Effect of shifting cultivation and charcoal production on structure, dynamic and above-ground biomass in the Angolan miombo and dry woodlands

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"In a moment the ashes are made, but a forest is a long time growing"

Lucius Annaeus Seneca (4 a.C.)

For consistency throughout the thesis, the figures, tables and appendices of all the manuscripts comprised in this thesis were renumbered and the references were summarised at the end in alphabetical order. Papers 1, 3, 4, and 5 were published Open access, paper 2 was reprinted with kind permission of Northeast University and Springer-Verlag GmbH Berlin, as part of Springer Nature, while paper 6 was reprinted with permission of the book editors.

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Resumo

As florestas de Miombo constituem um dos mais extensos ecossistemas em África. Cobrindo grande parte do território de Angola, estendendo-se para a República Democrática do Congo, Zâmbia, Zimbabwe, Malawi, Moçambique e Tanzânia. Caracteristicamente, são dominadas por espécies lenhosas dos géneros *Brachystegia*, *Julbernardia* e *Isoberlinia* pertencentes à família Fabaceae, subfamília Detarioideae. O Rio Cubango/Okavango tem a sua nascente no planalto central Angolano, onde o Miombo cobre extensas áreas ao longo do rio, descendo para sudoeste na província do Cuando Cubango, onde as formações de miombo vão gradualmente dando lugar às fllorestas secas de *Baikiaea plurijuga* e *Schinziophyton rautanenii*. Daqui o rio Cubango segue o seu curso normal em direcção à Namíbia e, finalmente, desaparece no Deserto do Kalahari no Botswana, formando uma extensa zona húmida, o Delta do Okavango. Esta extensa área de florestas ao longo da bacia do Cubango é vital para a manutenção da biodiversidade e dos múltiplos serviços ecológicos a esta associada. Contudo, a área tem sido sujeita a profundas e rápidas transformações, principalmente devido ao crescimento da população humana ao longo do rio, o que coincide com um aumento no uso da terra e com a sobre-exploração dos recursos naturais da região. Estes desenvolvimentos sugerem a necessidade de estudos mais profundos destes ecossistemas, para identificar as principais ameaças à biodiversidade da região e, ao mesmo tempo, proporcionar aos países que partilham a bacia, suporte técnico e científico para a utilização sustentável dos seus recursos naturais em benefício das suas populações (**Capítulo 1**).

Neste contexto, a presente tese teve como objectivos: (a) avaliar o efeito da agricultura itinerante na estrutura e dinâmica da vegetação lenhosa no miombo e nas formações secas de *Baikiaea* numa cronosequência de abandono, caracterizada por diferentes idades de pousios; (b) caracterizar a produção de carvão na região e avaliar a subsistência das famílias e rendimentos derivados da actividade; (c) documentar a diversidade florística da região, com ênfase para a ocorrência de espécies de plantas endémicas, potenciais espécies novas para a ciência e/ou registos novos de distribuição geográfica. Estes objectivos encontram-se detalhados em quatro artigos científicos que compreendem a presente tese. O primeiro artigo apresenta os resultados da dinâmica das espécies lenhosas do miombo após perturbação devido à agricultura itinerante, numa cronosequência caracterizada por diferentes idades de pousio, ao mesmo tempo que são discutidas as variações na composição das espécies nos estágios iniciais da sucessão e

comparadas às formações de miombo mais intactas (**Capítulo 2**). Abordagem similar foi aplicada às formações secas características da região de Caiundo na província do Cuando Cubango, embora não tenha sido possível estabelecer uma cronosequência de diferentes idades de pousios como no caso do miombo, uma vez que os campos agrícolas da região são geralmente utilizados por períodos de tempo relativamente longos. Entretanto, foi possível analisar as variações na composição e diversidade de espécies nas antigas várzeas, previamente identificadas como tendo sido utilizadas para agricultura, e comparadas com áreas de vegetação intacta, que não tenham sido sujeitas a qualquer tipo de perturbação de origem antropogénica. Este capítulo também se discute os principais aspectos que governam a dinâmica da regeneração das principais espécies lenhosas, que estão também sujeitas a exploração de madeira, com particular ênfase à frequência e sazonalidade das queimadas (**Capítulo 3**).

A análise e caracterização da produção de carvão, assim como a sua contribuição na geração de receitas das famílias envolvidas na actividade, foi outro aspecto importante abordado nesta tese. Devido ao aumento da produção de carvão na região e às ameaças que a actividade coloca para a preservação deste ecossistema, devem ser estudadas fontes alternativas de rendimento para reduzir a crescente procura dos recursos lenhosos da região. Ao mesmo tempo, isto poderá contribuir para a geração de rendimento das famílias envolvidas na produção de carvão, no contexto da iniciativa das Nações Unidas para a redução das emissões devidas à desflorestação e degradação das florestas nos países em desenvolvimento (REDD$^+$). Foi ainda possível caracterizar a biomassa lenhosa e área basal nas áreas previamente expostas à produção de carvão, em comparação com as florestas de miombo maduro (**Capítulo 4**).

Angola alberga uma variedade de habitats, incluíndo o miombo que cobre cerca de 47% da superfície do país. A diversidade de espécies lenhosas e a composição destas formações de miombo são pobremente conhecidas, uma vez que a maior parte dos estudos passados conduzidos no país, basearam-se em levantamentos básicos, objectivando a inventariação da diversidade florística do país, existem poucos levantamentos florísticos mediante os estabelecimento de parcelas. A província da Huíla é talvez uma das mais estudadas do ponto de vista botânico, existindo ainda enormes lacunas em termos de caracterização das comunidades vegetais da região, da composição de espécies, bem como da associação das espécies dentro da comunidade. O estudo levado a cabo na região apartir de 456 parcelas de 1000 m^2 resultou em treze principais comunidades vegetais. O miombo foi entre outras, a comunidade mais diversa da região, outras comunidades não menos importantes incluem as formações de

Mopane (*Colophopermum mopane*) e de *Baikiaea-Baphia-Terminalia*. Este estudo contribuirá para a elaboração do primeiro mapa de vegetação da Província da Huíla (**Chapter 5**). Alguns resultados relevantes são apresentados relativamente à diversidade florística da região, salientando-se uma espécie cuja ocorrência não tinha sido registada no país (**Capítulo 6**). As evidências botânicas das plantas colhidas neste trabalho levaram à descoberta de novas localidades com ocorrência de espécies de plantas endémicas.

A rica diversidade florística do país desde cedo despertou o interesse de botânicos de todo o mundo, e remota muito provavelmente dos meados do século dezasseis. Desde então muitas expedições botânicas foram conduzidas no país, a mais importante conduzida pelas autoridades portuguesas data de 1783-1804 conduzida por Joaquim José da Silva, cujo material colhido resultou na descrição da primera planta Angolana conhecida na literatura científica. Muitos outros estudos foram dirigidos nas áreas de particular interesse, tais como nas áreas destacadas na proposta da estratégia expansão de áreas protegidas, enquanto enormes lacunas ainda existem nalgumas áreas remotas do país. Outras iniciativas que visam documentar a diversidade de plantas do país deorreram no quadro de algumas iniciativas regionais, como é o caso do SAREP, OKACOM e mais recentemente o Projecto Futuro Okavango (TFO), esta última contribuiu grandemente para uma melhor compreenção da ecologia do miombo angolano, assim como das formações secas de *Baikiaea* no sudoestes de Angola, principalmente em termos de regeneração após perturbação. Além disso foi produzida uma Checklist de espécies lenhosas do miombo e das anharas de geoxylic suffrutices. Outra importante contribuição para a flora de Angola está a ser conduzida nas bacias dos rios Cuito e Cuanavale sob os auspícios do projecto Okavango Wilderness Project, financiado pelo National Geographic Society, os resultados preliminares têm contribuido para o vários novos registos a nível provincial, e novas espécies para a ciência, estes resultados são o reflexo da necessidade de mais programas de colheita que visem a documentação da flora do país, particularmente nas províncias a sudeste e nordeste de Angola (**Chapter 7**). Finalmente no **Capítulo 8**, estão resumidos os resultados mais relevantes abordados nos seis artigos que compõem a tese e que são discutidos no final desta num capítulo síntese.

Em conclusão, a presente tese oferece pela primeira vez resultados importantes para a compreensão da ecologia de dois importantes ecossistemas que existem em Angola. E vem preencher as enormes lacunas que existem na informação relativa à dinâmica da vegetação lenhosa do miombo e das florestas secas desta região da África austral, assim como oferece informações úteis para a gestão sustentável destes ecossistemas após perturbação antropogénica, devido à agricultura itinerante e produção de carvão. Da mesma forma chama-se a atenção para a necessidade de se adoptarem medidas de protecção efectivas para certas espécies de interesse comercial, tais como *Baikiaea plurijuga*, *Guibourtia coleosperma* e *Pterocarpus angolensis*, cuja análise da dinâmica das suas populações revelaram-se bastante preocupantes, uma vez que foram pouco frequentes, e apresentaram taxas de recrutamento relativamente baixas. O efeito do fogo na regeneração destas espécies foi outro aspecto abordado que no futuro deverá merecer particular atenção das autoridades florestais de Angola. Além disso, devido às necessidades energéticas nos principais centros urbanos e à pobreza extrema a que as populações no meio rural estão sujeitas, tem-se observado um aumento significativo na produção de carvão, o que coloca em risco a manutenção destes ecossistemas para as futuras gerações. Neste contexto, a tese apresenta algumas ideias que poderão contribuir para a redução na exploração da biomassa lenhosa, tais como a melhoria dos métodos de produção de mel, que por si só apresenta-se já como uma actividade alternativa para a geração de receita das famílias nas áreas rurais. A ocorrência de espécies com novas áreas de distribuição geográfica, mostra a necessidade de realizarem inventários florestais cobrindo as áreas mais remotas de Angola, que não foram devidamente estudadas no passado. Os resultados aqui apresentados constituem, sem dúvida, uma motivação adicional, enfatizando a necessidade de mais estudos para a melhoria da compreensão da ecologia destes ecossistemas, visando a implementação de acções efectivas de conservação e utilização sustentável dos recursos naturais da região.

Summary

Miombo woodlands are one of the most extensive ecosystems in Africa, covering large parts of the territory of Angola, extending to the Democratic Republic of Congo, Zambia, Zimbabwe, Malawi, Mozambique and Tanzania. It is characteristically dominated by woody species of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* which belong to the Fabaceae family, subfamily Detarioideae. The Cubango/Okavango river has its source on the central Angolan plateau, where Miombo covers extensive areas along the River, heading southeast through the provinces of Bíe and Cuando-Cubango, where the Miombo woodlands gradually give way to the drier woodlands of *Baikiaea plurijuga* and *Schinziphyton rautanenii*. From here the Cubango river flows towards Namibia, and finally disappears in the Kalahari Desert in Botswana, where it forms the extensive wetland area of the Okavango Delta. These large areas of woodland in the Cubango basin is vital for the maintenance of biodiversity and the multiple ecosystem services associated with it. The area, however, has been subjected to profound and rapid transformations, mainly due to the growth of the human population along the river, which coincides with an increase in land use and exploitation of natural resources. These recent developments call for more in-depth studies of the Okavango Basin to identify the main threats to biodiversity and to provide the countries sharing the Basin with technical and scientific support for sustainable land and resource management for the benefit of their population (**Chapter 1**).

In this context the present thesis aims to: (a) evaluate the effect of shifting cultivation on the structure and dynamics of woody vegetation in miombo woodlands and in dry *Baikiaea* woodlands in a chronosequence of abandonment, characterized by different fallow ages; (b) characterize the charcoal production in the region and evaluate the subsistence of families and income derived from the activity; (c) document the floristic diversity of the region, with emphasis on the occurrence of endemic plant species, likely new species to science and/or new geographic distribution records. These objectives are explored in six scientific papers comprising the present thesis.

The first paper describes the dynamics of woody species of the miombo, after disturbance caused by shifting cultivation. The study analysed a chronosequence of woodland recovery characterized by different fallow ages, studying variations in woody species composition from the initial stages of succession to intact miombo formations (**Chapter 2**). A similar approach was applied to dry woodlands in the Cuando-Cubango province, although it was not possible to establish a chronosequence of fallow age, since

the agricultural fields of this region are usually utilized for relatively long periods. Nevertheless, it was possible to analyze the variation in species composition and diversity of areas previously used for agriculture located in the old floodplain, compared to the areas with intact vegetation, which were not subject to major anthropogenic disturbance. This chapter also discusses the main aspects that govern the dynamics and regeneration of selected woody species, which are also subject to timber exploitation, with particular emphasis on fire frequency and seasonality (**Chapter 3**).

The analysis of charcoal production, as well as the contribution of the charcoal production to household incomes is another important aspect addressed in this thesis. Due to increased charcoal production in the region, and the threats that it poses to woodland integrity, alternative sources of income should be studied to assess their potential to reduce the pressure on wood resources of the region. At the same time, alternative uses could contribute to the generation of benefits through the United Nations initiative, aiming to reduce emissions from deforestation and forest degradation in developing countries (REDD$^+$). It was also possible to characterize the woody biomass and basal area from areas previously exposed to charcoal production, in comparison to mature miombo woodlands (**Chapter 4**).

Angola is host to a variety of habitat types, including the miombo woodlands which cover approximately 47% of the country’s land area. The woody species diversity and composition of these woodlands are poorly known, since the majority of past studies conducted in the country were focused on basic surveys aiming to document the floristic diversity of the country, and plot-based studies were generally lacking. Huíla province is perhaps one of the most botanically studied regions in Angola, but there still exist enormous gaps in terms of characterization of the vegetation communities of the region, the species composition as well as the species association within these communities. The study was conducted in Huíla province, using 456 vegetation plots of 1000 m^2 and resulted in thirteen distinct vegetation communities. Miombo woodland was one of the most diverse vegetation community of the region, other communities included Mopane (*Colophospermum mopane*) and *Baikiaea-Baphia-Terminalia* woodlands. This study will ultimately contribute to the elaboration of the first vegetation map of Huíla province (**Chapter 5**). Relevant results regarding the floristic diversity of the miombo ecoregion highlight the occurrence of species that had not yet been recorded for the country (**Chapter 6**). The botanical evidence collected in this work led to the discovery of many new localities of endemic plant species.

The rich floristic diversity of the country has attracted botanists from all over the world for centuries, with studies beginning probably in the middle of the sixteenth century. From then on, many expeditions were conducted in the country, the most important launched by the Portuguese authorities was conducted by Joaquim José da Silva 1783-1804, whose collected material resulted in the description of the first Angolan plant known to scientific literature. Hereafter several other studies were conducted in areas of particular interest, such as areas highlighted for the proposed strategy of protection, while enormous gaps still exists in some remote areas of the country. Other efforts to document the plant diversity of the country were also carried out in the framework of regional initiatives such as SAREP, OKACOM and more recently the Future Okavango Project (TFO). The latter greatly contributed to a better understand of the ecology of the Angolan miombo woodlands, as well as the dry woodlands of *Baikiaea* in southeast Angola, in terms of forest recovery after disturbance. Additionally, a checklist of woody species and geoxylic-suffrutex-grassland was produced. Another important contribution to the recording of the Angolan flora is being conducted in the upper catchments of the Cuito and Cuanavale rivers under the umbrella of the Okavango Wilderness Project, funded by the National Geographic Society. Preliminary results have provided several provincial records and species new to science, emphasizing the need for more botanical collecting programmes, aiming to document the Angolan flora, especially in the eastern and northern provinces of Angola (**Chapter 7**). Finally in **Chapter 8**, I summarize the most important outcomes of the six papers presented and discussed at the end in a synthesis chapter.

In conclusion, the present thesis presents relevant results for a better understanding of the ecology of two important woodland types from Angola. It contributes to fill the enormous gap that exists in the lack of information regarding the dynamics of miombo and dry woodlands of southern Africa, as well as providing useful information for the sustainable management of these ecosystems following anthropogenic disturbances caused by shifting cultivation and charcoal production. Similarly, attention is drawn to the need for the country to adopt effective protection measures for certain tree species of commercial interest, such as *Baikiaea plurijuga*, *Guibourtia coleosperma* and *Pterocarpus angolensis*, as analyses of their population dynamics showed low frequencies and very low recruitment rates. The effect of fire on the regeneration of these species was another important aspect that has been addressed here, and which in future deserves particular attention by the forestry authorities of Angola. Furthermore, a significant increase in charcoal production has been observed, caused by the energetic needs of the main urban centres and the extreme poverty to which rural populations are subjected. This poses risks in the maintenance of these ecosystems for future generations. In this context, the thesis offers some strategic ideas which may contribute to the reduction of biomass harvesting, such as the improvement of honey production, which represents an alternative source of income in rural areas. The occurrence of species with new geographical areas of distribution shows the need to carry out forest inventories covering the most remote areas of Angola, which have not been studied in the past. The results presented here are undoubtedly an additional motivation, emphasizing the need for more studies aiming to improve our understanding of the ecology of these ecosystems as baseline information for an effective conservation policies and sustainable use of the natural resources of the region.

Zusammenfassung

Die Miombo-Wälder sind eines der größten Ökosysteme in Afrika, die sich über weite Teile Angolas und bis in die Demokratische Republik Kongo, Sambia, Simbabwe, Malawi, Mosambik und Tansania erstrecken. Charakteristisch sind die holzigen Arten der Gattungen *Brachystegia*, *Julbernardia* und *Isoberlinia*, die innerhalb der Fabaceae zur Unterfamilie der Detarioideae zählen. Die Miombo-Wälder bedecken auch weite Teile des Einzugsgebietes des Cubango/Okavango im zentralen Hochland von Angola und weichen flussabwärts in Richtung Südosten in der Provinz Cuando Cubango nach und nach den trockeneren Formationen von *Baikiaea plurijuga* und *Schinziphyton rautanenii*. Von hier fließt der Cubango in Richtung Namibia und verschwindet schließlich in der Kalahari-Wüste in Botswana, wo er im Okavango Delta ein ausgedehntes Feuchtgebiet bildet. Diese ausgedehnten Waldgebiete entlang des Cubango-Beckens sind für die Erhaltung der biologischen Vielfalt und die damit verbundenen zahlreichen ökologischen Leistungen von entscheidender Bedeutung. Die Region ist jedoch mit tiefgreifenden und schnellen Veränderungsprozessen konfrontiert, die vorwiegend in dem Bevölkerungswachstum entlang des Flusses und der damit verbundenen Ausweitung der Landnutzung und der Übernutzung der natürlichen Ressourcen begründet liegen. In Anbetracht dieser Entwicklungen sind umfassende Studien dieser Ökosysteme erforderlich, um einerseits die Hauptbedrohungen für die Biodiversität in der Region zu ermitteln und anderseits den Ländern des Cubango-Einzugsgebietes technische und wissenschaftliche Unterstützung für ein nachhaltiges Landnutzungsmanagement der natürlichen Ressourcen zugunsten ihrer Bevölkerung bereitzustellen (**Kapitel 1**).

In diesem Zusammenhang ist es das Ziel der vorliegenden Arbeit: (a) den Einfluss von Wanderfeldbau auf die Struktur und Dynamik der Vegetation in den Miombo-Wäldern und den trockenen Formationen der *Baikiaea*-Wälder in einer, durch unterschiedliche Brachezeiten gekennzeichneten Chronosequenz zu bewerten; (b) die Holzkohleproduktion in der Region zu charakterisieren und deren Beitrag zum Lebensunterhalt und Einkommen von Familien zu ermitteln; (c) die floristische Vielfalt der Region zu dokumentieren, wobei das Vorkommen von endemischen Pflanzenarten, das Vorkommen von vermutlich noch nicht wissenschaftlich beschriebenen Arten sowie neue geographische Zuordnungen dieser im Fokus liegen. Die beschriebenen Ziele werden in den sechs wissenschaftlichen Artikeln, die der vorliegenden Arbeit zugrunde liegen, ausführlich behandelt.

Im ersten Artikel werden die Dynamiken von holzigen Arten des Miombo nach Störungen durch Wanderfeldbau dargestellt. Die Studie untersucht die Regeneration von Wäldern anhand einer Chronosequenz von unterschiedlich langen Brachezeiten seit Nutzungsaufgabe und betrachtet dabei die Veränderungen der Artenzusammensetzung von den ursprünglichen Stadien der Sukzession zu den intakten Miombo-Formationen (**Kapitel 2**). Ein ähnlicher Ansatz wurde für die trockeneren *Baikiaea*-Formationen in der Provinz Cuando Cubango angewandt, obgleich es hier nicht möglich war, eine chronologische Folge der Sukzessionsstadien auf den Bracheflächen wie im Fall von Miombo zu erstellen, da die landwirtschaftlichen Felder in dieser Region über relativ lange Zeitspannen kontinuierlich genutzt werden. Dennoch war eine Analyse der Unterschiede in der Artenzusammensetzung und -vielfalt der in den alten Flussauen landwirtschaftlich genutzten Flächen im Vergleich zu Gebieten, die zum Zeitpunkt der Untersuchung keinen anthropogenen Störungen unterlagen, möglich. Das Kapitel behandelt zudem die Hauptaspekte, die die Dynamiken und Regeneration der in Bezug auf die Nutzung wichtigsten Holzarten bestimmen, wobei ein besonderer Schwerpunkt auf der Häufigkeit und Saisonalität von Feuer liegt (**Kapitel 3**).

Die Analyse und Charakterisierung der Holzkohleproduktion sowie deren Beitrag zur Einkommensgenerierung der an der Produktion beteiligten Familien war ein weiterer wichtiger Aspekt der Arbeit. Aufgrund der Zunahme der Holzkohleproduktion in der Region und den damit für den Erhalt des Ökosystems einhergehenden Gefahren, sollten alternative Einkommensquellen untersucht und deren Potential, die Nachfrage nach Holzressourcen in der Region zu reduzieren, bewertet werden. Gleichzeitig könnten diese Alternativen im Rahmen der Initiative der Vereinten Nationen zur Verringerung der aus Entwaldung und Waldschädigung bedingten Emissionen (REDD$^+$) zur Einkommensgenerierung der an der Holzkohleproduktion beteiligten Familien beitragen. Zudem wurden die Holzbiomasse und die Fläche von identifizierten Gebieten, die zur Produktion von Holzkohle genutzt wurden, charakterisiert und mit jenen von intakten Miombo-Wäldern verglichen (**Kapitel 4**).

Angola beherbergt eine Vielzahl von Lebensraumtypen, einschließlich der Miombo-Wälder, die etwa 47% der Landesfläche ausmachen. Über die Artenvielfalt und -zusammensetzung dieser Wälder ist wenig bekannt, da sich die Mehrzahl der in der Vergangenheit durchgeführten Studien hauptsächlich auf gering aufgelöste Grunderhebungen konzentrierte, die auf die Erfassung der floristischen Vielfalt des Landes abzielten und dabei Plot-basierte Studien wenig zur Anwendung kamen. Die Huíla-Provinz ist aus botanischer Sicht eine der vielleicht am besten untersuchten

Regionen Angolas, dennoch verbleiben enorme Lücken bezüglich der Charakterisierung der Vegetationseinheiten der Region in Bezug auf die Artenzusammensetzung der Vegetationsgemeinschaften und deren Assoziation. Die Studie, die in dieser Region auf 456 Aufnahmeflächen (plots) von je 1000 m^2 durchgeführt wurde, ergab dreizehn verschiedene Vegetationsgemeinschaften. Miombo weist unter anderem die vielfältigste Vegetationsgemeinschaft der Region auf, andere Gemeinschaften umfassen die Mopane- (*Colophospermum mopane*) und *Baikiaea*-*Baphia*-*Terminalia*-Wälder. Diese Studie wird schließlich zur Ausarbeitung der ersten Vegetationskarte der Provinz Huíla beitragen (**Kapitel 5**). Relevante Ergebnisse zur floristischen Diversität der Miombo-Ökoregion zeigen das Auftreten einer Art auf, die für das Land bisher noch nicht erfasst wurde (**Kapitel 6**). Die im Rahmen dieser Arbeit gesammelten botanischen Belege führten zur Entdeckung zahlreicher neuer Lokalitäten endemischer Pflanzenarten.

Die reiche floristische Vielfalt des Landes zog schon früh Botaniker aus der ganzen Welt an und erste Erkundungen begannen höchstwahrscheinlich Mitte des 16. Jahrhunderts. Seitdem wurden viele Expeditionen in dem Land durchgeführt. Die bedeutendste, von portugiesischen Behörden unter der Leitung von Joaquim José da Silva ins Leben gerufen, fand von 1783 bis 1804 statt und das hierbei gesammelte Material erlaubte die Beschreibung der ersten in der wissenschaftlichen Literatur bekannten angolanischen Pflanze. Später wurden mehrere weitere Studien in Gebieten von besonderem Interesse durchgeführt, wie etwa in vorgeschlagenen Schutzgebieten, während in einigen abgelegenen Regionen des Landes weiterhin enorme Wissenslücken bestehen. Weitere Bemühungen zur Dokumentation der Pflanzenvielfalt des Landes wurden auch im Rahmen regionaler Initiativen wie SAREP, OKACOM und in jüngster Zeit dem Forschungsprojekt The Future Okavango (TFO) vorangetrieben. Letzteres hat wesentlich zu einem besseren Verständnis der Ökologie des angolanischen Miombo sowie der trockenen *Baikiaea*-Wälder in Südost-Angola bezüglich deren Regenerationspotential nach Störungen beigetragen. Zudem wurde eine Checkliste für Gehölzarten und Geoxylic-Suffrutex-Grasländer erstellt. Ein weiterer wichtiger Beitrag zur Erfassung der angolanischen Flora wurde im Rahmen des von der National Geographic Society finanzierten Okavango Wilderness Projects in den oberen Einzugsgebieten der Flüsse Cuito und Cuanavale geleistet. Vorläufigen Ergebnissen zufolge haben die Untersuchungen zu mehreren regionalen Neufunden und Funden bisher noch unbeschriebener Arten geführt, was den Bedarf nach botanischen Untersuchungsprogrammen zur Dokumentation der angolanischen Flora vor allem in den östlichen und nördlichen Provinzen Angolas betont (**Kapitel 7**). Abschließend werden in **Kapitel 8** die wichtigsten Ergebnisse der sechs Artikel zusammengefasst und schließlich in einem Synthesekapitel diskutiert.

Zusammenfassend bietet die vorliegende Arbeit erstmals relevante Ergebnisse, um die Ökologie zweier wichtiger Waldökosysteme in Angola zu verstehen. Sie schließt die große Informationslücken über die Dynamiken der Vegetation im Miombo und den trockenen Waldökosystemen im südlichen Angola, sowie stellt nützliche Informationen für die nachhaltige Bewirtschaftung dieser Ökosysteme nach anthropogenen Eingriffen wie Wanderfeldbau und Holzkohleproduktion zur Verfügung. Gleichzeitig wird auf die Notwendigkeit hingewiesen, wirksame Schutzmaßnahmen für bestimmte Holzarten von kommerziellem Interesse, wie *Baikiaea plurijuga*, *Guibourtia coleosperma* und *Pterocarpus angolensis,* zu ergreifen, da insbesondere diese Arten nur sehr selten und mit sehr niedrigen Bestandsregenerationsraten festgestellt werden konnten. Die Auswirkungen von Feuer auf die Regeneration dieser Arten war hierbei ein weiterer wesentlicher Aspekt, dem die nationalen Forstbehörden zukünftig besondere Aufmerksamkeit schenken sollten. Darüber hinaus ist aufgrund des Energiebedarfs in den städtischen Ballungszentren und der extremen Armut der ländlichen Bevölkerung ein signifikanter Anstieg der Holzkohleproduktion zu beobachten, der ein Risiko für den Erhalt des Ökosystems für zukünftige Generationen darstellt. In diesem Zusammenhang werden in der Arbeit strategische Ideen vorgestellt, die zur Verringerung des Biomasseverbrauchs beitragen können und die Etablierung alternativer Aktivitäten, wie etwa die verbesserte Produktion von Honig, die bereits jetzt zur Einkommenssicherung von Familien in ländlichen Gebieten beitragen, diskutiert. Das Vorkommen von Arten mit neuen geografischen Verbreitungsgebieten verdeutlicht die Notwendigkeit von Waldinventuren auch in den entlegenden Gebieten Angolas, die in der Vergangenheit nicht untersucht worden sind. Die im Rahmen dieser Arbeit dargestellten Ergebnisse sind zweifellos eine zusätzliche Motivation. Sie betonen aber auch die Notwendigkeit weiterer Studien, mit dem Ziel, die Ökologie dieser Ökosysteme besser zu verstehen, um so effektive Schutzmaßnahmen und nachhaltige Nutzungsmöglichkeiten der natürlichen Ressourcen in der Region zu entwickeln.

Chapter 1

General introduction

Francisco M. P. Gonçalves

Overview of Miombo woodlands

Miombo woodlands are one of the most extensive vegetation type in Africa, covering about 10% of the African landmass (White, 1983; Millington et al., 1994; Malmer, 2007). This extensive land area, estimated as 2.7 million km², is dominated by tree species of the genera: *Brachystegia*, *Julbernardia* and *Isoberlinia*, all of which belong to the Fabaceae, subfamily Detarioideae (Azani et al., 2017). Miombo woodlands extend to all south-central parts of Angola, into the Democratic Republic of Congo, Zambia, Tanzania, Malawi, Mozambique and Zimbabwe (Malmer, 2007). The woodlands are understood to owe their structure partially to human intervention, through shifting cultivation and deliberate fires. Fire is historically an integral component of African savannas, playing a crucial role in the dynamics of the miombo woodlands for at least 50,000 years ago (Tarimo et al. 2015; Lawton, 1978). Intentional burning in miombo woodlands and other savanna biomes is practiced, for many reasons including: to prepare land for cultivation, to clear areas around human settlements, for grazing management, charcoal production, honey collection and hunting (Chidumayo, 1997).

Fire also has a direct effect on the vegetation of woodlands by sharply increasing soil and air temperatures during burning, reducing soil organic matter and releasing nutrients. Indirect effects are related to modification of both the post-fire microclimate and the activity of the soil biota. Plant species differ widely in their response and tolerance to fire, and in their capacity to recover after fire. Thus, the effects of fire on the vegetation structure, floristic diversity, species composition and above-ground biomass of miombo ecosystems cannot be understood in isolation from the influence of other biotic and abiotic factors. The resilience of miombo woodlands to disturbance is largely due to the capacity to regenerate naturally from resprouts of stumps. However, the total number of sprouts, their basal area and resprouting effectiveness declines also with burning (Chidumayo, 2004). Other human pressures on above-ground woody biomass are directly linked to extraction of woody resources and clearance for slash-and-burn agriculture. In this type of agriculture, woodland sites are cleared, the vegetation debris is burned, and the abandonment of the site occurs after approximatelly 3-5 years of continuous cultivation, largely due to the decline in soil fertility (Karthik et al., 2009; Lumbwe, 2010). The abandonment of agricultural fields is followed by a long period of fallow during which cultivation is suspended, allowing the vegetation to recover along with soil fertility.

According to Williams et al., (2007) Africa plays a globally important role in carbon emissions through fire and land use. The magnitude of these terms, however, is still highly uncertain, as carbon emissions from land use changes for most tropical areas still constitutes one of the major uncertainties in the global carbon cycle. For the African woodlands, small-scale agriculture and charcoal production are thought to reduce vegetation carbon stocks, but quantification of these processes is hindered by the lack of ground data (Ryan et al., 2012). In terms of carbon budget, the African continent represents one of the major uncertainties as mentioned above, the current role of the continent in the global carbon cycle remains remarkably limited due to the lack of long-term measurements carried out in the region (Ciais et al., 2010). Due to the high variability of CO_2 fluxes and insufficient studies of ecosystems and ecosystem-human-climate interactions, there is a need to continue and enhance observations of carbon stocks, carbon fluxes, and atmospheric CO_2 concentrations, to enable a more precise and realistic assessment of Africa's carbon cycle and its sensitivity to natural and anthropogenic pressures. Long term carbon cycle observations are lacking for the whole continent, such observations can support both bottom-up and top-down methods of estimating carbon sources and sinks, stressing the need for regional inventories and monitoring of soil and vegetation carbon stocks.

As indicated above, miombo woodlands contribute significantly to the social and economic livelihoods of rural and urban dwellers, providing them with a wide range of forest products which include: fuelwood, timber, charcoal and other Non-Timber Forest Products (NTFPs). These woodlands are under high pressure from land use change, inappropriate management actions, weak institutional capacity and low agricultural productivity, which may ultimately determine their long term sustainability. Much of the newly cropped areas for instance are unsuitable for agriculture and degrades quickly, thereby forcing the farmers to convert even more land for cultivation. The impacts of woodland conversion to agricultural fields on ecological health have not been studied extensively within the miombo eco-region (Walker et al., 2004). A preliminary observation of the vegetation in previously cultivated areas around Cusseque in the Chitembo municipality of Bié Province, indicated tree dominance of *Brachystegia longifolia, B. bakeriana, B. spiciformis* and *Cryptosepalum exfoliatum* subsp. *pseudotaxus*. These observations give a good indication of regeneration just one year after first clearing for agriculture (Table 1).

Table 1: Number of saplings (N) and mean height in centimeters (Ht) recorded from a crop field after one year of woodland clearance in Cusseque.

Species	**Saplings**	
	N	**Ht**
Albizia gummifera (J.F.Gmel.) C.A.Sm.	5	23.6
Baphia bequaerti De Wild.	5	36.4
Bobgunia madagascariensis (Desv.) J.H.Kirkbr. & Wieserma	1	40
Brachystegia bakeriana Hutch. & Burtt Davy	38	51.6
Brachystegia longifolia Benth.	44	26.1
Brachystegia spiciformis Benth.	35	29.4
Burkea africana Hook.	5	24.6
Combretum zeyheri Sond.	2	34
Cryptosepalum exfoliatum De Willd. subsp. *pseudotaxus* (Baker f.) P:A. Duvign. & Brenan	29	22.9
Diplorhynchus condylocarpon (Müll. Arg.) Pichon	1	19
Erythrophleum africanum (Welw. ex. Benth.) Arms	4	65.8
Hymenocardia acida Tul. var. *acida*	3	46.7
Monotes africanus A. DC.	1	21
Ochna pulchra Hook.	6	16.8
Parinari curatellifolia Planch. ex Benth.	2	13.3
Pericopsis angolensis (Baker) Meeuwen forma *angolensis*	3	37.7
Faurea intermedia Engl. & Gilg.	2	29
Pseudolachnostylis maprouneifolia Pax var. *dekindtii* (Pax) Radcl.-Sm.	1	50
Pterocarpus angolensis DC.	3	19
Strychnos sp.	2	27
Uapaca nitida Müll. Arg. var. *nitida*	1	25
Vitex madiensis Oliv.	6	28.8
Xylopia tomentosa Exell	15	30.2
Unidentified	1	59

Widespread occurrence of *Pteridium aquilinum* var. *centrali-africanum* in many abandoned fields was also frequently observed (Figure 1). This opportunistic fern is a cosmopolitan species, normally associated with degraded and acidic soils. The species show a great capacity to dominate abandoned sites, and is sometimes found as part of the undergrowth of primary open forests or woodlands, the fern can also be found in recently burned and cleared areas, along paths and forest edges (Rasmussen, 2008). Deforestation and conversion of large areas for agricultural purposes as observed in the Cusseque study area seem to have contributed to the spread of *P. aquillinum* var. *centrali-africanum*, which rapidly colonizes abandoned sites.

Figure 1: Abandoned crop field in Cusseque dominated by the cosmopolitan fern *Pteridium aquilinum* var. *centrali-africanum* (Photo: F.Gonçalves).

Contrary to Cusseque, the Caiundo study area falls within *Baikiaea-Burkea* woodlands located in the Kalahari sands along the Angolan-Namibian border. The agricultural fields in Caiundo are reported to be cultivated for longer periods. Here, fire also plays an important role in determining woodland vegetation structure and regeneration of woody species, affecting shoot production and understorey development, as the area is mostly burned every year (Frantz et al., 2013). More recently large scale selective logging of timber species such as *Guibourtia coleosperma* and *Pterocarpus angolensis* is being observed in southeast Angola. This apparently unregulated activity may represent a problem for the management of these woodlands, with serious implications for their long-term sustainability.

Forest cover and forest degradation in Angola

Based on available historical data and effort being made for completion of the National Forestry Inventory, the forest cover in Angola was estimated to be around 57.85 million hectares, corresponding to 46% of the country's land surface (FAO, 2015). Of this area, only 2% corresponds to moist tropical forests confined to the northern parts of the enclave of Cabinda and Dembos forest, a triangle formed by the provinces of Uíge, Bengo and Cuanza Norte (FAO, 2007; FAO, 2015). Forest mosaic and woodlands including miombo, the latter distributed over Huíla, Cuando Cubango, Moxico, Bié, Huambo, Malange, Benguela and Cuanza Sul comprise about 65.2% of the forest cover. These important woodlands, with a tall tree canopy, continuous grass cover and variable woody species composition are considered one of the major woodland biomes in the world, reaching their greatest extent in the seasonally dry tropics (Maurin et al., 2014). The situation of forests and woodlands in the southern African region is concerning and represents an enormous challenge in terms of suitable forest management, which is a reflection of low income generated from the forest resources, the weak policies of the forestry sector, and inadequate development institutions (FAO, 2009). In the miombo region the main drivers of deforestation are related to shifting cultivation, charcoal production and construction or rehabilitation of infrastructures all driven by the rapid population growth within the region. Other identified causes of deforestation and forest degradation include frequent and uncontrolled fires, overstocking with livestock or over-harvesting of wood products, with China being the world's largest importer of tropical timber (Geldenhuys, 1997; Wertz-Kanounnikoff et al., 2013).

Shifting cultivation

Shifting cultivation is defined as an agricultural system characterized by rotation of fields, with an alternation of short periods of cropping (three to five years) accompanied by long fallow periods (up to twenty years or more), but often as short as six to eight years, and clearing by means of slash-and-burn methods (Pelzer, 1958; Christanty, 1986). The most important difference between shifting cultivation and other agricultural systems is the abandonment of the cleared area after a few harvests. Shifting cultivation or slash-and-burn agriculture comprises distinct phases, which generally start with site selection for clearing and establishment of the field. Some parameters, such as vegetation type, distance from villages and other agriculture fields, topography and soil type are taken into account during the establishment of the field (Tchiengué, 2012).

This agricultural system consists generally of small scale farming of a few hectares or less, practiced by local farmers in the tropics, and uses more than half of the available soil nutrients (Klemick, 2011; Tchiengué, 2012). Shifting cultivation is considered one of the major causes of deforestation in tropical regions and contributes significantly to land degradation (Luonga et al., 2000). In Tanzania for instance, about 50% of deforestation and land degradation is attributed to shifting cultivation (Luonga et al., 2000; Mwampamba, 2009). For Angola, there is no reliable data to quantify the extent of deforestation and/or land degradation due to shifting cultivation, but personal observation particularly in the Cusseque study area with miombo woodlands being the most dominant vegetation type, suggests that this agricultural system can be considered the main cause of deforestation and land degradation within this region. Furthermore, it has been observed that agricultural fields in Cusseque were mainly placed adjacent to human settlements, main roads or tracks (Schneibel et al., 2013). However, increasing demand for land appears to be forcing people to establish new fields further away from villages and main roads (personal observation).

Charcoal production

Charcoal, timber and others Non-Timber Forest Products (NTFPs) are part of a broad range of woodland resources extracted in the miombo, providing direct benefits to rural and urban livelihoods (Gumbo et al., 2013). The African continent uses more than 90% of harvested wood for energy production, and about 30% of fuelwood extracted is used directly for charcoal production, which is expected to increase further within the next twenty years (FAO, 2011a; May-Tobin, 2011). The high demand for fuelwood in developing countries is due to the relatively high cost of electricity, low capacity of electricity production and petroleum-based fuels, as well as rapid human population growth, particularly in urban areas (Deudney & Flavin, 1983). Charcoal, and additionally fuelwood are the major sources of cooking and heating energy for most urban households in sub-Saharan Africa, and are also one of the major drivers of land cover change, related to deforestation and land degradation (Schaafsma et al., 2012). The estimated rate of deforestation in Angola during 2000-2005 was reported to be around 0.2%, this rate increased substantially in the last decade up to 13.7% of intact forests landscape being lost between 2000-2013, the highest deforestation rates observed in the country after the civil war (Potapov et al., 2017). Charcoal production is fueled by energetic needs of the cities; the limited availability of affordable energy alternatives in the main cities, and high levels of poverty in rural areas (Lohri et al., 2016). About 62.3% of the Angolan population lives in urban areas and the rural areas represent the remaining proportion, this significant part of the population inhabiting the rural areas relies on fuelwood extraction, charcoal production and other Non-Timber Forest Products (NTFPs) as a principal source of income and subsistence (INE, 2016). The annual demand for fuelwood and charcoal in the country is estimated at 6 million m^3 yr^{-1} (MINADER, 2006). The country has enormous potential for forest biomass to generate energy, which is responsible for about 56.8% of the total domestic energy consumed in the country. Charcoal and fuelwood still represent the primary source of energy for domestic use, followed by petroleum (41.7%), electricity (1.45%) and natural gas (0.1%) (MINADER, 2006). Luanda is the major centre for consumption of charcoal produced in south-central Angola, particularly in the provinces of Huambo and Bié, where high levels of biomass extraction have been observed, causing serious implications for long-term sustainable management of the woodlands.

Rehabilitation of infrastructures

Another important cause of deforestation in the study area is associated with the rehabilitation of infrastructure, including roads. After more than 30 years of civil war, the Angolan government initiated an ambitious programme of reconstruction of infrastructures (Power, 2012). Many projects of construction and/or rehabilitation of basic infrastructures, including roads have been launched to ensure inter-provincial connectivity and consequent movement of people and goods. Deforestation rapidly became evident along the road margins (Figure 2), where high conversion rates are found, and decreases with increasing distance to roads (Röder et al., 2015). The vegetation along the roads is also reported to be constantly cleared to prevent the advance of regeneration, resulting in creation of permanent woodland edges (Lumbwe, 2010). The speed of deforestation recently observed in the country can be linked to the accessibility created by the rehabilitation of roads, being evident that the placement of roads in rural and forested areas increases deforestation rates and endangers biodiversity, suggesting that construction and/or rehabilitation of roads cause trade-offs between economic development and environmental damage (De Luca, 2007).

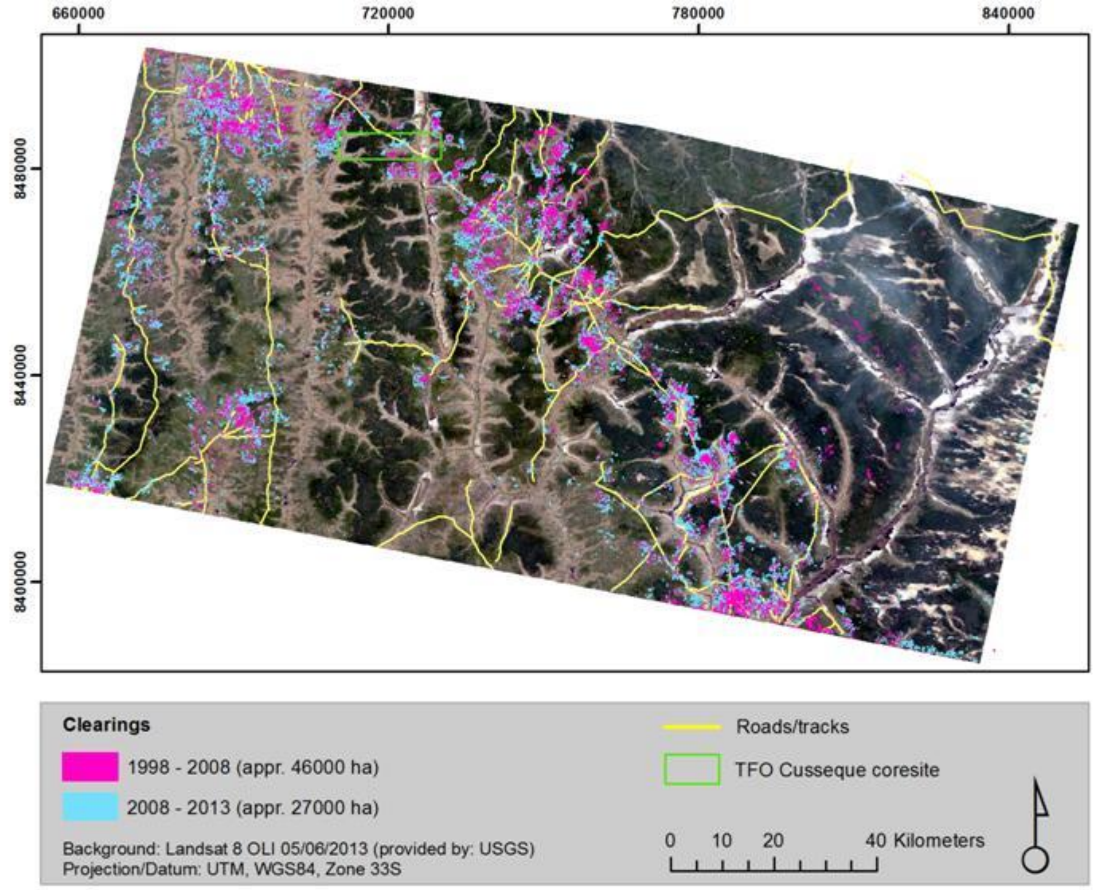

Figure 2: Remote sensing image of active (pink) and newly estabilished agriculture fields (blue) along the main road and tracks of the TFO Cusseque study area (Image prepared by: Anne Schneibel).

Utilization and quantification of forest resources

The use of forest resources in Angola is concerning due to the high demand for forest products and poor information available from previous studies (Buza et al., 2006). The quantification of forest resources is particularly challenging for the country, as most of the existing information related to the forestry sector dates from the 1950s, and the country expect to carry out a national forest inventory (FAO, 2007). The majority of forested areas of the country were probably extremely exploited in a selective manner from 1950 (*ca.* 326.000 m^3 yr^{-1}), with emphasis on valuable timber species (Buza et al., 2006). Based on this situation, the Angolan Ministry of Agriculture and Rural Development (MINADER) through its executing agency, the Instituto de Desenvolvimento Florestal (IDF) launched in 2008 the basis for carrying out the first National Forest Inventory (NFI) after independence, in collaboration with the United Nations Organization for Food and Agriculture (FAO). The forest inventory aimed to; (a) strengthen institutional capacity; (b) assess forestry resources; (c) map forest areas and land uses; (d) establish a forest monitoring system, and (e) harmonise the classification of forest/woodland systems and definitions. This ambitious program also aimed to ensure the alignment of national forestry policies with the important guidelines and international conventions of which Angola is a signatory, and as such provide a basis for financing multilateral instruments based on payment for environmental services under the platform of United Nations REDD$^+$ Programmes (UNDP, 2014). However, the implementation of this program is hindered by institutional barriers and human resources capacity, as well as being constrained by intermittent government funding. The data gathered from there, the availability of basic information that may have resulted from the National Forestry Inventory, specifically the actual percentage of the country’s forested area is not known, and not accessible to research institutions, universities, the private sector and general practitioners.

Management and conservation of forest resources

The state of management and conservation of forest resources in Angola is concerning. During the colonial era these two actions were mostly under the umbrella of the existing legislation for nature conservation, firstly consolidated by the Portuguese authorities in 1955 by the Decreto No. 40040. This document contains the principles for conservation of soil, fauna, flora, and complementary regulations which were subsequently approved (Huntley & Matos, 1994). The forestry sector was approved in 1962 by Decreto No. 44531, the Forestry Regulation in which the Directorate of Agriculture and Forestry was the institution responsible for regulation of the forestry sector in Angola, Mozambique and Portuguese Guinea (Huntley & Matos, 1994). This organization in fact only regulated timber exploitation, and many country’s forest reserves were designated as areas in which the Forestry Department reserved the right to grant or determinate timber concessions. As expected little was shown in terms of conservation of flora or reforestation of those areas previously extracted (Huntley, 1974).

The conservation of vegetation in Angola could only be achieved within the National Parks and Natural Reserves, which were under control of the Directorate of Veterinary Services until early 1970s (Huntley, 1974). Forestry activities in Angola during the colonial era appeared to bevery disorganized, tree harvesting was uncontrolled and the existing legislation was mostly only theorical (Baptista, 2014). Angola is considered one of the countries in the southern Africa region, where the exercise to formulate a joint forest policy and strategies for the implementation of a national forest action plan, have not been achieved or completed. Towards this end, many initiatives were carried out, for instance the first national meeting about forestry policy held in 1989, which aimed to formulate a national forest action plan. Unfortunately this objective has still not yet been achieved, due to the lack of an appropriate source of funding, and necessary inter-institutional participation (MINADER, 2006). The existing legislation on nature conservation is still mainly based in the Decreto No. 40040 (09.02.1955) and complementary regulations such as: the Forestry Regulation (Decreto No. 44 531; 21.08.1962), Hunting Regulation (Diploma Legislativo No. 2873; 11.12.1957) and regulation for creation of National Parks and Natural Reserves, firstly mentioned in 1936 (Caldecott et al., 2005). All of these instruments were subsequently amended, but remain outdated and are not adaptable to the actual socio-economic context of the country, as well as to the relevant international legislations for which Angola is a signatory state.

In 2006, a National Forestry Policy, Fauna and Conservation Areas was approved by the Angolan Government (Resolution No.1/10). This resolution aimed to create a legal basis and an institutional framework which is able to strengthen the sustainability and management of natural resources, which consequently may ensure the reduction of poverty in rural areas, ensuring food security of vulnerable communities and additionally promote an effective and integrated rural development. Years after its approval, this instrumentis still far from achieving these objectives. Despite the potential of timber resources in the country, the situation of the forestry sector is complex. This may not only be attributed to the long period of civil war that the country experienced, which significantly contributed to the highest deforestation rates observed around the main cities, as observed in Huambo where the observed land cover pattern may also be related to changes in land use associated with new settlement choices during and after the civil war (Cabral et al., 2010). The highest levels of poverty in rural areas, weak capacity of forestry institutions, lack of well trained staff, the abandonment of conservation areas, lack of an action plan for management of forest resources, as well as the low participation of the forestry sector in the economy of the country are, among others, the challenges faced by the forestry sector in Angola. Over-exploitation of valuable timber species throghout the country has increased during the last decade, practiced mainly by foreign companies operating under a license of local companies. The actual regime of timber exploitation in the country is therefore considered to be detrimental for sustainable utilization of forest resources, as most of these companies simply license themselves to exploit valuable commercial timber species (Chiteculo et al., 2018). Generally they do not undertake any forestry inventory before starting to exploit timber, as no efficient mechanism of control exists.

Research areas under the Future Okavango project

The Okavango river basin occupies an area of 149,700 km^2 of south-eastern Angola (Neto, 2011). Most of this area is located in the Cuando Cubango Province, but it crosses five other Angolan provinces, namely Bié, Cunene, Huambo, Huíla and Moxico (Mendelsohn & Obeid, 2005; Neto, 2011; Baptista, 2014). The Future Okavango Project (TFO) was funded by the German Federal Ministry of Education and Research (BMBF), and aimed to provide scientific support for sustainable land and resource management in the Okavango basin of Angola, Namibia and Botswana. The project has two study areas in Angola. The first is located in Cusseque village about 30 km from the municipality of Chitembo in the Bié Province. The second, Caiundo study area is located near the Mulemba village on the main road toward the Angolan-Namibia Katwitwi border post in the Cuando Cubango province. Two additional study sites were estabilished in the neighbouring countries of Namibia in Manshare and Botswana in Seronga (Figure 3).

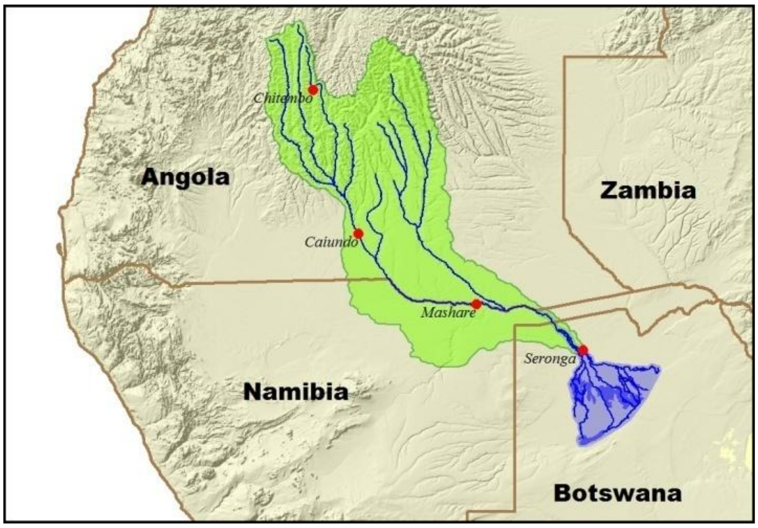

Figure 3: Map of The Future Okavango Research Area (FORA) in southern Africa (green) and the Okavango delta in Botswana (blue), Source: <http://www.future-okavango.org>.

The Okavango river basin, landscape and threats

The Okavango River basin is one of the most important shared water reserves in sub-Saharan Africa. The river rises from southeastern Angola, and flows down to Botswana in the Okavango Delta, a UNESCO classified world heritage site <www.okavangodelta.com>. The river has its larger catchment area in the highlands of central Angola and holds along its course large areas of woodland and wetlands. However, this impressive regional landscape is rapidly changing due to anthropogenic activities such as logging, charcoal production and clearance of woodlands for agricultural purposes. Changes are particularly being observed from the Angolan side, where the population density previously considered low is increasing rapidly. From the other angle the beauty of this immense landscape, combined with the concentration of wildlife along the river, and in the wetlands of the Okavango delta attracts tourism from all over the world, creating job opportunities and important sources of income for the economy of Namibia and Botswana. Other benefits for the countries economy, obtained from the river is directly linked to agricultural development, with large areas of woodland being converted to irrigated farmland, mainly on the Namibia side, but also increasing on the Angolan side (Figure 4).

Figure 4: Large irrigation scheme observed along the Longa River, Southeast Angola (Photo: F.Gonçalves).

Despite these benefits and opportunities created by the Cubango/Okavango River in terms of ecotourism and income generated from the large-scale agriculture schemes, there are many concerns in terms of management of this important resource, together with the conservation of biodiversity, the maintenance of important ecosystem services and the economic development of the countries. Namibia has experienced rapid population growth along the river, accompanied by the acceleration of deforestation and loss of natural resources, in addition to large woodland areas being converted to irrigated lands, aiming to reduce the dependence of the country on cereals, and simultaneously ensure food security (Mendelsohn & El Obeid, 2005). It is therefore important to maximize efforts to study the biodiversity of the river, to understand the multiple associated ecosystem services for better management of the river basin and to benefit the populations of the countries sharing this important resource.

Angola has experienced rapid changes during the last few decades, the pressure on natural resources along the Cubango/Okavango River is crearly evident with large woodland areas being converted to agriculture, or trees being cut for charcoal to supply the energy needs of the main cities, but also timber exploitation for export to China and European countries. Thus, the integration of the Angolan part of the Okavango River basin is crucial to promote appropriate management decisions, which will necessarily influence the Okavango delta in Botswana. Several initiatives are currently being implemented in this way, and the Future Okavango Project (TFO) is one of these initiatives.

Overall objectives

The overall objective of this thesis was: (1) to assess the effect of shifting cultivation on the tree species stand structure, species diversity, composition, as well as the regeneration of woody species in the Cusseque and Caiundo study areas; (2) to assess the household livelihoods, incomes derived from charcoal production and assess the above-ground biomass in fallow sites of charcoal production compared to mature woodlands; (3) to assess the woodlands and provide a preliminary classification of the plant communities of Huíla province; (4) to document the floristic diversity of the region, document potential new species to science and or new geographic distribution records; and finally (5) compile an overview of early and current botanical surveys, collectors, richness and endemism of the Angolan flora.

Chapter 2

Tree species diversity and composition of miombo woodlands in south-central Angola: A chronosequence of forest recovery after shifting cultivation

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Abstract

The study was carried out in the Cusseque area of the municipality of Chitembo in south-central Angola. Our objectives were to assess the floristic diversity, the species composition and stand structure of Miombo woodlands during regeneration after shifting cultivation. A total of 40 plots of 1000 m^2 were surveyed and analyzed, corresponding to mature forests/woodlands and three fallow types of different age. The analyses were based on plot inventories of all trees with DBH ≥ 5 cm. A total of 51 woody species, 38 genera and 19 families were recorded. The dominant family was Fabaceae, with sub-family Caesalpinioideae being very abundant. Shannon diversity and evenness were highest in mature forests and young fallows, while the mature forest stands showed the highest species richness. A Principal Coordinates Analysis (PCoA) showed many species shared between the intermediate fallow types, but only few species were shared with young fallows. Mature forests formed a clearly distinct group. This study shows potential pathways of forest recovery in terms of faster regeneration after agricultural abandonment and thus, the results presented here can be used in future conservation and management plans in order to reduce the pressure on mature forests.

Introduction

Forests and woodlands in Africa play an important role in the livelihood of many communities and in the economic development of many countries (Sebukeera et al., 2006). Forest ecosystems are not only important for supplying timber and other economically important products (*e.g.* charcoal), but also for generating indirect benefits such as controlling soil erosion, supporting soil fertility, providing shade and buffering hydrological cycles (Clarke et al., 1996).

The forest resources in most African countries are threatened by various natural and anthropogenic disturbances, especially over-exploitation. Thus, the problem of unsustainable use of forest resources is of increasing concern in these countries, due to the fact that forest losses are causing land degradation and habitat loss for forest *taxa* (Bila & Mabjaia, 2012). Direct causes of deforestation and land degradation in south-central Africa include land conversion, *e.g.* by expansion of shifting cultivation practiced by small-holders, infrastructural or agro-industrial expansion and over-exploitation, *e.g.* for timber, fuelwood and charcoal (Du Preez, 2014).

Shifting cultivation is an agricultural system practiced in the tropics for thousands of years, being the main source of subsistence for people in many rural areas (Júnior et al., 2008). This agricultural practice is characterized by a rotation of fields rather than of crops, by short periods of cropping (one to five years), alternated with long fallow periods (up to twenty or more years, but often as short as six to eight years), and by clearing the fields using slash-and-burn techniques. Fields are normally prepared using a hoe or digging stick, the plow only rarely being employed (Pelzer, 1957; Haney Jr., 1968). The use of fire serves to clear the field and enrich the soil with nutrients from the ash of the woody biomass (Dhakal, 2012).

This agricultural system has been labeled as the most serious land-use problem and a major driver of deforestation in tropical areas of Africa (Karthik et al., 2009; Aththorick et al., 2012). It has been, however, an ideal solution for soil fertility in the humid tropics, at least in the past when the human population density was low and fallow periods were long enough to restore soil fertility (Christanty, 1968; Watters, 1971). The rapid growth of human population in rural areas of Africa and increasing needs for food production has caused the shortening of fallow periods of abandoned fields and people to encroach into new areas that have not been subjected to agriculture before (Christanty, 1968). The increasing demands of the rapidly growing human population has lead to land scarcity, and the remaining forests are being increasingly over utilized, far beyond their capacity for regeneration (Neelo et al., 2015). This process, as a whole, seriously impacts forest biodiversity patterns, *e.g.* species richness and composition (Spencer, 1966).

The Angolan Miombo, which refers to dry tropical forests in south-central Africa dominated by tree species of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* (Kowero et al., 2003), are poorly known in terms of woody species diversity, composition and resilience after abandonment. Data on species diversity and composition are confined to sporadic and outdated studies [*e.g.* Monteiro, 1970]. Almost nothing is known on the dynamics of forest recovery following disturbance, which hampers any systematic management approaches aimed at sustainable use of forest resources. To obtain a holistic view on forest resources of the Angolan Miombo, it is crucial to understand variations in tree species composition, to analyze patterns of species distributions in the forests and to quantify the relative contribution of different species to overarching patterns (Durigan, 1999).

In order to manage disturbed and undisturbed stands and to understand the provision of non-timber ecosystem services, it is imperative to describe patterns of species composition (Neelo et al., 2015). Additionally, data on woody species composition serve as baseline information for projecting changes in vegetation over time, which is fundamental to understand regeneration processes, such as tree growth, tree mortality, understory development and the spread of disturbances (Isango, 2007).

The present study was conducted in the Cusseque area of the Municipality of Chitembo, in southern Bié Province, which is situated in the center of the Angolan Miombo region. This area is at the current front of deforestation of African dry tropical forests (Hansen et al., 2013). This study aims to assess the woody species diversity and composition on abandoned agricultural crop fields and mature forest stands in the Cusseque area in order to:

(a) Analyze changes on woody species composition during forest recovery;

(b) Assess changes of woody species diversity during a slash-and-burn cycle;

(c) Understand the temporal dynamics and timeline of forest regeneration from field abandonment to mature forest;

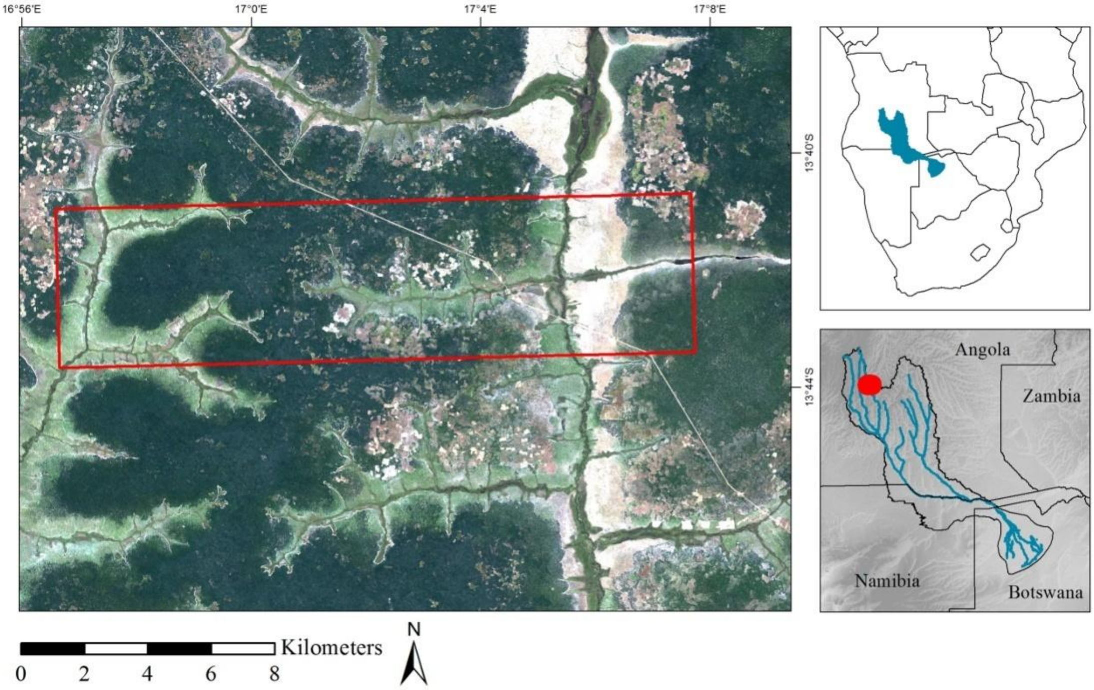
Material and Methods

Study area: The study area is located on the southern slope of the Angolan Central Plateau in the Bié province (13.6985°S, 17.0382°E), and it is one of the research sites of the Future Okavango Project in Angola (Figure 5). The mean elevation is 1560 m with a mean annual temperature of 20.4°C (Gröngröft et al., 2013; Weber, 2013).

The study area has a tropical sub-humid climate, with a rainy season of approximately six months lasting from October to April and a dry season corresponding to the remaining period of the year. For the period 1971 to 2000, the mean annual precipitation was 987 mm/year. However, the annual rainfall in Cusseque shows a high interannual variability with a slightly decreasing trend since the 1970s (Weber, 2013). During the dry season frosts frequently occur, especially in the valleys (Finckh et al. 2014). The soils of the study area correspond mainly to ferralitic soils, with a shallow sandy top horizon.

The vegetation of the study site is dominated mainly by typical Miombo woodlands species (Revermann & Finckh, 2013). *Brachystegia* spp., *Julbernardia paniculata*, *Cryptosepalum exfoliatum* subsp. *pseudotaxus* and *Erythrophleum africanum* are locally dominant tree species (Shaw, 1947; Monteiro, 1970; Barbosa, 1970; Diniz, 1973; Huntley & Matos, 1994; Revermann et al., 2013). The woodlands range from 4 to 15 m in height, with sparse to moderate grass or shrub layers below the continuous canopy (Huntley & Matos, 1994). While undisturbed forests seem to be mostly single stemmed, many stands show signs of earlier slash-and-burn agriculture with multi-stemmed trees above knee height. Fire also plays an important role in the current forest dynamics (Stellmes et al., 2013), especially during the grass dominated early fallow stages.

The human population of the study area mostly belongs to the ethnic group of Tchokwe. Subsistence agriculture based on shifting cultivation is their main source of livelihood, with maize (*Zea mays*), cassava (*Manihot esculenta*), beans (*Phaseolus vulgaris*) and peanut (*Arachis hypogaea*) being the main crops. Other sources of income include livestock keeping, wage labour and, notably in the nearby town of Chitembo, the retail of natural resources like charcoal, bushmeat and honey (Domptail et al., 2013).



Projection: WGS 1984; background: RapidEye high resolution satellite imagery, recorded 1st May 2013. We acknowledge the DLR for the provision of the data from the RapidEye Science Archive.

Figure 5: Location of the Okavango basin in southern Africa and the study site in Cusseque (denoted in red). The Okavango basin as shown here follows the definition of The Future Okavango project: <www.future-okavango.org> (Wehberg & Weinzierl, 2013).

Site selection and data collection: Forests and fallows were sampled to represent a chronosequence of forest recovery in order to study the state of origin and the dynamics of regrowth. The site selection was done through informal meetings with traditional authorities and the community in general, aiming to identify sites of former slash-and-burn agriculture and known age since abandonment. The information obtained regarding the fallows ages was confirmed with remote sensing data, obtained from LandTrendr, a programme that detects disturbance within Landsat time-series (Kennedy et al., 2010). The selected areas were then grouped into four categories, according to fallow age; young fallows (range 7-8 yrs), medium-aged fallows (range 10-14 yrs), old fallows (range 20-21 yrs) and mature forests (undisturbed forests or woodlands, showing structural features characteristic of later stages of stand and succession development).

Field work was carried out during March, May and June 2013 and in September 2014, using 20 m × 50 m plots, which were divided into ten 100 m^2 subplots (Felfili et al., 2005). A total of forty plots were surveyed, corresponding to ten mature stands and ten in each of the fallow stages. On every plot we recorded the occurrence of tree species with DBH ≥ 5 cm. As complementary information, cover of herbaceous and shrub species in a central 100 m^2 subplot were also recorded.

If not already known to the authors, the species were identified by their local name in Tchokwe (given by local field guides), collected and taxonomically identified following fieldwork. Voucher specimens are stored at the Herbarium of Lubango (LUBA) and Kew Herbarium (K). The scientific names and authors of the species follow the Checklist of Angolan vascular plants (Figueiredo & Smith, 2008).

Data analysis: Diversity refers to different measures of the species richness and composition. Measures include, among others, species richness and evenness (Begon et al., 2006). Species richness refers to the total number of species recorded in each forest stage. In this study we also calculated the Shannon Diversity Index from Equation 1 (Magurran, 2004).

$$\textbf{Equation }(\mathbf{1})\boldsymbol{H' = -\sum pi} \ \mathbf{ln}\ (\boldsymbol{pi})$$

In the Shannon Diversity Index ($\boldsymbol{H'}$), $\boldsymbol{p_i}$ is the number of individuals of species in a given plot divided by the total number of individuals in the plot, $\boldsymbol{ln}$ is the natural logarithm and $\sum$ is the sum of the calculations. The index incorporates the species richness and the proportion of each species in all sampled plots (evenness) (Begon et al., 2006; Heip et al., 1998). The evenness in species abundance was assessed by Buzas & Gibson's Evenness Index from Equation 2 (Heip et al., 1998).

$$\textbf{Equation }(\mathbf{2})\ \boldsymbol{E} = \frac{\boldsymbol{e^H}}{\mathbf{S}}$$

In the Buzas & Gibson's Evenness Index ($\boldsymbol{E}$), $\boldsymbol{H}$ is the Shannon Diversity Index, $\boldsymbol{e}$ is the natural logarithm base and $\boldsymbol{S}$ is the total number of species. Evenness is the equitability of the abundances of different species, and the index varies from 0 to 1, with 1indicating that all species have the same abundance (Heip et al., 1998; Kanieski et al., 2010).

To compare the diversity of the four forest stages, we calculated diversity profiles for every stage. Diversity profiles provide a graphical representation of the shape of a community and have the advantage of combining multiple diversity measures (*e.g.* Species richness, Shannon diversity and Simpson's diversity) at once and display one curve per category, in this case fallow stage (Leinster & Cobbold, 2012; Caranza et al., 2006; Oldeland et al., 2010).

This allows for a more complete picture of the multidimensional term biodiversity, instead of calculating a few isolated diversity indices only. The scale parameter alpha (α) gives the order of Renyi's diversity; $\alpha = 0$ gives the total number of species (Species richness), $\alpha = 1$ gives the index proportional to the Shannon diversity index, $\alpha = 2$ gives an index which behaves like Simpson's index, while α = Inf. refers to the relative abundance of the most abundant species (Hammer, 2012).

Stand structure was calculated from stems density in each fallow and mature forest sites. A non-parametric test (Kruskal-Wallis) was used to assess differences on stand density between fallows and mature forest stands. Population structure was used to assess dynamics in population for the mature stands. Woody species composition was analyzed using the Importance Values Index (Equation 3), which is the summation of the relative values of frequency, density and dominance (Curtis & McIntosh, 1951). The Importance Values Index (IVI) describes the floristic structure and composition of the woodlands and has been frequently used in the Miombo systems (Munishi et al., 2011; Kalaba et al., 2013; Jew et al., 2016).

$$\mathbf{Equation\ (3)\ IVI = \frac{(RF + RD + RDo)}{3}}$$

IVI: Importance Value Index; **RF:** Relative frequency; **RD:** Relative density and **RDo:** Relative dominance.

The frequency is a statistical parameter which reflects the spread of a species in a given area. The relative frequency (equation 4) of species was obtained from Absolute frequency, dividing the number of sampling units (100 m^2 subplots) in which the species occurs, by the total number of sampling units.

The density of a species reflects the abundance of a species in a given community. The Relative density (equation 5) was obtained from absolute density calculated from the total number of individual of a species present in a plot divided by the total area sampled (0.1 ha).

The dominance is defined as the area occupied by the basal area of a species per plot (0.1 ha). The Relative dominance (equation 6), was obtained by dividing the total basal area for a given species by the total basal area of all species per plot. To calculate Relative frequency, density and dominance of the species we used the standard formulas (Mueller-Dumbois & Ellenberg, 1974; Kent & Coker, 1992; Freitas & Magalhães, 2012).

$$\mathbf{Equation\ (4)\ RF = \frac{AF}{TF} \times 100}$$

RF: Relative frequency of species; **AF**: Absolute frequency of the species; **TF:** Sum of absolute frequencies of all species.

$$\textbf{Equation (5) } \mathbf{RD} = \frac{\mathbf{AD}}{\mathbf{TD}} \times \mathbf{100}$$

RD: Relative density of species; **AD:** Absolute density of species (per ha); **TD:** Total density of trees (per ha).

$$\textbf{Equation (6) } \mathbf{RDo} = \frac{\mathbf{ADo}}{\mathbf{TDo}} \times \mathbf{100}$$

RDo: Relative dominance of species; **ADo:** Absolute dominance (or basal area) of species; **TDo:** Total dominance (or basal area) of all species.

To explore information on samples and variables (species) we used a Principal Component Analysis biplot (Gabriel, 1971). A biplot analysis gives a graphical representation of a multivariate sample and it superimpose on the display a representation of the variables on which the sample is measured (Udina, 2005).

Patterns in the species composition of vegetation plots across fallow stages were explored using the Principal Coordinates Analysis (PCoA) based on the original abundance matrix data (Gabriel, 1971). The Principal Coordinates Analysis (PCoA) is an eigen-vector-based method which reduces the dimensionality by projecting multidimensional datasets into a smaller number of dimensions (Huntley, 2011), allowing a much wider definition of dissimilarity than simple Euclidian distance in the species space, focusing on the associations between individual observation in a dataset (Huntley, 2011; Clarke & Warwick, 2001). Calculation of Diversity indices, Evenness, Principal Coordinates Analysis (PCoA) and biplot of Principal Components Analysis (PCA) were computed in PAST-Paleontological Statistics Software (version 2.17).

The overlap of the vegetation composition of the four categories was assessed based on an Analysis of Similarity (One-way ANOSIM). Values of R_{ANOSIM} range from 0 to 1. Values close to 0 indicate strong overlap (Clarke & Warwick, 2001); while values close to 1 indicate complete separation among the groups (McCune et al., 2002). To illustrate how many woody species are shared between the four categories, a Venn diagram was drawn with the Bioinformatics & Evolutionary Genomic Tool <http://bioinformatics.psb.ugent.be/webtools/Venn/>. Additionally, an Indicator Species Analysis (ISA) was calculated in the R Statistical Analysis Software (R Development Team, 2015), to identify the diagnostic species of each fallow stage. Associations of species to more than one fallow stage were allowed (De Caceres et al., 2006; Dufrêne & Legendre, 1997).

Results

Woody species diversity: The species richness, measured by the total number of tree species recorded, was higher in mature forests (44) and medium-aged fallows (41), being lower in old (36) and young fallows (31). The overall species diversity as measured with the Shannon Diversity Index (*H'*) was highest in mature forests (2.91), followed by young fallows (2.81) and medium-aged fallows (2.71). The old fallows showed the lowest species diversity (2.61). The highest value of evenness (*E*) was found in young fallows (0.53), followed by mature forests (0.41) and old fallows (0.37). Medium-aged fallows showed the lowest evenness value (0.36).

The diversity profiles indicate that mature forests were more diverse than medium-aged fallows and old fallows as the graphs of the respective diversity profiles did not intercept, and also they feature higher species richness than young fallows (graph higher for low alpha). Only if evenness (high alpha) is considered, young fallows have higher values than mature forests (Figure 6).

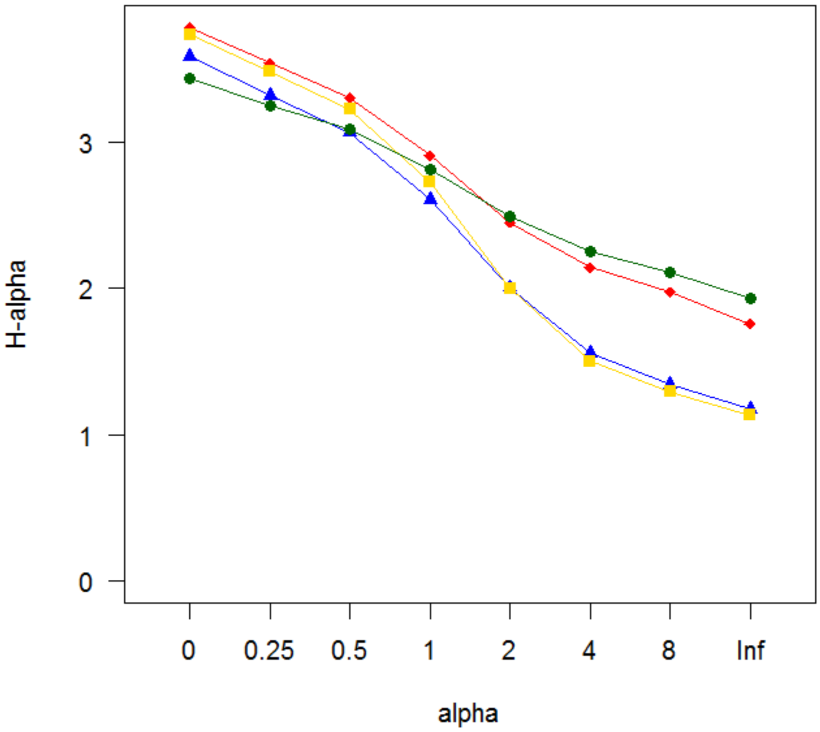


Figure 6: Diversity profiles using Renyi's diversity of three fallows stages and mature forest stands (mature forests, red; old fallows, blue; medium-aged fallows, yellow; young fallows, green).

Stand structure and species composition: We recorded a total of 3,157 individuals: 445 individuals in young fallows, 760 individuals in medium-aged fallows, 965 individuals in old fallows and 987 individuals in mature forests. The mean stand density in early regrowth fallows was 45 ± 16 stems ha^{-1} stems, ranged from 17 - 69 stems ha^{-1}. In the medium-aged fallows the mean stand density was 76 ± 28 stems ha^{-1}, ranging from 35 - 125 stems ha^{-1}. Old fallows showed a mean density of 97 ± 23 stems ha^{-1}, stems ranged from 65 - 140 stems ha^{-1}. While the mature forests mean stand density was 99 ± 48 stems ha^{-1}, ranging from 45 - 191 stems ha^{-1}. Stand density was significantly different between the fallow types and mature forests ($H = 16.18$; $p = 0.001$), being more evident between early regrowth stages, old fallows and mature stands. The mean diameter in mature stands was 13.2 ± 8.8 cm, showing a reverse J-shaped size class distribution with the majority of trees found in the smaller diameter classes, accounting for 47% of stems (Figure 7).

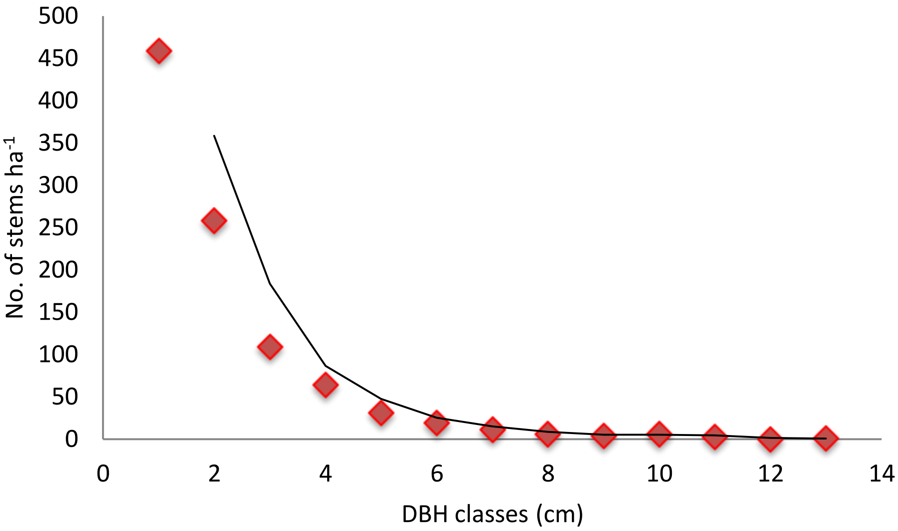


Figure 7: Size-class distribution of mature forests showing a reverse J-shape, the numbers represents the DBH classes in cm. 2 (10-15), 4 (20-25), 6 (30-35), 8 (40-45), 10 (50-55), 12 (60-65) and 14 (≥ 65).

These individuals belong to 51 species from 38 genera and 19 families. Two species could not be identified and other two were only identified to genus level (Appendix 1). The most diverse family was Fabaceae, sub-family Caesalpinioideae representing (30%) of all woody species, followed by Strychnaceae (Loganiaceae) and Combretaceae (9%), Myrtaceae and Proteaceae (7%), Euphorbiaceae (6%), Apocynaceae, Dipterocarpaceae, Euphorbiaceae and Melastomataceae (4%). Rubiaceae and other smaller families represent less than 2% of species.

The structural analysis of woody species represented by the relative values of Frequency, Density, Dominance and Importance Values Index (IVI) is summarized in alphabetical order of the species (Appendix 1). The dominant species ranked by their IVI in all categories were *Brachystegia spiciformis*, *Burkea africana*, *Combretum collinum*, *Combretum zeyheri*, *Cryptosepalum exfoliatum* subsp. *pseudotaxus*, *Diplorhynchus condylocarpon*, *Erythrophleum africanum*, *Julbernardia paniculata*, *Monotes africanus*, *Pericopsis angolensis* and *Terminalia brachystemma.*

The biplot analysis of PCA explained 60% (39% and 21% for the first and second axis respectively) of the species variation observed across the fallows and mature forest plots (Figure 8). The early regrowth stages are characterized by the dominance of *Albizia* spp., *Anisophyllea boehmii*, *Pericopsis angolensis* and *Combretum* species. *Cryptosepalum exfoliatum* subsp. *pseudotaxus* and *Brachystegia spiciformis* dominated the mature stands, while *Erytrophleum africanum*, *Julbernardia paniculata* and *Diplorhynchus condylocarpon* characterized the medium-aged stands and old fallows. *Strychnos* species showed high variation in terms of frequency, density and dominance in all stages. Two exploitable woody species *Guibourtia coleosperma* and *Pterocarpus angolensis* showed few individuals in all fallows stages.

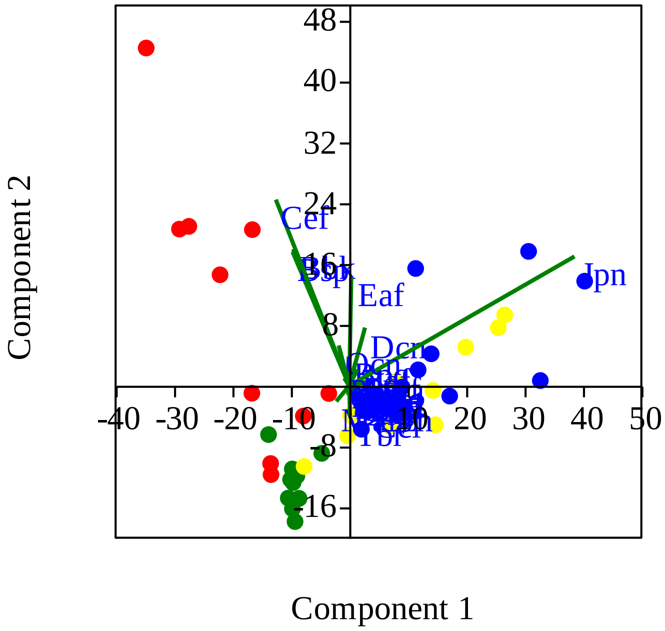


Figure 8: Biplot of the principal components analysis for the variables (species) quantified across the plots, (young fallows, green; medium fallows, yellow; old fallows, blue; mature forests, red).

Principal Coordinates Analysis (PCoA) and Analysis of Similarity (ANOSIM): The Principal Coordinates Analysis of species density and composition distinguished four different groups. The first axis explained 18.4% of variation (Eigenvalue = 1.9), and the second axis explained 14.8% of variation (Eigenvalue = 1.5). The first group was formed by the young fallows; the second and third group was formed by medium-aged and old fallows, while the fourth group was formed by the mature forests (Figure 9).

The old and medium fallows showed many shared species, as indicated by analysis of similarity (R_{ANOSIM} = 0.052). Only few species are shared between young and medium fallows (R_{ANOSIM} = 0.487). The group formed by mature stands is clearly separated from all fallow types. The more ample dispersion of the medium fallows in the ordination diagram indicates that they are more heterogeneous in terms of species composition than the others stages. The analysis of similarity also showed slight variations in species composition among fallows and mature stands.

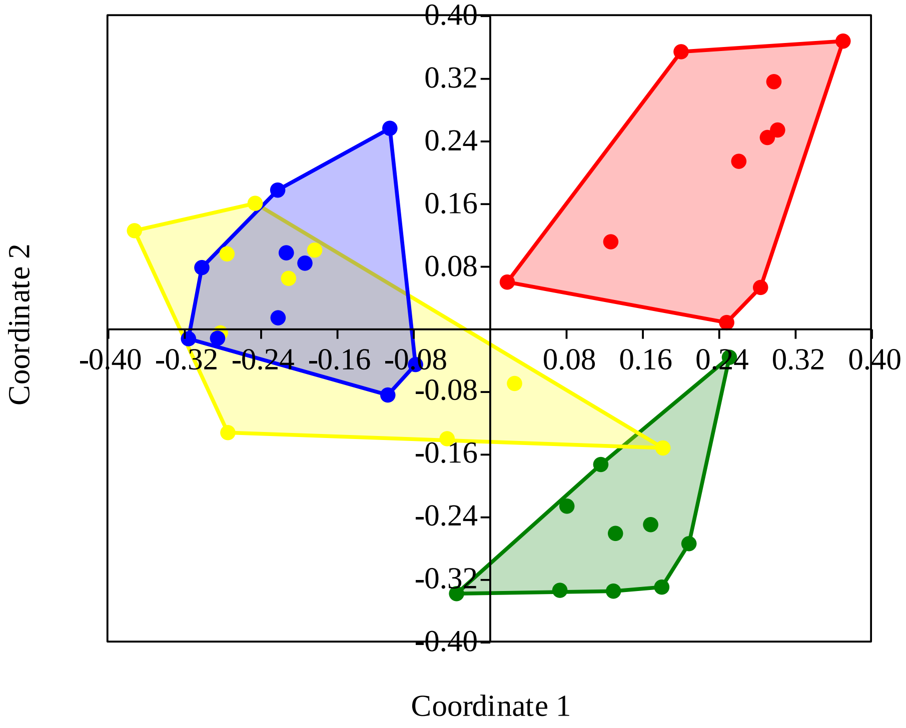


Figure 9: Principal Coordinates Analysis (PCoA) showing the relationship between the tree species composition and fallows stages in the Cusseque study area (young fallows, green; medium-aged fallows, yellow; old fallows, blue and mature forests, red).

The analysis of the Venn diagram found a total of twenty species shared between all categories. Mature stands showed ten unique species and medium fallows showed seven, while two species were found to be unique to old fallows (Figure 10).

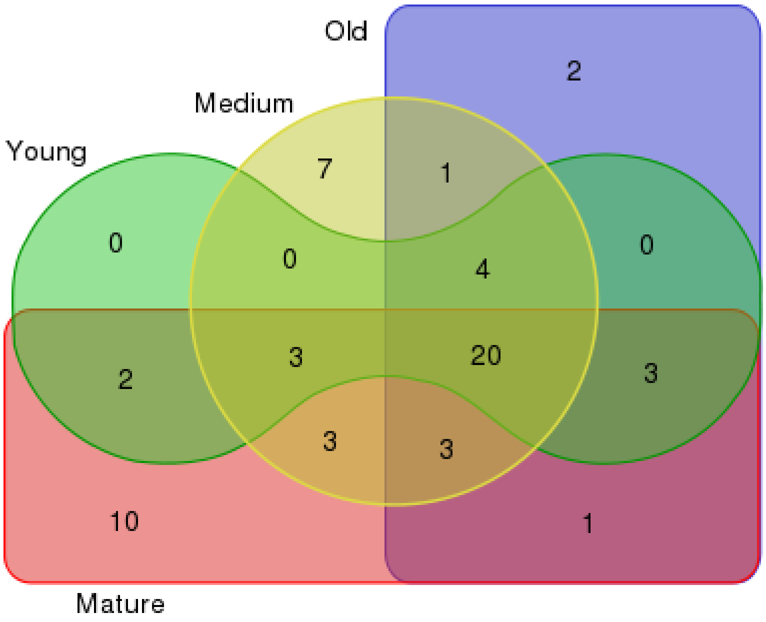


Figure 10: Non-symmetric Venn diagram showing the number of species shared between the forest stages (young fallows, green; medium fallows, yellow; old fallows, blue; mature forests, red).

Indicator Species Analysis (ISA): The analysis of indicator species (Table 2) identified 6 indicator species for the old-growth plots. For the fallow stages, however only a limited number of species were identified as diagnostic. *Combretum collinum* and *C. zeyheri* were indicative of all fallow types. *Albizia gummifera* was characteristic for young fallows and *Pericopsis angolensis* for old fallows. The indicator species analysis shows that typical Miombo species rarely were indicative of fallow types, with the exception of *Julbernardia paniculata* in medium-aged and old fallows.

Table 2: Indicator species, *p* values and significance stars [*] of single and combined groups of fallows stages and mature stands as observed in the Cusseque area.

Fallow age	**Species**	**Ind. value**	***p* values**	**Sig. stars**
Young fallows	*Albizia gummifera*	0.516	0.036	*
Old fallows	*Pericopsis angolensis*	0.808	0.001	***
Medium & Old fallows	*Julbernardia paniculata*	0.971	0.001	***
Medium fallows & Mature forests	*Parinari curatellifolia*	0.632	0.03	*
Medium, Old fallows & Mature forests	*Baphia bequaertii*	0.827	0.028	*
Medium, Old fallows & Young fallows	*Combretum collinum*	0.919	0.002	**
	Combretum zeyheri	0.919	0.001	***
Old fallows & Mature forests	*Ochna schweinfurthiana*	0.765	0.002	**
Mature forests	*Cryptosepalum exfoliatum* subsp. *pseudotaxus*	0.857	0.001	***
	Brachystegia bakeriana	0.796	0.002	**
	Strychnos cf. mitis	0.707	0.002	**
	Warneckea sapinii	0.674	0.009	**
	Combretum sp.	0.632	0.005	**
	Memecylon flavovirens	0.548	0.048	*

Discussion

Woody species diversity: Species diversity is the most commonly used representation of ecological diversity and can be measured from the number of species (species richness) and relative abundance of individuals within each species (species abundance) (Hamilton, 2005). We assessed woody species diversity in multiple ways including species richness, which was measured from the total number of species occurring in different fallows stages and mature forests. We observed an increase in species richness with fallow age. However, stand age may not necessarily be the most important determinant of floristic composition and even stand structure. Others factors, such as initial floristic composition and land use history may need to be considered further (Uhl, 1987; Kwibisa, 2000). The observed species richness values in the early stage of regrowth are comparable to those of mature stands, while the species composition did not completely recover in the observed time frame and may take several decades to be the same as mature forests (N'Dja & Decocq, 2008).

Further diversity measures such as Shannon diversity and Evenness (Buzas & Gibson's) were used to assess the diversity of woody species in the study area. The Shannon Diversity Index normally varies from 1.5 to 3.5, rarely exceeding 4.5 (Kent & Coker, 1992). The overall species diversity values found in our study area are in the range of the values encountered in other studies in Miombo woodlands of south-central Africa, indicating that young regrowth and mature forests had high species diversity, while the intermediate stages had low species diversity (Lumbwe, 2010).

The species diversity values encountered were considerably higher, compared to other studies conducted in Miombo woodlands in Tanzania where the values found were $H' = 1.31$, $H' = 1.32$ and $H' = 1.42$ (Isango, 2007), and close to those encountered in Zambian Miombo ($H' = 2.5$ in 20 yrs of fallow and $H' = 2.6$ in 30 yrs of fallow) (Kalaba et al., 2013). The evenness values found were similar in the intermediate stages, implying that the individuals of different species recorded had relatively similar abundances at both stages. Differences in species richness and diversity of the forests are reported to be dependent upon the amount of rainfall that the area receives annually (Jew et al., 2016).

The high diversity value found in young fallows is a bit unexpected, but can be explained by the high environmental heterogeneity of fallows in early successional stages. Young fallows still host some sprouts from stumps of mature forest species, while strong disturbances (like slash-and-burn agriculture) allow light demanding pioneer species to recruit and establish, thus increasing the number of species (Banda et al., 2006). With ongoing succession, some of the original forest remnants are disappearing, in part due to environmental stress and to losing out in light competition with early succession species, which causes a decline in species diversity in the mid succession stages. At the same time, the light demanding pioneer species are already disappearing in mid succession.

Other studies reported similarly that species diversity tended to reach levels close to mature forests relatively quickly after disturbance, by maximizing the co-existence of fast growing pioneers and more competitive canopy species, followed by delayed recovery of woody biomass (Uhl, 1987; Mwampamba & Schwartz, 2011; McNicol et al., 2015). However, the disturbance intensity of agricultural use may be too high for fast regeneration dynamics. The reestablishment of mature forest species is a slow process, which demands longer time periods than the chronosequence used in our study.

Species composition: We recorded a total of 3,157 individuals of 51 tree species in a total area corresponding to 4 ha. The total number of species encountered in our study area is sharply far from that encountered in Zambian Miombo, where a total of 2,761 individuals corresponding to 83 species was recorded for mature woodlands (Kalaba et al., 2013) and it is in the range of values reported in Tanzania and Zimbabwe (Mafupa, 2006; Gandiwa et al., 2013), although using different plot size. The total number of individuals found in the early stages falls within the range encountered in the Miombo woodlands of Kitulangalo Forest Reserve in Tanzania and in Miombo woodlands of Mozambique, using the same plot size or size thresholds for tree inclusion (Mbwambo et al., 2008; Ribeiro et al., 2013). Significant differences found regarding stand density between early regrowth stages and mature stands may be explained by the fact that abandoned sites are characterized by a continuous decrease in dominance of early-successional and fire resistant species, and an increase in the presence of slow-growing tree species commonly associated with mature forest habitats (McNicol et al., 2015). A reverse J-shape size class distribution observed in the mature stands may indicate a stable population and good recruitment of late successional species.

The woodlands of Cusseque area are dominated by the typical tree species that characterize Miombo forests all over south-central Africa (Grundy et al., 2004, Oyugi et al., 2007; Shirima et al., 2015a). The sole exception was *Isoberlinia angolensis* which was surprisingly not found in the area, although it is cited as a common co-dominant species in many Miombo forests (White, 1983; Chidumayo, 1987; Desanker & Prentice, 1992). The dominance of the Fabaceae subfamily Caesalpinioideae has also been reported in various studies (Francisco et al., 2014; Muboko et al., 2013; Mwakalukwa et al., 2014). In general, the forest stands showed high variation in terms of species composition, which may imply that each species has a different ecological importance (Wale et al., 2012). Strong environmental changes caused by slash-and-burn agriculture, particularly in terms of soil nutrients and microclimate, are slowly converging to the previous conditions with increasing of fallow age, and may also influence the changes in species composition.

The dominance of *Combretum* spp. often characterizes areas with high land use pressure, where the species becomes the fastest growing and most dominant tree in early succession stages (Jew et al., 2016). The occurrence of *Combretum* species after disturbance was also reported in various other studies on early secondary succession of Miombo in south-central Africa (Stromgaard, 1986; Backéus et al., 2006). The early stages of regrowth are frequently characterized by a high dominance of fire tolerant genera such as *Burkea*, *Pterocarpus*, *Pseudolachnostylis* and *Terminalia* (McClanahan & Young, 1996) and by light demanding genera such as *Albizia*, *Strychnos* and *Uapaca* (Kalaba et al., 2013). Kwibisa, (2000) found *Brachystegia spiciformis* and *Julbernardia paniculata* as dominant tree species among the canopy of Zambian Miombo, while the understory was dominated by *Combretum* spp., *Ochna shweinfurthiana*, *Pseudolachnostilis maprouneifolia*, *Diplorhynchus condylocarpon*, *Terminalia* spp. and *Burkea africana*.

Erythrophleum africanum and *Pericopis angolensis* were recorded in all stand stages, with the exception of the latter, which is not found in mature forest stands. This can be explained by the fact that these tree species are frequently left standing on fields because of the hardness of its trunks. The few individuals of *Guibourtia coleosperma* and *Pterocarpus angolensis* found in the study area can be explained by the importance of these woody species as timber and commercial value associated, both species were referred as the most exploited woody species in the Angolan part of the Okavango basin, at least in the colonial era (Baptista, 2014).

The mature forest plots were dominated by *Brachystegia spiciformis*, *Burkea africana*, *Cryptosepalum exfoliatum* subsp. *pseudotaxus* and *Monotes africanus.* The absence of *B. spiciformis* in the grass dominated stages of previously farmed areas may be due to the species being fire sensitive (McClanahan & Young, 1996). The Miombo species indicators showed low dominance in the early stages of regrowth and increased in dominance with age, with the exception of *J. paniculata*, which was more dominant in the intermediate stages of fallows than in mature forest stands, reinforcing the assumption that the mature stands in the study areas are characterized by the dominance of *C. exfoliatum* subsp. *pseudotaxus*. These findings are also in accordance with the biplot diagram displayed from the Principal Components Analysis.

The dominance of *C. exfoliatum* subsp. *pseudotaxus* may also be related to sites which are unsustainable for agriculture. Therefore, rarely hits by fire, according to local knowledge these areas are normally used for other activities, such as honey production. The long-term leaching processes caused by high precipitation made some of the soils of mature forests very acidic with the lowest pH values encountered also in the study area (Chidumayo, 1999; Gröngröft et al., 2013), which may explain the unsuitability of these areas for agricultural purposes.

The Miombo woodlands demonstrate remarkable capacity to return to mature stages after disturbance (Shirima et al., 2015a). Natural recovery from stumps and resprouts of suppressed saplings could explain the increasing number of species with age, as observed in our study site and also reported in various studies in southern Africa (*e.g.* Chidumayo, 2004). The demand of land for slash-and-burn agriculture means that much of the newly cropped lands quickly degrades and becomes unsuitable for agriculture. Therefore, efficiency of the agricultural systems needs to be enhanced to improve the longevity of fields and reduce the consumption of forests by slash-and-burn agriculture.

Principal Coordinates, Similarity and Indicator Species Analysis: The Principal Coordinates Analysis (PCoA) delimited four different groups. The group formed by the mature stands was consistent with the analysis of similarity, and the distinction of this group can be also explained by the dominance of *Cryptosepalum exfoliatum* subsp. *pseudotaxus*, as demonstrated by the Indicator Species Analysis. Local site-specific environmental characteristics such as relief, topography and physico-chemical soil properties may play a secondary role, as demonstrated in other studies in the woodlands of southern Africa and savanna biome of southern America (Syampungani, 2009; Lenza et al., 2015).

Conclusions

The Cusseque study area is characterized by a high diversity of tree species, with the number of tree individuals and species diversity increasing with fallow age. This trend shows an ongoing recovery process of the mature forest ecosystems after slash-and-burn agriculture, as long as the woodlands are not subjected to others disturbances. The recovery process may take several decades to reach mature forests status. Increasing pressure for land demand and other disturbances increasingly becomes a determining hindrance for forest recovery.

Conflict of Interests

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgements

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Chapter 3

Species diversity, population structure and regeneration of woody species in fallows and mature stands of tropical woodlands of Southeast Angola

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Abstract

This study in the dry tropical woodlands of SE Angola in Cuando-Cubango Province assessed the diversity and composition of woody species in fallows compared to those in mature woodlands. We assessed the population structure of the most harvested woody species by calculating size class distribution and evaluated their regeneration potential based on the density of saplings. The vegetation was surveyed in 20 plots of 20 m × 50 m (1000 m^2). In each plot, we measured the diameter at breast height (DBH) of all woody species with DBH $\geq$ 5 cm. The saplings were counted, identified and recorded; 718 individuals, corresponding to 34 species in 32 genera and 15 families were recorded. The size class distribution of target woody species showed three different patterns in fallows and mature woodlands. In general, most of the smaller diameter classes had more individuals than the larger ones did, showing that the regeneration may take place. However, in some diameter classes, the absence of larger stems indicated selective logging of larger trees. Few saplings were recorded in the fallows or mature woodlands; fire frequency and intensity is probably the main obstacle for seed germination and seedling survival rates in the studied area.

Keywords: *Baikiaea* woodlands, fallows, mature woodlands, regeneration, woody species.

Introduction

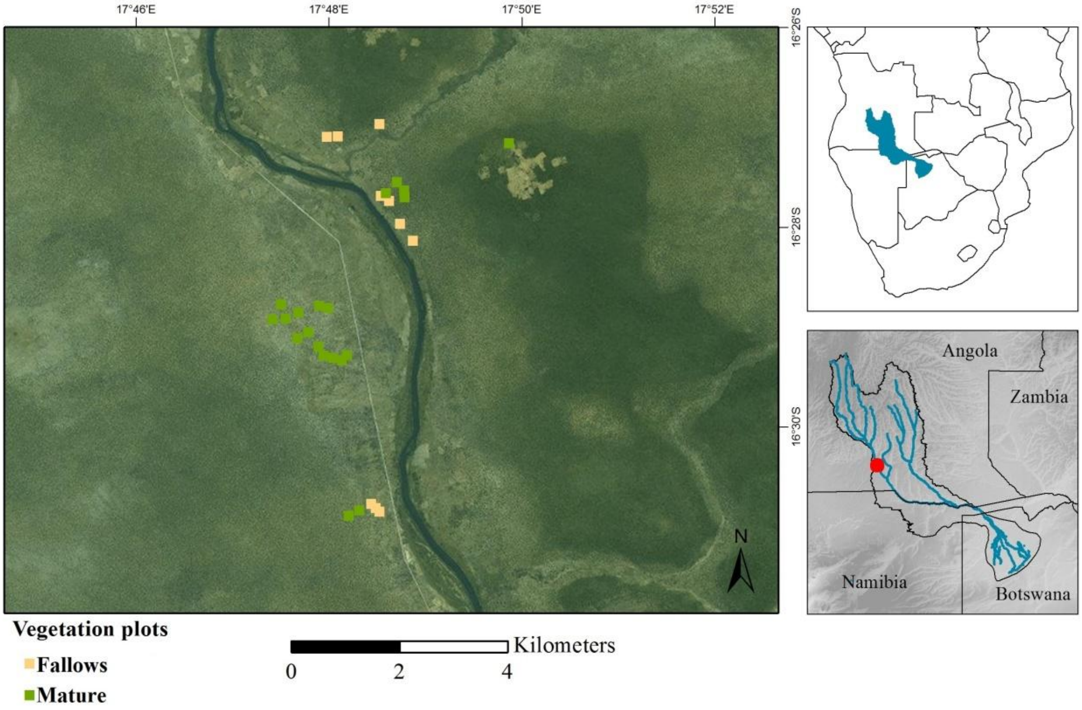
Southern African tropical woodland covers an estimated area of about 265,000 km^2 extending from south-eastern Angola to north-eastern Namibia, across north-eastern Botswana, south-western Zambia and north-western Zimbabwe (Timberlake et al., 2010). The region is dominated by open woodlands with numerous hardwood species, including *Baikiaea plurijuga*, *Pterocarpus angolensis* and *Guibourtia coleosperma* (Barbosa, 1970; Strohbach & Petersen, 2007). The study area in Caiundo lies within this ecoregion on deep Kalahari sand in a wide belt along the Angolan-Namibian border. Where other important vegetation subunits are present, they comprise *Erythrophleum africanum-Bauhinia urbaniana* vegetation unit (*Baikiaea-Burkea* woodlands, dense and medium dense), *Diplorhynchus condylocarpon-Gymnosporia senegalensis* unit (*Baikiaea-Burkea* woodlands, open grasslands), *Combretum celastroides-Baikiaea plurijuga* woodlands (*Baikiaea-Burkea* woodlands with thicket-like understory) and the *Acacia sieberiana-Piliostigma thonningii* vegetation unit (grasslands) located on the floodplains (Frantz et al., 2013; Revermann & Finckh, 2013). Dry woodlands support over 60% of people in Africa providing them with wide range of environmental goods and services (Shackleton et al., 2010). However, these benefits are threatened by deforestation and forest degradation. Globally, direct drivers of changes in dry tropical forests and woodlands encompass habitat change and land degradation, climate change and extreme weather events, fire and over-exploitation of natural resources (Milles et al., 2006). The area around Caiundo in south-eastern Angola contains relatively intact *Baikiaea-Burkea* woodland (Revermann & Finckh, 2013). However, demand for more agricultural areas in post-war Angola has lead to increased clearing of woodlands (Wallenfang et al., 2015). Illegal logging is a serious problem in nearby northern Namibia (Pröpper & Vollan, 2013). Although some studies have addressed the *Baikiaea* woodlands, hardly any investigations have been carried out in Angola. Thus, much still remains to be understood in terms of regional and local variation in community composition, diversity and especially responses to human disturbance (Zimudzi et al. 2013). With this study we aimed to:

a) Investigate the diversity and composition of woody species in fallows as compared to mature woodlands;

b) and to analyse the population structure of harvestable tree species and regeneration status of woody species;

Material and Methods

Study area: The study area is located along the Cubango/Okavango river (Figure 11), about 90 km south of the confluence of the Cubango and Cuebe rivers in Mulemba village at an elevation of 1155 m.a.s.l. (Weber, 2013). The climate is semi-arid with a pronounced rainy season between November and March and a dry period from May to September. October and April are considered transition months (Diniz, 1973). During the period 1971-2000, the mean annual precipitation was 732 mm. Over the period 1950-2009, the annual rainfall showed a high inter-annual variability without any obvious trend (Weber, 2013). Caiundo has an annual mean temperature of 22.5°C and an average temperature of 26.3°C in the hottest month, October, and 16.8°C in the coldest month, July (Diniz, 1973; Weber, 2013). The long-term annual mean temperature shows alow interannual variability with an increase in temperature since the mid 1960s. On average, 17 frost days per year were recorded between June and September (Weber, 2013). The vegetation in the study area represents mostly intact *Baikiaea*-*Burkea* woodlands of south-eastern Angola, and it is almost entirely restricted to sandy substrates (Revermann & Finckh, 2013). Pure stands of *Baikiaea plurijuga* rarely occur; typically, they are associated with *Shinziophyton rautanenii*, *Guibourtia coleosperma*, *Burkea africana*, *Pterocarpus angolensis*, *Dialium englerianum*, *Erythrophleum africanum*, *Parinari curatellifolia*, *Bobgunnia madagascariensis* and sparsely with *Julbernardia paniculata*. The woody tree species range from 5 to 12 m in height, and the shrub layer comprises *Baphia massaiensis* subsp. *obovata*, *Copaifera baumiana*, *Diplorhynchus condylocarpon*, *Ochna pulchra*, *Paropsia brazzaeana*, *Strychnos* spp. and *Xylopia tomentosa*. Grasses are sparse and wiry, up to 1.5 m tall; characteristic species are *Trachypogon spicatus*, *Schizachyrium jeffreysii*, *Tristachya superba*, *Aristida stipitata* and *Digitaria eriantha* (Wallenfang et al., 2015). The vegetation here may represent a reference state, as the human impact is relatively low compared to other areas near the river (Revermann & Finckh, 2013). However, the area is heavily impacted by fire with high fire return periods of only a few years (Frantz et al., 2013). The human population density in the study area is relatively low and largely governed by the ease of access to water (Diniz, 1973; Frantz et al., 2013). People mostly belong to the Ganguela ethnic group with various sub-groups (Diniz, 1973). Some significant but isolated and nomadic groups of San people also inhabit the study area. Agriculture, livestock keeping and fishing are the main socio-economic activities. Small businesses were also observed in the most populated villages such as the Savate and Caiundo villages and selling of freshwater fish, bushmeat and other forest goods has become common along the main Katwitwi-Caiundo-Menongue road (personal observations).



Projection: WGS 1984; background: ESRI ArcGIS basemap

Figure 11: Location of the Okavango basin in southern Africa and the study site in Caiundo with plots location. The Okavango basin follows the definition of the "The Future Okavango project". (reproduced with permission from: <www.future-okavango.org>, Wehberg & Weinzierl, 2013).

Data collection: Sites were selected through informal interviews with traditional authorities of Mulemba village and the wider community, aiming to identify sites with previous agriculture use and known age since abandonment. In contrast to the Miombo region of Cusseque area (Gonçalves et al., 2017), agricultural fields here can be cultivated for longer time spans, and local farmers have reported fields with more than 20 years of continuous cultivation. Thus, identifying suitable fallows for the study was very difficult. However, we were able to identify 10 sites abandoned during the post-electoral conflict (1992-1993). Woodlands were considered as mature if they showed no evidence of past disturbance, *e.g.*, agriculture or wood cutting. Because the western and eastern banks of the river have been reported to have a slightly different species composition (Revermann & Finckh, 2013), we included both sides of the river in the sampling scheme. The fieldwork was carried out in September 2014, using a 20 m × 50 m plot design (Felfili et al., 2005). Twenty plots were sampled: 10 in the fallows with an approximate age of *ca*. 15-20 years and 10 in mature woodlands. Plots were placed randomly in the area of the identified fallows and mature woodlands. On every plot, we measured all individuals with girth equal or above 15 cm, corresponding to a diameter at breast height (DBH) ≥ 5 cm, using a tape measure. Regeneration of woody species was inferred from saplings, which refers to young trees less than 5 cm in DBH, within one central 100 m^2 subplot and from size class distribution curves for harvestable woody species. The species were identified based on the first author's field experience with Angolan flora and available literature (Mannheimer & Curtis, 2009), and by their local names in Ganguela (given by local field guides). Field names were later replaced by scientific names following the identification of voucher specimens, which were deposited in the Herbarium of Lubango (LUBA). We choose to retain the recently published "Checklist of Angolan Vascular Plants" (Figueiredo & Smith, 2008) as the standard for scientific names of species and authors, despite some recent changes in botanical nomenclature.

Data Analysis

Woody species diversity and composition: Species richness was measured from the total number of species recorded in each stand. Woody species diversity in fallows and mature woodlands was measured by the Shannon-Wiener diversity index (Magurran, 2004), calculated as given in Equation 1. Significant differences in the species diversity and evenness between the fallows and mature woodlands were determined using *t* tests ($\alpha = 0.05$). The Shannon-Wiener diversity index H' was calculated as:

$$\textbf{Equation (1)}: \mathbf{H'} = -\sum_{i=1}^{n} \boldsymbol{pi} \ \mathbf{ln}\ (\boldsymbol{pi})$$

Where p_i is the number of individuals of species in a given plot, divided by the total number of individuals in the plot. Species evenness was measured by Pielou's Evenness Index (Pielou, 1966) given in Equation 2.

$$\textbf{Equation (2)}: \boldsymbol{E'} = \frac{\boldsymbol{H'}}{\boldsymbol{Hmax}}$$

Where: H_{max} is the natural logarithm of *S*, species richness. Additionally, we calculated diversity profiles for the mature woodlands and fallows. The diversity profiles play an important role in terms of diversity comparisons, using α as reference scale parameter (Tóthmérész, 1995). The scale parameter alpha gives the order of Renyi's diversity with $\alpha = 0$ refers to species richness, $\alpha = 1$ gives an index proportional to the Shannon diversity, $\alpha = 2$ corresponds to the Simpson's index (Hammer, 2012). Importance Value Index is an important parameter that indicates the ecological significance of species in a given ecosystem, and is being widely used to assess the floristic composition in forest systems, including African savanna and woodlands. The woody species composition of the plots was assessed by the IVI (Equation 3), which is a summation of the relative values of frequency, density and dominance (Curtis & McIntosh, 1951). A non-parametric sign *test* was used to test differences in IVI between fallows and mature woodlands of most abundant species:

$$\textbf{Equation (3)}: \boldsymbol{IVI} = \frac{(\boldsymbol{RF} + \boldsymbol{RD} + \boldsymbol{RDo})}{\mathbf{3}}$$

Where: *RF* is the relative frequency of species obtained from absolute frequency, dividing the number of sampling units (100 m^2 subplots) in which the species occurs, by the total number of sampling units; *RD* is the relative density of species obtained from absolute density calculated from the total number of individual of a species present in a plot divided by the total area sampled (0.1 ha) and *RDo* is the relative dominance of species obtained by dividing the total basal area for a given species by the total basal area of all species per plot. The similarity of woody species between fallows and mature woodlands was calculated from Jaccard similarity index (*J'*, Equation 4), as it is a useful measure to determine the extent of overlap of tree species between two forest communities in this case forest stages (Kalaba et al., 2013).

$$\textbf{Equation (4)}: \boldsymbol{J'} = \frac{\boldsymbol{A}}{(\boldsymbol{A} + \boldsymbol{B} + \boldsymbol{C})}$$

Where $\boldsymbol{A}$ is the number of species found in both communities, $\boldsymbol{B}$ is the species in community $\boldsymbol{A}$ and not in $\boldsymbol{B}$, $\boldsymbol{C}$ is the species in $\boldsymbol{B}$ and not in $\boldsymbol{A}$ (Chidumayo, 1997). The index assumes values between 0 and 1, with value 1 indicating that all species co-occur (Jaccard, 1912). To investigate the variation within the species composition, using the abundance of species, we calculated Detrended Correspondence Analysis (DCA). This ordination method is widely used in ecological data because it avoids the arch effect caused by unimodal species response curves by detrending, and rescaling in order to preserve ecological distances within the interactive calculation process (Hill & Gauch Jr., 1980). The axis in DCA are scaled into units of the average standard deviation (SD units), with the length of the first axis referring to the heterogeneity or homogeneity of the data set (Lepš & Šmilauer, 2003).

Population structure and regeneration of woody species: Traditionally, forest inventory practices have concentrated on the structural characteristics that are important for timber management (Graz, 2004). However, the analysis of population structures provides a deeper insight when assessed for each individual tree species, providing specific information on population dynamics and recruitment, which facilitates prediction of future states of the species in the forest community (Didita et al., 2010). The population structure in this study was assessed only for *Baikiaea plurijuga*, *Guibourtia coleosperma*, *Pterocarpus angolensis* and *Schinziophyton rautanenii* that are normally harvested due to their potential economic value. We constructed bar charts using the number of individuals (*y*-axis), categorized into 13 diameters classes (*x*-axis) with size class intervals of 5 cm (MacLaren & MacDonald, 2003; Neelo et al., 2015). The regeneration status of woody species can be determined from the profile. An inverted J-shaped size class distribution indicates a stable population (Bin et al., 2012), whereas a unimodal J-shape distribution with fewer juveniles than adults is taken as evidence of population decline (Condit et al., 1998). Under dry tropical conditions, vegetative regeneration is reported to be more effective than seed regeneration, which is more subject to negative anthropogenic effects. Regeneration of woody species was characterized from sapling density, where density is the number of recruits in a unit area (Yang et al., 2014).

Results

Species diversity: A total of 718 individuals were measured, 336 in fallows sites and 382 in mature woodlands sites, corresponding to 30 (12.8 ± 1.9) woody species in fallows and 28 (10.2 ± 1.6) in mature woodlands. We recorded 34 woody species in 32 genera, belonging to 14 families; only one species could not be identified (Table 1). The most diverse family was Fabaceae (12), followed by Euphorbiaceae (5), Combretaceae (3); Annonaceae, Anacardiaceae and Strychnaceae (2); and Apocynaceae, Burseraceae, Celastraceae, Ochnaceae, Polygalaceae, Rhamnaceae, Rubiaceae and Sterculiaceae (1). Species diversity measured by the Shannon diversity index was 2.98 (2.26 ± 0.15) in fallow sites and 2.68 (1.90 ± 0.39) in mature woodlands and was significantly higher in fallows compared to mature woodlands ($p = 0.012$). Diversity profiles indicated that the fallow plots had greater diversity than in mature woodlands plots, since the diversity profile curve of fallows was higher than that of mature woodlands and the curves did not intersect (Figure 12). The overall evenness was 0.88 (0.89 ± 0.03) in fallows sites and 0.80 (0.28 ± 0.12) in mature woodlands, and non-significant difference was found between the two stages ($p = 0.098$), indicating that species abundance distributions were more or less equal in both stages, fallows and mature stands.

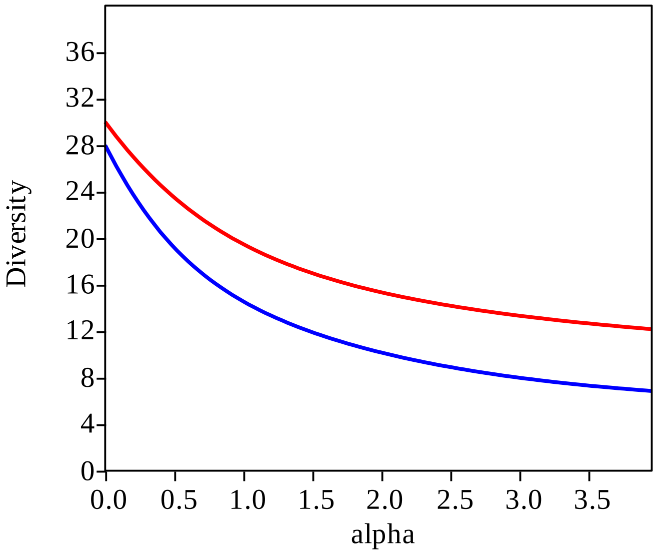


Figure 12: Diversity profiles using Renyi's diversity in the fallows (red) and mature woodlands (blue) in the Caiundo study area.

Species composition: Twenty-three woody species were recorded in both sites. Seven woody species occurred only in the fallows, while only five were unique to the mature woodlands (appendix 2). The most dominant species in both stages based on their IVI were *Baikiaea plurijuga*, *Combretum collinum*, *Diplorhynchus condylocarpon*, *Erythrophleum africanum*, *Ochna pulchra*, *Pterocarpus angolensis* and *Schinziophyton rautanenii*. *Baphia massaiensis* subsp. *obovata*, *Terminalia sericea* and *Combretum zeyheri* characterized the fallows sites, while the mature woodlands were characterized by the dominance of *Burkea africana*, *Dialium englerianum* and *Pseudolachnostylis maprouneifolia* var. *dekindtii*. No significant difference ($p = 0.754$) was found in IVI of most-abundant species between fallows and mature woodlands. The Jaccard similarity index (J') indicated high similarity of woody species composition of fallows and mature woodland sites (0.66). This result was also supported by the Detrended Correspondence Analysis (DCA) showing no separation in species composition among the fallows and mature woodlands (Figure 13). The first and second axes lengths equalled 4.48 and 5.40 and eigenvalues of 0.44 and 0.24, respectively, giving an indication of similar species composition among the two stand stages.

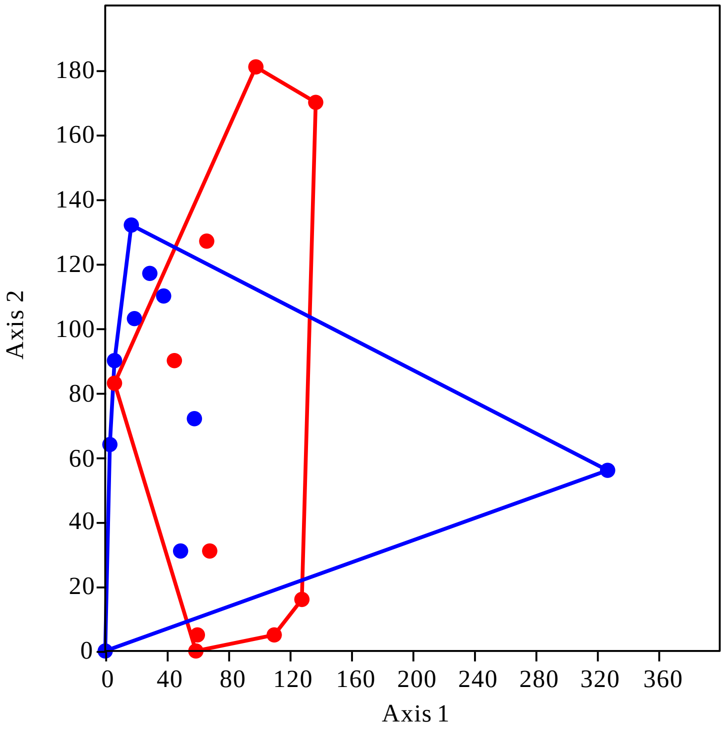


Figure 13: Detrended correspondence analysis (DCA) ordination showing the vegetation sample plots marked by convex hulls in both stand stages, fallows (red dots) and mature woodlands (blue dots).

Population structure and regeneration status of woody species: The population structure of the four most harvested woody species had three general size class distribution patterns in the fallows. An irregular J-shape for *B. plurijuga* resulted from few or no stems in the second and third diameter classes, and a bell-shape for *P. angolensis* resulted from having more stems in the middle diameter classes and fewer in the lower diameter classes. An interrupted, inverted J-shape was found for *S. rautanenii*, with more stems in the lower diameter classes and fewer in the higher diameter classes, but with few or no stems in the intermediate diameter classes (Figure 14). In the mature woodlands, the population structure for *B. plurijuga* followed a bell-shaped curve and an interrupted inverted J-shape for *P. angolensis* and *S. rautanenii* (Figure 15). For the fourth species with commercially important timber, *G. coleosperma*, there were too few individuals measured, making it difficult to conclude anything about the population status of the species in either the fallows or mature woodlands. In the fallows, the saplings had 104 stems 0.1 ha^{-1} ranging from 4 to 21 stems, but only 43 stems 0.1 ha^{-1}, with a range between 2 and 16 stems in the mature woodlands. In the fallows, *Baikiaea plurijuga*, *Diplorhynchus condylocarpon* and *Schinziophyton rautanenii* had the highest density of saplings with 11 individuals (ind.), followed by *Combretum zeyheri* (10 ind.); *Baphia massaiensis* subsp. *obovata* and *Terminalia sericea* (9 ind.); *Combretum collinum* and *Pterocarpus angolensis* (7 ind.); *Burkea africana* (6 ind.); *Ochna pulchra*, *Bauhinia urbaniana*, *Bobgunnia madagascariensis*, *Dialium englerianum*, *Hymenocardia acida* var. *acida*, *Pseudolachnostylis maprouneifolia* var. *dekindtii*, *Vangueriopsis lanciflora* and *Xylopia tomentosa* (2 ind.); and *Guibourtia coleosperma*, *Hexalobus monopetalus* and *Oldfieldia dactylophylla* (1 ind.). In contrast, in the mature woodland, the most common saplings belonged to *D. condylocarpon* (10 ind.); *O. pulchra* and *P. angolensis* (6 ind.), *Strychnos pungens* (4 ind.), *B. plurijuga*, *B. africana*, *C. collinum*, *Dombeya burgessiae*, *Erythrophleum africanum*, *Hymenocardia acida* var. *acida* and *O. dactylophylla* (2 ind.); and *B. madagascariensis*, *D. englerianum* and *S. rautanenii* (1 ind.).

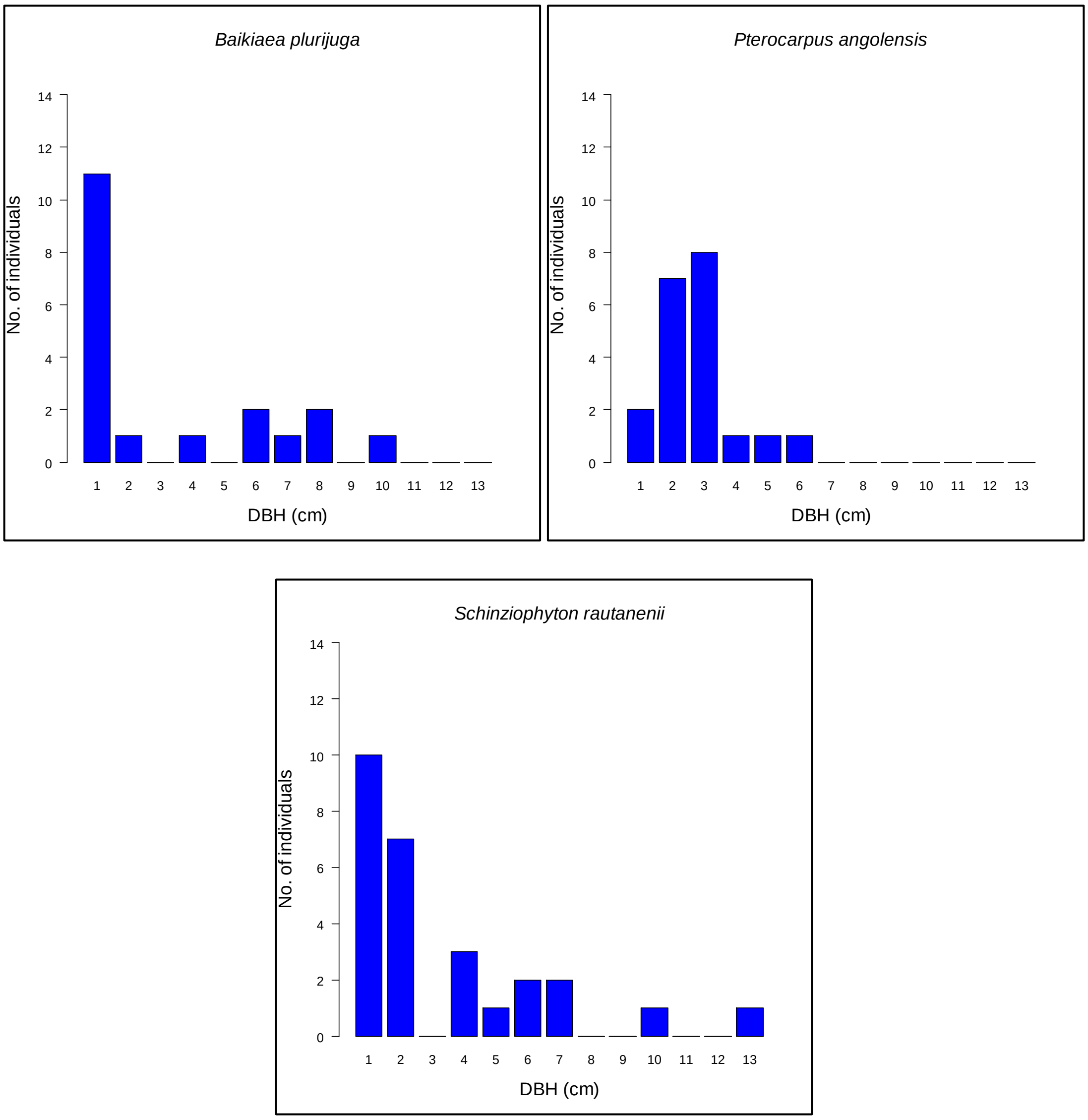


Figure 14: Size-class distribution of harvestable woody species in the fallows, the numbers (1-13) represents the DBH classes in cm, 1(5-10); 2(10-15); 3(15-20); 4(20-25); 5(25-30); 6(30-35); 7(35-40); 8(40-45); 9(45-50); 10(50-55); 11(55-60); 12(60-65) and 13(>65).

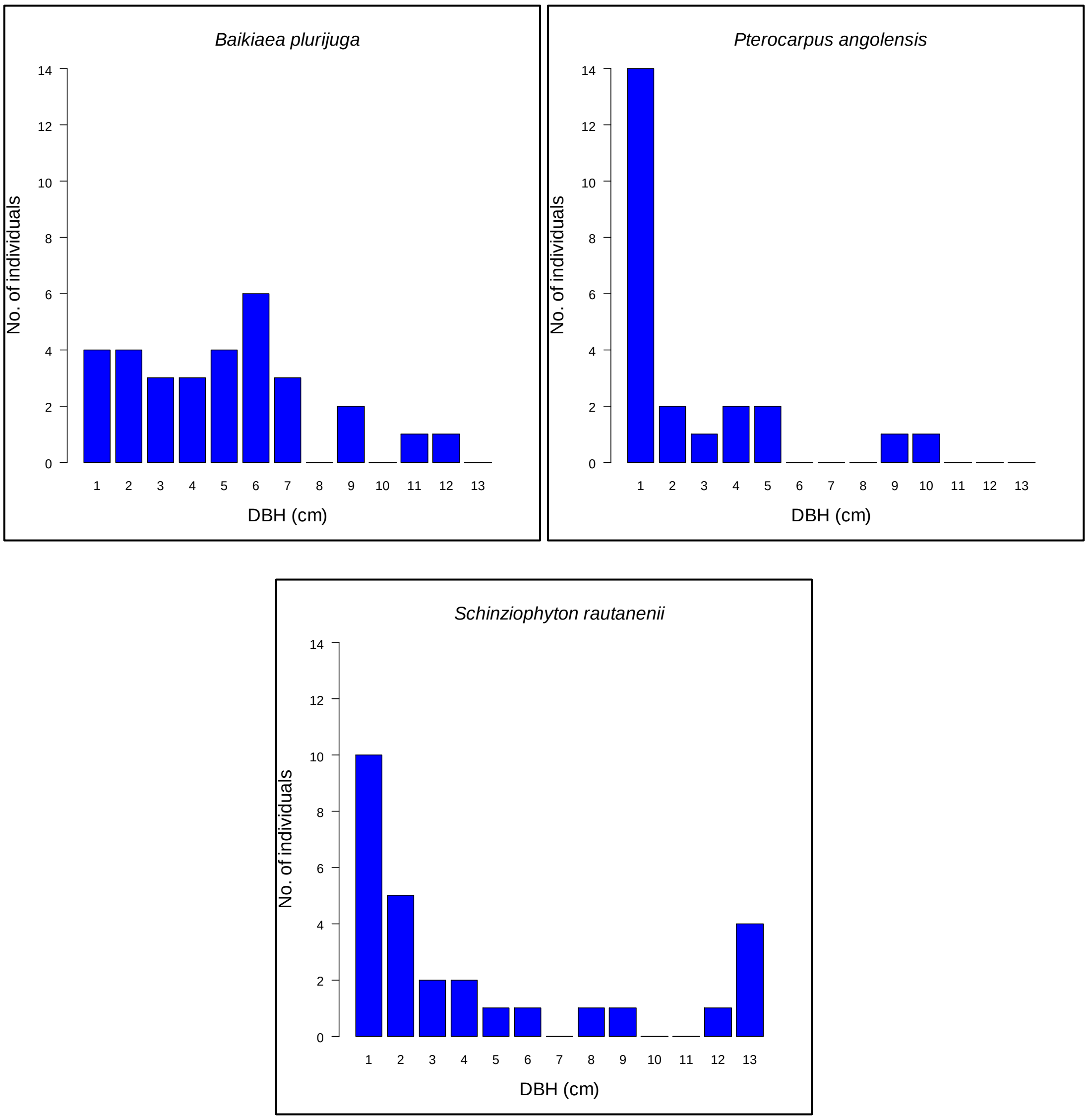


Figure 15: Size-class distribution of harvestable woody species in mature forest, the numbers (1-13) represents the DBH classes in cm, 1(5-10); 2(10-15); 3(15-20); 4(20-25); 5(25-30); 6(30-35); 7(35-40); 8(40-45); 9(45-50); 10(50-55); 11(55-60); 12(60-65) and 13(>65).

Discussion

Woody species diversity and composition: The canopy tree species *Burkea africana*, *Erythrophleum africanum, Guibourtia coleosperma* and *Pterocarpus angolensis* occurred in almost all plant communities as did the species of the lower tree layer *Combretum collinum*, *Diplorhynchus condylocarpon*, *Ochna pulchra*, and *Pseudolachnostylis maprouneifolia* var. *dekindtii*. These species can therefore be considered characteristic for the woody vegetation of the Cubango basin as a whole. Fallow sites varied slightly in species diversity as measured by the Shannon diversity index compared to mature woodlands, probably caused by the relatively high species richness in the fallows sites; this index may increase as richness also increases for a given pattern of evenness (Buzas & Hayek, 2005; Colwell, 2009), but also because the latter stages of abandonment are characterized by a reduction of the dominance of early-successional and fire resistant species and an increase in slow-growing, fire-tender tree species commonly associated with old-growth habitats (McNicol et al., 2015).

The overall species diversity in the fallows and mature stages was higher than reported for other woodlands of the ecoregion (Nduwayezu et al., 2015; Neelo et al., 2015), although these other studies used a smaller sample plot size, considered the minimal sampling area for upland forests and woodlands (Kent & Coker, 1992). Our results are therefore not directly comparable as the size of sample plots used may have a strong effect on the obtained results. Comparing diversity across different studies may also be an inadequate approach, since species diversity is dependent also on local and environmental conditions. The use of larger sampling areas is to be encouraged, as frequency of species and diversity levels increase with sampling effort (Kacholi, 2014). Evenness measures the homogeneity of abundances in a sample or in the community (Colwell, 2009). The overall evenness values found in the present study were more or less similar in the fallows and mature sites, implying that individuals of different species have moderately similar abundances in both stages (Neelo et al., 2015). *D. condylocarpon* and *Schinziophyton rautanenii* had the highest IVI. In general, these species are not commonly harvested for timber in the studied area. *D. condylocarpon* was reported to be harvested occasionally for firewood and medicinal uses, while *S. rautanenii* is harvested for multiple uses, including making crafts and other utensils (Kissanga, 2016). Attention should also be paid to other species with a lower IVI, as information gathered locally cites most of these woody species to be used by local communities, providing them with a wide range of goods such as wild fruits and medicinal products. The majority of the fallows in Caiundo are in old floodplains, one of the preferred areas for cultivation. These fallows are currently in a stage of intermediate shrubland (Gröngröft et al., 2013).

The abandonment of these fields for long periods may have been due to security issues during the long civil war in the recent past. These areas are strongly affected by fire, since most of the fallow sites and mature woodlands are burned annually during the dry season. Fire may thus explain the lower density of hardwood species (*i.e. B. plurijuga*, *G. coleosperma* and *P. angolensis*) in the fallows. Disturbance caused by humans also profoundly contributes to the degradation of natural vegetation in *Baikiaea* woodlands, generally resulting in secondary formations as observed in the fallows sites, which are dominated by *Acacia erioloba*, *Combretum collinum* and *Terminalia sericea*, with or without *Baikiaea plurijuga*. Pure stands of *B. plurijuga* were also only rarely recorded in northern Namibia (De Cauwer et al., 2016). Species composition similarity measured by the Jaccard similarity index was high, showing that the two woodland stages had almost the same species composition, is in accordance with the DCA that indicated a strong overlap in species composition and distribution. A similar study in the nearby communal area of Savate also demonstrated the same trend (Wallenfang et al., 2015).

Population structure and regeneration status of woody species: classifying tree distribution according to size classes is one of the most used methods in plant population biology; because it is a useful indicator of population structure and dynamics in forest systems (Bin et al., 2012). The population structure analysis of harvestable woody species in general indicated that there were fewer larger trees compared to smaller ones. The large proportion of small size classes found for *P. angolensis* and *S. rautanenii* in the fallows compared to large trees may represent a viable recruitment of the woody species (Lykke, 1998). *B. plurijuga* had low recruitment, probably due to disturbance caused by fire frequency and intensity, as the area is usually burned annually (Frantz et al., 2013). Intentional burning negatively affects woodlands, as it leads to reduced basal area and density of harvestable trees, also decreasing shoot production and growth rates (Gambiza et al., 2000; Ncube & Mufandaedza, 2013).

Natural regeneration is defined as the renewal of forest stands by natural seedling, sprouting, suckering or by layering seeds that may be deposited by wind, birds or mammals (Pardos et al., 2005). In dry tropical forests, edaphic and climatic constraints are the main limiting factors of tree growth and seedlings survival rates. In these habitats, shoots perform better than seedlings because they obtain water, nutrients and carbohydrates directly from the well-developed root system of the mother tree

(Lévesque et al., 2011). *Baikiaea plurijuga* may also regenerate easily from seeds, developing a root system that can grow fast during the first rains, reaching about 1.5 m after three seasons (Calvert, 1986). However, its seeds and seedlings are eaten by rodents, birds, duikers and monkeys, limiting its natural regeneration. The low proportion of saplings recorded in Caiundo may be related to fire frequency and seasonality, since fires in the Angolan/Namibian border mainly occur in August and September, the late season for fire. Fires in this season are generally hotter, consuming more biomass and affecting progressively larger stems and emerging shoots (Stellmes et al., 2013; Burger et al., 1993). Another study suggests that more intense fires, combined with increasing competition from grasses and shrubs, may severely hamper regeneration of *Baikiaea* woodlands after disturbance.

G. coleosperma had fewer larger stems and consequently fewer or no smaller stems in both stand stages, supporting the view that this species together with *P. angolensis* is subjected to selective logging as also reported in other studies of the ecoregion (Syampungani, 2008; Phiri et al., 2012). Past disturbance history caused by massive timber exploitation may also explain the few large-stemmed individuals of *G. coleosperma* found, as this species is reported to show slow growth rates, with a mean annual increase in bole diameter of about 3 mm, and survival rates of only 5%. Both species were also reported as the most harvested and exploited timber species in the Cuando-Cubango province at least during the colonial era (Baptista, 2014). *P. angolensis* exhibited stable population based on the higher number of individuals in lower diameter classes compared to larger stems, both in fallows and mature woodlands, which is an indication of a good recruitment. The species may also regenerate from seeds, but only 2% of seeds, mainly dispersed by wind, are reported to germinate. The young *P. angolensis* trees often remain in a suffrutex stages that may last up to 14 years (Thunström, 2012), due to annual die back of seedlings every dry season, a phenomenon characteristic of most woodland species (Boaler, 1967).

Regarding *S. rautanenii*, little is known about seedling development and seedling survival rates. Experiments conducted in neighbouring Namibia suggest that *S. rautanenii* seedlings may grow faster in light and moderate shade conditions, with germination rates around 26% (Graz, 2003; Rønne & Jøke, 2006), implying that environments totally open as encountered in the studied area, may facilitate the germination and establishment of seedlings, although frequent fires reduce the ability of species to emerge. Another important factor to consider is that the plant is fire sensitive due to its light and soft wood, and it is mainly harvested for floats, canoes, crafts and other utensils (Rønne & Jøke, 2006), which may explain the absence of larger stems in the population in the fallows and the mature woodlands.

Conclusion

We conclude that the Caiundo woodlands are dominated by hardwood species characteristic of the tropical woodlands of southern Africa. Species diversity was higher in fallows compared to mature woodlands. The fallows reached high similarity in terms of species composition compared to mature woodlands. The population structure showed three different patterns in the fallows and mature woodlands. The abundance of young trees in the lower diameter classes (which characterize most of the natural forests systems) indicates that regeneration is taking place. However, the density of saplings maybe strongly affected by fire frequency and intensity, which also may negatively influence seed germination and seedling survival rates. On the other hand, the absence of larger stems is an indication that the preferred timber species are subject to selective logging in the studied area. Controlling the harvest of these targeted woody species and preventing fire in the woodlands for long periods, long enough to allow the establishment of tree saplings, is probably the best way to promote regeneration of woody species and population stability of the targeted species.

Conflict of Interests

The authors declare that they have no conflict of interest.

Acknowledgements

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Chapter 4

Integrated socio-economic and ecological assessment of charcoal production in the miombo woodlands of south-central Angola

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Abstract

This study assessed household livelihoods and income from charcoal production to characterize charcoal production in the miombo woodlands of south-central Angola. We evaluated the cash return from the cleared area for charcoal production in order to explore alternatives to Reduce Emissions from Deforestation and Forest Degradation (REDD$^+$). Furthermore, we assessed the recovery of biomass and basal area on charcoal fallows in comparison to mature woodlands. The household survey was conducted in the villages of the study area within the Municipality of Chitembo, along the main Cuito-Menongue road (EN140). Data on household livelihoods and charcoal production process, as well as cash returned from the activities, was calculated from the semi-structured interviews with producers at kiln sites and ground data. Biomass was calculated using the mean of two allometric equations used and basal area from the area formula for a circle. All the equations use DBH as input. In general, the livelihoods of families come from subsistence agriculture combined with charcoal production and retail of NTFPs. Charcoal production comprises different steps and mainly occurs in areas with relative abundance of preferred tree species. The amount of charcoal produced was considered to be relatively low based on estimated number of bags produced and the frequency of production. The woodlands showed ability to recover species composition, biomass, and basal area after disturbance, providing insight into understanding the dynamics of the Angolan miombo. However, the clandestine nature of charcoal production, poor regulations systems, and weak institutional capacity are, among others, the major challenges identified for the management of this ecosystems. There is also a need for the country to reduce emissions from deforestation by replacing charcoal production to alternative activities, which may also contribute to conserve the indigenous woodland trees and consequently generate income for benefit of population in rural areas.

Keywords: Household livelihoods, miombo woodlands, charcoal production, biomass, basal area.

Introduction

Urbanization and population growth are increasing demand for charcoal production, whilst deforestation reduces biomass stocks (Doggart and Meshack, 2017). Global production of charcoal was estimated at 52 Mt yr^{-1} in 2015, and increased substantially to its current rate, which is 19% higher than 2015 (FAO, 2016a). This increase in charcoal production was strongly influenced by the African continent alone, accounting for 62.1% of global production (FAO, 2017). Charcoal is the most important source of domestic energy for most south-central African countries, due to high poverty levels, low coverage of electricity, and limited access to affordable and reliable energy services (Kambewa and Chiwaula, 2010; Lohri et al., 2016). The production of charcoal involves several steps. First, the kiln site is selected. Then, trees of preferred size and species are selected and loaded into the kiln. The tree logs are then combusted, and emptied from the kiln as charcoal. Finally, the charcoal is packaged (Nahayo et al., 2013). Depending on kiln size, combustion may take several weeks for completion, and normally requires large amounts of biomass relative to the low charcoal return. For instance, in 1995, Zambian charcoal production was estimated at about 721,000 tons while the total amount of wood used in combustion was estimated at 4,290,000 tons (Banda et al., 1996). In south-central Africa, charcoal is produced, packed and partially sold along the main roads, causing also forest disturbance and degradation along road axes (Luonga et al., 2002; Malimbwi et al., 2005). Consequently, charcoal is traded to major urban settlements, where it is frequently sold for much higher prices.

Only 37.7% of Angolans live in rural areas, in comparison to the *ca*. 62.3% that lives in urban areas (INE, 2016), the latter group relies on biomass to meet their daily energy needs (International Energy Agency, 2006). Additionally, people in rural areas depend on charcoal production and other Non-Timber Forest Products (NTFPs) as main sources of subsistence (MINADER, 2006). Communities in rural areas also use fuelwood for heating and cooking, and this usage was found to be responsible for *ca*. 54% of the total woodfuel consumed in the country in 2012 (Ryan et al., 2016). Currently, Luanda is the main center of charcoal consumption from national production, with annual demand estimated at 270,000 tons consumed by at least two-thirds of population living in the capitol city (UNEP, 2013). These high levels of biomass consumption may seriously impact the woodlands as people in rural areas are driven to produce charcoal at a large scale. Mostly promoted by wholesalers from major cities, this production is usually undertaken without any official authorization and transported in secret on personal or hired container trucks. The charcoal is then traded at the wholesaler's places of origin.

Areas with high demand for charcoal can successively become completely deforested as tree selectivity for size and species is increasingly superseded by economic incentives (Ahrends et al., 2010) and shortage of wood resources.

In the province of Bié where our study site is located (and which is covered by miombo woodlands), both land demand for shifting cultivation and the recent increase in charcoal production were identified as key causes of ongoing deforestation (Schneibel et al., 2013). However, charcoal production in sub-Saharan Africa does not necessarily result in deforestation, which is defined by the Intergovernmental Panel on Climate Change as conversion of forest to non-forest land use (*e.g.* pasture, cropland, or other managed uses), but should be regarded as a form of forest degradation (Chidumayo, 2018). The important point is that both shifting cultivation and charcoal production are activities characterized by abandonment of the sites after utilization, followed by a recovery process to original species composition and recovery of biomass and carbon stocks. In other places where miombo woodlands are the dominant vegetation type, it has been demonstrated that this ecosystem can be highly resilient to disturbance caused by both shifting agriculture and charcoal production, that a fallow period allows the vegetation to recover and attain many of the key characteristic tree species of mature woodlands, that there is an increase in biomass, and that there is an increase in fallow C-storage in the mid-term until after 20 years (McNicol et al., 2015; Kalaba et al., 2013). There are currently no studies of the entire proportion corresponding to the Angolan miombo that quantify most of these processes, and in our study site only a few very recent studies are available (Piedade, 2013; Gonçalves et al., 2017).

In regard to Carbon emissions are fast becoming a global concern. The 1997 adopted Kyoto Protocol committed developing countries to legally cut their emissions to an average of 5% (relative to 1990 levels) over a period of five years (UNFCCC, 2009). Through the rules guiding this mechanism of implementation and adding the possibility of transacting emission reduction credits, the Kyoto Protocol has fostered a growing carbon market and has been the framework for guiding mitigation actions in mainly developing countries (FAO, 2016b), specifically in terms of providing financial incentives to countries that voluntarily choose to reduce their national deforestation rates and associated carbon emissions under $REDD^+$ (Gibbs et al., 2007). Thus, with this study we aim to:

(a) assess the household livelihoods and the income derived from charcoal production in the study area; (b) estimate cash-return per cleared area to promote sustainable forest management based on REDD$^+$ initiatives; (c) characterize the charcoal production process in the study area; and (d) quantify tree biomass (t/ha) and basal area (m^2/ha) on former sites of charcoal production compared to mature woodlands;

Material and Methods

Study area: Charcoal production was studied in the Cusseque area (Chitembo municipality, Bié Province), along the main road EN140 between the towns of Cuito and Menongue. Four villages were surveyed for this purpose (Figure 16). The area is characterized by a tropical sub-humid climate with a rainy season of approximately six months, lasting from October to April, and a dry season corresponding to the remaining period of the year (Weber, 2013). The area lies in the western miombo ecorregion (Olson et al., 2001), and is part of the larger miombo area that covers over 3.6 million square kilometers across eleven countries of southern Africa (Timberlake and Chidumayo, 2011). The woodlands in Cusseque are dominated by the trees *Brachystegia spiciformis*, *Julbernardia paniculata*, *Cryptosepalum exfoliatum* subsp. *pseudotaxus,* and *Erythrophleum africanum* (Barbosa, 1970; Revermann et al., 2013). Tchokwe constitutes the main ethnic group in the villages, with subsistence agriculture as their predominant source of income, and selling of Non-Timber Forest Products (NTFPs) as complement (Domptail et al., 2013).

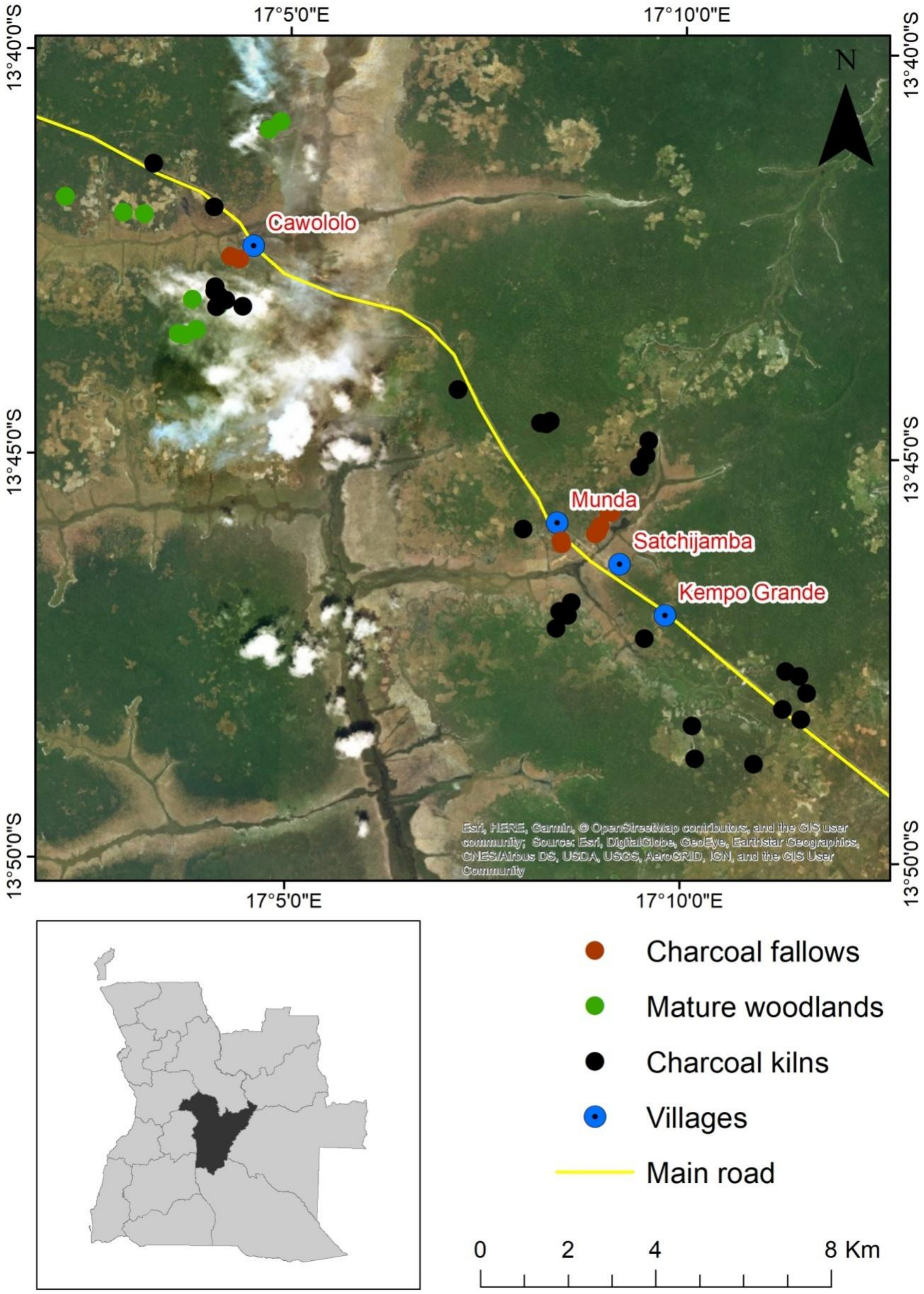

Figure 16: Map of Angola and location of the four surveyed villages in the municipality of Chitembo (along the main road EN140). The map shows the location of kiln sites, the fallow vegetation plots, and mature woodland vegetation plots.

Ethical Approval: The project under which the study was conducted was approved by the governments of Angola, Namibia, Botswana and Germany, under the framework of the Future Okavango Project (TFO). Procedures to carrying out interviews for statistics purposes in Angola are regulated by law (Decreto Presidencial No. 28/17 de 22 de Fevereiro), which is not extensive for data gathering by individuals from research institutions or universities, and an ethics approval was not required for this research as per national and institutional guidelines. A previous contact with the local government, the traditional authorities, the local population and all the interested parts is therefore highly recommended (FAO, IDF, 2009). In this way the interview process with charcoal producers in the study area was approved prior start of data collection by the local authorities of the municipality of Chitembo. For the selected villages consent of the participants was implied through completion of the questionnaire.

Data collection: Data were collected using semi-structured interviews following Bhattacherjee (2012). This structure was chosen because it adopts a more flexible attitude, asking questions which stimulate the interviewee to present his point of view, expressing his opinion or justify his behavior (Fortin, 1999). It also allows the interviewer flexibility to present a question when convenient or appropriate in any stage of the conversation (Silvestre & Araújo, 2011). The questionnaire (see Appendix 5) consisted in a set of questions divided into two sections. The first section addressed household livelihoods and woodland resource utilization, while the second section addressed technical aspects of charcoal production, preferred tree species, associated costs, and income derived from charcoal production. We conducted a total of 33 interviews with charcoal producers. These interviews took place at their respective kiln sites in order to minimize peer influence and thus improve data quality (Kalema, 2010). Additionally, we used multiple approaches to estimate the total area cleared in order to produce the specific of quantity charcoal from that site, and finally estimated cash income per hectare of woodland cleared for charcoal production based on the density of trees (measured from the diameters of the smallest and largest tree stumps). Total number of stumps from harvested trees was counted, and the number of charcoal bags expected to be extracted from the kilns was estimated based on experience of the producers.

To evaluate the woodland recovery after charcoal production in terms of biomass and basal area, we identified ten charcoal fallows which ranged from 4-9 years old after harvesting. The fallow age was calculated with LandTrendr, a program that uses statistical algorithms of temporal segmentation to capture a wide range of forest change, which ranges from abrupt disturbance and chronic mortality to varying rates of vegetation recovery (Cohen et al., 2010). We collected data on the former charcoal production sites using vegetation plots of 20 m × 50 m (Felfili et al., 2005). All tree species with DBH ≥ 5 cm within the plots were measured using a tape measure and identified by their scientific names or by local names in Tchokwe (as given by the local field guides). The latter were replaced by the corresponding scientific names following the identification of collected specimens in the Herbarium of Lubango (LUBA). The nomenclature of the species follows the Checklist of Angolan Plants (Figueiredo and Smith, 2008), despite some recent changes in botanical nomenclature. Saplings, defined as all emerging shoots under tree canopy and below the above mentioned inclusion criteria for tree measurement, were counted within one central 10 m × 10 m subplot of the main vegetation plot. To assess forest recovery after disturbance caused by clear-cutting of trees for charcoal production, we compared the estimated biomass and basal area of charcoal fallows with a corresponding number of plots in mature woodlands from a vegetation survey conducted in the region that was sampled in the same way.

Data Analysis

Charcoal economics: The total amount of charcoal produced by each household (N=25) was determined from the number of bags of charcoal expected to be extracted from the kiln, multiplied by the frequency of production per annum. As we were not able to trace all the charcoal making processes and weight of the charcoal produced at each kiln site, we used the mean weight (as determined in the Urban Household Energy Strategy Study conducted in Zambia) of 40 kg per bag (World Bank, 1990) to calculate the amount of charcoal (kg) produced in our study region. Several charcoal producers (N=8) were excluded from the analysis because they didn't know the quantity of charcoal they produces, had only recently started making charcoal, or because the frequency of production could have been influenced by the health of the producer (making charcoal is physically demanding). Gross household income from charcoal production was calculated by multiplying the number of bags of charcoal produced per mean unit price for a bag among the villages. Charcoal prices and all costs associated with production were computed in Angolan Kwanzas (AOA, ISO 4217). For reference, over the period we conducted this study (2014-2015) the mean exchange rate was 1 (USD) equal to 106 (AOA) based on the available online currency at <http://www.oanda.com/lang/pt/currency/converter/>.

Cash return from non-charcoal production: We evaluated the potential of cash-return per hectare of woodlands cleared for charcoal production (based on data from the number of trees felled per kiln) and the estimated number of bags of charcoal expected to be extracted. This approach allowed us to estimate the amount of trees needed to produce at least one bag of charcoal. An estimation of the total area cleared for charcoal at kiln site was determined by dividing the number of stumps by the total tree density obtained from the measured trees. Additionally, the number of bags of charcoal produced per hectare of woodland cleared and monetary return per hectare of woodland cleared (based on the mean price for a bag of charcoal among the four villages) were calculated.

Biomass estimation: Based on the similarity of the woody species within the miombo region, we used two allometric equations (Table 3) developed in the miombo woodlands of Tanzania and Zambia (Mugasha et al., 2013; Chidumayo, 2013) to estimate the above-ground biomass (AGB) in charcoal fallows and mature woodlands.

Table 3: Allometric equations used for estimation of aboveground biomass (t/ha). In the equations, (D) is the diameter at breast height in centimeter and (ln) is the natural logarithm to the base of the mathematical constant value (*e*).

Author	Equation	Source country	DBH range/model
Mugasha et al., 2013	$AGB = 0.1027 \times D^{2.4798}$	Tanzania	1.1-110 cm
Chidumayo, 2013	$AGB = 2.5553 \times \ln(D)-2.5265$	Zambia	Log. Model

Estimation of biomass using more than one equation is widely encouraged, as this may result in a more realistic estimation and minimize uncertainties to be generated (William et al., 2008). This is especially true for regions where local equations to assess forest biomass are scarce or do not exist (Brown et al., 1989; Cias et al., 2011). Above-ground biomass can be easily assessed from DBH (as most inventories of woodland trees worldwide include DBH measurements), and it is easy to measure accurately in the field (Segura and Kanninen, 2005). However, substantial tree biomass may also come from below-ground data that is poorly known (yet generally neglected, as it requires labour and time-intensive *in situ* measurement) but may represent up to 40% of total biomass (Magalhães, 2015; Cairns et al., 1997). For the study area total biomass was obtained from the mean of the two allometric equations used. The resulting amount of total living biomass (kg) per plot size (ha) was converted into dry weight of total living biomass per hectare, using the ratio of plot area to one hectare (1 ha/plot size). Additionally, we calculated tree Basal Area (BA), obtained from the area formula for a circle (Equation 3), using also the diameter at breast height as input (Torres and Lovett, 2013).

Equation (3) $BA = (D/200)^2 \times \pi$

Where: BA is the Basal Area of a tree ($m^2\ ha^{-1}$); D is the diameter at a breast height in cm (DBH); and π is a constant value equal to approximately 3,142.

Statistical analysis: The collected field data were computed and analyzed in Microsoft Excel and R Software (v3.4.4, R Development Core Team, 2018). To assess the differences in the estimated amount of charcoal produced among the villages, gross income derived from charcoal production, and producer sale, we used a non-parametric Kruskal-Wallis test, One-way ANOVA was used to assess differences in above-ground biomass and Basal Area distributions between the charcoal fallows and mature woodlands at a significance level of $p_{value} \leq 0.05$.

Results

Household surveys and woodland resources utilization: In total, 33 heads of household were interviewed, corresponding to 91% men and 9% to women. The age of charcoal producers ranged from 18-66 years old, although the activity appears to be dominated by young to medium-aged men (21-30 years old). Family size was larger, as expected with a total of 167 children reported among both males and females (Mean of 5 children per household). The majority of charcoal producers were not from the surveyed villages. They usually came from neighbouring villages, while a few were from major urban centres as Cuito (Bié), Menongue (Cuando Cubango) and Luena (Moxico). Visiting family was the most important reason appointed of coming (73%), followed by security reason during the period of war (14%), marriage (5%), charcoal production (4%) and religious reasons (4%). In general, young charcoal producers had attended school up to the 9th grade. Only a single woman had attended school until the 2nd grade. In addition to charcoal production, most producers also had 1-3 crop fields. This is due to the fact that they had no permanent job (Table 4) and only a few traditional authorities and teachers who were involved in the business of charcoal had a fixed job with a monthly salary ranging between 16.000,00-30.000,00 AOA. This excludes other sources of income from charcoal production and selling of Non-Timber Forest Products.

Table 4: Socio-economic and demographic characteristic of the four surveyed villages (N=33 respondents).

Variables	Proportion	Villages			
		Cawololo	**K.Grande**	**Munda**	**Satchijamba**
Gender the households	Male	9	8	6	7
	Female	1	1	0	1
Mean age of households	Male	37	43	36	33
	Female	46	Undet.	0	38
Family size	Adult equivalent	17	16	12	13
	Children	37	62	24	43
No. of children	Male	20	30	11	20
	Female	18	32	13	23
Provenance of producers	Major urban centre	5	0	2	2
	Neighbouring villages	3	6	1	3
	Local village	2	3	1	2
Educational level	Primary school	2	5	1	2
	Secondary school	2	1	1	2
	Post-secondary school	5	0	0	1
No. of crop field	One crop field	4	3	3	4
	More than one	4	6	2	2
Employment	Employed	1	1	1	2
	Non-employed	9	8	5	6

The basic, traditional source of income for rural households is subsistence agriculture. Recently, income has been complemented with charcoal production mostly during the dry season, when people are not occupied by agricultural labour or when the clearing of new fields can be combined with charcoal production. Occasional selling of NTFPs and cultivated products also takes place. The households listed eight cultivated products, maize (26%), cassava (23%), beans (23%), pumpkin (17%), millet (2%) and potato (2%). Furthermore, seven forest products normally collected from the woodlands to meet their daily needs (Figure 17) were cited. Note that multiple responses were possible during the interview.

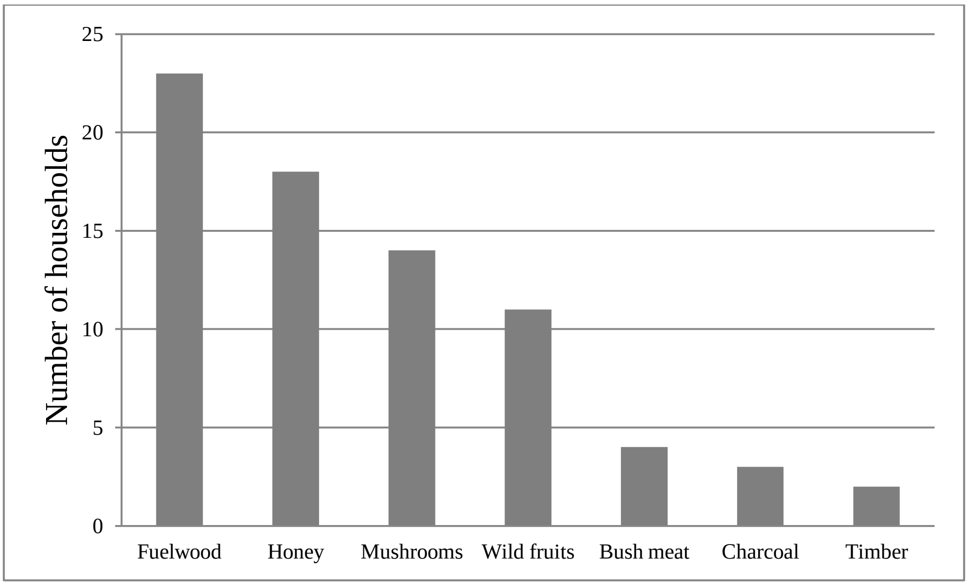

Figure 17: Forest resources used by households in the four surveyed villages (N=33 respondents).

The most commonly used forest resource is fuelwood followed by other NFTPs; charcoal and timber were seldom reported as shown in Figure 2 (note that all the interviewees produce charcoal, but did not properly indicate this during the interview process). Charcoal is mainly sold, thus rarely used by the households for heating or cooking. Furthermore, cash income was also generated from selling cultivated products as cassava, beans, maize, or goods extracted from the woodlands as honey and mushrooms (Figure 18).

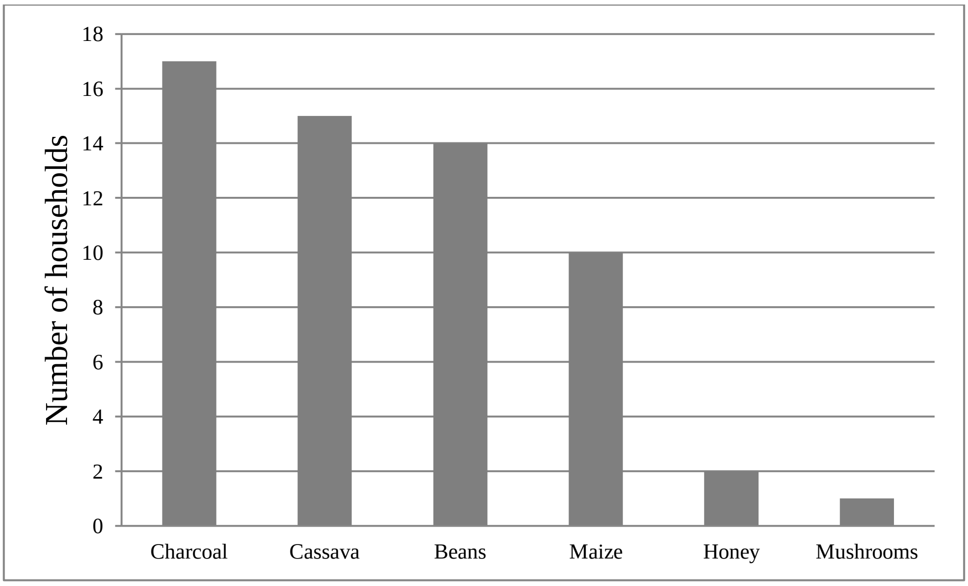

Figure 18: Sources of income claimed by the households in the four villages (N=33 respondents).

Charcoal production and incurred costs: In one year, the total amount of charcoal produced was estimated to be 6,763 bags yr^{-1}, corresponding to 270,520 kg (assuming that the mean weight of a bag is 40 kg), within the 22 surveyed households. We found no significant differences among the villages regarding the amount of charcoal production expected ($H = 5.08$; $p \geq 0.05$). We also found no significant difference regarding gross income from charcoal production ($H = 2.313$; $p \geq 0.05$), estimated to be around 783.300,00 AOA. This figure excludes the producers who claimed to produce charcoal for Luanda wholesalers, which was sold at much higher relative prices compared to those in the villages along the road. The mean sale price of a bag of charcoal along the main road was estimated to be 636 AOA per bag, and ranged from 500-800 AOA in the villages. This value did not differ significantly among the four sites ($H = 0.231$; $p \geq 0.05$). However, most charcoal producers reported only a few bags being sold along the main road, suggesting that most of the charcoal produced is ordered by the major-city wholesalers, specifically from Luanda, where a bag of charcoal during the time we conducted the study was reported to be 2.400,00 AOA. In most of these cases, the wholesalers are also responsible for bringing the empty bags and therefore the associated cost of empty bags is deducted from the final sale price. We also observed that young producers normally tend to share the labour involved in charcoal production, to make bigger kilns, and to store the resulting charcoal in the villages of their origin or along the road in order to attract wholesalers because of the ease of loading the bags onto trucks, while they pass between the villages. Other costs involved in charcoal production including cash payment for tree cutting, purchase of empty bags, and final product sales are summarized in Table 5. The estimated costs to produce one bag of charcoal among the villages were estimated to be around 391 AOA. There is no cost associated to transportation or rental of tools, generally they use their own tools (e.g. axe, shovel, machete, hoe, rake and fork) for the entire labour-and the tools were reported to have long life spans with an average of almost 4-5 years (see Holden, 2015).

Table 5: Other estimated costs involved in charcoal production in Angolan Kwanzas (AOA). This includes tree cutting and purchase of empty bags, which are estimated from the number of expected bags based on number of kilns and the estimated number of charcoal kilns made per annum.

Variables	N	Minimum	Maximum	Mean	Std. Error
Tree cutting per day	17	50	500	321	33
Purchase of empty bags	17	50	250	103	10
Sale price per bag of charcoal	28	500	800	635	18
No. of bags of charcoal per kiln	25	6	200	65	12
No. of kilns per year	25	1	12	5	1
Amount of charcoal per year	25	6	665	271	39

Cash return per cleared area: Based on the data from the number of stumps counted at kiln sites, the expected number of bags to be produced, and tree density obtained from the sampled plots, we estimated an average of 2.74 trees required to produce at least one bag of charcoal. We therefore determined that a total of 15.8 bags of charcoal can be produced from one hectare of woodland cleared for this purpose (Table 4). Based on a mean price of 638 AOA per bag of charcoal, we estimated a cash return of 10.037,70 AOA per hectare of woodlands cleared at the time we conducted the study. However, this amount represents a gain of only 286.79 AOA ha^{-1} yr^{-1}, based on the estimated 35 years that miombo woodlands may require to recover to their original state following strong anthropogenic activities (shifting cultivation or charcoal production).

The process of charcoal production: The charcoal production process was assessed during the dry season, as producers are not fully engaged with cropping during this time. At the beginning of the rainy season, the frequency of production decreases due to the villagers' engagement in subsistence agriculture. Charcoal making comprises different steps (Figure 19). The process starts with the identification of suitable kiln sites, which are generally sites that are relatively abundant with trees of preferred species and size, and not too far from the main road and villages. Trees are then felled and cut into logs approximately 1-2 m long (a, b). This process may take days or weeks depending on the size of the kiln, the skills of the producer, and the health and physical fitness of the producer. It was occasionally observed that the few women involved in the activity had to pay another person to complete the process. Tree species producing poor quality of charcoal, trees that are difficult to cut, and trees with a good timber quality (such as *Pterocarpus angolensis* and *Guibourtia coleosperma*, although rarely found with threshold diameter size for timber) are normally left uncut by the charcoal producers. The kiln construction follows the process of charcoal making, where the producers prepare the base of the kiln followed by stacking and arrangement of logs for the main body of the kiln (c). The kiln is then covered with grasses, fresh leaves and earth (d). Once this stage is completed, carbonization is initiated, a process which occurs with restricted access of air oxygen, by lighting a fire in the open base of the kiln (e). During this process, the wood biomass is converted into charcoal (f). After several weeks (1-4 or more weeks) of slow combustion, the obtained product is extracted using rakes, hoes and shovels (g). The charcoal is sorted, bagged, and carried to the villages overhead or by motorbike. The charcoal is then stored to be sold in large quantities to wholesalers or placed along the roads (h) for sale in smaller quantities to passing vehicles.

Figure 19: Observed charcoal production: (a) tree felling, (b) cutting stems into logs, (c) construction of the kiln, (d) kiln insulation with grasses, fresh leaves and earth, (e) ignition and combustion control, (f) carbonization, (g) sorting and packing of charcoal, (h) sale of charcoal along the roadside.

Tree species selection for charcoal production: The charcoal fallows were characterized by a dominance of tree species reported to be most frequently used for charcoal production. The target tree species also showed a high density of saplings compared to mature woodlands (Table 6). *Julbernardia paniculata*, *Cryptosepalum exfoliatum* subsp. *pseudotaxus* and *Brachystegia spiciformis*, in addition to other miombo characteristic tree species, were also abundant in the fallows sites, supporting the information given by the producers that the charcoal sites were generally placed in areas with relative abundance of target species.

Table 6: Dominant tree species based on tree and sapling density (stems ha^{-1}) in charcoal fallows and mature woodlands sites.

Stand stage	**Dominant species**	**Density**	
		Trees (stems ha^{-1})	Saplings (stems ha^{-1})
Charcoal fallows	*Julbernardia paniculata*	42	108
	Cryptosepalum exfoliatum subsp. *pseudotaxus*	9	14
	Brachystegia spiciformis	8	12
	Ochna schweinfurthiana	0	11
	Brachystegia bakeriana	1	10
	Burkea africana	8	10
	Combretum zeyheri	2	8
	Erythrophleum africanum	5	7
	Terminalia brachystemma	4	7
	Protea gaguedi	1	5
Mature woodlands	*Erythrophleum africanum*	14	9
	Monotes africanus	6	8
	Cryptosepalum exfoliatum subsp. *pseudotaxus*	15	6
	Brachystegia spiciformis	19	3
	Hymenocardia acida var. *acida*	3	3
	Parinari curatellifolia	1	3
	Securidaca longepedunculata	0	3
	Diplorhynchus condilocarpon	6	2
	Uapaca nitida var. *nitida*	2	2
	Baphia bequaertii	3	1

According to the producers, the four most-harvested tree species for charcoal production, as defined by tree size (priority is given to medium-large trees) and quality of charcoal produced, were *Julbernardia paniculata*, *Brachystegia spiciformis*, *Cryptosepalum exfoliatum* subsp. *pseudotaxus* and *Brachystegia longifolia*. Other tree species like *Burkea africana*, *Diplorhynchus condylocarpon* and hardwood species like *Pericopsis angolensis* and *Erythrophleum africanum* were rarely found in the kilns, but less frequently used due to their poor quality for charcoal or difficulty of harvesting and cutting into small logs (Table 7). *Isoberlinia angolensis* was cited as preferred for charcoal production by producers coming from neighboring villages, where the tree dominates the miombo landscape. However, it was not recorded in our study area. During the interview process, we observed that charcoal producers in the area never cut down any tree for charcoal if the preferred or target-sized trees are absent; in these cases they simply move to other areas where the target trees can be easily found. This may be attributed to the producers’ perception of target tree abundance within the study area in contrast to other places in the country, where small charcoal producers may have fewer options. Additionally, in many cases it was observed that the removal of remaining stumps included roots for the process of charcoal making (personal observations).

Table 7: Citation number of preferred and non-preferred trees (delimited by taxonomic species and local Tchokwe names) for charcoal production in the four villages (N=33 respondents).

Species	Local name	Preferred	Non-preferred
Julbernardia paniculata	Munhumbe	24	
Brachystegia spiciformis	Mumanga	16	
Erythrophleum africanun	Mukosso		20
Pericopsis angolensis	Muambo		11
Hymenocardia acida	Mukatcha-kabonga		7
Cryptosepalum exfoliatum subsp. *pseudotaxus*	Mukuwe	3	6
Pterocarpus angolensis	Mukula		4
Brachystegia longifolia	Mussamba	3	
Diplorhynchus condylocarpon	Muhli	2	3
Burkea africana	Mussesse	1	3
Bobgunnia madagascariensis	Mutete		3
Faurea rochetiana	Muzungue		3
Monotes africanus	Muhala	1	2
Guibourtia coleosperma	Mussivi		2
Uapaca kirkiana	Mumbula		2
Strychnos cocculoides	Mukolo		2
Uapaca nitida var. *nitida*	Mundengo	1	1
Monotes katangensis	Tchipalameia	1	1
Isoberlinia angolensis	Mut'ho	1	
Brachystegia bakeriana	Tchicungo		1
Pseudolachnostylis maprouneifolia var. *dekindtii*	Mussala		1
Parinari curatellifolia	Mut'hongo		1
Terminalia brachystemma	Mueia		1
Syzygium guineense	Muzele		1

Biomass and Basal Area estimation: Based on mean ± S.E of the two allometric equations used in this study, the total biomass of trees found on charcoal fallows was 51.7 ± 6.6 t/ha, ranging from 21.4 - 81.0 t/ha. Biomass in mature woodlands, here defined as tree or stands did not show any evidence of past disturbance (*e.g.* agriculture or wood cutting), was estimated to be 117.7 ± 10.0 t/ha, ranging from 89.0 - 197.4 t/ha (Figure 20). Total biomass was significantly different between the fallows and mature woodlands ($F = 30.44$; $p \leq 0.05$). In charcoal fallows, Basal Area (BA) was estimated at 8.5 ± 0.9 m^2/ha with a range of 4.0 - 12.1 m^2/ha, while BA in mature woodlands was estimated in 19.9 ± 1.6 m^2/ha[1] with a range of 14.7 - 30.1 m^2/ha. Basal Area also differed significantly among charcoal fallows and mature woodlands ($F = 40.88$; $p \leq 0.05$).

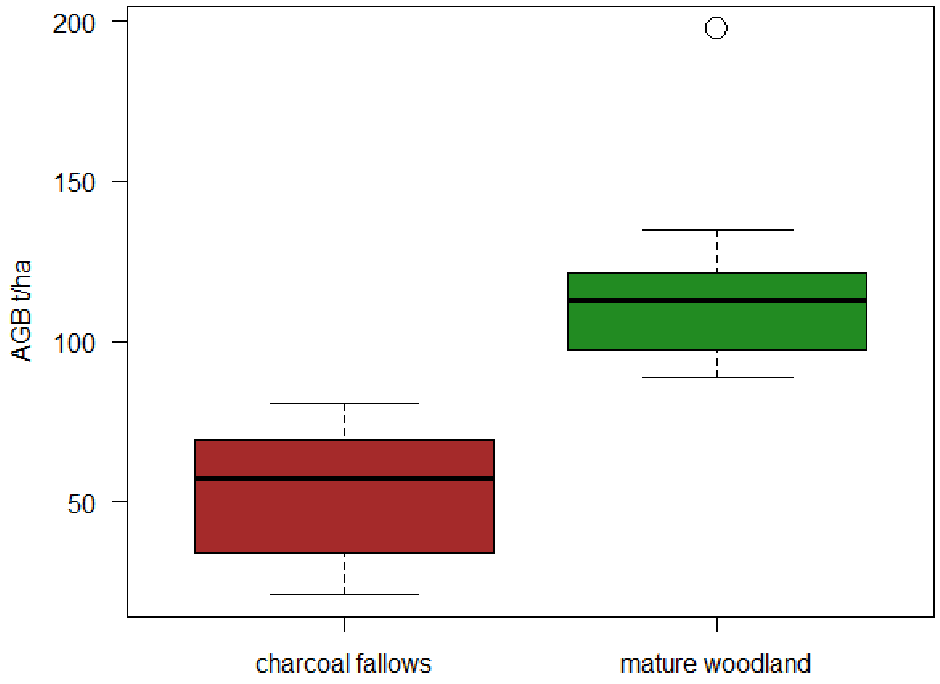

Figure 20: Aboveground biomass (t/ha) in charcoal fallows and mature woodlands within the south-central Angolan miombo woodlands of the study area.

Discussion

Household surveys and woodland resources utilization: The household survey identified a total of 33 heads of households between men and women of different ages, with male-headed households dominant. This is consistent with customs particularly in African countries where the men are expected to be the heads of households and the women only attain this role through death of the head of household (Langat et al., 2016) or by separation of the married couple. The number of children reported in this study is within the range of the national average with a fertility rate of about 5.7 children among Angolan women and more female children than male (INE, 2016). However, the family size is expected to increase in the area due to the high proportion early marriage among teenagers and also due to the absence of family-based counseling among the female population to promote or disseminate the use of contraceptives. We generally observed very few educational infrastructures (*e.g.* schools) in the villages. If these existed, they are normally rudimentary infrastructures built by the community members using only the few available resources. This situation partially explains the low education levels encountered in older producers, because the boys normally left the villages to major towns, where they may continue their studies probably through 12th grade. However, most of the older producers (> 45 years old) did have a chance to attend school during the colonial era up to 4th or 6th grade. Angola holds one of the lowest populations of youths (18 - 24 years old) with secondary school completed in the region, amounting to only 13% (INE, 2016). At the same time, the country has one of the highest illiteracy rates in southern Africa around to 58% (DPRU, 2001).

Apart from small-scale agriculture and charcoal production, very few interviewees have another occupation, with the exception of the traditional authorities (sobas) and teachers. The latter generally come from major towns or cities, but are nonetheless involved in charcoal production. This situation implies that a major proportion of the population in these areas tends to be very dependent on woodland resources and use a great variety of available resources. This finding is in accordance with the studies conducted elsewhere in southern and central Africa savanna and woodlands (Shackleton et al., 2002; Kalema, 2010). The recent demand on the miombo woodlands resources in the study area may be stimulated by the rising food prices in local markets due to the low agricultural yield caused by a severe rainy season and long drought that most of the southern African countries have experienced, driven by a strong El Niño event (Hoell et al., 2015; Quan et al., 2018). Additionally, it could also be due to the sharp decline of oil prices which caused an enormous deceleration of the country's economy, which is based only on crude export (AfDB/OECD/UNDP, 2017). The charcoal produced in our study area is mainly used to meet the energetic needs of major cities. A lesser amount was reportedly to be used in the villages for cooking or heating, but this account for only 42.9 kg of charcoal used or 300 kg of trees being cut down for this purpose per household during one year (Holden, 2015). The results of our study revealed that the main income-generating activity among households is subsistence agriculture, followed by charcoal production, and then by honey collection. Reportedly, charcoal production was used to contribute to savings for critical situations (*e.g.* diseases or death of a relative). However, it seems that charcoal production also contributed to an increase in purchasing capacity for a few families, such as for the acquisition of certain goods. Radios, TVs, satellite dishes, generators, and motorbikes are becoming very common in the villages, mainly driven by the modern consumerism as also observed in the Namibian side of the Okavango region (Pröpper et al. 2013). The cultivated products are mostly for consumption, although the surplus may be sold to purchase products of daily use such as sugar, salt, cooking oil, soap, clothing, and other goods.

Charcoal production and incurred costs: Charcoal production represents the second major source of income for the majority of the households involved in this activity, as mentioned above. The production of charcoal has become one of the most important forest-based activities and a large proportion of some villages, such as Satchijamba, are fully engaged in charcoal production, leaving subsistence agriculture as a backup option. The activity seems to generate mediocre financial incentives at local scale, but negative implications may be expected with long-lasting effects on both biodiversity and financial income for local communities (Kalaba et al. 2013). A cross-study on charcoal production in some eastern African countries concluded that charcoal is becoming one of the most important and reliable cash-based income source. For instance, this is found to be true in Ethiopia when compared to semi-subsistence crop farming and livestock activities, which can be subject to climatic and other natural calamities (Liyama et al., 2017). Studies conducted in Uganda and Tanzania also revealed that charcoal production in rural areas is rapidly growing among many small but independent producers (Hofstad, 1999). Although the amount of charcoal produced in our study area is currently still considered low, observation of the site clearly shows that the amount of charcoal produced increases along the main road and in the proximities of major towns as Cuito, Huambo or Menongue. In general, the growing demand for charcoal has been driven by population growth in the cities and urbanization. It is common practice for people moving from rural areas to the cities to switch from using fuelwood to charcoal, because fuelwood becomes scarce and charcoal is easily obtained in local markets and is relatively clean and requiring a smaller storage space (Lohri et al., 2016).

The gross income from charcoal in the villages is considered to be high relative to the amounts of charcoal reported by the interviewers. This may be due to charcoal producers reporting smaller quantities of charcoal output than is actually produced. For instance, in Tanzania, annual productivity relative to the number of kilns made per year and total households involved was estimated at about 44.2 bags person^{-1} year^{-1} (Luonga et al., 2000). The absence of reliable data on the amount of charcoal produced in the country may represent contribution losses within the forestry sector in national Gross Domestic Product (GDP), since most of the activity is undertaken clandestinely, without official licensure, and because generally no fee is charged from the activity. According to the Angolan forestry authorities, the charcoal produced in rural areas is limited to few quantities, representing a low impact on the woodlands. Nevertheless, during this study we observed that wholesalers coming from major cities are approaching rural communities to produce charcoal on a larger scale to, in turn, supply the markets of the larger cities they came from originally. In only a few cases did the forestry authorities charge fees based on the amount of charcoal transported, which is reverted as income from the charcoal produced. However, this amount was larger compared to what was reported. This type of situation has led to a rapid degradation of the woodlands with long-term implications, since there currently doesn't exist an effective mechanism of control by the forestry authorities relative to the amounts of charcoal being produced or being transported. There are few forest rangers, and in many forested rural areas there are none. In addition, there is no central governmental department dealing with policy issues that may influence the demand of biomass extraction (International Energy Agency, 2006). The existing forest legislation based on Forestry Regulations continues to be unapproved, and it is not specific in terms of protected tree species and/or specific size thresholds for tree harvesting regardless.

Cash return per cleared area: Deforestation led by human activities has contributed to an increase in greenhouse gas (GHG) emissions to the atmosphere, with negative effects on the global climate. Reducing emissions from deforestation may contribute to help minimize the negative effects of emissions on the global climate. This can be achieved by implementation of programs aiming to support local communities in rural areas to better manage their natural resources, promoting sustainable use of natural resources, and simultaneously generating marketing of non-timber forest products for income, in the aim to achieve long-term utilization of the woodlands.

Our estimates for cash-return per hectare of woodland cleared in the study area is based on many assumptions, as the figures mostly show the results based on information gathered from interviews with the charcoal producers. However, researching these assumptions may represent a significant opportunity for the country to explore options for reducing deforestation caused by anthropogenic activities (particularly in the miombo woodlands), and contribute to global efforts to reduce emissions from deforestation based on REDD$^+$ initiatives, such as rewarding people for their effort to conserve the environment. However, obtaining funds in order to implement projects for countries to willingly desist from deforestation is hindered by complex institutional policies and ethical issues (Martin, 2008). Despite these constraints, Payment for Environmental Services (PES) has gained international interest, becoming one of the main ingredients in a grassroots recipe for forest conservation within Latin America and Africa (FAO, 2016b). In the meantime, PES does not always mean that people will receive funding for protecting their environment, this goal can also be achieved by replacing activities directly linked to deforestation with others that represent low impacts to the environment, and simultaneously generating incomes to improve local livelihoods and promote better management of the woodlands.

Community-based forest management has becoming one of the ways to promote these types of initiatives within the miombo ecoregion (Topp-Jorgensen et al., 2005; Zulu 2008). In the context of Angola, implementation of community-based forest management systems may be complex, since land tenure in rural areas is not clear despite the recognized customary domain of land and the use of natural resources by the all members of the community (Domptail et al., 2013). Legalization of land, and collective land concessions at the community level is also not clear (COSPE, 2014). On the other hand, projects based on REDD$^+$ have focused on countries with more forest cover (UNDP, 2011), and other countries such as Angola are generally classified as low priority (*i.e*. low forest cover at low deforestation rates), meaning that the country is not an immediate priority for national REDD$^+$ implementation (Leite, 2015). Considering the fact that charcoal production is a physically demanding activity, and is not always renumerative, it may be useful to study other income alternatives in this study area in order to gradually reduce the demand for woodland resources and replace charcoal production with other activities that are low-impact to the woodlands. Honey production appears to be one of the alternatives as marketable product, commercialized at local price of 400 AOA per liter. The activity appear to contribute in generation of income for the households; however our interviewers have reported that the activity is being hindered by noxious gases released directly to the atmosphere from nearby charcoal kilns. As a result, a significant decrease in honey production has been observed. Improving the traditional methods of honey production (presently based on ring-barking of trees for making beehives) may also represent a significant opportunity to preserve the indigenous trees by reducing tree mortality. Currently, ring-barking is responsible for about 73% of tree mortality in areas that experienced high intensity of honey harvest, for instance, in the miombo woodlands of northern Mozambique (Snook et al., 2016). Another alternative to be considered is undoubtedly the improvement of kiln efficiency in order to reduce biomass consumption for equal charcoal return. Once most of the charcoal produced is to supply the cities, the use of alternative energies in the cities should also be explored to reduce the consumption of charcoal and associated woody biomass in rural areas.

The process of charcoal production: The process of charcoal production is labour-intensive and mainly carried out by household members, although mutual labour sharing is common, especially during tree feeling, cross-cutting, piling, and stacking of logs (Luonga et al., 2000). In general, the activity occurs in the same way as reported in various other studies across south-eastern Africa (Chidumayo, 1991; Hibajene and Kalumiana, 1996; Herd, 2007). Taking into account proximity to the villages and main road, kiln locations indicate the pull of the consumer markets to urban areas. Other phases include material preparations such as tree felling, branch dismemberment, cutting logs into uniform lengths (*ca*.1-2 m long), stacking, thatching with grass, and covering with earth (leaving a small window at the kiln base through which the fire is ignited) (Luonga et al., 2000). The carbonization process is initiated with ignition, and this allows the logs to transform into charcoal. This process only occurs in complete absence of air oxygen; the window used to set up the fire is plugged with earth to ensure the controlled combustion of wood to a temperature normally beyond 270ºC (Syred et al., 2006). The carbonization process occurs in two distinct reaction phases: primary and secondary. The primary reaction comprises conversion of basic wood constituents into products (including gases, liquid tars, and solid char); whereas the second reaction reduces the products of primary reaction (in particular, the tars) to lighter fragments that result in gases (Syred et al., 2006). In the assessed villages the construction of kiln bases is characterized by the removal of earth by digging 30-50 cm deep before staking and arranging the logs. This is the unique difference we found when comparing charcoal kilns with other sites in sub-Saharan Africa, in addition to the kiln shape, which tends to be more rectangular in our study sites in comparison to circular kilns reported in the savannas biome of central-African countries.

Tree species selection for charcoal production: A total of four trees species were repeatedly mentioned as good for charcoal production in our study sites. These include: *Brachystegia spiciformis*, *B. longifolia*, *Julbernardia paniculata* and *Cryptosepalum exfoliatum* subsp. *pseudotaxus*. Other tree species such as *Burkea africana* were also reported in the kilns, although were not preferred due to the poor output quality of the charcoal, while *Bobgunnia madagascariensis* was reported as non-preferred for charcoal making. These findings are in accordance with the Zambian household survey indicating that *Albizia antunesiana*, *B. africana* and *B. madagascariensis* are less preferred by charcoal producers due to poor quality charcoal output (Hibajene and Kalumiana, 1996). Studies conducted in Mozambique and Tanzania preferred *Brachystegia boehmii*, *B. spiciformis*, *Julbernardia globiflora* and *Burkea africana* for charcoal making (Herd, 2007; Luonga et al., 2000). This is in line with our findings indicating that tree species of the genera *Brachystegia* and *Julbernardia* are preferred for charcoal production. Due to local perceptions of relative abundance of the target tree species in the miombo woodlands, likely combined with little experience of charcoal production, they normally never cut down trees such as *Diplorhynchus condylocarpon*, *Monotes africanus*, *Uapaca kirkiana* (mentioned as non-preferred in our study), *Erythophleum africanum* or *Pericopsis angolensis* (reported to be to be difficult to cut). They reported simply moving to other areas where the target species could were more abundant. A study conducted in Zambian miombo also found that small uncut trees dominated by tree species of *D. condylocarpon*, *Lannea discolor* and larger trees of *E. africanum*, *A. antunesiana* and *Pericopsis angolensis*, the latter reportedly difficult to cut with axes, dominated woodland previously subjected to charcoal production (Chidumayo, 1991). However, if the preferable tree species for charcoal become scarce, Zambian producers (for instance) have been shown to use less-preferred species as *Piliostigma thonningii* and indigenous fruit trees such as: *Uapaca kirkiana* and *Anisophyllea boehmii* for charcoal production (Gumbo et al., 2013).

Biomass and basal area estimation: Currently, considerable efforts are being made globally to quantify total forest biomass. Biomass estimation is considered a key parameters and the first step for assessment of carbon stocks that may result from land use changes in tropical ecosystems (Avitabile et al., 2016). Additionally, Basal Area is considered a good predictor for biomass and carbon, since this measurement integrates the effects of number of trees and size of trees (Burrows et al., 2000). Charcoal production by the earth-kiln method is reported to remove *ca*. 93% of woody biomass, while uncut trees remain as residual trees at the kiln sites (Chidumayo, 1991). The remaining trees are generally difficult to cut or non-preferred trees for charcoal, but can also be shoots from stumps and small trees that can reportedly be considerable contributions to biomass in charcoal fallows, as saplings and small trees presumably invest more belowground biomass to take up nutrients and water in order to grow fast and survive (Poorter et al., 2012). For that reason, we have assessed tree biomass and Basal Area from charcoal fallows in order to understand the tree recovery after cessation of charcoal production in comparison to mature woodlands. The aboveground biomass results we found in mature woodlands in our study area are similar to those recorded using similar approaches of plot size and DBH range in Zambia, where total biomass found in mature woodlands was equal to 81.0 t/ha (Chidumayo, 1991). In another recent study conducted in miombo woodlands of western Zambia, the researchers found that total biomass was equal to 82.2 t/ha, contrasting to only 60.4 t/ha estimated for the Angolan miombo (Sichone et al., 2018). In pristine woodlands of

Tanzania, total biomass was found to be equal to 87 t/ha (Lupala et al., 2014), while a mean biomass of 19.2 t/ha was reported for the miombo ecosystem of southern highlands Tanzania (Munishi et al., 2010). In semi-arid woodlands of Kenya, total biomass was found to range from 3 to 19 t/ha in farmland/open areas and transitional woodlands, respectively (Kiruki et al., 2017).

However, there are other aspects besides anthropogenic factors to take into account, such as the differences in species composition, stand age, type of woodland, size of plots, and total number of plots sampled. These aspects may heavily influence changes on biomass across the miombo ecoregion, making our results not directly comparable to others studies. Other aspect to consider is the variety of allometric models used in different studies, as they are reported to be much more effective and statistically valid only at the sites where they were generated (Cias et al., 2011). Moreover, different forest ecosystems have also evidenced different biomass estimative, for instance total biomass found in central scarp forests of Angola was around 190.1 t ha^{-1}, estimated from 49 random sampling plots of 100 m^{2} (Leite, 2015), despite the generalized concerns of using small sample plots to estimate biomass and carbon from forest ecosystems, where larger plots are generally encouraged to include any variability related to type and site trees density (Walker et al., 2011). Total biomass from two montane forests of Costa Rica was estimated to be *ca*. 457 ± 108 t ha^{-1} and 159 ± 23.7 t ha^{-1} respectively (Tanner et al., 2017), while in the Philippines total biomass estimative was around 101.1 ± 55.9 t ha^{-1} in fallows sites with stand age between 6-10 years and 321.3 ± 131.0 t ha^{-1} in mature forest habitats (Mukul et. al., 2016). Basal Area also varied in different studies across miombo ecoregion and forest ecosystems, estimated at 8.2 ± 3.0 m^{2}/ha in the miombo woodlands of Mozambique (William et al., 2008). In addition, total Basal Area of 36.8 ± 10.9 m^{2}/ha and 12.9 ± 7.7 m^{2}/ha respectively was reported in primary and secondary tropical forest ecosystems of Colombia (Sierra et al., 2007).

Charcoal fallows seem to having the ability to recover biomass and Basal Area relatively quickly after disturbance, especially if those sites are not subjected to other anthropogenic activities (*e.g.* agriculture). This trend was clearly evident in the study area when comparing charcoal fallow sites to former agriculture sites (Gonçalves et al., 2014). This might be explained by the fact that sites subjected to agriculture are completely depleted from soil nutrients by years of continuous cultivation, as also suggested in a study conducted in the Zambian miombo woodlands (Kalaba et al., 2013). However, contribution to biomass in these sites may also come from non-preferred tree species normally left stand in the fallows sites, and shoots from stumps as mentioned above. The relative high rates of biomass encountered in charcoal fallows can be also explained by higher regeneration rates attributed to miombo trees after disturbance (Malimbwi and Zahabu, 2008; Kalaba et al., 2013). These tree species are reported to generally develop from coppices of surviving stems or recruited from old stunted seedlings that are already present in the grass layer at the time of tree felling (Chidumayo and Frost, 1996).

Conclusions

Our study was conducted in four villages along the main road between the towns of Cuito and Menongue, capital cities of Bié and Cuando Cubango Angolan provinces. The villages are characterized by relatively low human population with increasing use of woodland resources due mainly to absence of other income alternatives and the increasing demand of woody biomass in the larger cities. The low level of formal education the villagers have completed make them unqualified for formal paid employment, thus forcing them to rely on over-exploitation of natural resources to meet their daily needs. Up to now, charcoal production in the study area was considered low in comparison to other small places in southern Africa. However, it was observed that people with some financial capacity are involved in the business, and are approaching rural communities to encourage them to produce charcoal, clandestinely, on a large scale in order to transport it back to major urban and peri-urban areas. This suggests that more woodland will be cleared for charcoal production in the near future in order to supply the energetic needs of the cities, representing losses both for the forestry sector and for the gross national income (as no fees are charged from charcoal production). The lack of an effective mechanism of control (characterized by the absence of forestry patrols), the high levels of poverty in rural areas, and the increasing energy demand in the cities have been identified as the major drivers of charcoal production and commercialization. The trend of natural resource overexploitation may constitute one of the main challenges for management of miombo woodlands in Angola. The study also showed that miombo woodlands may recover floristically, in biomass, and in Basal Area, especially if the previous used sites for charcoal are not subjected to other anthropogenic activities (*e.g.* subsistence agriculture). There are few studies exploring the potential of countries to reduce emission from deforestation and land degradation under REDD$^+$. Our results clearly demonstrate the need for more studies that aim to quantify the amount of carbon dioxide released to the atmosphere due to deforestation (via agriculture or charcoal production), and this may contribute to making the country eligible in the emerging international carbon market through exploring alternatives for reducing the consumption of woodland resources for charcoal production (and simultaneously generating income for the benefit of rural communities). This study represents an important contribution towards deeply understanding charcoal production processes and the social effect derived from the activity. In turn, this study may provide insight into understanding ecological parameters such as biomass increment from sites previously disturbed by charcoal production in comparison to mature woodlands. Finally, the research addresses conservation and land-use management issues that will assist in exploring alternative woodland usage to the benefit of rural communities in Angola and this important ecosystem. The authors declare that they have not received any financial support or established personal relationships with other people or organizations that could inappropriately influence this work.

Conflict of Interests

The authors declare that they have not received any financial support or established personal relationships with other people or organizations that could inappropriately influence this work.

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Chapter 5

Vegetation Survey of the Woodlands of Huíla Province

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Abstract

We conducted a vegetation survey in the woodlands of Huíla Province, Angola, with the aim of investigating woodland tree communities and species associations. Vegetation sampling was conducted using vegetation plots of 1000 m^2 where all tree species with or above 5 cm trunk diameter (DBH) were measured. A total of 456 vegetation plots were assessed and a total of 32,080 individual trees measured. Vegetation classification using the ISOPAM algorithm resulted in 13 distinct tree communities. The most dominant family was Fabaceae, subfamily Caesalpinioideae, followed by Combretaceae and Euphorbiaceae. The classification resulted in seven tree communities belonging to the miombo woodlands, two tree communities from Mopane, two from the *Baikiaea-Baphia-Terminalia* woodlands, and two other distinct tree communities. In general, the miombo communities were the most diverse. The study represents the first plot-based vegetation survey for the region, and will provide the basis for the elaboration of the first vegetation map of Huíla Province.

Resumo

O levantamento da vegetação foi realizado nos bosques da Província da Huíla, Angola, com o objectivo de investigar as comunidades arbóreas e associações de espécies. O processo de amostragem da vegetação foi realizado em parcelas de 1000 m^2, onde todas as árvores com diâmetro altura peito (DAP) igual ou acima de 5 cm foram medidas. Avaliamos no total 456 parcelas de vegetação, que resultou num total de 32.080 indivíduos medidos. A classificação da vegetação foi feita com recurso ao algorítimo ISOPAM que resultou em 13 comunidades distintas. A família mais dominante foi Fabaceae, subfamília Caesalpinioideae, seguida da família Combretaceae e Euphorbiaceae. A classificação da vegetação resultou em sete comunidades de miombo, duas comunidades de Mopane, duas comunidades de *Baikiaea-Baphia-Terminalia*, e duas outras comunidades distintas. Em geral, as comunidades de miombo foram as mais diversas. O estudo representa o primeiro levantamento feito na região com uso de parcelas, e poderá proporcionar as bases para a elaboração do primeiro mapa de vegetação da Província da Huíla.

Introduction

Angola harbours an enormous variety of habitats, with the miombo woodlands covering about 47% of the land area of the country (Huntley & Matos, 1994). Within Huíla Province, miombo is also the dominant vegetation type. Other important vegetation types include afromontane forests and grasslands in the area of the escarpment, and *Baikiaea plurijuga* and *Colophospermum mopane* woodlands in the south-western parts of the province. Although the region is probably one of the most botanically studied parts of the country and hosts one of the largest botanical collections in Angola at the Herbarium of Lubango (LUBA), it remained unstudied in terms of species composition and distribution of vegetation communities, as most of the previous documentation of tree species diversity conducted in the country was based commonly on floristic itineraries and not on detailed vegetation surveys (dos Santos, 1982).

Huíla Province, like many parts of Angola, faces challenges such as land degradation and deforestation, and as a result thereof, loss of biodiversity (Cabral et al., 2011). The main drivers of these processes are demand for agricultural land, fire frequency, fuelwood extraction, charcoal production, and rapid urban development (Röder et al., 2015; De Cauwer et al., 2016; Schneibel et al., 2017). There is no doubt that conservation actions are needed, aimed at preventing and mitigating ecologically harmful consequences caused by habitat modifications and land use change (Simila et al., 2006). To do so effectively first requires knowledge of the present ecosystems as well as plot-based inventories that documents the floristic diversity and species composition of the woodlands.

Due to the long period of civil war experienced by Angola, information on vegetation is scarce and is generally based on early botanical work, such as the phytogeographic map of Angola (Barbosa, 1970). For the woody vegetation of Angolan miombo, only a single study is known, which resulted in the first provincial map of the Bié Province based on 144 plots (Monteiro, 1970). Recently, a few initiatives have started to document the floristic diversity of the region, though attention has been paid mostly to areas of particular botanical interest, such as the Angolan escarpment (Barker et al., 2015; Gonçalves & Goyder, 2016; Gonçalves et al., in prep.). Studies addressing floristic diversity and woody species recovery following disturbance of the miombo woodlands in south-central Angola have also been conducted (Gonçalves et al., 2017; Revermann et al., 2018). However, much remains to be done in terms of vegetation assessment to characterise the main vegetation types and species associations of Huíla

Province. Thus, this study aims to provide an initial classification of the woodland plant communities of the region. This will ultimately lead to the creation of vegetation maps that are urgently needed as a tool for conservation planning and forest management.

Material and Methods

Study site: The woody vegetation was assessed in the woodlands of Huíla Province, located in south-western Angola. The province occupies an estimated area of about 78 879 km^2, divided into 14 municipalities (Figure 21). The climate of the region is considered tropical, with dry and cold winters and temperate rainy summers; the mean annual temperature varies from 18°C in the highlands of Humpata to 20°C in the eastern parts of the province (Köppen-Geiger, 1936). Annual precipitation increases from 700 mm in the southwest of Huíla Province to 1000 mm in the east (Azevedo et al., 1972). According to Barbosa (1970), Huíla Province comprises at least eight vegetation types. The woodlands include the miombo, Angolan Mopane and the Zambezian *Bakiaea-Baphia* woodlands.

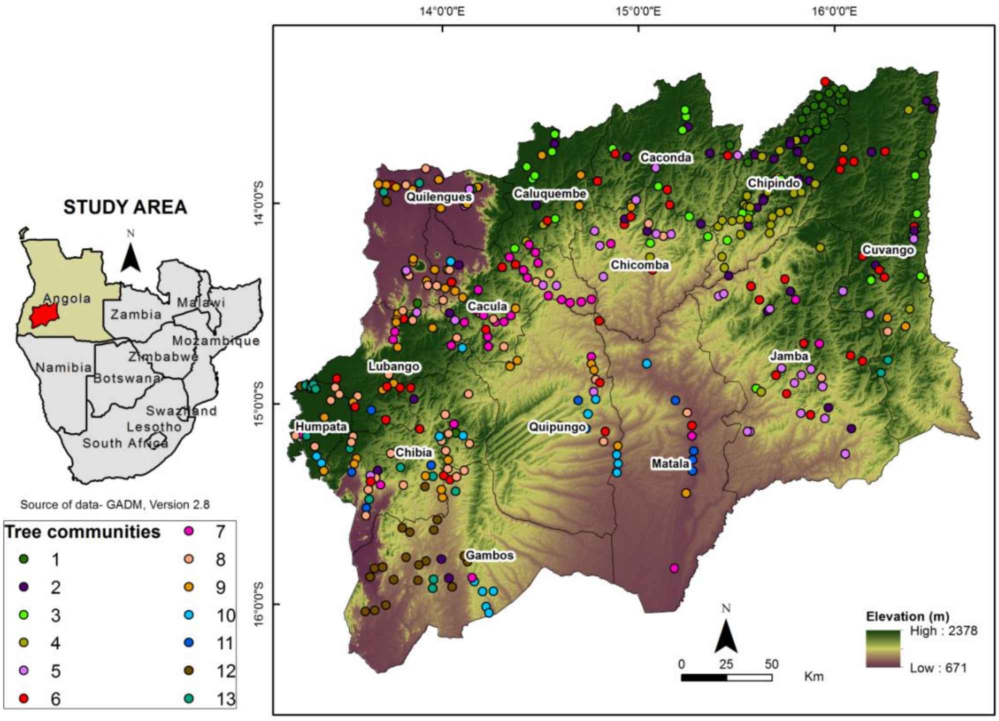


Figure 21: Map of Southern Africa with the location of the study area corresponding to Huíla Province (in red) and its administrative division into 14 municipalities. Plot locations are coloured by their corresponding woodland community types, derived from the ISOPAM algorithm.

Vegetation sampling: We used the preliminary classification of a time-series (2001-2013) of MODIS satellite imagery and derived phenology metrics to identify major vegetation units (Stellmes et al., 2013). The map so obtained was used to create a random stratified plot sample design across the vegetation units of the study area. A total of 456 vegetation plots of 20 m × 50 m were used to assess the vegetation; within each plot, all woody species reaching a diameter at breast height (DBH) ≥ 5 cm were measured. The taxonomy of woody species followed the Angolan Checklist of vascular plants (Figueiredo & Smith, 2008).

Data analysis: To understand variation in tree species and diversity within each of the derived tree communities, we calculated species richness (S) and Shannon diversity index (H'). The number of individual tree species per plot was subject to a vegetation classification using the ISOPAM algorithm in hierarchical capacity, which is based on the ordination scores from isometric feature mapping and partitioning around medoids (Schmidtlein et al., 2010). These were performed in R Version 3.2.3 (R Development Core Team, 2017) with the package ISOPAM. We selected the third hierarchical level of the dendrogram to describe tree communities and determined the diagnostic species using the *phi* coefficient with a threshold of 30 and a *p-value* of $p \leq 0.05$.

Results

Tree species richness: Within the 456 vegetation plots surveyed in the woodlands of Huíla Province, we recorded a total of 32,080 tree individuals corresponding to 176 tree species of 94 genera and 43 botanical families. The Fabaceae family was the most abundant in the study, reaching 34% of the total number of species. According to a recent classification, the Leguminosae/Fabaceae family comprises six subfamilies (Azani et al., 2017). Of all Fabaceae, 20% of species belonged to subfamily Caesalpinioideae, 9% to Detarioideae, and 5% to Papilionoideae, while the subfamilies Cercidoideae and Dialioideae were each represented by one species only. Other abundant families included Combretaceae (10%), Euphorbiaceae (9%), Burseraceae (7%), and other smaller families (Figure 22).

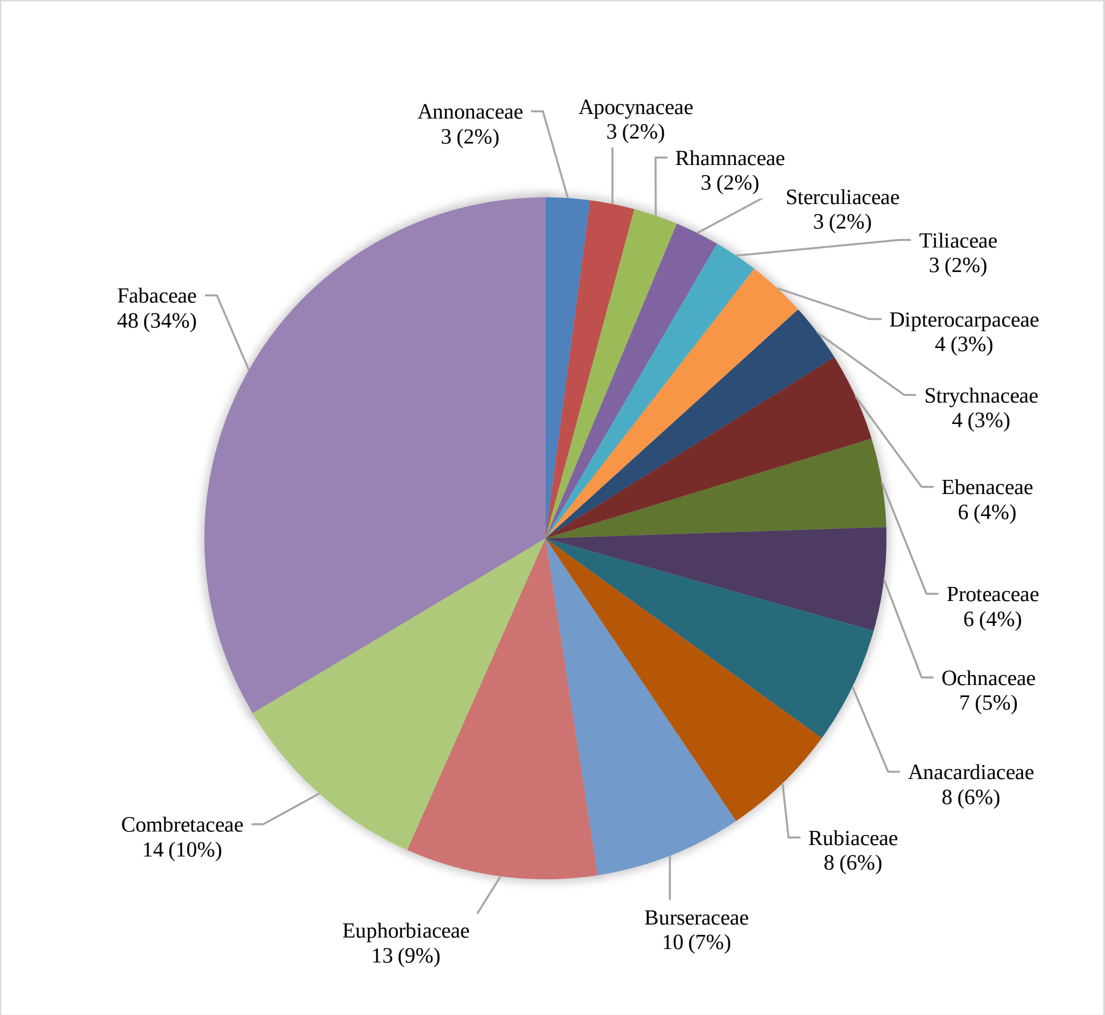


Figure 22: Number of tree species per botanical family found in Huíla Province; only families with more than two species are shown in the pie chart.

The species accumulation curve shows that the 456 plots used in this study were sufficient to cover much of the variation observed and species diversity encountered in the studied area. At 400 plots, the graph has not yet reached its asymptotic level but is starting to converge (Figure 23).

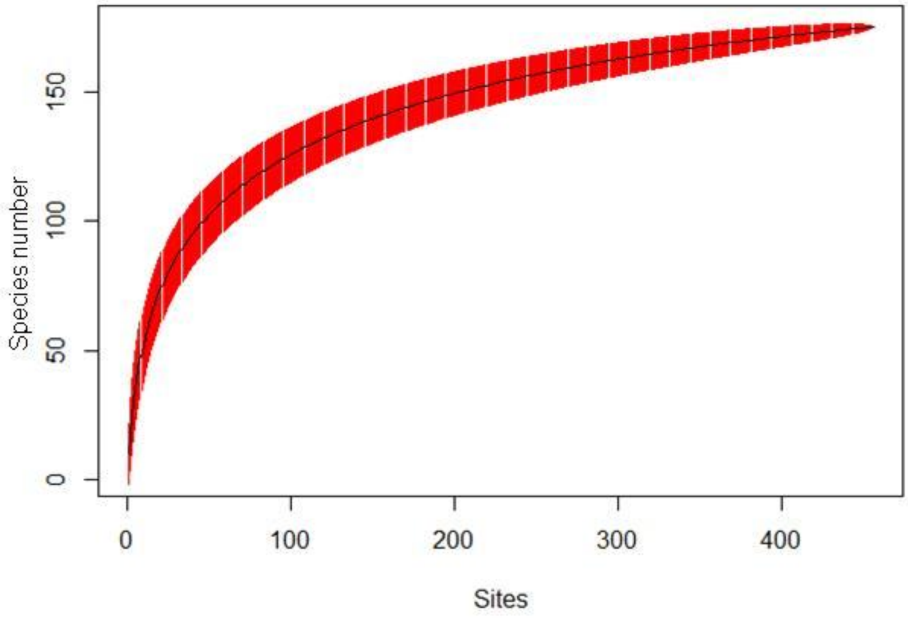


Figure 23: Species accumulation curve for trees with a diameter at breast height ≥ 5 cm measured within the sampling plots of the study area.

Vegetation classification: The vegetation classification of the ISOPAM algorithm resulted in a dendrogram in which the tree species communities can be seen. At the second hierarchical level of the dendrogram, five major floristic groups were differentiated. The dendrogram featured 13 terminal clusters corresponding to the 13 tree communities differentiated from the fourth hierarchical level (Figure 24).

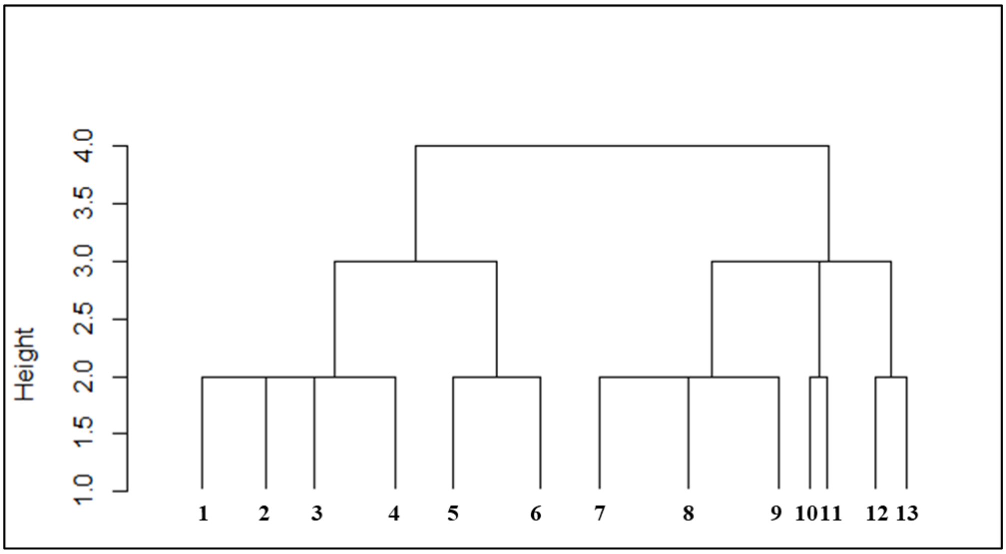


Figure 24: Community dendrogram from the ISOPAM algorithm classification with tree communities of Huíla Province; the numbered clades indicate the different tree communities.

The tree species communities and species associations can be detailed as seen in Appendix 5, and respective photographs at the end of chapter. The first tree communities (**Communities 1, 2, 3, 5, 6, 7,** and **8**), with the exception of Community 4 [*Combretum collinum-Pericopsis angolensis* woodlands], constitute typical miombo woodlands with open, dense, or medium dense tree canopy, sometimes with dense understorey development (Figures 27, 28, 29, 30, 31, 32, and 33). These communities were dominated by multiple miombo key-species such as: *Brachystegia boehmii*, *B. floribunda*, *B. longifolia* and *B. spiciformis*. The unique exception is *Julbernardia paniculata* found in four of the identified communities. **Community 4** [medium dense woodlands], this community, despite holding few key miombo species, can be considered a successional stage of miombo due to the high dominance of *Combretum* species (Figure 34). These woodlands are normally accompanied by medium-sized tree species around 3-4 m in height, and hardwood trees of *Pericopsis angolensis*.

Community 9 [medium dense woodlands]. This community occurred in lower-altitude areas covering large patches of the northwest parts of the region (Figure 35). *Pteleopsis anisoptera* is the dominant tree species, and is a generally small tree. Occasionally it was found associated with other tree species such as *Cassia angolensis* and *Commiphora mollis*. In the highlands of Humpata, communities of *P. anisoptera* generally formed dense and impenetrable thickets where we also documented *Dichrostachys cinerea*, *Tarchonanthus camphoratus*, *Haplocoelum foliolosum*, *Combretum engleri,* and *Buxus benguellensis,* the latter being endemic to the region. **Community 10** [closed dense woodlands] In the study area, this community occurs in southeastern parts of the municipality of Gambos, where it forms closed dense woodlands dominated by *Combretum celastroides, C. engleri, Hippocratea parvifolia,* and sparsely trees of *Baikiaea plurijuga.* In the herbaceous layer, we documented *Adenium boehmianum*, *Gloriosa superba* and *Hibiscus phoeniceus,* among others. These communities give way to shrublands dominated by *Baphia massaiensis* ssp. *obovata.* In reality, most of these areas are occupied by private farmers, moving towards more open woodlands in the municipality of Quipungo, where *Baikiaea plurijuga* constitutes the tallest canopy tree, occasionally associated with *Phylenoptera nelsii*, *Combretum apiculatum* subsp. *apiculatum, C. collinum, C. psidioides,* and *C. zeyheri*. Below the tree canopy, the vegetation is dense, being dominated again by *Baphia massaiensis* ssp. *obovata*, *Bauhinia urbaniana*, *Croton gratissimus*, *C. mubango,* and *Ochna pulchra* (Figure 36). Communities of *Baikiaea-Baphia* also cover large parts of Bicuar National Park (BNP). Here, these woodlands formerly appeared associated with

Schinziophyton rautanenii, though at present, we found few and sparse trees at the woodland edges of the park and also in the municipal limits of Quipungo and Chicomba.

Community 11 [medium open woodlands] Patches of *Baphia-Terminalia* were also found in the municipality of Matala, and partially along Bicuar moving south on the way to Mulondo (Figure 37). The understorey was commonly dominated by *Mundulea sericea, Vitex mombassae, Ximenia americana* and *X. caffra,* while in the herbaceous layer we documented *Scadoxus multiflorus, Grewia monticola,* and *Erithrina baumii*. **Community 12** [open woodlands] This community represents woodlands dominated primarily by *Colophospermum mopane* and normally occurs at low altitudes below 1000 m, as in the municipalities of Chibia, Gambos, and Quilengues. Here, *C. mopane* constitutes the most dominant tree species (Figure 38), and appears occasionally associated with *Spirostachys africana*, *Acacia nilotica,* and *Pterocarpus rotundifolius*. The shrub layer is dominated by *Commiphora africana*, *Grewia welwitschii, Bolusanthus speciosus,* and *Pseudomussaenda monteiroi,* mostly found associated with mopane woodlands of Quilengues. In some of drier areas of the region, we found *Commiphora mollis, Commiphora multijuga, Terminalia prunioides*, *Schrebera alata*, and *Rhigozum obovatum,* also associated with *Colophospermum mopane* woodlands.

Community 13 [medium dense woodlands] These communities cover areas in the southwestern parts of the region around Chibia and Gambos. *Colophospermum mopane* is sparsely distributed along with *Pterocarpus lucens* ssp. *antunesii*; other tree species include *Commiphora angolensis, Kirkia acuminata, Peltophorum africanum, Ptaerxylon obliquum,* and *Entada abyssinica*. The generally closed understorey is dominated by thorny species such as *Acacia nilotica*, *A. ataxacantha*, *A. welwitschii*, *A. tortilis*, and *Commiphora africana* (Figure 39).

Tree species diversity: The inspection of diversity of the main floristic groups showed that in general, miombo woodlands with *Brachystegia spiciformis-Parinari curatellifolia*, *B. longifolia-Diospyros kirkii,* and *Julbernardia paniculata-Diplorhynchus condylocarpon* [Communities 1, 3, 5] have the highest species richness (Table 8), followed by *Hexalobus monopetalus-Pteleopsis anisoptera* woodlands [Community 9] and *Colophospermum mopane-Pterocarpus lucens* ssp. *antunesii* woodlands [Community 13].

Table 8: Overview of the tree communities of Huíla Province, their diversity values, number of indicator species, and total number of plots surveyed per tree community.

Tree Communities (Cluster Hierarchical Level)	**Formation**	**Mean Shannon index**	**Mean Richness**	**Number of Indicator species**	**Number of plots per community**
1: *Brachystegis spiciformis-Parinari curatellifolia* (1.1.1)	Open woodlands	1.91	15.62	19	29
2: *Julbernardia paniculata-Brachystegia spiciformis* (1.1.2)	Open woodlands	1.18	11.23	10	39
3: *Brachystegia longifolia-Diospyros kirkii* (1.1.3)	Open woodlands	1.88	16.41	17	29
4: *Combretum collinum-Pericopsis angolensis* (1.1.4)	Medium dense woodlands	2.07	18.29	24	49
5: *Julbernardia paniculata-Diplorhynchus condylocarpon* (1.2.1)	Open dense woodlands	1.6	9.23	6	35
6: *Julbernardia paniculata-Combretum collinum* (1.2.2)	Medium dense woodlands	1.43	8	3	53
7: *Brachystegia spiciformis-Pteleopsis anisoptera* (2.1.1)	Open woodlands with dense understorey	1.4	6.78	3	36
8: *Julbernardia paniculata-Burkea africana* (2.1.2)	Open woodlands with dense understorey	1.2	6.07	2	54
9: *Hexalobus monopetalus-Pteleopsis anisoptera* (2.1.3)	Medium dense woodlands	1.74	9.53	6	55
10: *Baikiaeae plurijuga-Baphia massaiensis* ssp. *obovata* (1.1.1)	Closed dense woodland	0.56	3	2	19
11: *Baphia massaiensis* ssp. *obovata-Terminalia sericea* (2.2.2)	Medium open woodland	0.7	3.4	2	10
12: *Colophospermum mopane-Spyrostachis africana* (2.3.1)	Open woodlands	1.11	5.38	5	29
13: *Colophospermum mopane-Pterocarpus lucens* ssp. *antunesii* (2.3.2)	Medium dense woodlands	1.79	9.53	11	19

The tree community with the highest tree species richness was *Combretum collinum-Pericopsis angolensis* woodlands [Community 4]. Communities of *Julbernardia paniculata-Brachystegia spiciformis* [Community 2], *Baikiaea plurijuga-Baphia massaiensis* subsp. *obovata* [Community 10], *Baphia massaiensis* subsp. *obovata-Terminalia sericea* [Community 11], and *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii* [Community 12] showed the lowest species richness (Figure 25).

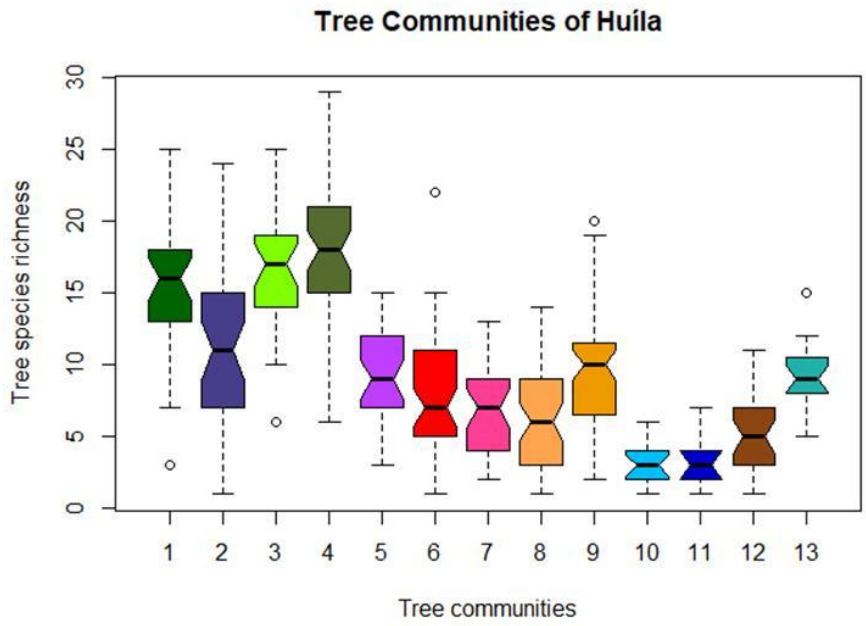


Figure 25: Box plots depicting the tree species richness in the 13 identified communities for Huíla Province.

The communities of the first major cluster, Communities 1-5, were the most diverse as measured by the Shannon diversity index, with the exception of Community 2. These communities also showed the highest species richness and greatest number of indicator species of communities. The second most diverse community was represented by tree communities 6 to 9 and 13 (Figure 26). Community 9 showed also the highest number of plots sampled. The second highest number of plots sampled was found in Community 8. Despite the high sampling effort in these communities, they demonstrated very low species richness as well as low numbers of indicator species, as seen in Table 8.

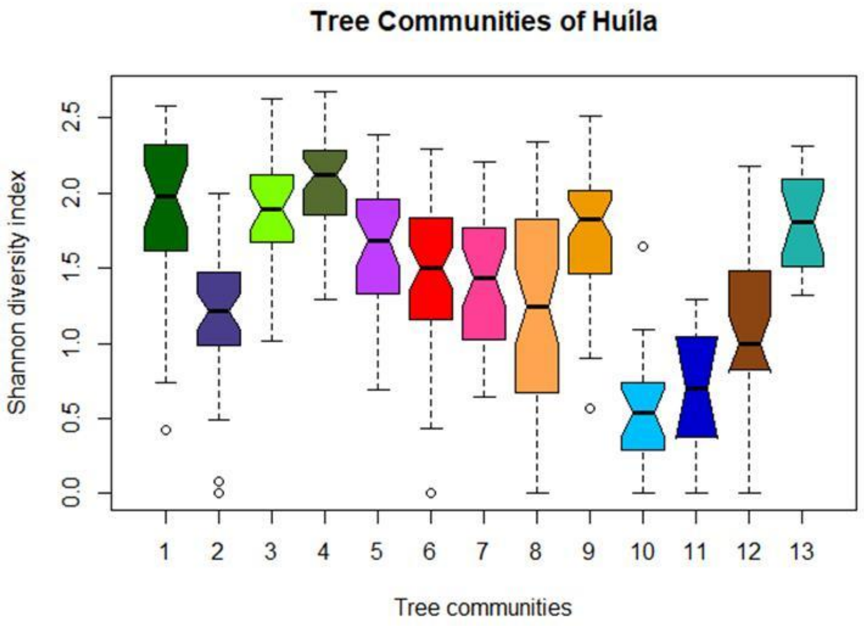


Figure 26: Shannon diversity index of the plots of the 13 tree communities documented for Huíla Province.

Discussion

Diversity of the woodlands of Huíla Province: This study represents the first plot-based woody vegetation assessment of Huíla Province in Angola, aiming to characterise and describe the woodlands of the region. A total of 456 plots were surveyed in the region, sufficient to document major floristic groups occurring in the study area, as evidenced by the species accumulation curve. This pattern may imply that any further increase of sampling effort would be expected to lead to inclusion of additional rare species, as the sample size of 456 was high and may capture almost all woody species occurring in the region, and can be useful to characterize the species diversity and relationship between woody species and site conditions. As mentioned before, most of the previous studies carried out in the country date to the colonial era. These studies characterised the vegetation types based on general aspects or were limited to dominant tree species only (see Revermann et al., 2018). As with other parts of Angola, there is still a great deal of work to be done to describe the vegetation of Huíla Province. Barbosa (1970) recognises about eight vegetation types for the Huíla region, including the most important woodlands surrounding the study area. With the present study, we are able to document 13 distinct tree communities within the region; most of them constitute fairly typical miombo woodlands, dominated by the Fabaceae family, of which the subfamily Caesalpinioideae is the largest. The dominance of the Fabaceae family within the miombo ecoregion has been widely reported in various studies (Byers, 2001; Munishi et al., 2011). Within the study area of Huíla Province, miombo woodlands occupy large areas, being relatively dense with canopy tree species around 12-15 m in height in the municipalities of Chipindo and Cuvango. The woodlands become open with increasing of altitude, as observed in Caconda, Caluquembe, and patches of the Humpata plateau, and due to high land use pressure caused by agriculture, the woodlands appear also relatively open in the municipality of Jamba.

The mean Shannon index values found in the study area were generally low, with the exception of Community 4 [*Combretum collinum-Pericopsis angolensis* woodlands] with a mean H' equal to 2.07. The highest value of Shannon diversity found in this community supports the view that these woodlands may represent regrowth of typical miombo woodlands, as areas heavily impacted by agriculture are reported to hold tree species with high light demand and fast growth, like many *Combretum* species (Jew et al., 2016). These species recruit and establish easily following disturbance and in this way additional species are added to the otherwise typical miombo species (Banda et al., 2006; Gonçalves et al., 2017). The presence of standing trees of the hardwood species *Pericopsis angolensis* was also documented in early succession of the south-central Angolan miombo woodlands (Gonçalves et al., 2017). A threshold of H' = 2 has been mentioned as the minimum value above which an ecosystem can be regarded as medium to high diversity (Giliba et al., 2011). The mean Shannon diversity index found in the Mopane woodlands of the study area was relatively low compared to similar habitats in northern Botswana; this is attributed to anthropogenic disturbance, suggesting that non-protected woodlands are negatively impacted by human activities, with a direct effect on the composition and diversity of species (Teketay et al., 2018). Within the study area we found H'values below 1; this may not only be related to the minimum number of plots surveyed, but also to the mono-dominance of single tree species such as *Baikiaea plurijuga-Baphia massaiensis-Terminalia sericea*. The Shannon index may be strongly influenced by the occurrence of rare species such as *Entandrophragma spicatum,* which can be found in the area associated to these woodlands. *E. spicatum* was reported to be very rare in the study area and probably in risk of local extinction due to its high value as timber (Barbosa, 1970).

Vegetation classification: The Angolan miombo woodlands cover an extensive area of central Angola, extending into Democratic Republic of Congo (Burgess et al., 2004). Most of this ecoregion is found at elevations between 1000-1500 m a.s.l and includes the highlands of Huíla, Huambo, and Bié provinces (Barbosa, 1970; Huntley, 1974a). Within our study area, miombo woodlands covered large areas, ranging from high rainfall sites in the north, where the woodlands seem to be much denser and almost intact, towards the southeastern and western parts of the region, where the woodlands are generally sparser (**Communities 1, 2, 3, 5, 6, 7,** and **8**). Miombo woodlands show variations in terms of density and species composition throughout the region, with differences in species composition being more evident at local scale. Local abiotic conditions and changes from *Brachystegia spiciformis* to *Julbernardia paniculata* communities, together with various other woody species, may also influence the stand structure and composition of the woodlands (Revermann & Finckh, 2013). Signs of tree damage caused by fire, wood cutting, and/or agriculture activity were also documented; this is a stark reminder that fire frequency, together with other human disturbance, plays a major role in miombo woodland dynamics, affecting physical structure, composition of species, and also woodland recovery following disturbance (Chidumayo, 2002; Furley et al., 2008).

Community 4 [*Combretum collinum-Pericopsis angolensis* woodlands] was found associated with key miombo and non-miombo species, mainly in the municipalities of Caconda, Caluquembe, and Chicomba. Similar patterns of key miombo species occurring together with other woody species have also been documented in the Tanzanian miombo woodlands (Banda et al., 2008). These findings contrast with the pattern usually considered common for miombo woodlands, suggesting that on a larger spatial scale, the species composition of miombo is very high, and common genera as *Brachystegia*, *Julbernardia,* and *Isoberlinia* are not always dominant at the local scale (Mwakalukwa et al., 2014).

Community 9 [*Hexalobus monopetalus-Pteleopsis anisoptera* woodlands], was widely distributed across the region. Stands of *Hexalobus monopetalus* are reported to occur mainly at low altitudes in southern Africa (Coates Palgrave, 2005), but in the study area, these species also appeared to be very common in disturbed woodlands. This community was also found on rocky outcrops and mountainous areas of the Quilengues and Humpata plateau. Small trees of key miombo species such as *Brachystegia spiciformis* and *Julbernardia paniculata* were commonly found associated to the community (Gonçalves, 2009).

Community 10 [*Baikiaea plurijuga-Baphia massaiensis* subsp. *obovata* woodlands] belongs to the Zambezian *Baikiaea* woodlands ecoregion, which forms a mosaic of *Baikiaea plurijuga*-dominated forest, woodlands, thickets, and secondary grassland in Angola, Namibia, Botswana, Zambia, and Zimbabwe (Burgess et al., 2004). These dense woodlands, described in the southeastern parts of Gambos, appear similar to the dense *Baikiaea-Burkea* woodlands first described for the Okavango basin along the Cubango River, characterised by a closed canopy and thicket-like understorey (Revermann & Finckh, 2013; Wallenfang et al., 2015). Further north of Gambos, *Baphia massaiensis* subsp. *obovata* dominates the landscape; this attracts private farmers to these areas, as this species is of high nutritional value for livestock (Maiato & Sweet, 2011). The *Baikiaea* woodlands become more open and constitute one of the dominant vegetation types of Quipungo within the administrative division of Bicuar National Park (BNP). A detailed vegetation account of this area points to about six vegetation communities occurring within the BNP, including woodlands, shrublands, and grasslands with aquatic and semi-aquatic vegetation (Teixeira, 1968). We documented *Baikiaea plurijuga-Baphia massaiensis* subsp. *obovata* woodlands during the field survey as one of the major woody vegetation components of the region, which is not clearly described in this previous study. Barbosa (1970) described these woodlands as occupying large areas of the BNP. The *Baikiaea-Baphia* woodlands here can be considered part of an extensive area of dry tropical woodland in southern Africa; in Angola, it has its southeast limit in deep Kalahari sands along the Angolan-Namibian border. Here the canopy is dominated by tree species such as *Schinziophyton rautanenii*, *Guibourtia coleosperma,* and *Pterocarpus angolensis*; pure stands of *Baikiaea plurijuga* only rarely occur (Gonçalves et al., 2018). The woodlands in the BNP may represent the most intact unit of this vegetation community in Huíla Province, as the surrounding areas of Matala and Quipungo were largely depleted, most likely by timber over-exploitation and clearance of large areas for agriculture purposes in the two municipalities.

To the south, moving towards Mulondo in the municipality of Matala, we were able to characterise woodland as *Baphia massaiensis* subsp. *obovata-Terminalia sericea* woodlands [**Community 11**]. This community also covers large areas of Bicuar National Park. Shrubby species within the community were generally very few, and included *Vitex mombassae* and *Grewia* spp. The previous vegetation studies refer to this community as *Terminalia sericea, Acacia nilotica, A. tristis,* or *Hippocratea-Baphia-Croton-Combretum* spp. shrublands, where *Baikiaea* may or may not occur (Teixeira, 1968; Barbosa, 1970). In fact, *T. sericea* may also appear associated to these species in our study area; however, we were not able to assess these shrublands, as they generally form dense and almost impenetrable thicket, and standing trees rarely occur.

Mopane woodlands cover an estimated area of 55,000 km^2 in southern Africa (Makhado et al., 2014). The woodlands stretch between Angola and Namibia in the southwest, from the marginal mountain chain at the base of Serra da Chela to more open and sub-desert habitats (Barbosa, 1970; Menezes, 1971). The Mopane woodlands in Angola grow over vast areas, and are typically associated with ferralitic and black clay soils. Within these areas, *C. mopane* appears associated with tree species, which mirrors the much drier climate previously documented between the municipalities of Caraculo and Virei in the Namibe Province (Maiato & Sweet, 2011). In our study, two communities [**Communities 12** and **13**] with *C. mopane* as a character species were identified with only slightly differing species composition. Community 13, *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii* woodlands was mostly characteristic of the drier areas of Huíla Province. This community may represent a vegetation of contact between medium open miombo woodlands of *Julbernardia paniculata*, *Brachystegia spicifomis* and *B. boehmii* of Chibia and typical Mopane woodlands further south (Barbosa, 1970). Further indicator species of the community were *Commiphora* species, and shrubs of *Croton mubango*, commonly found in the understorey.

Conclusion

Information on Angolan vegetation is scarce, as most studies conducted in the country date back to the colonial era. This study, carried out in Huíla Province, represents the first plot-based vegetation survey in this province and provides the first vegetation classification for this region. A high sampling effort guaranteed that most tree species expected to occur in the Huíla were recorded and that representative tree communities were identified. As such, this survey constitutes the basis for the first detailed vegetation map of the province. Additionally, a deeper analysis of environmental drivers of vegetation patterns will be needed in order to explain the distribution and variation of species composition and diversity in the woodlands of Huíla Province.

Figure 27: *Brachystegia spiciformis-Parinari curatellifolia* woodlands [open woodlands] (Photo: F.Gonçalves).

Figure 28: *Julbernardia paniculata-Brachystegia spiciformis* woodlands [open woodlands] (Photo: F. Gonçalves).

Figure 29: *Brachystegia spiciformis-Diospyros kirkii* woodlands [open woodlands] (Photo: F.Gonçalves).

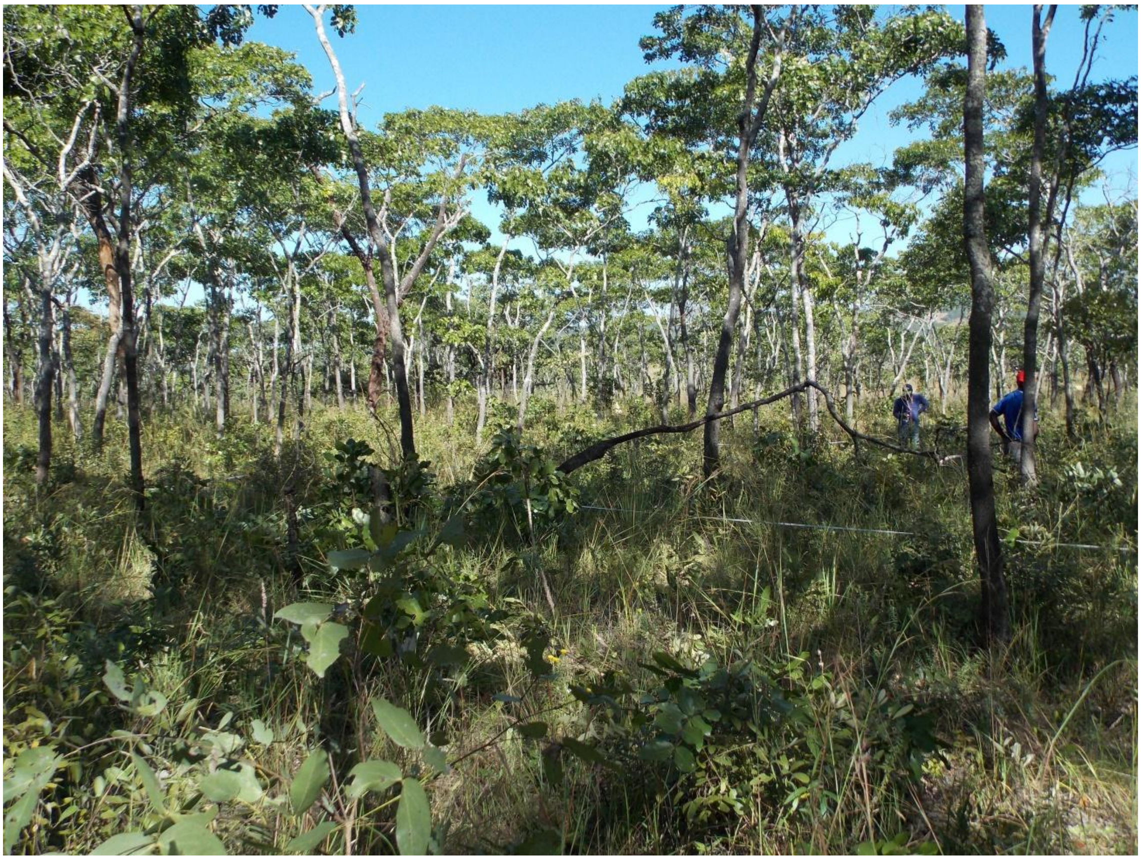


Figure 30: *Julbernardia paniculata-Diplorhynchus condylocarpon* woodlands [open dense woodlands] (Photo: F.Gonçalves).

Figure 31: *Julbernardia paniculata-Combretum collinum* woodlands [medium dense woodlands] (Photo: F.Gonçalves).

Figure 32: *Brachystegia spiciformis-Pteleopsis anisoptera* woodlands [open woodlands with dense understorey] (Photo: F.Gonçalves).

Figure 33: *Julbernardia paniculata-Burkea africana* woodlands [open woodlands with dense understorey] (Photo: F.Gonçalves).

Figure 34: *Combretum collinum-Pericopsis angolensis* woodlands [medium dense woodlands] (Photo: F.Gonçalves).

Figure 35: *Hexalobus monopetalus-Pteleopsis anisoptera* woodlands [medium dense woodlands] (Photo: F.Gonçalves).

Figure 36: *Baikiaea plurijuga-Baphia massaiensis* subsp. *obovata* woodlands [closed dense woodlands] (Photo: F.Gonçalves).

Figure 37: *Baphia massaiensis* subsp. *obovata-Terminalia sericea* woodlands [medium open woodlands] (Photo: F.Gonçalves).

Figure 38: *Colophospermum mopane-Spirostachys africana* woodlands [open woodlands] (Photo: F.Gonçalves).

Figure 39: *Colophospermum mopane-Pterocarpus lucens* subsp. *antunesii* [medium dense woodlands] (Photo: F.Gonçalves).

Acknowledgements

The research was carried out in the framework of SASSCAL and was sponsored by the German Federal Ministry of Education and Research (BMBF), under promotion number 01LG1201M. We also thank the Angolan Ministry of Science and Technology through the "*Angolan Escarpment Floristic Diversity Project*" for partially financing the field surveys. Additionally, we thank the Vice-Governor of Huíla Province, Mrs Maria João Tchipalavela, for her personal commitment and support given; the Municipal Administrators of Huíla Province; and traditional authorities and the local population for their collaboration during field surveys. We thank our colleagues from the University of Hamburg, Rasmus Revermann and Manfred Finckh, for supporting us with methodology and fieldwork, and John Lister Godlee at the University of Edinburgh, who kindly revised the English of the manuscript.

Chapter 6

Schistostephium crataegifolium (Compositae: Anthemideae), a new generic record for Angola

Gonçalves, F.M.P., Tchamba, J.J. & Goyder, D.J.

Bothalia-African Biodiversity and Conservation, **2016**

Background: The African genus *Schistostephium* has eight species in southern and south tropical Africa. The most widely distributed species, *Schistostephium crataegifolium*, occurs in upland or montane areas towards the eastern side of the continent.

Objectives: The objective of this study was to document a new geographic distribution record of this species from the Bié Plateau of central Angola.

Method: Specimens of *S. crataegifolium* were collected near Chitembo, Bié Province, during fieldwork for the Future Okavango Project Grant 01LL0912A; task SP05, a project aimed at providing scientific support for sustainable land and resource management of the Okavango basin of Angola, Namibia and Botswana. The specimen was identified at the Herbarium of the Royal Botanic Gardens, Kew, UK.

Results: The collection represents a new generic record for Angola, which is disjunct from the nearest population in Katanga by approximately 1000 km.

Conclusion: New generic records such as this underline the need for basic botanical inventories in the large, ecologically diverse but poorly documented country of Angola.

Introduction

The African genus *Schistostephium* Less. (Lessing, 1832:251) was revised by Harris (2012), who recognised eight species. Five of these have restricted distributions in South Africa and Swaziland, but three species are recorded from tropical Africa. *Schistostephium oxylobum* S. Moore (1911:117) occurs in the eastern highlands of Zimbabwe and neighbouring Mozambique, and *Schistostephium heptalobum* Oliv. & Hiern (Oliver & Hiern, 1877:399) is found in southern Zambia, northern and eastern Zimbabwe and central Mozambique. *Schistostephium crataegifolium* (DC.) Fenzl ex Harv. (De Candolle, 1838:134; Harvey, 1865:169) is by far the most widely distributed species in the genus and ranges from southern Tanzania and the Katanga region of the Democratic Republic of Congo through to the Eastern Cape Province of South Africa. However, neither this species nor indeed the genus has been recorded from Angola, Botswana or Namibia (Figueiredo, Beentje & Ortíz, 2008; Harris, 2012; Setshogo, 2005). *Schistostephium* can be distinguished from related genera in the subtribe Cotulinae Kitt by its four lobed rather than five-lobed corollas. All species are herbs or shrubs, and specific delimitation relies on vegetative characters, on the shape and size of the capitulum and the number of florets. *Schistostephium crataegifolium* has deeply dissected leaves distributed along the main stem and relatively small, non-cylindrical capitula.

Research Method and Material

Material: The specimen was collected in May 2013, during fieldwork in the Cusseque core site for the Future Okavango Project, in one central 100 m^2 subplot of a 20 m × 50 m plot (Felfili, Carvalho & Haidar, 2005). The other two records were collected in a general walking survey method (Filgueiras et al., 1994). Fertile material was collected and prepared using traditional botanical methods (Fish, 1999; Victor et al., 2004). A set of duplicate specimens was prepared and sent to Kew Herbarium (K), where the specimen was determined.

Procedure: The collection was identified in consultation with the author of the recent taxonomic revision of *Schistostephium*, applying the characters listed in that work, and by comparison of the material with herbarium collections at Kew (K), British Museum of Natural History (BM) and electronic resources available through JSTOR Plants and the LISC Online Catalogue. The specimen was mounted and labelled in LUBA, the barcode was created from collector number and printed in Zebra Printer (TLP 2844), the digitalisation was done in a Scan Epson (10000 XL), following JSTOR Protocols, and the resultant image was saved in standardised format.

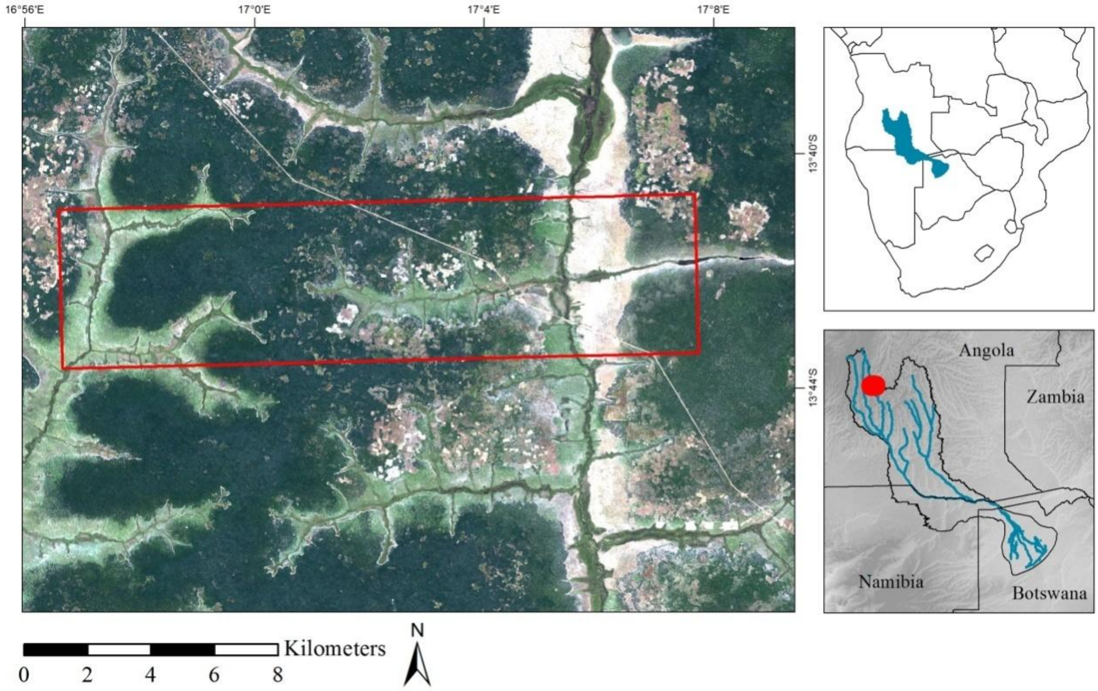
Ethical Considerations

Permits: Collection of biological materials in Angola is not currently regulated by specific legislation. The project during which the material was collected comes under the framework of a bilateral agreement between Angola, represented by the Instituto Superior de Ciências de Educação da Huíla (ISCED-Huíla) in Lubango, and Germany, represented by the University of Hamburg (UHH). Transfer of biological material to Kew was approved by Provincial Department of Agriculture, Fisheries and Environment. All International Conventions to which Angola is signatory, such as Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973), Convention on Biological Diversity (1992), International Treaty on Plant Genetic Resources for Food and Agriculture (2004), and all other national and international relevant instruments concerning biodiversity were taken into consideration.

Taxonomic treatment: ***Schistostephium crataegifolium*** (DC.) Fenzl ex. Harv. Compositae. *In:* W.H. Harvey & O.W. Sonder, Flora Capensis 3:169 (1865). Basionym: ***Tanacetum crataegifolium*** DC. 134 (1838).

Type: SOUTH AFRICA. [Eastern Cape Province], between Grahamstown and Blue Krantz, 08 Sept. 1813, Burchell 3619 (G-DC lectotype, designated by Harris (2012:108), K001044982! isolectotype).

Description (adapted from Harris 2012): Erect woody herb or small shrub to 1.2 m with striate pubescent stems. *Leaves* distributed along the main stem, alternate, sessile or shortly petiolate, blade variably pinnatisectly divided, often with two or three orders of branching, pubescent on both surfaces. *Capitula* solitary or in branched clusters, involucre broadly and shallowly campanulate, (4-) 6-8 mm diameter; phyllaries c. 30, multiseriate and subequal but apex and margins of inner phyllaries becoming more hyaline; receptacle broadly domed and hollow. *Florets*: outermost florets female, 5 or fewer (often absent), corolla yellow, tube 1.6-2.3 mm long, glabrous, lobes 0.2-0.4 mm long, acute and slightly inturned, style drying yellow. *Cypselas* of female florets flattened and winged, c. 0.8 × 0.6 mm; pappus absent. Inner florets hermaphrodite, 30-60(-110), corolla yellow, tube c. 1.5 mm long, lobes 0.3-0.4 mm long, acute and slightly inturned forming a hood, outer surface of lobe apex with granular yellow glands; anthers yellow, c. 0.8 mm long, anther appendages acute or rounded, base acute, anther collar pigmented. *Cypselas* of hermaphrodite florets c. 1.3 mm long, sometimes glandular, innermost achenes sometimes with apparently unicellular setulae on inner angle; pappus absent.



Projection: WGS 1984; background: RapidEye high resolution satellite imagery, recorded 1st May 2013. We acknowledge the DLR for the provision of the data from the RapidEye Science Archive.

Figure 40: Location of the Okavango basin in southern Africa and the Cusseque core site denoted in red, where *Schistostephium crataegifolium* was collected. The Okavango basin follows the definition of the Future Okavango project <www.future-okavango.org>, (Wehberg & Weinzierl, 2013). **Data source:** DLR-German Aerospace Center; RapidEye Science Archive.

Distribution and ecology: *Schistostephium crataegifolium* occurs from the Eastern Cape of South Africa through to southern Tanzania and the Katanga region of the Democratic Republic of Congo, mostly following the more upland or montane regions towards the eastern side of the continent. The new record represents a westward disjunction of around 1000 km from Katanga (DRC) to the Bié Plateau of central Angola (Figure 40), where it occurs at moderate altitude (c. 1560 m) in an area with mean annual precipitation of around 1000 mm per year (Gröngröft et al., 2013; Weber, 2013). Two other records were made by a team member in the study area (13.699870 S, 17. 074210 E) and close by Comuna do Mumbué (13.931679 S, 17.197102 E). The area where the species was collected is covered in moist miombo woodland dominated by *Brachystegia* spp., *Julbernardia paniculata* and *Cryptosepalum exfoliatum* subsp. *pseudotaxus* (Barbosa, 1970; Revermann & Finckh, 2013; Revermann et al., 2013; Figure 41).

New record: ANGOLA. **Bié Province:** Cusseque study area, Chitembo, 13.70056 S, 17.05258 E, 14 May 2013, *Francisco Maiato FM971* (K! LUBA!), Figures 3 & 4.

Conclusions

This new generic record for Angola is a reflection of the uneven collecting activity and consequent inadequacies in the documentation of the flora of this large and ecologically diverse country. Despite the relatively recent publication of a national Checklist of vascular plants (Figueiredo & Smith, 2008), field surveys in several parts of the country conducted by the last author (DJG) and colleagues have added over 70 species to this list, and many potentially new species. All botanical inventories undertaken by this author in Angola over the last five years have resulted in new records for the country or for regions within it.

Figure 41: Open woodlands in Cusseque area of the Bié plateau where the species was collected, the woodlands were dominated by *Brachystegia* spp., *Julbernardia paniculata* and *Cryptosepalum exfoliatum* subsp. *pseudotaxus* (Photo: F.Gonçalves).

Figure 42: Digitised image of *Schistostephium crataegifolium* (DC.) Fenzl ex. Harv. (Image supplied by LUBA).

Figure 43: *Schistostephium crataegifolium* (DC.) Fenzl ex. Harv., as it is found in the Cusseque study area **(**Photo: R.Revermann).

Acknowledgements

F.M.P.G is extremely grateful to BMBF (Germany Federal Ministry of Education and Research) for providing financial support for this study through the Future Okavango project. Thanks to Rasmus Revermann for providing the map of the study area, additional species records and a photo of *Schistostephium crataegifolium*. We also thank the traditional authorities of Cusseque village, local communities and field guides. D.J.G is also grateful to D.J. Nicholas Hind and Tim Harris at Kew for their specialist knowledge of *Schistostephium*.

Chapter 7

The Flora of Angola: Collectors, Richness and Endemism

Goyder, D.J. & **Gonçalves, F.M.P**.

Biodiversity of Angola, Science and Conservation: A Modern Synthesis

Abstract

Angola is botanically rich and floristically diverse, but is still very unevenly explored with very few collections from the eastern half of the country. We present an overview of historical and current botanical activity in Angola, and point to some areas of future research. Approximately 6,850 species are native to Angola and the level of endemism is around 14.8%. An additional 230 naturalised species have been recorded, four of which are regarded as highly invasive. We draw attention to the paucity of IUCN Red List assessments of extinction risk for Angolan vascular plants and note that the endemic aquatic genus *Angolaea* (Podostemaceae), not currently assessed, is at high risk of extinction as a result of dams built on the Cuanza river for hydro-electric power generation. Recent initiatives to document areas of high conservation concern have added many new country and provincial records and are starting to fill geographic gaps in collections coverage.

History of Botanical Exploration in Angola

It appears that the earliest extant botanical collections from Angola date from either 1669 (Exell, 1939; Martins, 1994) or more probably 1696 (Dandy, 1958; Exell, 1962, Mendonça, 1962; Figueiredo et al., 2008), and were made by Mason in the Luanda region, and by John Kirckwood in Cabinda. These reached Hans Sloane whose plant and insect collections formed the core of the British Museum (now the Natural History Museum), London, via James Petiver who encouraged surgeons on English ships to send him natural history collections from their overseas travels. Other Pre-Linnean collections from Angola in the Sloane Herbarium were made by Gladman and William Browne (Figure 44). The earliest known Portuguese collector was the naturalist Joaquim José da Silva, who collected along the Angolan coast and the western escarpment between 1783 and 1804. This material was taken from Lisbon to Paris, where it now resides, in 1808 during the Napoleonic Peninsula War (Mendonça, 1962; Figueiredo et al., 2008).

Figure 44: One of the earliest herbarium specimens collected in Angola, in 1706 or 1707, by W.Browne and now housed in the Sloane Herbarium at the Natural History Museum in London. The New World starch crop - cassava *Manihot esculenta* (Euphorbiaceae).

Mendonça (1962) presents a historical account of plant collectors in Angola, giving helpful insights to the itineraries of a number of early expeditions. A more complete list of collectors is given by Figueiredo et al. (2008), which volume also includes a useful listing of references relevant to the study of the flora of Angola. Most eighteenth and early nineteenth century explorers visited only coastal regions of Angola, but by the 1850s, botanists and explorers were starting to document plants from more elevated parts of the interior. Friedrich Welwitsch, who spent six years in Angola, amassed over 8,000 collections of plants representing around 5,000 species, of which around 1,000 were new to science (Albuquerque, 2008; Albuquerque et al., 2009, Albuquerque & Figueirôa, 2018). He spent his first year in Angola in the coastal zone between the mouth of the Rio Sembo ('Quizembo') just north of Ambriz, and the mouth of the Cuanza. In September 1854 he embarked on a three-year excursion, initially following the Bengo River and reaching Golungo Alto (Cuanza Norte). He based himself eventually at Sange from where he made excursions to Ndalatando ('Cazengo') and the banks of the Luinha. In October 1856 he arrived at Pungo Andongo (Malange) where he was based for the next eight months, making collections from Pedras Negras, Pedras de Guinga and localities along the Cuanza River - the furthest point he reached upstream was Quissonde, south of Malange. After an extended period back in Luanda, he headed south via Benguela to Namibe ('Little Fish Bay') in June 1859, gradually extending his journeys along the coast to Cabo Negro, the port of Pinda (probably Tômbwa) and Baía dos Tigres. In October 1859 he headed inland from Namibe, following the Rio Giraul ('Maiombo river') to Bumbo on the slopes of the Serra da Chela. He was based at Lopollo (Lopolo) on the Huíla plateau until 1860. In 1866, José Anchieta moved to Angola and was based at Caconda on the Huíla plateau. And by the 1880s, missionaries such as José Maria Antunes and Eugène Dekindt, and collectors such as Francisco Newton and Henry Johnston were also making significant collections from this region.

Three nineteenth century German expeditions to the Congo travelled through Angola - Pechuël-Lösche's 1873 Loango Expedition with Paul Güssfeldt and Hermann Soyaux started from Cabinda; Pogge, Buchner and Wissmann's Cassai Expedition made collections from Malange and the Lundas (Mona Quimbundo, Saurimo, Cuango River) in 1876; while Teucsz and Mechow's Cuango Expedition made collections from Dondo (Cuanza Norte), Pungo Andongo and Malange (Malange), and the Cuango river (Uíge) in 1879-1881. A fourth German expedition, the Kunene-Sambesi Expedition, left Namibe on 11 August 1899 and travelled east, through present-day Cunene and Cuando Cubango provinces, reaching the Cuando River in March 1900 before returning to Namibe in June of that year. Over 1000 collections were made on this expedition by the botanist Hugo Baum (Warburg, 1903; Figueiredo et al., 2009b). The first half of thetwentieth century was dominated by the efforts of Kew-trained Swiss botanist John Gossweiler who in the course of 50 years' work collected in all of Angola's provinces, and amassed over 14,000 collections. His final two years' collections, in 1946 and 1948, were from the remote northeast of the country, and formed the basis of Cavaco's Flora of Lunda (Cavaco, 1959). Other significant colonial era collectors included Portuguese and British participants of the *Missões Botânicas* such as Luiz Carrisso, Francisco Mendonça, Arthur Exell and Francisco de Sousa (as well as John Gossweiler), whose work formed the basis of early parts of the *Conspectus Florae Angolensis*, and the first vegetation map of Angola (Gossweiler & Mendonça, 1939). There are too many other collectors from 1950-1975 to list (see Figueiredo et al., 2008), but two specialist collections are here noted - Hans Hess's aquatic and wetland plants from many of the rivers of western Angola in 1950-1952 are now housed principally in Zurich, and Larry Leach and I.C Cannell who travelled up the arid and semi-arid coastal plain between 1967 and 1973, focussed mostly on the succulent flora. After Angolan independence in 1975 and the commencement of the long-running civil war, collection of plants essentially ground to a halt until the end of the twentieth century. Several recent collecting programmes will be described in a later section of this paper. Despite Gossweiler and his successor Brito Teixeira's efforts to survey little known regions of Angola, plant collection coverage and intensity is skewed heavily to the western half of the country, and large parts of Moxico, Cuando Cubango, the Lundas and Uíge are still devoid of collections (Sosef et al., 2017, Figure 45 <http://rainbio.cesab.org>).

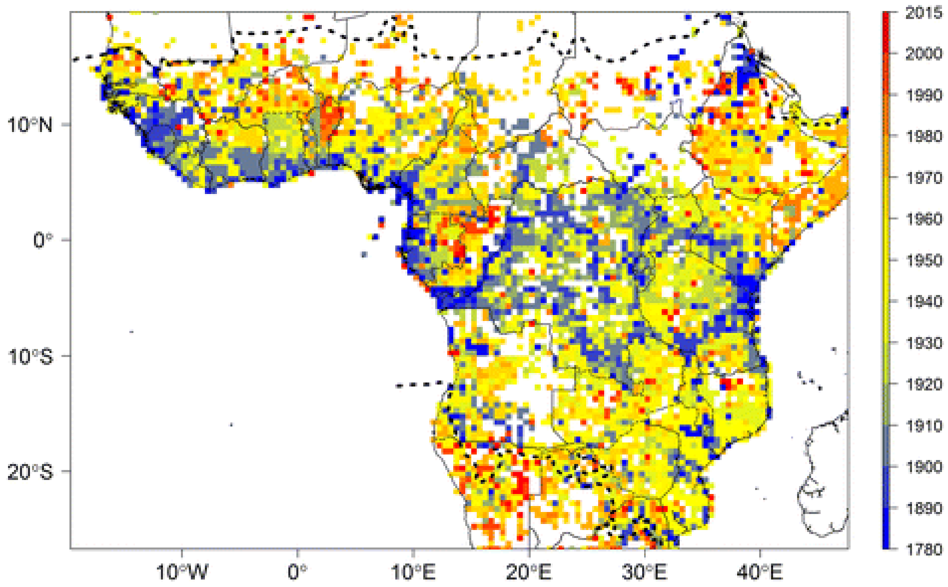


Figure 45: Time lapse of botanical collecting history across tropical Africa. The map represents the date of the first botanical collection made within each 0.5° sampling unit. Dashed lines represent the limits for tropical Africa as defined by Sosef et al. (From Sosef *et al.* 2017: <http://rainbio.cesab.org>).

Floristic Diversity and Endemism

Under the leadership of Estrela Figueiredo and Gideon Smith, thirty-two authors from around the world compiled the first Checklist of vascular plants for Angola (Figueiredo & Smith, 2008; Smith & Figueiredo, 2017). A total of 6,735 native species were recorded with an additional 226 non-native species. The exotic flora of Angola was documented by Gossweiler (1948-1950). Four of these alien species pose particular threats as they are highly invasive in Angola (Rejmánek et al., 2017). Forty-four additional species have been described or entered onto the International Plant Names Index since publication of Figueiredo & Smith (2008), and inventories in Lunda Norte (see below) and elsewhere added a further 70 or so species to the Angolan list. So the current estimate of the vascular plants native to Angola is around 6,850 species. Current accepted nomenclature for plants can be checked on the African Plants Database (2018), and local plant names in Gossweiler (1953) and Figueiredo & Smith (2012). Figueiredo et al. (2009a) reported that 997 species (14.8%) are endemic to the country. This percentage is considerably lower than the estimate of 27.3% by Exell & Gonçalves (1973) based on a limited sample of the flora, or studies of individual families of plants where 19% of both Rubiaceae (Figueiredo, 2008) and legume species (Soares et al., 2009) were recorded as endemics. Several genera are endemic to Angola, including *Calanda* K.Schum. and *Ganguelia* Robbr. (Rubiaceae); *Carrissoa* Baker f. (Leguminosae); and *Angolaea* Wedd. (Podostemaceae) - the latter now possibly extinct as it was described from the Cambambe rapids on the now heavily dammed Cuanza River.

Legumes (934 spp.), grasses (526 spp.), Compositae (463 spp.) and Rubiaceae (444 spp.) are the most diverse families in the flora, and *Crotalaria* L. and *Euphorbia* L. each have more than 40 Angolan endemic species. Two of the six tropical African centres of endemism identified by Linder (2001) fall partially or entirely within Angola. A recent analysis of RAINBIO data (Droissart et al. 2018) identifies the western Angolan highlands as a distinct floristic bioregion, although the limited data preclude statements on the remainder of the country. The Huíla plateau consistently stands out as being rich in endemic species (Exell & Gonçalves, 1973; Brenan, 1978: 472; Linder, 2001) and Soares et al. (2009) record 83 endemic legumes from the province. For Rubiaceae, Cabinda has the highest level of diversity with 175 species, but Huíla possesses the most endemics (Figueiredo, 2008). Figueiredo (2008) also demonstrates that for Rubiaceae, Huíla is the most intensively collected province. However, our experience is that many of these collections have not necessarily been well studied. Clark et al. (2011) state that the western highlands of Angola comprise the least well-documented stretch of the Great Escarpment of southern Africa. The western margin of the Huíla Plateau reaches its highest elevation along the Lubango Escarpment of the Serra da Chela and runs in a southwesterly direction from near Tundavala c. 15 km NW of Lubango to

Bimbe c. 20 km NW of Humpata. It reaches a height of just over 2200 m and Goyder et al. (in prep.) estimate around 200 species are endemic to this area. However, as other mountains further to the north are surveyed botanically, some of these supposed local endemics may prove to be more widely distributed than currently thought. Linder's (2001) second area of high species diversity and endemism, the Zambezi-Congo watershed, encompasses eastern Angola, northern Zambia and the Katanga region of the DR Congo. This area has not been well documented in Angola.

Biogeography, Regional Centres of Endemism and Vegetation

With its extremes of landform, climate and rainfall, Angola is host to six of White's (1983) phytochoria, or regional centres of endemism. Outliers of the Guineo-Congolian forests in Cabinda, Uíge and Cuanza Norte are progressively smaller in area to the south, ending in the isolated coffee forests of Gabela and Kumbira in Cuanza Sul. The northward-draining tributaries of the Cuango and Cassai rivers in Uíge and Lunda Norte have fingers of pure Congolian forest along them. However, much of northern Angola forms a transition zone between Guineo-Congolian vegetation and Zambezian - the latter covers the rest of the country with the exception of the fragmented Afromontane centre of endemism at higher elevations, and the more arid Karoo-Namib and Kalahari-Highveld zones in the southwest. Geologically, the eastern half of Angola is notable for its deep deposits of Kalahari sand, while to the west crystalline rocks predominate. Marine sediments and recent sands cover the coastal plain (Huntley & Matos, 1994). The coastal plain is arid in the south due to the cold, upwelling Benguela current, and semi-arid further to the north. Most of the rainfall occurs on the escarpment and the plateau, again with a steady increase to the north. Central Angolan headwaters of major river systems drain into the Okavango (Cuito and Cubango), the Indian Ocean (Cuando, Lungué Bungo and Zambesi) and the Atlantic (Cassai, Cuango, Cuanza and Cunene).

The standard work for vegetation is Barbosa's (1970) *Carta Fitogeográfica de Angola* which recognises 32 vegetation types ranging from desert to moist evergreen and swamp forests. Huntley and Matos (1994) present a concise summary. Barbosa's vegetation map built on the painstaking pioneering work of Gossweiler and Mendonça (1939) - a major contribution that reached a wider audience through the extended English summary by Airy-Shaw (1947). Angola has a diverse seaweed flora and 169 species have been recorded (Lawson et al., 1975; Anderson et al., 2012). Biogeographically, Angola's marine algae group with those of tropical West Africa, but with a well-developed southern element from around 13°S comprising mainly coolerwater species from the Benguela Marine Province of Namibia and western South Africa.

Recent Botanical Surveys Initiatives

In 1968, Angola had only three National Parks (Quiçama, Cameia and Iona) and two Nature reserves (Mupa and Luando), plus a number of forest and game reserves (Teixeira, 1968a). Between 1971 and 1975 a programme of field surveys was undertaken to identify areas of high importance for biodiversity conservation (Huntley, 1973-1974; Huntley and Matos, 1994). These were supplemented by fieldwork in Huíla, Namibe, Cuanza Sul and Huambo (Huntley, 2009; Mills et al., 2011), and synthesised into an ‘Angolan Protected Area Expansion Strategy - APAES’ (Huntley, 2010). The APAES report was submitted to the Angolan Ministry of Environment in 2010, and formed the basis for the proposals approved by the Angolan *Conselho do Ministros* on 28th April 2011 (GoA, 2011). Much of the recent botanical activity in Angola has focused on the eleven areas highlighted in this conservation planning document. The areas proposed for protection were: Maiombe (Cabinda), Serra do Pingano (Uíge), Lagoa Carumbo (Lunda Norte), Serra Mbango (Malange), Gabela and Kumbira Forests (Cuanza Sul), Morro da Namba (Cuanza Sul), Morro do Moco (Huambo) Serra da Neve (Namibe), Serra da Chela (Huíla) and Luiana (Cuando Cubango). A listing of post-independence botanical collectors in Angola is given in Appendix 5.1, following the format used for earlier collectors used by Figueiredo et al. (2008).

A collaborative Rapid Biodiversity Assessment and training expedition to the Huíla Plateau and to Iona National Park, with 30 scientific participants from 10 countries and with 15 Angolan students, was convened in 2009. Over 2,700 botanical collections were made and deposited in the National Herbarium, Pretoria with duplicates deposited in the ISCED-Huíla Herbarium in Lubango (Huntley, 2009).

In northern Angola botanical surveys have been initiated in the moist coffee forests of Serra do Pingano, and more widely in Uíge Province, by a team from Dresden in cooperation with the Universidade Kimpa Vita (Lautenschläger & Neinhuis, 2014, Neinhuis & Lautenschläger 2014). These have resulted in a revised list of bryophytes for Angola (Müller, 2014; Müller et al., 2018), the description of new species of vascular plant (Abrahamczyk et al., 2016), and ethnobotanical assessments (Göhre et al., 2016, Mawunu et al., 2016, Heinze et al., 2017, Lautenschläger et al., in press.). In total, about 820 species were identified; several of these are new records for Angola. Lagoa Carumbo and the Luxico, Luele and Lovua valleys were surveyed by a team from Kew, the Ministry of the Environment and Agostinho Neto University, Luanda in 2011, and again in 2013, trebling the known flora of Lunda Norte as compared to Cavaco (1959) - the combined report documents 752 taxa including 72 additions to the flora of Angola, and 22 potential new species (Darbyshire et al., 2014, Cheek et al., 2015). This part of Lunda Norte has Congolian swamp forest in the river valleys, moist miombo woodland on the slopes, and Zambezian savanna grasslands on the plateau. The isolated patch of Guineo-Congolian forest at Kumbira was the subject of a rapid botanical assessment with more than a hundred botanical specimens collected, including new Guineo-Congolian records for Angola and species potentially new to science (Gonçalves & Goyder, 2016).

Plants collected from Mount Namba are currently being studied by the Kew/Lubango team - this work may inform studies on the Lubango Escarpment further to the south. Both share a mosaic of Afromontane forest, grassland and miombo woodland habitats, although most of Lubango's woody vegetation is now heavily degraded. Comparisons with the much better preserved vegetation on Mount Namba might inform habitat restoration initiatives in the area. Serra da Neve and Serra da Chela were visited briefly in 2013 as part of a wider floristic survey of the Angolan Escarpment led by a team from Rhodes University in South Africa, ISCED-Huíla in Lubango, and Kew. One or two new species have been published from these collections (Hind & Goyder, 2014), but wider analysis of the flora is still on-going. Through the German-funded Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) project, researchers at the Lubango Herbarium are working on vegetation classification of the woodlands of Huíla Province, towards a new vegetation map for the region (Chisingui et al., 2018). A checklist of the Huíla flora is one of the expected early outputs. In addition to the Protected Areas Expansion Strategy sites mentioned above, three cross-border initiatives have focused on the catchment of the Okavango system in Angola, Namibia and Botswana in recent years. Botswana's flagship wetland ecosystem - the Okavango Delta - is dependent entirely on the two main Angolan tributaries (Cuito and Cubango) for its hydrology. The Southern Africa Regional Environmental Program (SAREP) and OKACOM organised fieldwork in Cuando Cubango in 2013 with botanists from Kew and the University of Botswana. About 350 collections were made from the southeast corner of Angola, as far east as the Cuando river, thus contributing to the documentation of the Luiana proposed protected area. The Future Okavango (TFO) project led by a research team from Hamburg focused on two research sites in Angola (Cusseque, Bié Province; Caiundo, Cuando Cubango Province) both in the more westerly Cubango catchment, one in Namibia (Mashare), and Seronga in Botswana. This project contributed significantly to a better understanding of Angolan miombo and *Baikiaea-Burkea* woodlands in terms of recovery following disturbance caused by shifting cultivation (Wallefang et al., 2015, Gonçalves et al., 2017, Gonçalves et al., 2018). A checklist of woody species and geoxylic suffrutices in the grasslands of south-central Angola was provided, documenting potential new species and new records for the country (Gonçalves et al., 2016, Revermann et al., 2017-2018). Further vegetation and ecological studies are published in Oldeland et al. (2013). The easterly Cuito and Cuanavale catchment has been the focus of the National Geographic Okavango Wilderness Project from 2015 onwards. Surveys in the upper Cubango were initiated in 2017. To date, over 1,300 plant collections have been made by a Kew, South African and Angolan team, who have recorded 365 species of vascular plant from the high-rainfall upper Cuito and Cuanavale drainage system, and 176 from the lower rainfall zones further south (*e.g.* Figure 46). Over 100 new provincial records were reported for Moxico, with a further 24 for Cuando Cubango, underlining how poorly documented and understood this vast and sparsely inhabited part of Angola is, even now. Baseline botanical collection data such as these feed into wider biodiversity assessments of the area and provide vital evidence in building a case to protect the headwaters of not only the Okavango system, but other major river systems originating in central Angola (National Geographic Okavango Wilderness Project 2017).

Figure 46: Some plants collected during recent fieldwork in central and eastern Angola as part of the National Geographic Okavango Wilderness Project. Top to bottom, left to right: *Protea poggei* subsp. *haemantha* (Proteaceae); *Clerodendrum baumii* (Lamiaceae); *Erythrina baumii* (Leguminosae); *Monotes gossweileri* (Dipterocarpaceae); *Gloriosa sessiliflora* (Colchicaceae); *Raphionacme michelii* (Apocynaceae). All photos: David Goyder.

Future Botanical Work

Almost every botanical survey made in recent years in Angola has revealed undescribed species and new country or provincial records. Eastern and northern provinces are in most need of collecting programmes and botanical documentation. Most national parks lack basic botanical inventories. To give one example, Teixeira's (1968b) work on plant diversity in Bicuar National Park (Huíla Province) resulted in the recognition of six vegetation types in the park. But recent SASSCAL-funded surveys revealed species unaccounted for by Figueiredo & Smith (2008), underlining the need for more botanical surveys in both existing and newly proposed areas of conservation concern. Analysis of the collections from recent surveys is starting to reveal little-documented areas of endemism. The Lubango Escarpment is one obvious focus, but so too is the highly leached high-rainfall Kalahari sand system of Moxico Province and adjacent area that has its own peculiar and little-understood flora.

Only 399 species of vascular plant in Angola have been formally assessed for extinction risk through the IUCN Red List system (IUCN, 2018), and a mere 36 of these appear in threatened categories. None of the genera listed in an earlier section of this paper as Angolan endemics have been assessed. Much work is needed in this area. Four Angolan institutions are listed in Index Herbariorum (Thiers, continually updated), LUAI (ex-Centro Nacional de Investigação Cientifica (CNIC), Luanda), LUA (Instituto de Investigação Agronómica, Huambo), LUBA (Instituto Superior de Ciencias da Educação, Lubango), and DIA (Museu do Dundo). While the Dundo Museum has been refurbished and reopened to the public in 2012, it appears that the herbarium collections formerly housed there no longer exist. The LUA herbarium contains 40,000 collections. It was evacuated to Luanda in 1995, and has now returned to Huambo, but is in poor condition and funds are needed to employ well-trained young staff to conserve, rehabilitate and work on this important collection. LUAI contains 35,000 collections and LUBA around 50,000. There are ongoing digitisation programmes at both institutions that will make these collections more widely accessible.

Outside of Angola, Portuguese institutes in Coimbra (COI) and Lisbon (LISC, LISU) hold the largest collections of Angolan plants, an estimated 90,000 collections (Figueiredo & César, 2008). 8,700 of Gossweiler's Angolan collections are housed at COI and these are available online. The collections at LISC are also available digitally, and are now being incorporated into the Lisbon University herbarium LISU. Most other herbaria with significant Angolan holdings have only digitised their type collections, although mass digitisation of entire national collections has made material in the Paris Natural History Museum (P) and Leiden’s Naturalis (L, WAG, U) accessible. In the UK, the Natural History Museum (BM) and Royal Botanic Gardens, Kew (K) in London - both of which contain significant Angolan holdings, and Royal Botanic Gardens, Edinburgh (E) have plans to follow suit. In Germany, Angolan collections in the Technische Universität Dresden (DR) comprise 2,400 specimens, kept separately from the main herbarium. The Future Okavango project has augmented Hamburg’s (HBG) Angolan collections by around 2000 numbers. Once these combined resources are available online, georeferencing the Angolan material should be a priority. Such collections data could then be used in a variety of projects or programmes. Georeferenced specimen data underpins IUCN conservation assessments, for example, and these in turn inform Important Plant Area designations (Darbyshire et al., 2017) and other forms of conservation planning.

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List of Post-Independence collectors in Angola. Entries follow a format developed from Figueiredo et al. (2008).

Surname, first names (birth-death)

C: period when collecting in Angola; **H:** herbaria [abbreviations after Thiers, continuously updated; FC-UAN = Faculdade de Ciências, Universidade Agostinho Neto, Luanda; INBAC = Instituto Nacional da Biodiversidade e Áreas de Conservação of the Ministério do Ambiente, Luanda]; **L:** provinces abbreviated after Figueiredo & Smith 2008: principal localities; **B:** biographical information.

Alcochete, António (1963 -)

C: 1991; **H:** K; **L:** CU HI NA; **B:** Angolan botanist, collected with Gerrard, Matos and Newman.

Baragwanath, S.

C: 1994. **H:** PRE.

Barker, Nigel P. (1962 -)

C: 2013, 2015, 2017; **H:** GRA, INBAC, K, LUBA, PRE; **L:** CC HI NA: Lubango Escarpment, Mt Tchivira, Serra da Neve, Mundondo Plateau, Okavango, Cuito and Longa Rivers; **B:** South African Professor of Plant Science at University of Pretoria, formerly at Rhodes University.

Bester, Stoffel Petrus (Pieter) (1969 -).

C: 2009, 2015; **H:** GRA, INBAC, K, LUBA, PRE; **L:** CC CU HI NA: Iona, Lubango Escarpment, Bicuar, Okavango, Cuito and Longa Rivers; **B:** South African botanist based at PRE.

Bruyns, Peter Vincent (1957 -)

C: 2006, 2007; **H:** BOL, E, K, NBG, PRE; **L:** BE HI NA: Lubango Escarpment and coastal plain; **B:** South African mathematician and botanist with particular interest in succulent plants.

Cardoso, João Francisco (1974 -)

C: 2005, 2006; **H:** LISC, LUAI; **L:** HI NA: Serra da Leba, Virei, Caraculo, Cainde; **B:** Agronomist with Agostinho Neto University.

Cheek, Martin Roy (1960 -)

C: 2012; **H:** K; **L:** CA; **B:** British botanist at Royal Botanic Gardens Kew, specialist on West African flora.

Clark, Vincent Ralph (1977 -)

C: 2013; **H:** GRA, K, LUBA, PRE; **L:** HI NA: Lubango Escarpment, Mt Tchivira, Serra da Neve; **B:** South African botanist.

Cooper, C.E.

C: 1997; **H:** PRE.

Crawford, Frances Mary (1981 -)

C: 2009, 2011; **H:** INBAC, K, PRE; **L:** HI LN NA: Lucapa, Lagoa Carumbo, Iona, Lubango Escarpment; **B:** British botanist, Curator of WIND herbarium, formerly at Royal Botanic Gardens, Kew; collected with Darbyshire and Goyder in LN.

Daniel, José Maria (1943 - 2015)

C: 1964 - 2008; **H:** LUBA, LUA, LUAI, **L:** Collected in all Angolan Provinces; **B:** Angolan botanist at Lubango Herbarium until his retirement; collected with Huntley, Matos and Gonçalves.

Darbyshire, Iain Andrew (1976 -)

C: 2011 -, 2013; **H:** INBAC, K, LISC; **L:** LN: Lucapa, Lagoa Carumbo; **B:** British botanist at Royal Botanic Gardens, Kew; collected with Crawford, Gomes, Goyder & Kodo.

Dexter, Kyle Graham (1980 -)

C: 2017 -; **H:** E, COLO, WIND, LUBA; **L:** CU HI NA; **B:** Senior Lecturer at University of Edinburgh and Associate Researcher at Royal Botanic Garden Edinburgh (E).

Ditsch, Barbara (1961 -)

C: 2013, 2015 **H:** DR, LUA; **L:** UI: Serra do Pingano, Municipality of Uíge, Kimbele, Damba, Mucaba; **B:** German botanist at Dresden Botanic Garden.

Finckh, Manfred (1963 -)

C: 2011 -; **H:** HGB, LUBA, WIND; BI CC HA HI MO: Chitembo (Cusseque), Caiundo, Cachingues, Savate, Cuangar, Bicuar National Park, Cameia National Park, Tundavala Observatory under TFO and SASSCAL Projects; **B:** Ecologist at Institute for Plant Science and Microbiology, University of Hamburg, Germany.

Francisco, Domingos Mumbundu (1974 -)

C: 2008 -; **H:** LISC, LUAI, LUBA; **L:** CA CC LA MA NA ZA: Barra do Cuanza,Iona, Cangandala, Quiçama National Parks; **B:** Angolan botanist at Universidade Agostinho Neto, Centro de Botânica, LUAI Herbarium, collected with Gomes in Cabinda and Gonçalves in Mt. Tchivira, Serra da Neve and Lubango Escarpment.

Frisby, Arnold

C: 2016, 2017; **H:** INBAC, K, LUBA, PRE; **L:** BI CC: Cubango and Cuito Rivers; **B:** South African botanist at University of Pretoria.

Gerrard, Jacqueline

C: 1991; **H:** K; **L:** CU HI NA.

Godinho, Elizeth

C: 2013; **H:** INBAC, K, LISC; **L:** LN: Lagoa Carumbo; **B:** Angolan botanist at INBAC; collected with Darbyshire, Goyder and Kodo.

Göhre, Anne (1990 -)

C: 2014 - 2016; **H:** B, BR, BONN, P; **L:** UI: Municipality of Uíge, Kimbele, Damba, Mucaba; **B:** German botanist at Dresden Botanic Garden.

Gomes, Amândio Luís (1971 -)

C: 2010 -; **H:** FC-UAN, INBAC, K, LISC, LUAI, LUBA; **L:** BE BI BO CC CN CS HA LN ZA: Lucapa, Lagoa Carumbo, Chitembo (Cusseque), Tundavala Observatory under TFO and SASSCAL Projects; **B:** Angolan botanist at Universidade Agostinho Neto, Luanda; collected with Crawford, Darbyshire and Goyder in LN.

Gonçalves, Francisco Maiato Pedro (1982 -)

C: 2008 -; **H:** HBG, INBAC, K, LUBA; **L:** BI CC CU CS HA HI LA NA MO: Chitembo (Cusseque), Kumbira forest, Mt. Namba, Lubango Escarpment, Okavango headwaters, Huíla Province within SASSCAL project; **B:** Angolan botanist at Lubango Herbarium, ISCED-Huíla, Lubango.

Goyder, David John (1959 -)

C: 2011 -; **H:** GRA, INBAC, K, LUBA, PRE; **L:** BI CC CS HI LN MO NA: Kumbira, Mt. Namba, Serra da Neve, Lubango Escarpment, Mt Tchivira, Okavango headwaters, Lucapa, Lagoa Carumbo; **B:** British botanist at Royal Botanic Gardens, Kew; collected with Crawford, Darbyshire, Godinho, Gomes and Kodo in LN, with Barker and Clark on the western escarpment, with Gonçalves in CS and Okavango headwaters, with Barker, Bester, Frisby and Janks in CC.

Harris, Timothy (1982 -)

C: 2013; **H:** K, LUAI, PSUB, WIND; **L:** CC: Okavango, Cuito and Cuando Rivers; **B:** British botanist; collected with Mike Murray - Hudson.

Heinze, Christin (1993 -)

C: 2014 - 2017; **H:** DR, LUA; **L:** CN: all municipalities; **B:** German botanist at Technische Universität Dresden.

Janks, Matthew

C: 2015; **H:** GRA, INBAC, LUBA, PRE; **L:** CC: Okavango, Cuito and Longa Rivers; **B:** South African botanist; collected with Barker, Bester & Goyder.

Jürgens, Norbert (1953 -)

C: 2008 -; **H:** HGB, WIND, LUBA; **L:** CU HI NA; **B:** Professor at Institute for Plant Science and Microbiology, University of Hamburg, Germany.

Kodo, Felipe Mpembele

C: 2013; **H:** INBAC, K, LISC; **L:** LN: Lagoa Carumbo; **B:** Angolan botanist at INBAC; collected with Darbyshire, Godinho and Goyder.

Lautenschläger, Thea (1980 -)

C: 2012 - 2018; **H:** DR, LUA; **L:** UI: Municipality of Uíge, Mucaba, Maquela do Zombo, Quitexe, Milunga, Sanza Pombo, Kimbele, Ambuila, Songo, Bungo, Bembe, Puri, Negage, Altocauale, Damba; **B:** German botanist at Technische Universität Dresden.

Luís, José Camôngua (1984 -)

C: 2015 -. **H:** K, LUBA; **L:** CS HI: Lubango Escarpment, Mt Namba; **B:** Angolan Geographer, collected with Goyder and Gonçalves in Morro da Namba.

Maiato, Francisco

See **Gonçalves, Francisco Maiato Pedro**.

Manning, Stephen D.

C: 1986 - 1998.

Matos, Elizabeth (Liz), Merle (1938 -)

C: 1975 -; **B:** British botanist, founder and director of Angola's National Plant Genetic Resources Centre, Agostinho Neto University, Luanda. Retired in 2008.

Mawunu, Monizi (1973 -)

C: 2013 2018; **H:** DR, LUA; **L:** UI, whole province; **B:** Angolan botanist at Universidade Kimpa Vita.

Müller, Frank (1966 -)

C: 2015; **H:** DR, LUA; **L:** UI: Municipality of Uíge, Songo, Mucaba; **B:** German botanist at Technische Universität Dresden.

Murray-Hudson, Frances

C: 2013; **H:** K, LUAI, PSUB, WIND; **L:** CC: Okavango, Cuito and Cuando Rivers; **B:** Volunteer at Peter Smith University of Botswana Herbarium (PSUB); collected with Harris.

Neinhuis, Christoph (1962 -)

C: 2012-2018; **H:** DR, LUA; **L:** UI: Municipality of Uíge, Mucaba, Maquela do Zombo, Quitexe, Milunga, Sanza Pombo; **B:** German botanist at Technische Universität Dresden, director of the Botanical Garden TU Dresden.

Newman, Mark Fleming (1959 -)

C: 1991; **H:** K; **L:** CU HI NA; **B:** British botanist at Royal Botanic Garden Edinburgh. In 1991, at the Seed Bank, Royal Botanic Gardens, Kew; collected with Alcochete, Gerrard and Matos, mainly for seeds, with herbarium voucher specimens for identification.

Rejmánek, Marcel (Marek/Marc) (1946 -)

C: 2014; **H:** LUBA, STE; **L:** BE BO CN CS HA HI MA NA UI; **B:** Czech botanist based at University of California, Davis, working on biological invasions. Conducted a rapid inventory of invasive plants in Angola in 2014 with Huntley, Roux and Richardson.

Revermann, Rasmus (1979 -)

C: 2011 -; **H:** HGB, WIND, LUBA; **L:** BI CC HA HI: Chitembo (Cusseque), Caiundo, Cachingues, Savate, Cuangar under TFO and SASSCAL Projects; **B:** Ecologist at Institute for Plant Science and Microbiology, University of Hamburg, Germany.

Roux, Jacobus Petrus (Koos) (1954-2013)

C: 2001; **H:** PRE; **B:** South African Pteridophyte specialist.

Tripp, Erin Anne (1979 **-**)

C: 2017-present; **H:** COLO, E, WIND, LUBA; **L:** CU HI NA; **B:** Researcher at Colorado Herbarium, University of Colorado, USA.

Chapter 8

Synthesis

Francisco M. P. Gonçalves

General overview of miombo and dry woodlands: Here, I summarized and discussed the general aspects related to miombo woodland distribution, and threats due to impacts of human activities in these woodlands. Specifically I discussed the most important drivers of change in the miombo, such as shifting cultivation, charcoal production and other infrastructure such as roads. I analyzed general aspects related to this important ecosystem in Angola, the lack of information to quantify the forest resources of the country, and the implications for their conservation and management in the context of the Cubango/Okavango basin. The figures outlined here are in accordance to the objectives defined for this thesis which are: (a) to assess how shifting cultivation affect the stand structure, species diversity and composition, as well as the regeneration of woody species in the Cusseque and Caiundo study areas; (b) to characterize charcoal production in four villages of Cusseque study area along the main road, assess the household livelihoods derived from charcoal production, and the implications of the activity for future management of the woodlands. Additionally I've explored alternatives aiming to generate useful ideas which could gradually replace the activity to others with a lower environmental impact on the woodlands, and generate income at the same time. Finally I have assessed the above-ground biomass and basal area in the woodlands areas previously used for charcoal production compared to mature stands; (c) and to document the floristic diversity of the study area, and describe potential new species or new geographic distribution records.

Vegetation recovery of the woodlands following disturbance due to shifting cultivation: As shown in Chapter 1, the vegetation of Angola in general is poorly studied and documented. For the miombo woodlands of Bié Province for instance, only a single plot based-study conducted in the early 1970s by Monteiro was known, the study provided the first overview of woody vegetationin miombo of the Bié plateau, including the first provincial woodland map, containing three main vegetation associations and sub-associations. However, very little was known in terms of species diversity, composition and dynamics of woody vegetation following disturbance. In the framework of the Future Okavango Project (SP05) we were able to carry out vegetation surveys aiming to analyze the changes in species diversity and composition of the miombo woodlands of Cusseque in the municipality of Chitembo (Bié province), and in the *Baikiaea-Burkea* woodlands of Caiundo (Cuando Cubango province), following a chronosequence of vegetation recovery after disturbance caused by shifting cultivation (**Chapter 2** and **3**). In general the woodlands showed different stand age (Appendix 6) and evidenced an increase in species richness with fallow age in the miombo woodlands. The total number of species in early regrowth tends to reach that of mature forests, but composition of species did not recover within the same time frame. It may take several decades to attain the species composition of mature woodland stands. We also observed that the early regrowth sites were dominated by *Combretum* species and other fire tolerant and light demanding tree species, and in the later stages these species are gradually replaced by more competitive canopy tree species such as *Brachystegia spiciformis* and *Julbernardia paniculata*. The dominance of *Combretum* species is related to areas characterized by high land use pressure caused by slash-and-burn agriculture as observed in Cusseque. Contrary to miombo, *Baikiaea-Burkea* woodlands are dominated by agricultural fields used for much longer periods of cultivation, which made it difficult to estabilish a chronosequence of age of abandonment. However, we were able to identify fallow sites in the old floodplains which have been abandoned over a period of about 15-20 years. These sites when compared to mature stands contained very few individuals of hardwood species and differed slightly in species composition, since at this fallow stage the woodlands tend to already reach the species composition of mature woodlands, replacing the tree species composition of initial successional stages with more competitive tree species which characterize old-growth habitats. The low stem abundance of hardwood species encountered in fallow sites may be caused by the high frequency and intensity of fires, affecting the production of emerging shoots from root stocks and stumps normally left uncut in the fallow sites. Edaphic, climatic and biotic constraints were also identified as some of the limiting factors which may affect tree growth, seed germination and seedling survival rates of dry woodlands typical tree species. We observed that the harvestable woody species showed signs of continuous decline, with a general absence of small stems of *Guibourtia coleosperma* and *Pterocarpus angolensis*, indicating selective tree harvesting for timber exploitation, while the larger stems of *Schinziophyton rautanenii* were also very few, with larger stems harvested for making floats, canoes and other useful utensils as reported in other studies conducted in the region.

Household livelihood survey and income generated from charcoal production: Charcoal production is rapidly increasing in the study area, representing another driver of change in the miombo woodlands of south-central Angola, followed by small scale agriculture, based mainly on shifting cultivation. The activity took off recently with the recovery of the main road network in the Bíe and Cuando Cubango provinces. Charcoal production increases along the main roads, driven by energy demand in the main urban and peri-urban centres and is facilitated by a lack of control along the road axes. The basic livelihood activities identified in the villages like subsistence agriculture, honey production, selling of Non-Timber Forest Products, thus are more recently combined with charcoal production. In general family size in the villages was high, accounting for more females than males. The villagers generally have attended primary and secondary school up to 6th grade, which makes the adult population not elegible for formal employment. Therefore, many people depend on the exploitation of natural resources for income. Charcoal production consists of multiple steps. Depending on kiln size the combustion may take several days, with very low charcoal return when compared to the number of trees cut down for this purpose.

Based on this observation, we have estimated the total area being cleared and number of trees being cut at kiln sites, in order to estimate the cash-return based on the charcoal sale price among the four villages. The activity in general is physically demanding and is not always a remunerated activity. Thus, other alternative activities might be explored aiming to reduce biomass consumption, and at the same time protect the indigenous woodland trees. Following the recommendations of the UN-REDD$^+$initiatives, aiming to reduce emissions from deforestation and forest degradation in developing countries improving the efficiency of kilns and enhancing the honey production in the study area appear to be reasonable alternative options to reduce the consumption of woody resources and to generate income for the families.

Finally, we quantified tree biomass and basal area on fallow charcoal sites, compared to mature woodlands. This approach allowed us to understand the recovery process of this important ecological parameter, showing that charcoal fallows recover biomass relatively quick when compared to formal agricultural sites of approximately the same stand age. This is maybe explained by site soil depletion after agricultural use compared to former sites of charcoal production if these sites are not converted to agriculture fields. Another important point is that part of the contribution to biomass in charcoal fallows may come from trees not suitable for charcoal production and left standing in the fallow sites (**Chapter 4**).

Vegetation classification of the woodlands of Huíla province: The study fills some important gaps by documenting the woody vegetation of one of the most diverse areas of the country. The region was in past subjected to various botanical surveys, aiming mostly to document the floristic diversity of the region. However, important parts of this region were not included in previous studies and until recently no plot-based studies documenting the woodland diversity of the Huíla province had been conducted.

Additionally, no vegetation maps have been elaborated. Thus, this study represents the first study to achieve this objective which resulted in the description of thirteen vegetation communities based on 456 surveyed vegetation plots. Important new vegetation types were described for the Huíla Province, and their relationship to other vegetation types was established. The study represents an important contribution for the Angolan flora and will contribute to the elaboration of the first vegetation map for the region.

New species to science and new geographical distribution records: During the field survey a potential new grass species of the subfamily Chloridoideae was discovered in the riverine peatlands of the Angola central plateau by a team member. Anatomical comparisons combined with molecular analysis are under way, and will be fundamental to determine the final placement of the species in an existing genus (Revermann 2016). Specimens of *Shistostephium crataegifolium* (DC.) Fenzl. ex Harv. (Compositae: Anthemideae) were collected, the species has not been recorded before and represents a new geographical record for Angola (**Chapter 5**). Additionally, we collected more than 100 botanical specimens both in Cusseque and Caiundo study areas (Appendix 4). From the species collected in Cusseque four were endemic to Angola: *Polygala stenopetala* subsp. *casuarina*, *Memecylon huillense*, *Cystostemom hispidissimus* subsp. *hispidissimus* and *Dianthus angolensis* subsp. *angolensis*. Other specimens of *Barleria eburnea* I.Darbyshire were collected in Cusseque, a duplicate was sent to Kew Herbarium (K), where it is being described, additional samples and aerial parts are needed for a detailed description of the species. *Combretum schumannii* constitutes among others a new provincial record and additions to the published Checklist of Angolan vascular plants. This information on the plant diversity of the miombo represents one of the key findings of the thesis, emphasizing the need for more botanical surveys in Angola, in order to document the floristic diversity of remote and poorly studied areas of Angola.

Overview of historical and recent botanical surveys to Angola: Angola constitutes one of the most diverse parts of the southern Africa region. The rich biodiversity of the country early attracted researchers from many parts of the world, though many parts of the country remain understudied with enormous gaps observed in the northern and eastern parts. Recent studies have been conducted in Angola, these have contributed additional species records at provincial levels, new species to science have been described, contributing in this way to the existing checklist of vascular plants.

Unfortunately, most of these studies are focused mainly on regions of particularly rich biodiversity, while important parts of the country still remain poorly studied.

Final remarks: The presented study has contributed to further understanding the vegetation dynamics of the miombo and dry southern African woodlands of the Cubango basin, following human impacts from shifting cultivation. We have established a chronosequence of forest recovery after slash-and-burn agriculture in the miombo and *Baikiaea*-*Burkea* woodlands, providing useful data to inform better management of these woodlands for future generations. The thesis also presents a comprehensive account of tree species composition and species diversity on agricultural and charcoal fallow sites compared to intact woodland areas. The thesis deals for the first time with environmental impacts of charcoal production in Angola, analyzing at the same time the income generated from the activity by households in four villages along the main road between the cities of Cuito in Bié and Menongue in Cuando Cubango. We have established a linkage between socio-economic assessment and vegetation ecology, studying the recovery process after human disturbance caused by charcoal production. Additionally we were able to collect botanical specimens which allowed us to discover a new species record for the country, a potential new plant species and additions to the Angolan Checklist of Vascular Plants. Further botanical inventories of poorly studied and undocumented areas of the country are heavily recommended in order to amend species extension records, and to document potential new species. There is still much work to do regarding the documentation of the entire Angolan flora, as the country is highly biodiverse, and very few studies have been conducted in the country due to the long period of civil war, compared to other countries within the Southern African region.

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Author's contributions

Chapter 1: This chapter was writenfully by my own and adapted from the inicial project proposal, presented for a doctoral degree at the Department of Biology, Institute of Plant Science and Microbiology of the University of Hamburg.

Chapter 2: Data for this paper were gathered during field work in the Cusseque study area conducted by the first author, togheter with Amândio L. Gomes and Marcos P. M. Aidar. The first author conceived the structure of the manuscript and performed the data analysis. Rasmus Revermann performed additional data analysis with Diversity profiles of Renyi's entropy, and Indicator Species Analysis (ISA). The co-author's contributed equally during writing and revision process of the manuscript.

Chapter 3: The field work for this paper was carried by the first and second authors respectivelly, following a previous visit in order to identify sites of previous agriculture utilization with Marcos P. M. Aidar and Amândio L. Gomes. FMPG conceived the manuscript structure, writing and performed all the statistical analysis. Rasmus Revermann provide the map of the study area, the other co-authors contributed during writing of the manuscript and the revision process.

Chapter 4: The study was conceived together with Rasmus Revermann and Manfred Finckh in order to fill in gaps on the miombo woodlands utilization, especially due to the emerging activity of charcoal production at the time we carried out our study. Field work for this study, and the interview process was carried out by Francisco M. P. Gonçalves (FMPG), as the first author FMPG outlined the writing of the manuscript, and performed the analysis and interpretation of questionnaires. Rasmus Revermann and Manfred Finckh contributed with additional data analysis, the co-authors contributed also with writing and the revision processes.

Chapter 5: The study was conducted under SASSCAL, task 154: Plant and vegetation assessments in the region and elaboration of regional vegetation databases and vegetation maps. The authors conducted the field work under which vegetation data was obtained for this paper, and equally contributed in writing, data analysis and the revision of the manuscript.

Chapter 6: Francisco M. P. Gonçalves conducted the fieldwork during which the new record was collected, and co-wrote the account with two other authors. José J. Tchamba performed all the herbarium work, including the digitisation of the specimen for the manuscript and David J. Goyder identified the specimen at Kew and contributed with writing of this account.

Chapter 7: This chapter was written joitly by the authors looking at the past and recent exploration of the Angolan flora. The manuscript looks at the most important historic steps of exploration of the Angolan flora and at some important recent initiatives. DJG conceived the main body structure of the manuscript, synthetised the most recent and past studies related to the Angolan flora and elaborated the provisional list of collectors for the country. FMPG contributed with additional recent studies and expected outcomes, and added recent botanical collectors to the previous list prepared by the first author.

Chapter 8: This chapter was entirely written by my own synthetising the most important findings comprises the thesis.

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Dedication

This work is dedicated to my dear mom (*in memoriam*), to my wife (Paula Cristina Gonçalves Faria Gonçalves), to my children (Rafael Costa Faria Gonçalves, Anayeli Vayekela Faria Gonçalves and Svetlana Deolinda Faria Gonçalves) for their unconditional love, support and patience during the long periods of my absence, sometimes without any communication.

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Appendices

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Appendix 1: Stand structure of woody species and Importance Value Indices (IVI) of four forest stages. YF = Young Fallows; MF = Medium fallows; OF = Old Fallows and MW = Mature Forests/Woodlands.

Species	**Relative Frequency**				**Relative Density**				**Relative Dominance**				**Importance Value Index**			
	YF	**MF**	**OF**	**MW**	**YF**	**MF**	**OF**	**MW**	**YF**	**MF**	**OF**	**MW**	**YF**	**MF**	**OF**	**MW**
Albizia antunesiana Harms	---	1.47	---	0.43	---	0.64	---	0.11	---	0.18	---	0.02	---	2.17	---	0.55
Albizia gumífera (J.F.Gmel.) C.A.Sm.	2.58	---	---	0.43	0.97	---	---	0.23	0.43	---	---	0.03	3.69	---	---	0.67
Anisophyllea boehmii Engl.	0.65	2.45	---	0.43	0.24	0.9	---	0.11	0.09	1.68	---	0.05	0.92	3.91	---	0.56
Baphia bequaertii Welw. ex Baker	2.58	3.92	4.71	3.88	1.21	1.67	2.39	3.31	0.57	1.86	1.32	2.98	3.98	6.21	7.54	8.18
Bobgunnia madagascariensis (Desv.) J.H.Kirkbr. & Wiersema	4.52	2.94	3.14	2.16	3.62	0.9	0.87	0.91	1.86	0.35	0.53	0.81	8.76	3.96	4.19	3.34
Brachystegia bakeriana Hutch. & Burtt Davy	1.94	1.47	4.19	4.31	1.21	0.39	0.87	0.46	0.4	0.17	0.53	0.52	3.28	1.91	5.23	4.94
Brachystegia spiciformis Benth.	5.81	4.9	5.24	4.31	3.62	4.37	3.8	19.06	3.25	5.41	6.92	27.4	10.51	11.08	11.34	**32.51**
Burkea africana Hook.	5.16	4.9	4.71	3.88	6.28	4.63	4.23	3.54	6.52	2.05	3.09	2.12	**13.61**	10.21	9.97	8.13
Chrysophyllum bangweolense R.E.Fr.	---	1.47	---	---	---	0.39	---	---	---	0.13	---	---	---	1.9	---	---
Combretum collinum Fresen	6.45	3.43	5.24	2.16	13.04	2.44	6.51	1.26	7.45	1.44	6.94	0.62	**21.98**	6.35	**14.06**	3.62
Combretum sp.(139009)	---	---	---	3.88	---	---	---	1.71	---	---	---	0.9	---	---	---	5.89
Combretum zeyheri Sond.	6.45	4.9	4.71	1.29	10.39	6.17	6.51	0.46	7.99	10.06	14.93	0.19	**19.5**	**14.43**	**16.19**	1.81
Copaifera baumiana Harms	---	---	---	0.86	---	---	---	0.34	---	---	---	0.03	---	---	---	1.22
Cryptosepalum exfoliatum De Wild. subsp. ***pseudotaxus***	1.29	1.96	4.71	4.31	1.21	0.9	1.41	15.3	0.72	0.48	0.64	10.76	2.74	3.02	6.34	**23.19**
Dialium englerianum Welw. ex Oliv.	3.23	4.41	3.14	1.72	2.42	2.19	0.76	0.8	3.16	2.42	1.36	0.7	6.7	7.4	4.35	2.76
Diospyros batocana Hiern	---	---	---	0.86	---	---	---	0.23	---	---	---	0.14	---	---	---	1.14
Diplorhynchus condylocarpon (Müll.Arg.) Pichon	6.45	3.92	5.24	3.88	6.28	3.08	10.2	6.05	2.14	3.36	8.45	5.65	13.45	8.13	**18.25**	**11.81**
Ekebergia benguelensis Welw. ex C.DC.	---	1.96	---	---	---	0.51	---	---	---	0.3	---	---	---	2.57	---	---
Erythrophleum africanum (Welw. ex Benth.) Harms	6.45	4.9	5.24	4.31	13.29	11.95	11.82	13.47	18.63	8.86	14.13	14.88	**25.95**	**19.81**	**21.77**	**22.74**
Faurea rochetiana (A.Rich.) Chiov. ex Pic.Serm.	---	---	---	0.86	---	---	---	0.23	---	---	---	0.09	---	---	---	1.12
Guibourtia coleosperma (Benth.) J.Léonard	2.58	0.49	0.52	2.59	0.97	0.13	0.11	1.26	0.23	0.04	0.04	3.25	3.62	0.63	0.64	4.93

Hymenocardia acida Tul. var. *acida*	4.52	4.41	4.71	3.88	3.14	3.98	2.71	2.51	6.75	3.63	1.77	0.97	9.91	9.61	8.01	6.71
Julbernardia paniculata Benth.	5.81	4.9	5.24	4.31	4.83	33.68	32.21	2.85	3.72	25.83	27	6.6	11.88	**47.19**	**46.45**	9.36
Memecylon flavovirens Baker	---	---	---	2.16	---	---	---	1.26	---	---	---	1.17	---	---	---	3.8
Monotes africanus A.DC.	1.94	2.94	2.09	4.31	1.69	1.29	0.76	5.82	1.24	1.44	0.45	8.23	4.04	4.71	3	**12.87**
Monotes katangensis (De Wild.) De Wild.	2.58	2.45	1.57	3.45	2.42	0.77	0.76	1.26	1.61	0.27	0.33	1.91	5.53	3.31	2.44	5.34
Ochna schweinfurthiana F.Hoffm.	---	---	4.19	3.45	---	---	1.19	3.08	---	---	0.29	0.73	---	---	5.48	6.77
Oldfieldia dactylophylla (Welw. ex Oliv.) J.Léonard	---	0.49	2.09	0.43	---	0.13	0.54	0.11	---	0.04	0.3	0.03	---	0.63	2.74	0.56
Parinari curatellifolia Planch. ex Benth.	---	1.47	---	2.59	---	0.39	---	1.03	---	0.38	---	0.36	---	1.98	---	3.73
Pericopsis angolensis (Baker) Meeuwen forma ***angolensis***	1.29	4.41	5.24	---	0.48	2.7	4.88	---	3.34	8.09	3.55	---	2.89	**9.81**	11.3	---
Protea gaguedi J.F.Gmel. subsp. *gaguedi*	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Protea petiolaris (Hiern) Baker & C.H.Wright subsp. *petiolaris*	1.29	---	1.05	0.43	0.48	---	0.22	0.11	0.34	---	0.07	0.09	1.89	---	1.29	0.57
Protea sp.(139072)	---	1.96	---	---	---	0.64	---	---	---	0.38	---	---	---	2.73	---	---
Pseudolachnostylis maprouneifolia Pax var. dekindtii (Pax) Radcl.-Sm.	1.29	2.45	4.19	3.02	0.48	0.9	1.52	1.48	0.29	2.2	2.86	1.34	1.87	4.08	6.66	4.95
Pteleopsis anisoptera (Welw. ex M.A.Lawson) Engl. & Diels	0.65	0.49	0.52	3.02	0.24	0.13	0.11	1.6	0.07	0.02	0.01	0.82	0.91	0.63	0.64	4.89
Pterocarpus angolensis DC.	3.87	1.47	2.09	3.02	2.17	0.51	1.08	1.94	0.57	0.11	1.52	1.04	6.24	2.02	3.68	5.3
Rothmannia engleriana (K.Schum.) Keay var. *engleriana*	---	0.49	0.52	1.72	---	0.13	0.11	0.46	---	0.02	0.02	0.27	---	0.63	0.64	2.27
Schrebera trichoclada Welw.	3.87	2.94	1.57	0.86	1.45	1.03	0.33	0.34	0.51	0.75	0.06	0.13	5.49	4.22	1.91	1.25
Securidaca longepedunculata Fresen	0.65	0.98	2.62	0.43	0.24	0.39	0.65	0.23	0.04	0.17	0.57	0.11	0.9	1.42	3.46	0.7
Strychnos cocculoides Baker	1.94	---	2.09	1.29	0.97	---	0.43	0.34	0.31	---	0.3	0.16	3.01	---	2.63	1.69
Strychnos pungens Soler	---	0.49	---	---	---	0.13	---	---	---	0.54	---	---	---	0.8	---	---
Strychnos mitis S.Moore	---	---	---	1.72	---	---	---	0.68	---	---	---	0.21	---	---	---	2.48
Strychnos spinosa Lam.	1.94	0.49	1.05	1.29	0.97	0.13	0.22	0.34	0.74	0.02	0.04	0.11	3.15	0.62	1.28	1.67
Syzygium benguelense (Welw. ex Hiern) Engl.	0.65	---	---	0.86	0.24	---	---	0.34	0.05	---	---	0.08	0.9	---	---	1.23
Syzygium cordatum Hochst. ex Krauss subsp. *cordatum*	---	0.49	0.52	0.86	---	0.13	0.11	0.46	---	0.49	0.03	0.35	---	0.78	0.64	1.43
Syzygium guineense (Willd.) DC. subsp. *guineense*	3.23	3.92	2.09	---	3.38	3.73	0.65	---	1.14	4.28	0.33	---	6.99	9.08	2.85	---

Terminalia brachystemma Welw. ex Hiern	6.45	4.9	2.62	1.29	11.35	4.37	1.19	1.14	25.47	8.45	1.12	0.31	**26.29**	**12.09**	4.18	2.54
Uapaca kirkiana Müll.Arg.	---	3.43	---	0.43	---	2.19	---	0.11	---	2.78	---	0.03	---	0.62	---	0.56
Uapaca nitida Müll.Arg. var. *nitida*	0.65	0.49	2.09	4.31	0.24	0.13	0.54	2.05	0.07	0.02	0.39	2.71	0.91	6.54	2.77	7.27
Unidentified sp. 1 (139230)	---	0.49	0.52	---	---	0.13	0.11	---	---	0.04	0.05	---	---	0.63	0.65	---
Unidentified sp. 2 (139236)	---	1.47	---	---	---	0.39	---	---	---	0.13	---	---	---	---	---	---
Vitex madiensis Oliv. subsp. *madiensis*	1.29	2.94	0.52	1.29	0.48	0.9	0.22	0.46	0.3	0.35	0.06	0.4	1.87	3.96	0.76	1.88
Warneckea sapinii (De Wild.) Jacq.-Fél.	---	0.49	---	3.02	---	0.13	---	1.14	---	0.07	---	0.7	---	0.64	---	4.39

Appendix 2: Stand structure of woody species and Importance Value Indices (IVI) of fallows and mature woodlands vegetation plots. RF = Relative Frequency; RD = Relative Density and RDo = Relative Dominance (Basal Area). The ten most dominant species ranked by their IVI in both stand stages are highlighted.

Species	Relative Frequency		Relative Density		Relative Dominance		Importance Value Index	
	Fallows	Mature	Fallows	Mature	Fallows	Mature	Fallows	Mature
Acacia erioloba E. Mey.	1.99	1.48	0.89	0.53	5.4	0.47	4.68	2.17
Baikiaea plurijuga Harms	4.64	7.41	5.65	8.27	7.74	10.57	**12.9**	**19.2**
Baphia massaiensis Taub. subsp. ***obovata*** (Schinz) Brummit var. *obovata*	5.3	0.74	5.95	0.53	1.19	0.19	**11.65**	1.34
Bauhinia urbaniana Shinz.	1.32	----	0.89	----	4.49	----	3.71	----
Bobgunia madagascariensis (Desv.) J. H. Kirkbr. & Wiersema	2.65	4.44	1.79	2.93	1.8	2.3	5.03	8.14
Bridelia mollis Hutch.	1.32	----	0.6	----	0.98	----	2.25	----
Burkea africana Hook.	3.97	7.41	2.38	8	1.34	7.95	6.8	**18.1**
Combretum collinum Fresen.	5.96	6.67	11.9	9.6	9.99	2.03	**21.2**	**16.9**
Combretum zeyheri Sond.	6.62	5.93	6.55	3.2	6.52	1.21	**15.3**	9.53
Commiphora angolensis Engl.	----	2.22	----	0.8	----	0.15	----	3.07
Dalbergia nitidula Welw. ex Baker	----	0.74	----	0.27	----	0.27	----	1.1
Dialium englerianum Henriq.	3.97	5.19	2.38	6.13	0.61	6.97	6.56	**13.6**
Diplorhynchus condylocarpon (Müll. Arg.) Pichon	5.96	7.41	11.61	21.6	27.68	14.67	**26.8**	**33.9**
Dombeya burgessiae Gerrard ex Harv.	2.65	0.74	1.49	0.27	0.32	0.03	4.25	1.02
Erythrophleum africanum (Welw. ex. Benth.) Arms	4.64	5.93	4.17	3.73	1.22	4.64	**9.21**	**11.21**
Guibourtia coleosperma (Benth.) J. Léonard	1.99	2.96	1.49	1.87	0.5	14.78	3.64	9.76
Gymnosporia senegalensis (Lam.) Loes.	0.66	1.48	0.3	0.8	0.02	0.07	0.97	2.31
Hexalobus monopetalus (A.Rich.) Engl. & Diels	3.31	0.74	3.27	0.27	2.77	0.4	7.51	1.14
Hymenocardia acida Tul. var. *acida*	3.31	1.48	2.08	0.53	3.36	0.03	6.51	2.02
Lannea discolor Engl.	1.32	1.48	0.6	0.53	0.88	0.04	2.21	2.03
Ochna pulchra Hook.	5.3	6.67	5.65	4.53	9.16	2.18	**14.0**	**11.93**

Oldfieldia dactylophylla (Welw. ex. Oliv.) J. Léonard	1.32	----	0.89	----	0.08	----	2.24	----
Ozoroa cf. *paniculosa* (Engl.) R. Fern.	----	0.74	----	0.27	----	0.01	----	1.01
Philenoptera nelsii (Schinz) Schrire	----	1.48	----	0.53	----	0.32	----	2.12
Pseudolachnostylis maprouneifolia Pax *var*. ***dekindtii*** (Pax) Radcl.-Sm.	3.97	4.44	3.27	5.33	1.21	1.59	7.65	**10.31**
Pterocarpus angolensis DC.	5.3	5.93	5.95	6.13	3.08	3.33	**12.28**	**13.17**
Schinziophyton rautanenii (Schinz) Radcl.-Sm	6.62	5.93	8.04	7.47	6.49	19.95	**16.8**	**20.0**
Securidaca longepedunculata Fresen.	0.66	----	0.3	----	1.59	----	1.49	----
Strychnos cocculoides Baker.	1.99	2.96	1.19	1.07	0.23	0.42	3.25	4.17
Strychnos punges Soler.	3.97	5.93	2.38	4.27	0.69	4.23	6.58	11.6
Terminalia sericea Burch. ex. DC.	5.96	0.74	6.85	0.27	0.09	0.27	**12.83**	1.1
Unidentified sp. (uncollected)	0.66	----	0.3	----	0.11	----	1	----
Vangueriopsis lanciflora (Hiern) Robyns	1.32	----	0.6	----	0.33	----	2.03	----
Xylopia tomentosa Exell	1.32	----	0.6	----	0.13	----	1.96	----
Ziziphus abyssinica Hochst. ex A.Rich.	----	0.74	----	0.27	----	0.93	----	1.32

Appendix 3: Total area of woodlands being cleared for charcoal production in the four villages surveyed, estimated from the expected number of bags, total number of stumps and density of trees.

Name of the villages	DBH		Amount		Density of trees	Treebag^{-1}	Bags ha^{-1}	Cleared area^{-1}
	Small stems	Large stems	Trees per kiln	Bags per kiln				
Cawololo	8.0	18.8	23	50	652	0.46	2.2	0.04
Cawololo	14.6	22.0	118	40	287	2.95	8.9	0.41
Cawololo	11.8	56.7	230	100	426	2.30	43.5	0.54
Cawololo	13.1	76.7	158	200	346	0.79	59.7	0.46
Cawololo	7.6	22.9	40	13	689	3.08	1.0	0.06
Cawololo	9.5	36.0	52	20	568	2.60	2.0	0.09
Cawololo	10.2	26.7	72	18	512	4.00	2.4	0.14
Cawololo	3.5	30.9	300	200	988	1.50	113.4	0.30
Cawololo	3.5	22.3	200	90	988	2.22	34.0	0.20
Cawololo	13.1	41.7	203	NA	346	NA	NA	0.59
Kempo Grande	18.5	32.8	154	80	178	1.93	23.3	0.87
Kempo Grande	12.7	56.0	22	50	383	0.44	2.1	0.06
Kempo Grande	14.0	30.6	100	60	321	1.67	11.3	0.31
Kempo Grande	6.4	24.8	20	20	781	1.00	0.8	0.03
Kempo Grande	13.4	55.4	35	5	335	7.00	0.3	0.10
Kempo Grande	10.8	30.9	36	20	494	1.80	1.4	0.07
Kempo Grande	17.2	45.5	58	50	214	1.16	5.5	0.27
Kempo Grande	17.2	42.3	3	6	214	0.50	0.0	0.01
Kempo Grande	5.7	22.0	148	40	875	3.70	11.2	0.17

Munda	9.5	34.7	37	15	568	2.47	1.0	0.07
Munda	7.0	23.2	192	50	750	3.84	18.1	0.26
Munda	7.3	22.9	110	60	715	1.83	12.5	0.15
Munda	6.4	24.5	180	60	781	3.00	20.4	0.23
Satchijamba	12.4	32.2	112	57	404	1.96	12.1	0.28
Satchijamba	10.8	21.6	164	20	494	8.20	6.2	0.33
Satchijamba	4.1	41.1	120	100	987	1.20	22.7	0.12
Satchijamba	6.7	18.1	104	40	750	2.60	7.9	0.14
Satchijamba	5.7	23.9	168	25	875	6.72	7.9	0.19
Satchijamba	4.1	17.2	33	6	987	5.50	0.4	0.03
Satchijamba	6.4	24.5	198	68	781	2.91	25.5	0.25
Mean	**9.7**	**32.6**	**113.0**	**53.4**	**589.6**	**2.74**	**15.4**	**0.23**
S.D.	**4.3**	**14.0**	**76.2**	**48.8**	**257.0**	**1.97**	**23.6**	**0.19**

Appendix 4: Vegetation classification of the woody vegetation of Huíla province based on the 1000 m^2 vegetation plots. The table displays the indicator species of every vegetation community identified in the analysis. Species are ordered according to Pearson's *phi* coefficient of association p <= 0.05. The *phi* value ranges from 0 to 100 where *phi* > 30 is regarded as diagnostic of tree species. Species can be associated with more than one group or group combinations, only species with *p-value* ≤ 0.05 are shown in the table.

Vegetation Communities	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**1+2**	**1+4**	**2+3**	**2+5**	**2+6+7**	**12+13**	***p-value***
Community 1: *Brachystegia spiciformis - Parinari curatellifolia* woodlands																				
Brachystegia boehmii Taub.	90														71					0.001
Parinari curatellifolia Planch. ex Benth.	86													69						0.001
Brachystegia spiciformis Benth.	83													82				100		0.001
Uapaca kirkiana Müll.Arg.	76													44						0.001
Brachystegia floribunda Benth.	72																			0.001
Brachystegia longifolia Benth.	72																			0.001
Syzygium guineense (Willd.) DC. subsp. *guineense*	69													51						0.001
Anisophyllea boehmii Engl.	62													41						0.001
Faurea rochetiana (A.Rich.) Chiov. ex Pic.Serm.	62													36						0.001
Bobgunnia madagascariensis (Desv.) J.H.Kirkbr. & Wiersema	62													49						0.001
Albizia antunesiana Harms	55																			0.001
Uapaca nitida Müll.Arg. var. *nitida*	55																			0.001
Burkea africana Hook.	55																			0.001
Monotes africanus A.DC.	41																			0.001
Bridelia mollis Hutch.	41																			0.01
Pterocarpus angolensis DC.	31																			0.01
Community 2: *Julbernardia paniculata - Brachystegia spiciformis* woodlands																				
Julbernardia paniculata (Benth.) Troupin		92														100	97	92		0.001
Brachystegia spiciformis Benth.		82																		0.001
Bobgunnia madagascariensis (Desv.) J.H.Kirkbr. &		49																		0.01

Wiersema						
Uapaca kirkiana Müll.Arg.	44					0.001
Syzygium guineense (Willd.) DC. subsp. *guineense*	51					0.001
Faurea rochetiana (A.Rich.) Chiov. ex Pic.Serm.	36					0.001
Combretum collinum Fresen	36				36	0.01
Community 3: *Brachystegia longifolia - Diospyros kirkii* woodlands						
Brachystegia longifolia Benth.		100				0.001
Diospyros kirkii Hiern		66				0.001
Pseudolachnostylis maprouneifolia Pax var. *dekindtii* (Pax) Radcl.-Sm.		62				0.001
Dombeya rotundifolia (Hochst.) Planch.		59				0.001
Ekebergia benguellensis Welw. ex C.DC.		45				0.001
Bridelia micrantha (Hochst.) Baill. var. *micrantha*		38				0.001
Cussonia angolensis (Seem.) Hiern		31				0.001
Vitex madiensis Oliv. subsp. *madiensis*		31				0.001
Bobgunnia madagascariensis (Desv.) J.H.Kirkbr. & Wiersema		72				0.001
Community 4: *Combretum collinum - Pericopsis angolensis* woodlands						
Combretum collinum Fresen			86			0.001
Pericopsis angolensis (Baker) Meeuwen forma *angolensis*			69			0.001
Diplorhynchus condylocarpon (Müll.Arg.) Pichon			63			0.001
Baphia bequaertii De Wild.			55			0.001
Bridelia mollis Hutch.			51			0.001
Combretum zeyheri Sond.			47			0.001
Phyllanthus reticulatus Poir. var. *glaber* (Thwaites) Müll.Arg.			47			0.001
Rothmannia engleriana (K.Schum.) Keay var. *engleriana*			41			0.001
Community 5: *Julbernardia paniculata - Diplorhynchus condylocarpon* woodlands						
Julbernardia paniculata Benth.				97		0.001

Diplorhynchus condylocarpon (Müll.Arg.) Pichon	83									0.001
Pseudolachnostylis maprouneifolia Pax var. *dekindtii* (Pax) Radcl.-Sm.	57									0.01
Brachystegia boehmii Taub.	51									0.01
Diospyros kirkii Hiern	49									0.001
Community 6: *Julbernardia paniculata - Combretum collinum* woodlands										
Julbernardia paniculata Benth.		92								0.001
Combretum collinum Fresen		36								0.001
Community 7: *Brachystegia spiciformis - Pteleopsis anisoptera* woodlands										
Brachystegia spiciformis Benth.			100							0.001
Pteleopsis anisoptera (Welw. ex M.A.Lawson) Engl. & Diels			58							0.01
Julbernardia paniculata Benth.			31							0.001
Community 8: *Julbernardia paniculata - Burkea africana* woodlands										
Burkea Africana Hook.				50						0.001
Julbernardia paniculata Benth.				30						0.001
***Community 9: Hexalobus monopetalus - Pteleopsis anisoptera* woodlands**										
Hexalobus monopetalus (A.Rich.) Engl. & Diels					42					0.001
Pteleopsis anisoptera (Welw. ex M.A.Lawson) Engl. & Diels					33					0.01
Commiphora mollis (Oliv.) Engl.					31					0.001
Community 10: *Baikiaea plurijuga - Baphia massaiensis* ssp. *obovata* woodlands										
Baikiaea plurijuga Harms						100				0.001
Baphia massaiensis Taub. subsp. *obovata* (Schinz) Brummitt						63				0.001
Community 11: *Baphia massaiensis* ssp. *obovata - Terminalia sericea* woodlands										
Baphia massaiensis Taub. subsp. *obovata* (Schinz) Brummitt							80			0.001
Terminalia sericea Burch. ex DC.							70			0.001
Community 12: *Colophospermum mopane - Spirostachys africana* woodlands										
Colophospermum mopane (J.Kirk ex Benth.) J.Léonard								90	84	0.001

Spirostachys Africana Sond.	62				0.001
Terminalia prunioides Burch. ex DC.	62			42	0.001
Acacia nilotica (L.) Willd. ex Delile subsp. *kraussiana* (Benth.) Brenan	45				0.001
Community 13: *Colophospermum mopane - Pterocarpus lucens* ssp. *antunesii* woodlands					
Colophospermum mopane (J.Kirk ex Benth.) J.Léonard		84			0.001
Acacia nilotica (L.) Willd. ex Delile subsp. *kraussiana* (Benth.) Brenan		58			0.001
Commiphora mollis (Oliv.) Engl.		53			0.001
Kirkia acuminate Oliv.		53			0.001
Pterocarpus lucens Lepr. ex Guill. & Perr. subsp. *antunesii* (Taub.) Rojo		42			0.001
Commiphora angolensis Engl.		37			0.001
Croton mubango Müll.Arg.		32			0.01

Appendix 5: List of species collected during the field survey in Cusseque and Caiundo study areas.

Botanical family, Species name (Col. No.)

Acanthaceae: *Barleria eburnea* I.Darbysh. ined. (FM1011)
Acanthaceae: *Monechma virgultorum* S.Moore (FM898)
Acanthaceae: *Phaulopsis* cf. *marceloi* Manktelow (FM1005)
Acanthaceae: *Strobilanthopsis linifolia* (C.B.Clarke) Milne-Redh. (FM966)
Anacardiaceae: *Lannea discolor* (Sond.) Engl. (FM1366)
Anacardiaceae: *Rhus gracilipes* Exell (FM961)
Anacardiaceae: *Rhus kirkii* Oliv. (FM989)
Anacardiaceae: *Rhus* sp. 1 (FM1040)
Anacardiaceae: *Rhus* sp. 2 (FM990)
Anacardiaceae: *Rhus* sp. (FM1414)
Anisophylleaceae: *Anisophyllea boehmii* Engl. (FM899)
Annonaceae: *Hexalobus monopetalus* (A.Rich.) Engl. & Diels (FM1358)
Annonaceae: *Xylopia tomentosa* Exell (FM901)
Apocynaceae: *Landolphia camptoloba* (K.Schum.) Pichon (FM897)
Asparagaceae: *Chlorophytum* sp. (FM1408)
Balanophoraceae: *Thonningia sanguinea* Vahl. (FM951)
Boraginacaea: [e]*Cystostemon hispidissimus* (S.Moore) A.G.Mill. & Riedl. subsp. *hispidissimus* (FM1032)
Campanulaceae: *Wahlenbergia* sp. (FM1061)
Caryophyllaceae: [e]*Dianthus angolensis* Hiern ex F.N.Williams subsp. *angolensis* (FM975)
Clusiaceae: *Garcinia huillensis* Welw. ex Oliv. [or possibly *G. buchneri* if pyrophyte] (FM1060)
Colchicaceae: *Gloriosa superba* L. (FM1020)
Combretaceae: *Combretum collinum* Fresen. (FM960)
Combretaceae: *Combretum schumannii* Engl. (FM924)
Combretaceae: *Combretum zeyheri* Sond. (FM1380)
Combretaceae: *Pteleopsis anisoptera* (Welw. ex M. A. Lawson) Engl. & Diels (FM936)
Commelinaceae: *Commelina africana* L. var. a*fricana* (FM1001)
Compositae: *Psiadia* sp. (FM1361)
Compositae: *Bidens flabellata* O. Hoffm. (FM948)
Compositae: *Crassocephalum rubens*(Juss. ex Jacq.) S. Moore var. *sarcobasis* (DC.) C. Jeffrey & Beentje (FM1015)
Compositae: *Elephantopus mollis* Kunth. (FM923)
Compositae: *Felicia welwitschii* (Hiern) Grau (FM974)
Compositae: *Helichrysum* sp. (FM947)
Compositae: *Laggera brevipes* Oliv. & Hiern (FM1028)
Compositae: *Macledium poggei* (O.Hoffm.) S.Ortíz (FM982)
Compositae: *Pleiotaxis huillensis* O.Hoffm. subsp. *argentea* (M. Taylor) S. Ortiz & Rodr. Oubiña (FM1016)
Compositae: *Pleiotaxis rugosa* O.Hoffm. (FM1053)
Compositae: *Schistostephium crataegifolium* (DC.) Fenzl ex Harv. (FM971)
Compositae: *Vernonia bullulata* S.Moore (FM968)
Compositae: *Vernonia incompta* S.Moore (FM1017)
Compositae: *Vernonia melleri* Oliv. & Hiern var. *melleri* (FM956)

Compositae: *Vernonia subplumosa* O.Hoffm. (FM925)

Convolvulaceae: *Ipomoea* sp. (FM985)

Dennstaedtiaceae: *Pteridium aquilinum* (L.) Kuhn subsp. *centrali-africanum* Hieron. ex R.E.Fr. (FM945)

Dipterocarpaceae: *Monotes dasyanthus* Gilg. (FM1033)

Dipterocarpaceae: *Monotes glaber* Sprague (FM941)

Dipterocarpaceae: *Monotes* sp. (FM902)

Ebenaceae: *Diospyros batocana* Hiern (FM1377)

Ebenaceae: *Diospyros chamaethamnus* Mildbr. (FM1367)

Ebenaceae: *Diospyros pseudomespilus* Mildbr. subsp. *brevicalyx* F.White (FM1411)

Ebenaceae: *Diospyros virgata* (Gürke) Brenan (FM963)

Ericaceae: *Erica benguellensis*(Welw. ex Engl.) E.G.H. Oliv. (FM1051)

Euphorbiaceae: *Maprounea africana* Müll. Arg. (FM1023)

Euphorbiaceae: *Schinziophyton rautanenii* (Schinz.) Radcl. -Sm (FM1360)

Euphorbiaceae: *Sclerocroton oblongifolius* (Müll. Arg.) Kruijt & Roebers (FM958)

Fabaceae: *Albizia antunesiana* Harms (FM1392)

Fabaceae: *Albizia* sp. 1 (FM903)

Fabaceae: *Albizia* sp. 2 (FM935)

Fabaceae: *Baphia bequaertii* De Wild. (FM927)

Fabaceae: *Bauhinia urbaniana* Schinz (FM1018)

Fabaceae: *Bobgunnia madagascariensis* (Desv.) J.H.Kirkbr. & Wiersema (FM913)

Fabaceae: *Brachystegia bakeriana* Hutch. & Burtt Davy (FM900)

Fabaceae: *Brachystegia* cf. *longifolia* Benth. (FM944)

Fabaceae: *Copaifera baumiana* Harms (FM1031)

Fabaceae: *Crotalaria amoena* Welw. ex Baker (FM972)

Fabaceae: *Crotalaria angulicaulis* Harms (FM954)

Fabaceae: *Crotalaria cistoides* Welw. ex Baker (FM1059)

Fabaceae: *Crotalaria florida* Welw. ex Baker (FM1007)

Fabaceae: *Crotalaria* sp. (FM920)

Fabaceae: *Crotalaria tenuirama* Welw. ex Baker (FM973)

Fabaceae: *Cryptosepalum exfoliatum* De Wild. subsp. *pseudotaxus* (Baker f.) P.A.Duvign. & Brenan (FM906)

Fabaceae: *Dalbergia nitidula* Welw. ex Baker (FM997)

Fabaceae: *Dialium englerianum* Henriq. (FM915)

Fabaceae: *Guibourtia coleosperma* (Benth.) J.Léonard (FM928)

Fabaceae: *Humularia welwitschii* (Taub.) P.A.Duvign. (FM983)

Fabaceae: *Indigofera congesta* Welw. ex Baker (FM1036)

Fabaceae: *Indigofera subulifera* Welw. ex Baker var. *subulifera* (FM1043)

Fabaceae: *Kotschya strobilantha* (Welw. ex Baker) Dewit & P.A. Duvign. var. *strobilantha* (FM981)

Fabaceae: *Pericopsis angolensis* (Baker) Meeuwen (FM998)

Fabaceae: *Philenoptera nelsii (*Schinz.) Schrire (FM1355)

Fabaceae: *Pterocarpus angolensis* DC. (FM1412)

Fabaceae: *Rhynchosia procurrens* (Hiern) K.Schum. subsp. *procurrens* (FM957)

Gentianacaeae: *Chironia palustris* subsp. t*ransvaalensis* (Gilg) Verd. (FM1378)

Graminae: *Eragrostis chapelieri* (Kunth.) Nees (FM1050)

Graminae: *Eragrostis sclerantha* Neessubsp. *villosipes* (Jedwabn.) Launert (FM1049)

Graminae: *Loudetia angolensis* C.E.Hubb. (FM930)

Graminae: *Sporobolus sanguineus* Rendle (FM952)
Graminae: *Ctenium concinnum* Nees (FM1390)
Graminae: *Eragrostis* sp. (FM1416)
Hypericaceae: *Psorospermum baumii* Engl. (FM1009)
Hypericaceae: *Psorospermum febrifugum* Spach. (FM916)
Iridaceae: *Moraea schimperi* (Hochst.) Pic.Serm. (FM1054)
Ixonanthaceae: *Phyllocosmus lemaireanus* (De Wild. & T. Durand) T. Durand & H. Durand (FM909)
Lamiaceae: cf. *Clerodendrum* (FM926)
Lamiaceae: *Plectranthus tenuicaulis* (Hook.f.) J.K.Morton, sensu lato (FM919)
Lamiaceae: *Vitex madiensis* Oliv. subsp. *milanjiensis* (Britten) F.White (FM939)
Laganiaceae: *Strychnos cocculoides* Baker (FM940)
Laganiaceae: *Strychnos mitis* S.Moore (FM1046)
Laganiaceae: *Strychnos pungens* Soler. (FM993)
Malvaceae: *Triumfetta angolensis* Sprague & Hutch. (FM895)
Melastomataceae: *Antherotoma debilis* (Sond.) Jacq.-Fél. (FM912)
Melastomataceae: *Dissotis welwitschii* Cogn. (FM908)
Melastomataceae: *Memecylon flavovirens* Baker (FM1044)
Melastomataceae: [e]*Memecylon huillense* A.Fern. & R.Fern. (FM932)
Melastomataceae: *Warneckea sapinii* (De Wild.) Jacq.-Fél. (FM980)
Meliaceae: *Ekebergia beguellensis* Welw. ex. C.DC. (FM1371)
Menispermaceae: *Cissampelos mucronata* A.Rich. (FM950)
Myrtaceae: *Syzygium guineense* (Willd.) DC. (FM977)
Nymphaeaceae: *Nymphaea nouchali* Burm.f. (FM1363)
Ochnaceae: *Brackenridgea arenaria* (De Wild. & T. Durand) N. Robson (FM979)
Ochnaceae: *Ochna* cf. *serrulata* Walp. (FM1415)
Ochnaceae: *Ochna pulchra* Hook.f. (FM934)
Ochnaceae: *Ochna pygmaea* Hiern (FM949)
Ochnaceae: *Ochna* sp. (FM937)
Oleaceae: *Jasminum dichotomum* Vahl. (FM1388)
Oleaceae: *Jasminum pauciflorum* Benth. (FM1037)
Oleaceae: *Schrebera trichoclada* Welw. (FM1004)
Orobanchaceae: *Sopubia karaguensis* Oliv. var. *macrocalyx* O.J.Hansen (FM914)
Orobanchaceae: *Striga asiatica* (L.) Kuntze (FM999)
Oxalidaceae: *Biophytum helenae* Buscal. & Muschl. (FM931)
Passifloraceae: *Paropsia brazzaeana* Baill. (FM904)
Phyllanthaceae: *Bridelia* sp. (FM959)
Phyllanthaceae: *Hymenocardia acida* Tul. var. *acida* (FM938)
Phyllanthaceae: *Phyllanthus angolensis* Müll. Arg. (FM1058)
Phyllanthaceae: *Phyllanthus* sp. (FM1039)
Phyllanthaceae: *Phyllanthus welwitschianus* Müll. Arg. (FM1000)
Phyllanthaceae: *Pseudolachnostylis maprouneifolia* Pax var. *dekindtii* (Pax) Radcl.-Sm. (FM918)
Phyllanthaceae: *Uapaca* sp. (FM946)
Phyllanthaceae: *Oldfieldia dactylophylla* (Welw. ex Oliv.) J.Léonard (FM978)
Polygalaceae: [e]*Polygalastenopetala* Llotzsch. subsp. *casuarina* (Chodat)Paiva (FM962)
Polygonaceae: *Oxygonum fruticosum* Dammer ex Milne-Redh. (FM933)
Primulaceae: *Myrsine africana* L. (FM907)

Proteaceae: *Faurea intermedia* Engl. & Gilg (FM942)
Ranunculaceae: *Clematis villosa* DC. (FM905)
Rubiaceae: *Rothmannia engleriana* (K.Schum.) Keay var. e*ngleriana* (FM1418)
Rubiaceae: *Rytigynia orbicularis* (K.Schum.) Robyns (FM929)
Rubiaceae: *Tricalysia* sp. (FM1382)
Rubiaceae: *Vangueriopsis lanciflora* (Hiern) Robyns (FM1354)
Rutaceae: *Clausena anisata* (Willd.) Hook.f. ex Benth. var. *anisata* (FM922)
Santalaceae: *Thesium* sp. (FM988)
Sapotaceae: *Chrysophyllum bangweolense* R.E.Fr. (FM1379)
Sapotaceae: *Englerophytum magalismontanum* (Sond.) T.D.Penn. (FM917)
Smilacaceae: *Smilax anceps* L. (FM1030)
Thymelaeaceae: *Craterosiphon quarrei* Staner (FM967)
Thymelaeaceae: *Gnidia capitata* (L.f.) Burtt. Davy (FM911)
Umbelliferae: *Diplolophium zambesianum* Hiern (FM910)
Zingiberaceae: *Aframomum alboviolaceum* (Ridl.) K.Schum. (FM955)

Appendix 6: Questionnaire addressed to the charcoal producers in the study area (Adapted from: Herd, 2007).

CHARCOAL PRODUCERS QUESTIONNAIRE

Date:......./........./...........

Name:..Sex: M / F; Age: (Year of birth):..................;

Locality:

(village):..................................GPS Location: S............................E..........................Elevation (m)...........;

PART I: LIVELIHOOD QUESTIONS

1. Municipality…………………………Where were you born?……………………..What year did you arrive?…………What your reason to coming?..................Marital status? S (single)………....M (married)……....D (divorced/separated)…..…...W(widower/widow)...……

2. Do you have children? Y / N; How many? Female……….Male………..Did you go to school? Y / N; Up to what level?...........Are you employed? Y / N, if yes which income bracket do you fall (AOA)?

0 - 5.000.............; 5.000 - 10.000..............; 10.000 - 15.000..............; 15.000 -20.000..............;

20.000 - 25.000.............; 25.000 - 30.000.............; 30.000 - 35.000.............; > 35.000.............;

3. Do you have a crop field (lavra) Y /N;How many crop fields do you have?..........................;

4. What crops do you cultivate in your field?

Maize.............; Cassava.............; Groundnut.............; Beans.............; Sorghum.............; Pumpkin.............; Potato.............; Others.............;

5. Do you have enough to eat? Y / N; Do you have to buy food? Y / N; Do you hunt? Y / N; Do you fish? Y / N; Do you use the forest products? Y / N; If so what are your preferred products?

Forest product (1).............; Forest product (2).............; Forest product (3).............; Others..;

6. Do you sell some cultivated products? Y / N.

Maize.............; Beans.............; Cassava.............; Others..;

7. When do you work your field?...................When do you make charcoal?..........................Do you have any savings? Y / N. In crisis where do you get money help?

Family.............; Friends.............; cultivated products selling.............; charcoal seeling.............;

CHARCOAL PRODUCTION QUESTIONNAIRE

Date:......./........./...........

Name:...Sex: M / F; Age: (Year of birth):..................;

Locality:

(village):...................................GPS Location: S.............................E..........................Elevation (m)...........;

PART II: CHARCOAL QUESTIONS

1. Local of Kiln?..; Stage of construction?...................................;

Size of kiln; Lenght (m).............; Width (m).............; Height (m).............;

2. What are the tree species in your kiln?

Tree species (1).............; Tree species (2).............; Tree species (3).............; Tree species (4).............; Others tree species...;

3. What are your preferred tree species for charcoal?

Preferred tree sp. (1).............; Preferred tree sp. (2).............; Preferred tree sp. (3).............; Preferred tree sp. (4).............; Other tree species..;

4. How do you select trees for charcoal?

Size....................; Good for charcoal...................; Easy to fell....................; Others...................;

5. Do you fell the trees alone? Y / N; If not, who helps.................................; and how much do you pay (AOA)?.......................;

6. Which trees would you not fell and why?

Tree sp. (1)..............................; Tree sp. (2)..............................;Tree sp. (3)..............................;Tree sp. (4)..............................; Others...;

7. Would you fell these trees if there was no choice? Y / N; How long does it take you to fell (days/weeks)?..............................;

SIZE OF TREES

Largest tree: Circumference (m).............; Tree height (m).............; **Smallest tree:** Circumference (m).............; Tree height (m).............;

9. How many trees per kiln? (count.).......................................Do you own or rent any tools? Y /N. If so, which ones?

Tools owned: Axe.............; Hoe.............; Machete..............; Shovel.............; Rake.............; Others...................;

Tools rented: Axe............. .; Hoe.............; Machete..............; Shovel.............; Rake.............; Others...................;

10. How long did it take you to construct the kiln (days/weeks)?................................How long does the kiln burn for (days/weeks)?..................................;

11. Did your kiln burn well? Y / N; If no, why not?...How long does sorting take?..............................How many bags per kiln you sorted out?....................................;

12. Do you have to buy empty sacks? Y / N. If yes, how much it cost (AOA)?................................;

13. Where do you sell the produced charcoal? Road side.............; Market.............; Who do you sell your charcoal to?..............................;

14. How much do you sell a bag of charcoal (AOA)?............................;How many bags do you sell per day?1 - 5 bags..............; 6 - 10bags.............; more than 10 bags.............;

15. Do you need a license to produce charcoal? Y / N. If yes, do you have one? Y / N; If yes what is yourLicense No.…………………......or name?……………………;

16. Which is the authority responsible for issuing the license?...............................; How much do you pay for (AOA)?..............................;

17. The authority indicates the area to explore? Y / N................................And treespecies/size to be felled? Y / N..;

18. Are you going to make another kiln? Y / N. If yes, where?……………………………and when?......................................How many kilns do you make per year?.......................................;

19. Do you will use the area for another purpose after charcoal? Y / N; If yes, for which purpose.......................................;

20. In your opinion the trees grows well after charcoal? Y / N. If no why?..................................;

21. In your opinion, what is the current condition of the miombo: Good..............; Bad..............; Worse..............;Why?... do you think so?...;

22. What was the miombo woodland in your village like 10 years ago: Better..............; Same..............; Worse..............;

23. Why it was better or worse?..;

ADDITIONAL COMMENTS:

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End of questionnaire, thank you!

Appendix 7: Different fallow stand stage in the study areas. Top to bottom, left to right: young fallow, medium-aged fallow, old fallow and mature stand forestin Cusseque, and Caiundo as found in the dry season: fallow (left) and mature stand (right) with deciduous trees of *Pterocarpus angolensis* DC and *Schinziophyton rautanenii*(Schinz) Radcl.-Sm. (Photos: F.Gonçalves).

Declaration of oath

I hereby declare on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

Eidesstattliche Versicherung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Hamburg, den **Unterschrift**

___/___/______ ________________

English Proofreading Declaration

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1st August 2018

Re: Ph.D Thesis by Francisco Maiato Pedro Gonçalves

To whom it may concern,

As a native English speaker and experienced proof-reader, I do hereby declare that the Ph.D thesis "**Effect of shifting cultivation and charcoal production on structure, dynamic and above-ground biomass in the Angolan miombo and dry woodlands**" has been written in concise and correct UK English.

Yours sincerely,
John L. Godlee

JLG

English Proof-reader, Ph.D. Student, School of Geociences, University of Edinburgh, UK.