5 espécies e a Euphorbiaceae com 3 espécies, as outras famílias foram representadas apenas como uma única espécie. Uma dominância forte das espécies *B. spiciformis* e *J. paniculata* no miombo, *C. mopane* e *S. africana* e de *A. senegal* no mopane em quase todos os pousios. *J. paniculata* e *B. spiciformis*, revelaram-se como espécies indicadoras da vegetação tardia, resultados similares aos obtido por Gonçalves et al. (2017), uma vez que são consideradas de espécies tolerante ou semi-tolerante à sombra e semi-resistente ao fogo (Frost, 1996, Backéus et al., 2006; Timberlake, et al., 2010), enquanto as espécies *S. africana*, *C. mopane*, *A. senegal* revelaram-se como espécies indicadoras nos pousios recentes e com grandes pertubações, uma vez que são consideradas espécies heliófilas e resistente ao fogo e à herbivoria (Hines & Eckman, 1993; Eyog Matig et al., 2000; Helm et al., 2011; Abebe, 2018).

O modelo NMDS (*Non-metric Multidimensional Scaling*), demostrou que a partir de 10 a 20 anos os pousios de Miombo podem estar mais próximos dos pousios antigos, enquanto que os de Mopane levam mais tempo (Capítulo 3, Figura 2). Mesmo assim, a composição específica parece não se alterar como se altera a estutura da floresta. Por exemplo, o DAP, a área basal, a biomassa ou o biovolume são cada vez maiores à medida que aumenta a idade dos pousios (Capítulo 3, Suplemento1). As variáveis ambientais (e.g. declive, altitude) não apresentaram quaisquer diferenças significativas entre os pousios tanto no Miombo quanto no Mopane. Porém, quando combinadas com outras variáveis e analisadas no NMDS a correlação é significativa, é o caso da distância dos pousios à estrada no Miombo (r2=0.52) e da altitude no Mopane (r2=0.52), a distância à estrada já parece ser muito importante para as comunidades do Miombo, indicando que a produção do carvão é cada vez mais distante das aldeias e longe da fiscalização.

O presente estudo procurou amostrar pousios resultantes apenas da exploração do carvão vegetal, com resultados importantes em relação à evolução das florestas do Miombo e do Mopane após o corte selectivo das espécies lenhosas. Entretanto, se for praticada com intensidade moderada, a produção de carvão vegetal pode não ter um impacto drástico na desflorestação e na degradação florestal em comparação com outras actividades humanas, nomedamente o aumento da produção agrícola, da exploração de minas e da expanção urbana. O abate das árvores para produção de carvão em geral não implica a respetiva morte, pois sendo espécies que rebentam por toiça, após o corte rebrotam rapidamente. Infelizmente, as altas temperaturas, a baixa pluviosidade e a pobreza do solo características da região de Mopane podem não ajudar na rápida recuperação da vegetação após o corte (White, 1983).

O abate indiscriminado das árvores expõe os estratos inferiores à acção das queimadas e das chuvas intensas, provocando a aceleração da erosão e a lixiviação do solo tornando a desflorestação como um fenómeno irreversível (Baptista, 2014). Pensa-se que estudos detalhados sobre a regeneração das principais espécies utilizadas para a produção do carvão em vários locais de Angola são uma mais valia e podem auxiliar na implementação de medidas e práticas de boa gestão das espécies florestais. Mesmo assim, as taxas de regeneração da produção de madeira nas florestas secas requerem longos ciclos de corte para a maturação, o que restringe a produção sustentável de carvão vegetal (Chidomayo, 2019). A substituição do carvão vegetal por outras fontes de energia e uma maior diversificação das fontes de rendimento das populações rurais, nomeadamente com a valorização de produtos florestais não lenhosos como cogumelos, frutos e folhas silvestres comestíveis, apicultura, etc., pode ser uma alternativa para a gestão sustentável da recursos florestais.

3. Valorização e Impactos da Utilização dos Produtos Florestais não Lenhosos Alimentares na Província da Huíla

Os produtos florestais não lenhosos alimentares são muito valorizados mundialmente, devido à sua importância na diversificação da dieta alimentar, na saúde alternativa e no bem-estar das pessoas. Em Angola, em particular na região sudoeste, existe uma grande disversidade de produtos florestais não lenhosos alimentares comercializados em mercados e ao longo das estradas. Grande parte dos produtos são silvestres, extraídos na vegetação envolvente, colhidos pelas comunidades rurais e vendidos à população urbana. A maioria representam partes de organismos vegetais (raízes, caules, cascas, frutos, flores e sementes, resinas, óleos, fibras, etc) de espécies herbáceas (Kissanga, et al., 2021) e arbóreas (Tchamba & Camongua, 2019), assim como cogumelos (Kissanga et al., 2022, Bastos et al., 2023). Os produtos não lenhosos alimentares mais comercializados na área de estudo foram os cogumelos, folhas, frutos, raízes e sementes. Os produtos são vendidos principalmente em fresco e em menor escala secos.

Frutos

A colheita de frutos silvestres é feita sazonalmente, e praticada quase exclusivamente pelas crianças das comunidades rurais. Existem cerca de doze espécies arbóreas e arbustivas cujos frutos são comercializados nos mercados, nomeadamente *Adansonia digitata*, *Anisophyllea boehmii*, *Carissa spinarum*, *Capsicum annuum* var. *glabriusculum*, *Englerophytum magalismontanum*, *Grewia avellana*, *G. flavescens*, *Landolphia parvifolia*, *Parinari curatellifolia*, *Strychnos cocculoides* e *Sclerocarya birrea*, assim como as raízes de *Eriosema* spp. Com execpção dos frutos de *Capsicum annuum* var. *glabriusculum* e das raízes de *Eriosema* spp. os outros frutos são comidos frescos como fruta. Algumas dessas espécies podem ter múltiplas utilidades, ou seja, além de fornecerem alimentos, são usadas com fins medicinais, cosméticos, como pastagem e como produtos de madeira para construção, carvão, lenha e matéria-prima industrial, como reportaram Urso et al. (2013); Bruschi, et al. (2016); Urso et al. (2016); Gonçalves et al. (2019) e Tchamba & Camongua (2019).

Dependendo da espécie, os frutos podem ser carnudos, secos, drupas e aquênios e a sua utilização é variável, desde a polpa até a casca. Com excepção dos frutos de *Capsicum annuum* var. *glabriusculum*, que são utilizados como condimento picante, as raizes das espécies de *Eriosema* e os restantes frutos são aproveitados para o fabrico de bebidas alcoólicas. Além disso, utilizam-se as sementes de outras espécies, nomeadamente Adansonia *digitata* e *Sclerocarya birrea*, para extração de óleos alimentares. Contudo, a conservação e a técnica de armazenamento são um assunto em discussão, visto que há ausência de meios e equipamentos para a conservação. Mais, a falta de acesso a electricidade em muitas zonas rurais e periurbanas colocam em causa a qualidade dos produtos, quer para armazenanto no local de venda, quer para o seu transporte. Futuros estudos podem ser realizados no sentido de se aperfeiçoar os métodos de conservação dos produtos alimentares perecíveis com vista a uma melhor segurança alimentar.

Folhas

No sul e centro de Angola, vegetais cozinhados como esparregado são denominados *lombi*, e a sua maioria são cultivadas, nomeadamente couves, folhas de batata-doce, folhas de abóbora e de *Amaranthus caudatus*. No presente trabalho, foi estudado o *lombi* que consiste numa mistura de espécies herbáceas, transacionada habitualmente nos mercados do Lubango, composta nomeadamente de *Bidens pilosa*, *Amaranthus hybridus* e *Galinsoga parvifolia*. Embora sejam espécies distribuídas mundialmente, consideradas invasoras, não são cultivadas localmente e são consumidas como forma de reaproveitamento dos terrenos em pousios e lugares marginais. Estas espécies, ruderais e de fácil crescimento são vendidas nos mercados informais ao longo do ano, a cerca de 50kz/kg e, devido à grande quantidade de água e à falta de meios de conservação das folhas são colhidas diariamente. Importantes resultados obtidos revelaram que a mistura de *lombi* contém uma quantidade significativa de proteína (20–28 g/100 g, base seca), altos valores de macronutrientes e micronutrientes, bem como de compostos fenólicos (10–40mg GAE/g) e têm boa capacidade antioxidante.

Cogumelos

Os cogumelos representam em Angola uma importante classe de produtos florestais não lenhosos alimentares muito importantes para as populações locais. O reconhecimento das espécies comestíveis, o modo de colheita, processamento e venda são uma prática tradicional relevante que garante uma adequada disponibilidade destes produtos florestais não lenhosos. As comunidades rurais são as que detêm o correcto conhecimento tradicional dos cogumelos comestíveis, apesar de ainda permanecem muitas lacunas para análises científicas relacionadas a morfologia, propriedades alimentares, genética e bioquímica. Diante desse paradigma, o presente estudo apresentou pela primeira vez uma combinação de análises socioconómicas, morfológicas e de perfis nutricionais, bioactivos e moleculares de exemplares de cogumelos comercializados nos mercados locais da Huíla com vista a uma melhor caracterização das propriedades das espécies comercializadas após secagem. Foram identificados 35 vendedores de cogumelos nos quatro mercados e recolhidas oito amostras de cogumelos. Cerca de 31.5 kg de cogumelos secos são vendidos diariamente correspondendo a 11.3 tons por ano. Cada vendedor pode ganhar AKZ 900 por dia (c. USD 1.8) e contribuir com uma renda de AKZ 21,600 por mês (USD~43.2).

Dos oito morfotipos de cogumelos estudados, cinco foram identificados com base em abordagens fenotípicas e moleculares (quatro *Russula* spp. e uma *Amanita loosei*). Outras espécies do género *Amannita, Cantharellus, Lactarius* e *Termitomyces* também foram identificados morfologicamente a partir de amostras frescas. Dos quatro morfotipos do género *Russula*, é possével que pelo menos dois possam ser novidade para a ciência. O primeiro caso trata-se dos morfotipos M4, M5, M6 e M7, que apresentaram o mesmo perfil molecular, supostamente correswpondendo a uma espécie do sector Heterophyllae afim de *R. madagassensis* (*R.* aff. *madagassensis*) e o morfotipo M3 (*Russula* spp.3) classificada como *Russula* do sector Cyanoxantinae sem nenhuma espécie similar apesar de estar proxima da *R. cyanoxantha*. Outro importante dado obtido está reclacionado com a classificação que se obteve do morfotipo M2, uma vez que foi 100% similar a duas amostras de *R. rosea* (= *R. lepida)* e *R. falvisiccans* Billis classificadas como duas espécies diferentes; por esse facto recomenda-se em futuros estudos a revisão taxonómica das duas espécies.

Os cogumelos demonstraram ser uma fonte rica de carboidratos, proteínas, saisd minerais e baixas quantidades de gordura. Em relação a propriedades funcionais possuem em geral boa atividade antioxidante, antibacteriana e antifúngica.

O conhecimento tradicional sobre a utilização dos recursos naturais deve ser valorizado, mas até ao momento ainda é transmitido por via oral. Um dado interessante, foi o facto da análise multivariada das caracterististcas funcionais e nutricionais dos morfotipos de cogumelos, separar os cogumelos do género *Russula* (cujo nome tradicional é *chelene*) dos outros cogumelos (*opembe*), e de *amanita* (*ndenda*).

O presente estudo pode ser usado como exemplo em novas pesquisas sobre as propriedades alimentares das plantas e cogumelos silvestres, com vista à caracterização de novas espécies alimentares, contribuindo para uma alimentação de qualidade e mais segura, por parte das populações.

4. Uso dos recursos naturais em Angola: tendências recentes e perspectivas futuras

Angola tem um rico património natural, com uma grande variedade de ecossistemas desde a floresta sempre densa ao deserto, com uma grande extensão de floresta de Miombo, em que muito ainda para se conhecer. Após a guerra civil houve uma grande pressão sobre os ecossistemas, no sentido da sobreexploração dos recursos naturais, particularmente nos ecossistemas florestais. A falta de sistematização do conhecimento pode permitir que grande número de espécies nativas estejam em grau de ameaça grave, apesar de que se trata de um território subpovoado e o impacto das práticas de colheitas ser variado. A guerra arrastou o país para uma crise humanitária e económica, que em larga medida ainda persiste actualmente. A má distribuição dos rendimentos e a falta de emprego no período pós-guerra, levou muitos cidadãos a optarem pela utilização dos recursos florestais lenhosos como fonte de subsistência e de renda.

O presente estudo vem mostrar que a utilização dos produtos florestais lenhosos, em particular o carvão, tem um impacte ecológico significativo nos ecossistemas florestais, uma vez que o processo que envolve a produção e a venda de carvão não é sustentável com a intensidade atual. Enquanto isso, os produtos florestais não lenhosos alimentares, como os apresentados no presente estudo estão subaproveitados, embora a sua exploração tenha menor impacto e seja mais sustentável em relação aos produtos florestais lenhosos, que implicam o abate das árvores. Por exemplo um forno de carvão pode degradar um hectare de floresta e afetar drasticamente a biodiversidade do solo, enquanto a colheita dos vegetais folhosos é feita durante a limpeza dos campos agrícolas após a rotação das culturas, aumentando o controlo das espécies ruderais. Quanto aos cogumelos silvestres comestíveis, são colhidos tanto nas lavras como nas florestas e a sua utilização não parece ter impacto significativo nos ecossistemas florestais. Os cogumelos são vendidos frescos e também secos e conservados para estarem disponíveis no período sem chuvas. Além disso, o consumo dos *lombi* e dos cogumelos proporcionam às populações locais uma fonte de alimento acessível e gera rendimento para coletores e vendedores

Neste contexto, no sentido de compatibilizar a utilização dos recursos florestais pelas comunidades rurais com a conservação da biodiversidade e dos ecossistemas em Angola, será importante promover a utilização sustentada e valorização económica dos produtos florestais não lenhosos e a limitação do uso de produtos florestais lenhosos.

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